Migration patterns of acoustic scatterers in the southern Baltic Sea

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Diurnal migration
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Joanna Szczucka,
Zygmunt Klusek
Institute of Oceanology,
Polish Academy of Sciences,
Sopot

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Abstract

Echosounding records made at a fixed point of the Gdańsk Deep at different seasons (spring, summer, autumn, winter) were used to determine the seasonal and diurnal migration patterns of plankton layers in connection with thermohaline conditions. Apart from some seasonal differences, a major, common pattern of vertical migrations at sunrise and sunset was observed. The width and scattering strength of the layer formed at night in the water column depends on the temperature gradient in the thermocline. The differences in the total energy backscattered by biological aggregations at different frequencies allow inferences to be drawn about the dominant size of scatterers.

1. Introduction

Hydroacoustic methods based on the backscattering of acoustic energy in seawater are widely applied in oceanic investigations, especially in the assessment of fish abundance, and provide a high recording speed and high resolution in a two-dimensional field. They offer two advantages over conventional net sampling: a greater volume of sampled water and a continuous, two-dimensional record. These techniques are relatively nonintrusive and can provide data in near-real time. Up till now echosounding has been little used in the Baltic Sea to measure plankton distribution, or to observe its diurnal migrations and seasonal changes.

At ultrasonic frequencies, a significant part of the volume scattering is biological in origin (Anderson and Zahuranec, 1977; Greene *et al.*, 1989).

A significant fraction of the acoustic echo is associated with large zooplankton and micronekton, which exhibit striking variations in spatial and temporal distribution, due in part to behavioural activities such as diel migration and social aggregations, and partly to mesoscale processes in the physical environment. This results in temporal changes in the acoustic volume backscattering of different scales – from daily through seasonal to interannual. The biological and physical factors affecting the acoustic echo levels in many areas – coastal regions in particular – are not well understood. Complicating the situation is a basic problem in bioacoustics: to what extent is volume reverberation due to backscattering by organisms, and to what extent by the physical microstructure of the ocean? This is obviously a serious problem from the biological point of view, and also a problem for physical oceanographers using acoustics to visualise strong gradients and flow fields. The first acoustic measurements of volume reverberation in the Baltic Sea (Klusek and Szczucka, 1984; Krauss *et al.*, 1973; Lenz, 1965) suggested the step-like density structure as a reason for the acoustic backscattering from the water column. Further confirmation of this hypothesis was the lack of any correlation between the acoustic data and the amount of detritus and plankton found in the same location (Krauss *et al.*, 1973; Lenz, 1965). Nevertheless, in some seasons and during some hours at the thermo- and halocline depth, there persist aggregations of small marine organisms recorded in the lower ultrasound frequency range. Although the individual planktonic organisms are too small to be detected at these frequencies, the overlapping echoes from a dense population combine to produce signals comparable to those from bigger objects. Owing to resonance, any gas-bubble-carrying plankter can have a profound sound scattering effect, regardless of its small size. Since plankton are drifters, one would expect their distributions to be controlled to a large extent by oceanographic conditions.This implies that their distribution is determined by the motion of the water and that they are incapable of independent horizontal movement to other areas. They thus move horizontally with the sea currents and vertically with the light intensity, rising at night and falling during the day. In accordance with bioacoustic practice, the term zooplankton in this paper will be used for both zooplankton and micronekton (Greene *et al.*, 1989).

A large number of relationships found for oceanic waters are by no means valid for the Baltic Sea, although some of them differ only in scale. The determination of the typical Baltic features of scattering layers and their comparison with commonly accepted oceanic characteristics was one of the reasons for the acoustic investigation of this particular area. The main objective of this research was to record scattering layers in different seasons, recognise diurnal vertical migration patterns and find the relationship between the acoustically-detected plankton layers and the structure of the thermohaline field in Baltic Sea waters. Some statistical parameters, like the centre of gravity, the normalised moment of inertia and the integrated backscattered energy, have been introduced in order to classify different forms of scatterer aggregations and their migratory habits.

2. Experimental; 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 of the years 1991–1995. Station P116, located in the Gdańsk Deep ($\phi = 54°40'$N, $\lambda = 19°20'$E), was selected as the fixed point for the seasonal observations of the plankton migration patterns. The maximum depth at that station was 90 m. An ELAC 4700 echosounder with LHZ 135 transducer sounding vertically at a frequency of 30 kHz was used. A pulse length of 1 ms and trigger rate of 1 s were established. During winter cruises (February and March 1995) an additional echosounder was used, working at a frequency of 210 kHz and a pulse length of 0.3 ms and 1 s trigger rate. The echo envelope was sampled with a frequency of 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 enabled echograms to be retrieved during data processing. Simultaneous CTD sampling was also done. Unfortunately, species could not be identified as no net samples were taken during the acoustic measurements.

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

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

where

U_i – voltages of successive samples,
SL – source level,
VR – voltage response,
G – receiver gain,
DI – directivity index.

SL, VR and DI are calibration values that are constants for any given transceiver. In order to compensate for the geometrical spreading of the acoustic beam and absorption loss in the seawater, the standard time-varied gain was used

$$TVG = 20 \log R + 2\alpha R,$$

where R is the one-way distance, and α is the absorption coefficient expressed in dB/m.

The following parameters of the averaged backscattered signals were examined:

- the depth of the centre of gravity
  $z_{gc} = \Sigma_{i=1}^{N} U_i^2 z_i / \Sigma_{i=1}^{N} U_i^2$
- the normalised moment of inertia
  $I = \Sigma_{i=1}^{N} U_i^2 (z_i - z_{gc})^2 / \Sigma_{i=1}^{N} U_i^2$
- the total backscattered energy
  $E = \Sigma_{i=1}^{N} U_i^2 / k_U$
- the profile variance
  $\sigma = \Sigma_{i=1}^{N} U_i^2 / N - \left(\Sigma_{i=1}^{N} U_i / N \right)^2 ,$

where

N – the number of samples in the ping,
U_i – the averaged voltage of the i th sample,
z_i – the depth related to the i th sample,
k_U – the electrical gain ($G = 10 \log k_U$).

The depth of the centre of gravity is the depth where the maximum backscattered energy is concentrated. Both the variance and the normalised moment of inertia are measures of the dispersivity of the scatterers in the water column. The value of I is close to unity and σ is large when the scatterers are concentrated in a distinct, narrow layer. On the other hand, when they are dispersed throughout the water column the variance falls to a minimum and the moment of inertia increases. The total (integrated) backscattered energy is a parameter enabling the absolute values of energy backscattered from the whole water column to be compared at different moments of observation.

3. Results

Multiseasonal observations of the scattering layers in the Baltic Sea lead to the general conclusion that a common pattern of diel (24-hour cycle) migration exists that is independent of season. 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 colour scale represents backscattering strengths: the greater the echo intensity, the warmer the colour.

Typical diurnal variations of the sound-scattering patterns in the Baltic Sea, with visible vertical migrations in the morning and evening observed

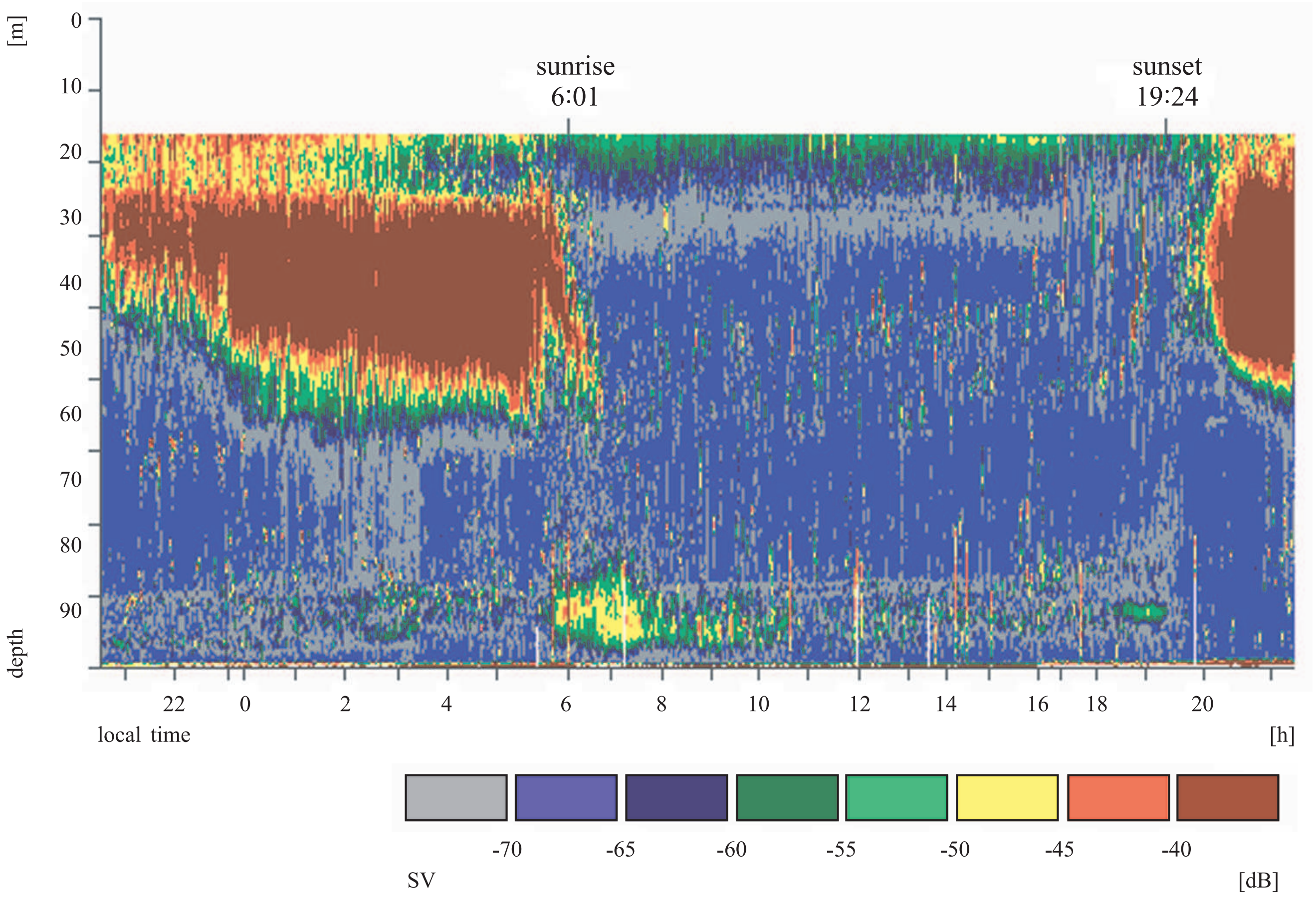

Fig. 1. Condensed echogram prepared on the basis of 26-hour acoustic sounding at station P116 in September 1994 (frequency 30 kHz)

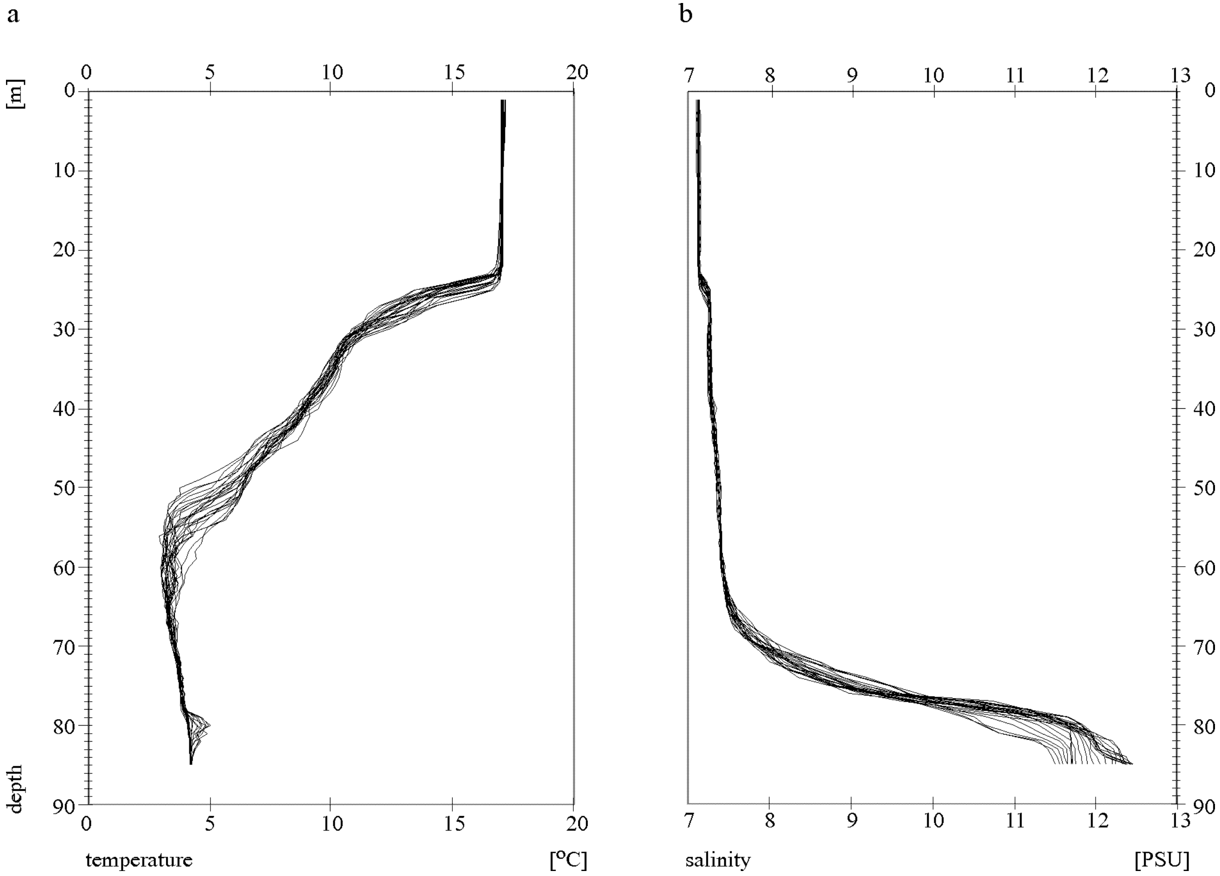

Fig. 2. Consecutive vertical profiles of temperature (a) and salinity (b) measured at 1-hour intervals at station P116 in September 1994

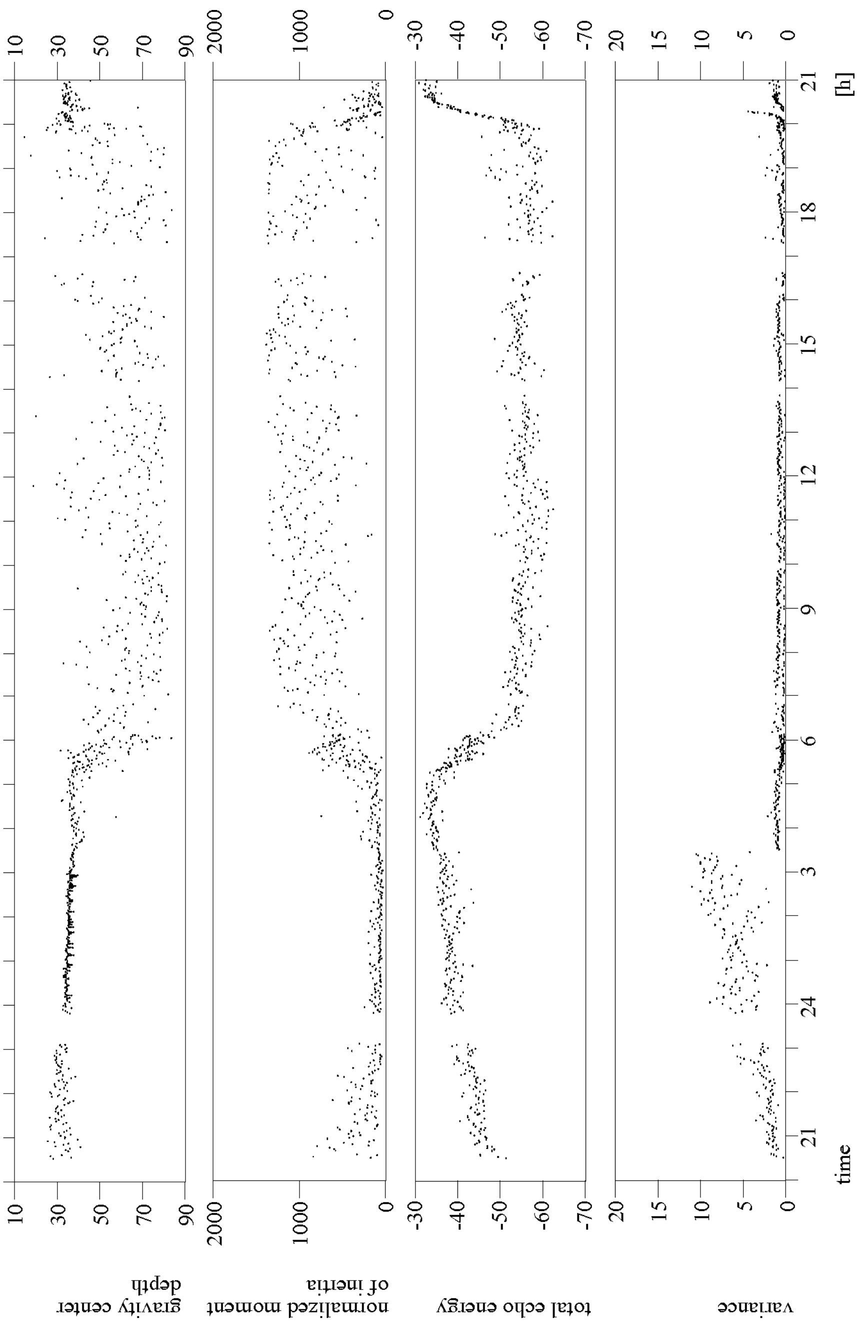

Fig. 3. Depth of the centre of gravity, normalised moment of inertia, integrated backscattered energy and variance for the multihour records at station P116 in September 1994

in September 1994, are shown in Fig. 1. In this illustration the subsurface 12 m layer with strong scattering from gas bubbles as well as the sub-bottom layers have been cut off for clarity. This echogram can be compared with the TS diagram. Fig. 2 displays 26 overlapping vertical temperature and salinity profiles recorded at hourly intervals at the same time as acoustic sounding. As in every season, the nocturnal convergence of plankton in the subsurface layer can be seen. At night there is a uniform, dense layer of plankton close to the sea surface down to the depth of the thermocline. Immediately after sunrise downward migration takes place, and the depth of the centre of gravity drops simultaneously. In the different seasons this migration starts at different times in accordance with the sunrise and sunset times, but intensive migration is always closely connected with these moments and is very short-lived (a few minutes). As the sun sets, a change in the distribution is noted – the organisms migrate upwards and the near-bottom layer of scatterers associated with the halocline weakens.

The diurnal migration of zooplankton is reflected in the changes in the statistical parameters examined, *i.e.* the depth of the centre of gravity, the normalised moment of inertia, the total backscattered energy and the signal variance. By way of example, all these parameters determined at the multi-hour station in the Gdańsk Deep in September 1994 are presented in Fig. 3. The normalised moment of inertia turned out to be a good parameter, enabling the different forms of scatterer aggregations to be distinguished. It can be seen that low values of the normalised moment of inertia I correspond to a distinct layer of scatterers and conversely, larger values of the moment of inertia are related to scatterers diffused in the water column. It is also interesting to note that the more densely the scatterers are packed, the higher is the total backscattered energy E (most probably due to coherent reflection). This evidently causes the change in the depth of the centre of gravity z_{gc}. At night this is located in a fairly narrow layer close to the sea surface, whereas during the day its values are scattered throughout the water column. After sunrise the total echo energy decreases and the normalised moment of inertia increases, which is further confirmation that the scattering bodies have dispersed.

When there is a strong thermocline, as was the case in late summer 1991, the situation is slightly different. At night a dense, narrow layer of scatterers is present at the thermocline depth only (maximum values of the vertical temperature gradient), whereas the water column above and below is almost empty. During the day the scattering layer becomes much weaker. This case is shown in Figs. 4 and 5. It is very interesting (and mysterious) that the total energy backscattered within the entire water column changes significantly between day and night. It is as if the organisms disappeared

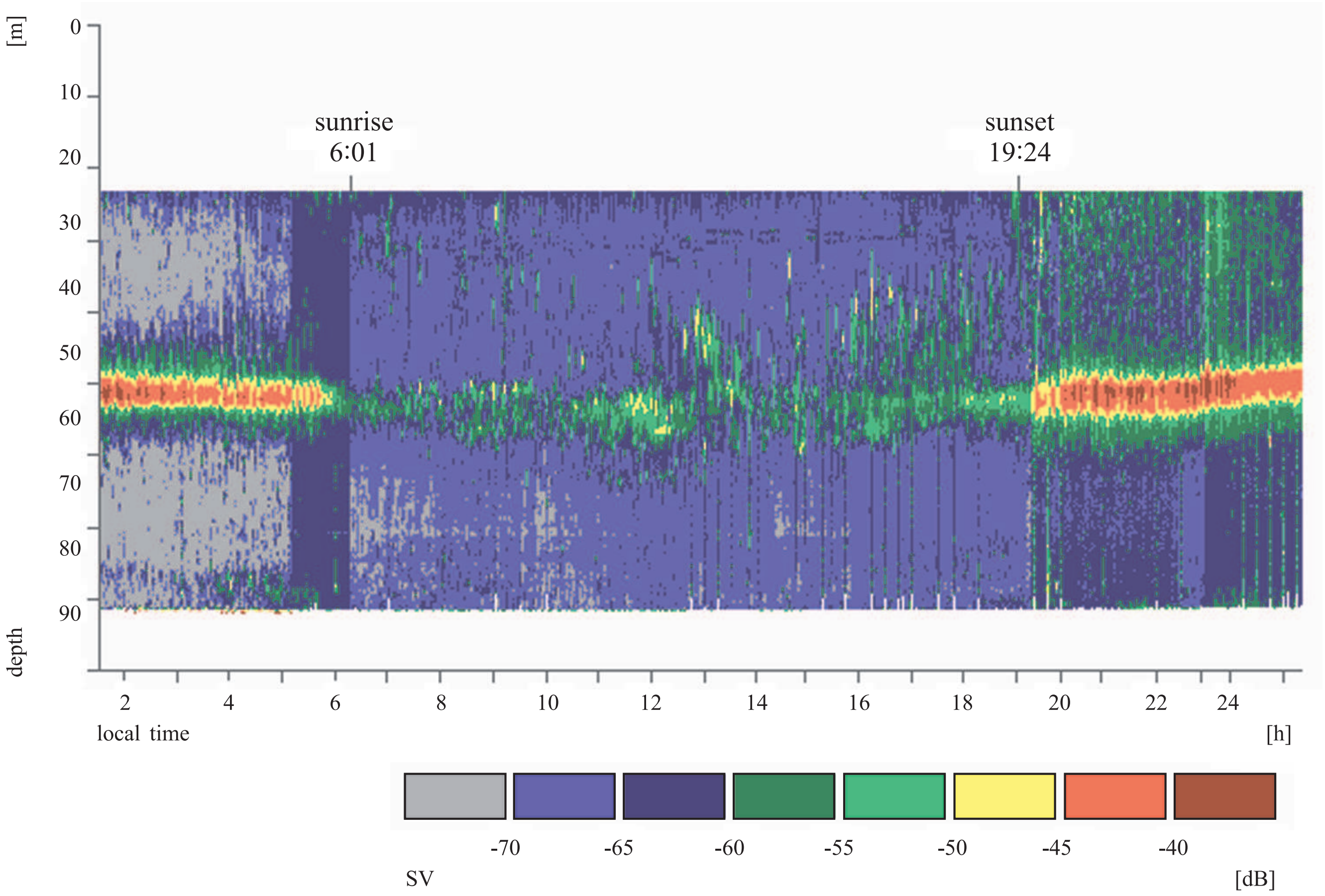

Fig. 4. Condensed echogram prepared on the basis of acoustic sounding at station P116 in September 1991 (frequency 30 kHz)

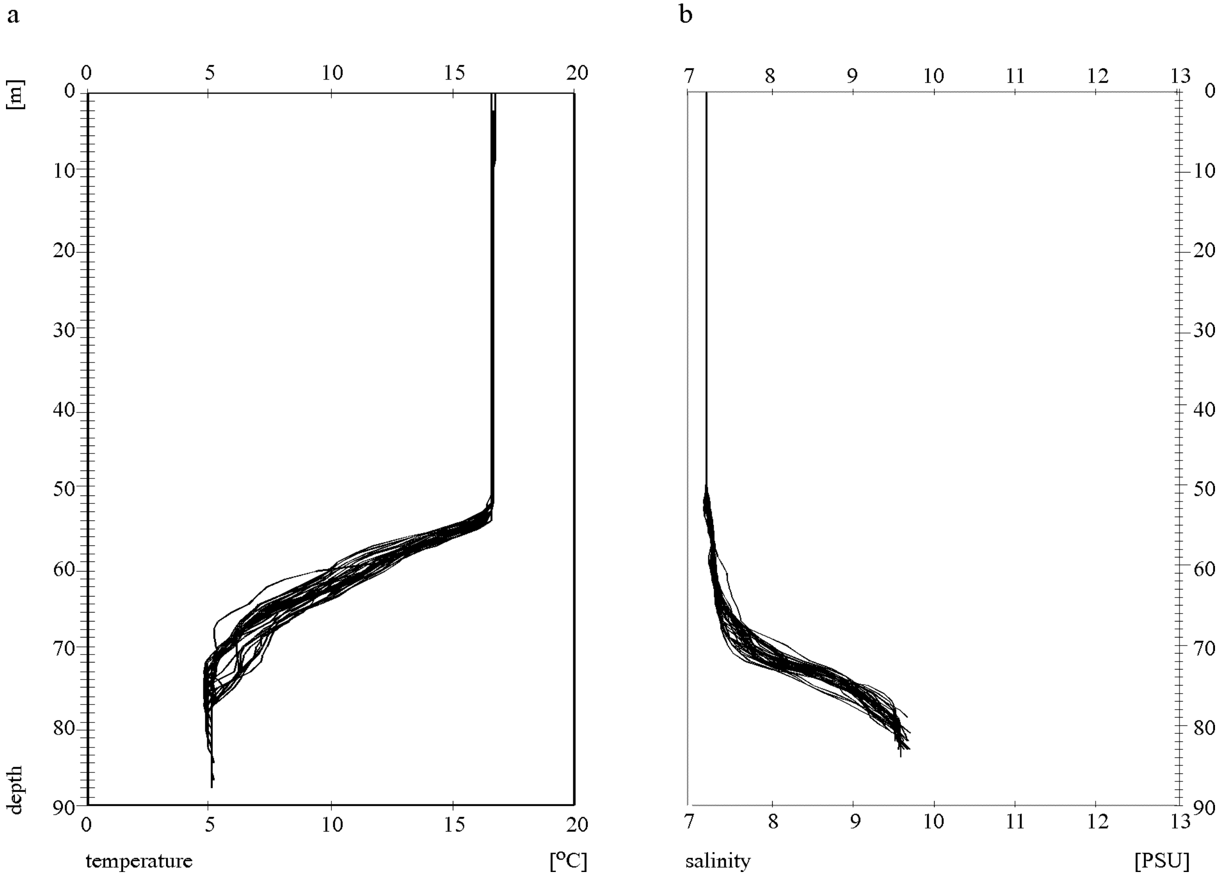

Fig. 5. Consecutive vertical profiles of temperature (a) and salinity (b) measured at 0.5-hour intervals at station P116 in September 1991

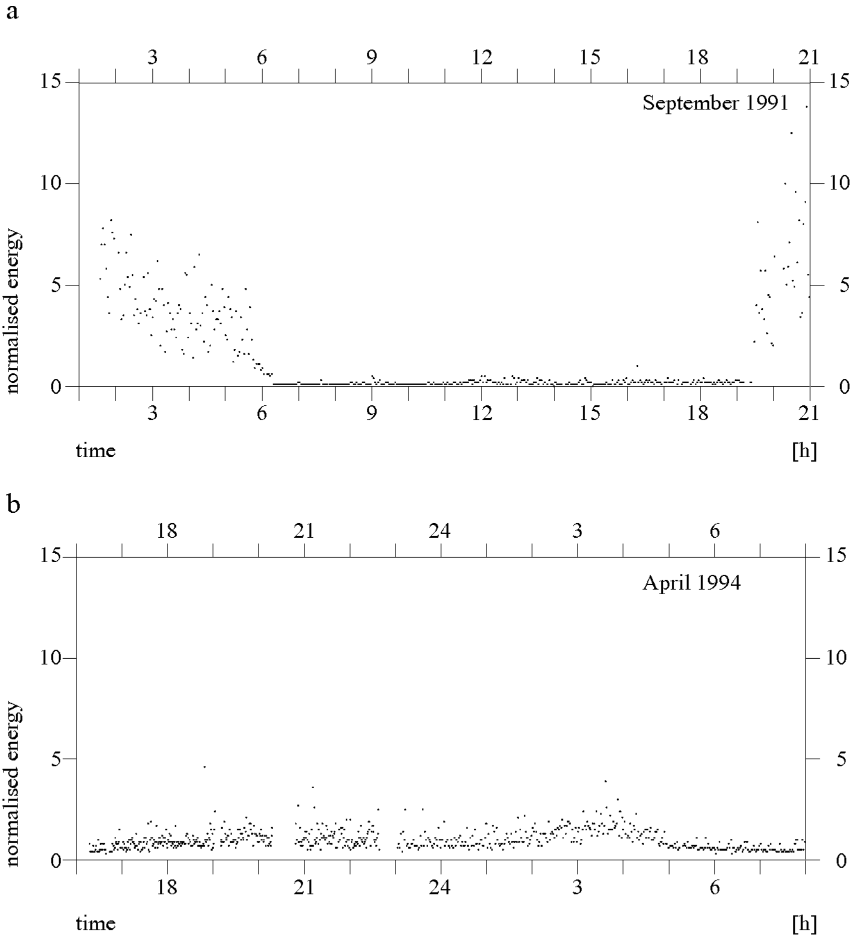

Fig. 6. Temporal dependence of the integrated backscattered energy normalised by the mean integrated ping energy for September 1991 (a) and April 1994 (b)

during the daytime. This is depicted in Fig. 6a, where the total energy of individual pings normalised by the average total ping energy calculated for the September 1991 case is shown. This leakage of echo energy cannot be explained. There may be a variety of reasons for this phenomenon, such as changes in the tilt angle of the organisms, or changes in swimbladder volume influencing the target strength of the individual scatterer. Moreover, coherent scattering may be stronger in very dense aggregations, whereas incoherent scattering is predominant in the case of diffuse objects. Sometimes, the total energy accompanying the rising and setting of the Sun does not change abruptly. This occurs only when there is a strict interchange of scatterers between the upper and lower water layers. Fig. 6b presents such an example recorded in April 1994.

It is important to note that the thermal conditions in the area investigated change significantly from one end of the year to the other. In summer the temperature amplitude within the water column can reach 16°C, while in spring it is no greater than 1°C and in winter it is less than 0.5°C. In autumn the summer thermocline with its steep temperature gradient and temperature amplitude of *ca* 7 °C lingers on. Despite these variations and the different light conditions, similar migration patterns were also recorded in winter. Figs. 7 and 8 show the diurnal behaviour of zooplankton at station P116 in March 1995 and the related temperature-salinity diagrams. There is no thermocline and only a slight halocline, but a strong acoustic contrast between day and night does exist. The morning and evening vertical migrations of the scattering layers take place as usual, and at night the organisms are to be found in the whole of the lower water column, from the bottom to a depth of *ca* 40 m. The development of the average echo profile at dawn and dusk recorded in March 1995 at a frequency of 210 kHz is shown in Fig. 9.

Comparison of the energy backscattered at two different frequencies from the whole water column (Fig. 10) shows a higher level of energy at a higher frequency. This implies that small organisms constitute the predominant proportion of living scatterers. Their equivalent radius is *ca* 1 mm, or even 100 μm, if they contain gas bubbles and resonate with the sound wave.

In October 1993 an opportunity occurred of observing a very interesting phenomenon: this was the passing of the mesoscale front, accompanied by a 20 m change in the position of the thermocline in the space of a few hours. (Szczucka *et al.*, 1994). Fig. 11 shows a 26-hour echogram with simultaneously measured temperature profiles: there is good correlation between the location of the scattering organisms and the depth of the maximum temperature gradient. Echo-producing patches evidently follow the deepening thermocline.

4. Conclusions

Intense vertical migrations of organisms were observed during the investigation of diurnal scattering patterns in the southern Baltic Sea in spring, summer, autumn and winter. During the warm seasons, when there is a well-defined thermocline, the scatterers form a well-marked layer after sunset at or above the thermocline, but this formation disappears during the day. During the cold periods of the year, when the water temperature is uniform, the scatterers occupy the whole lower part of the water column at night, whereas during the day they stay in the vicinity of the halocline.

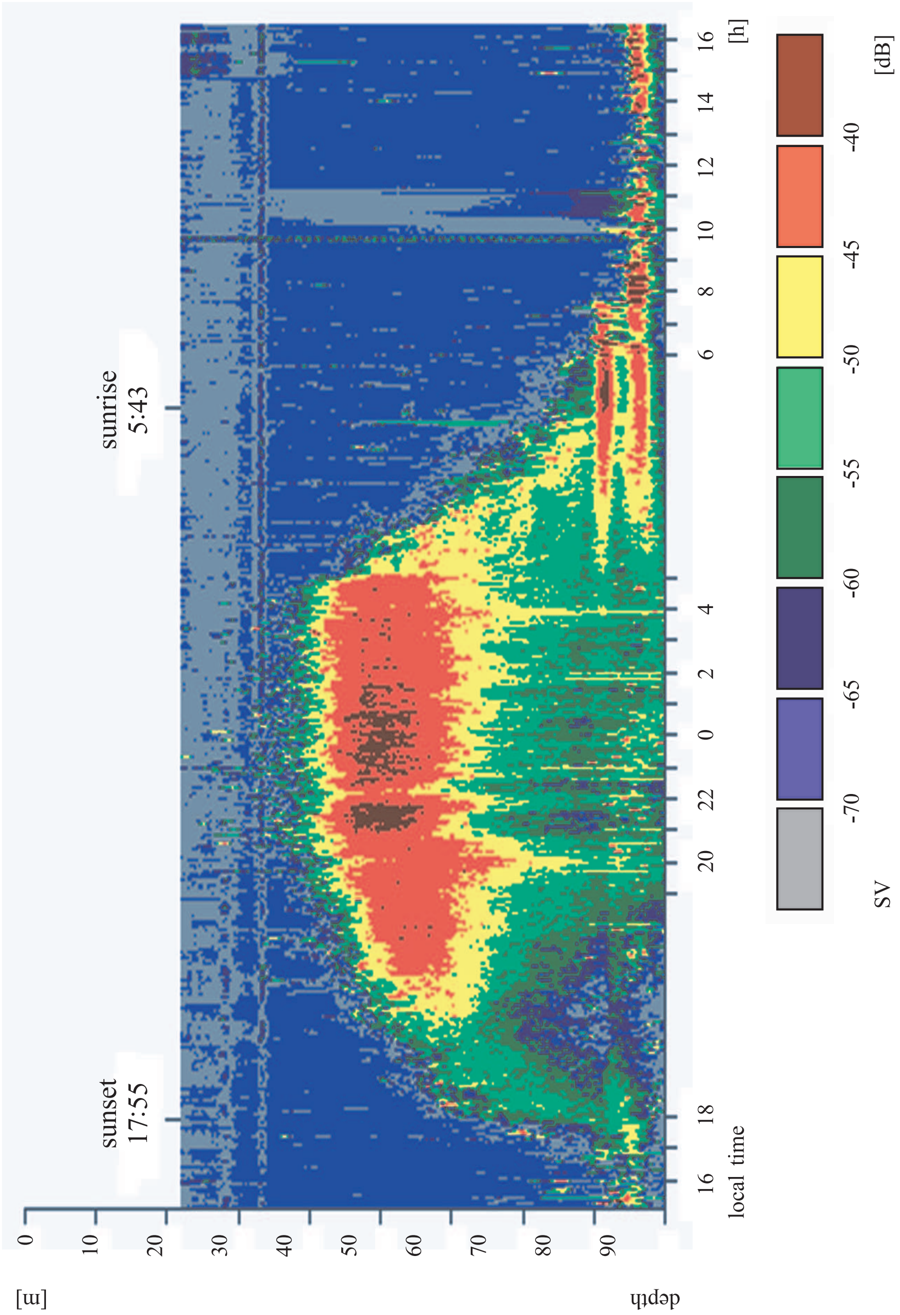

Fig. 7. Condensed echogram prepared on the basis of acoustic sounding at station P116 in March 1995 (frequency 30 kHz)

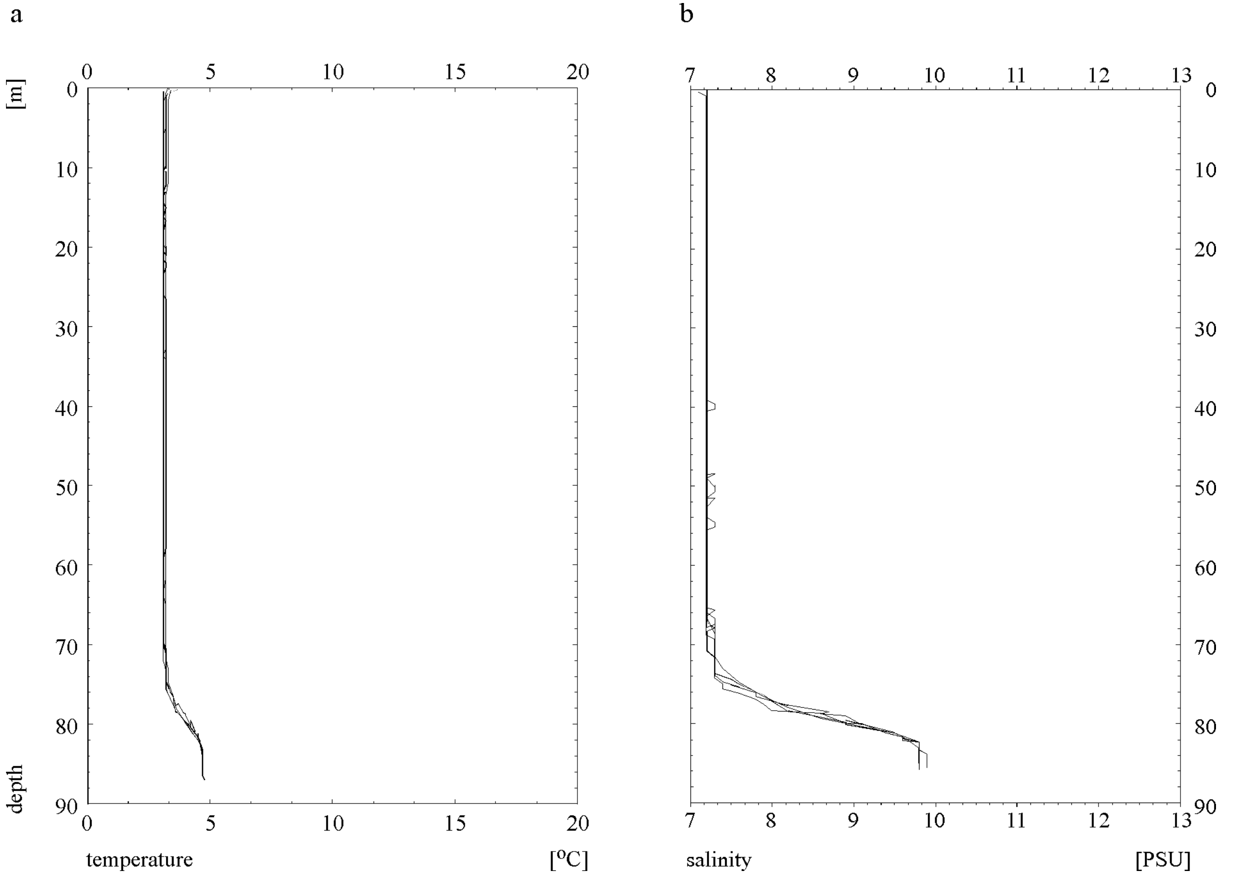

Fig. 8. Consecutive vertical profiles of temperature (a) and salinity (b) measured at station P116 in March 1995

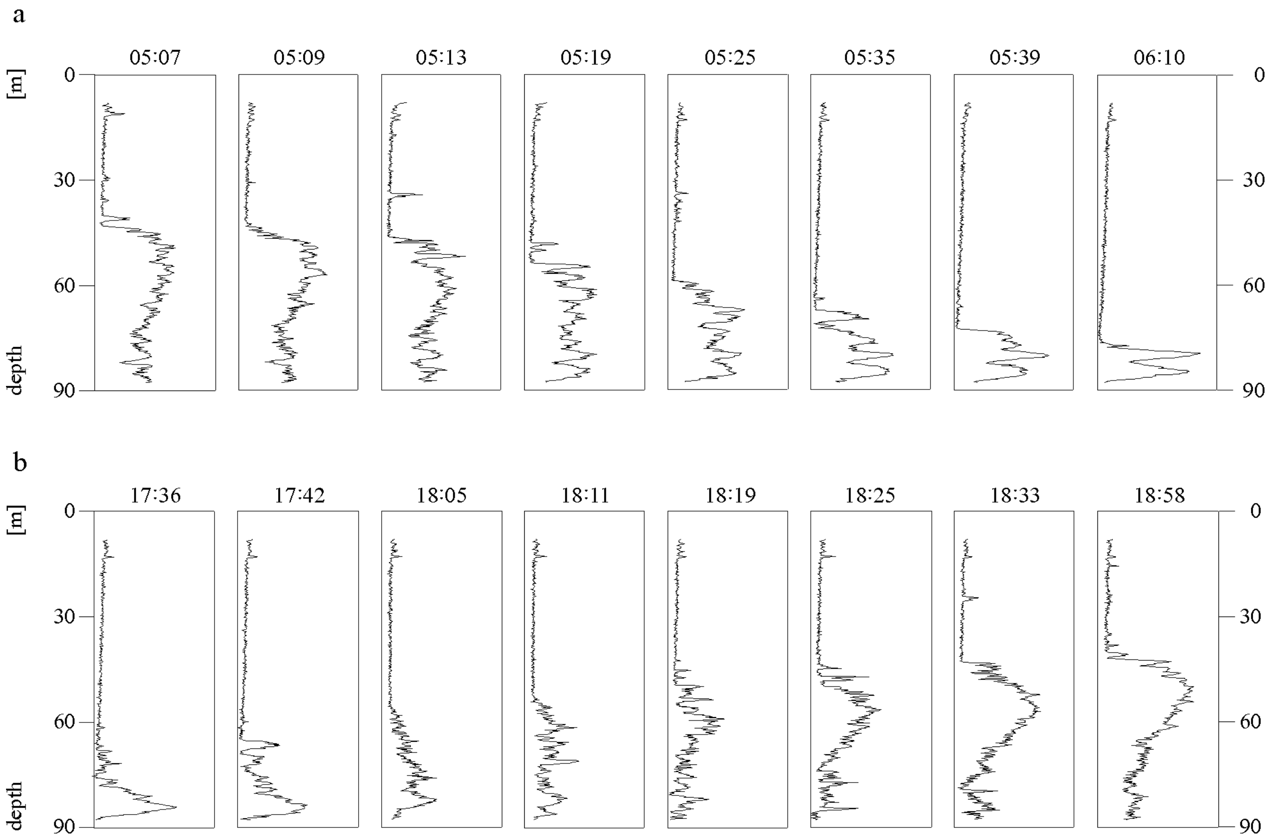

Fig. 9. Time changes of the vertical backscattering strength profile averaged over 64 successive pings: dawn (a), dusk (b); March 1995; frequency 210 kHz. The time of the record is marked at the top of each diagram

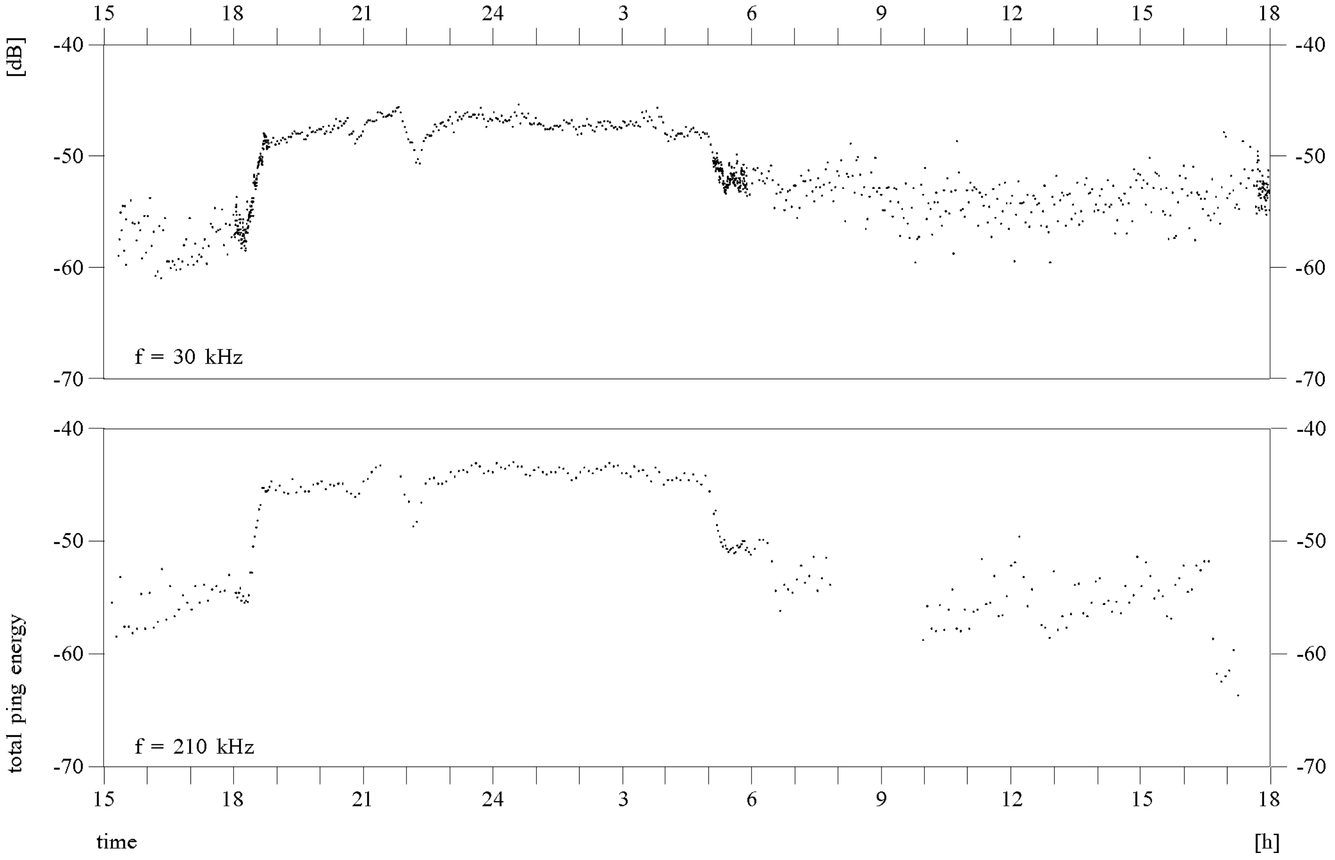

Fig. 10. Integrated backscattered energy for two frequencies *vs.* period of observation

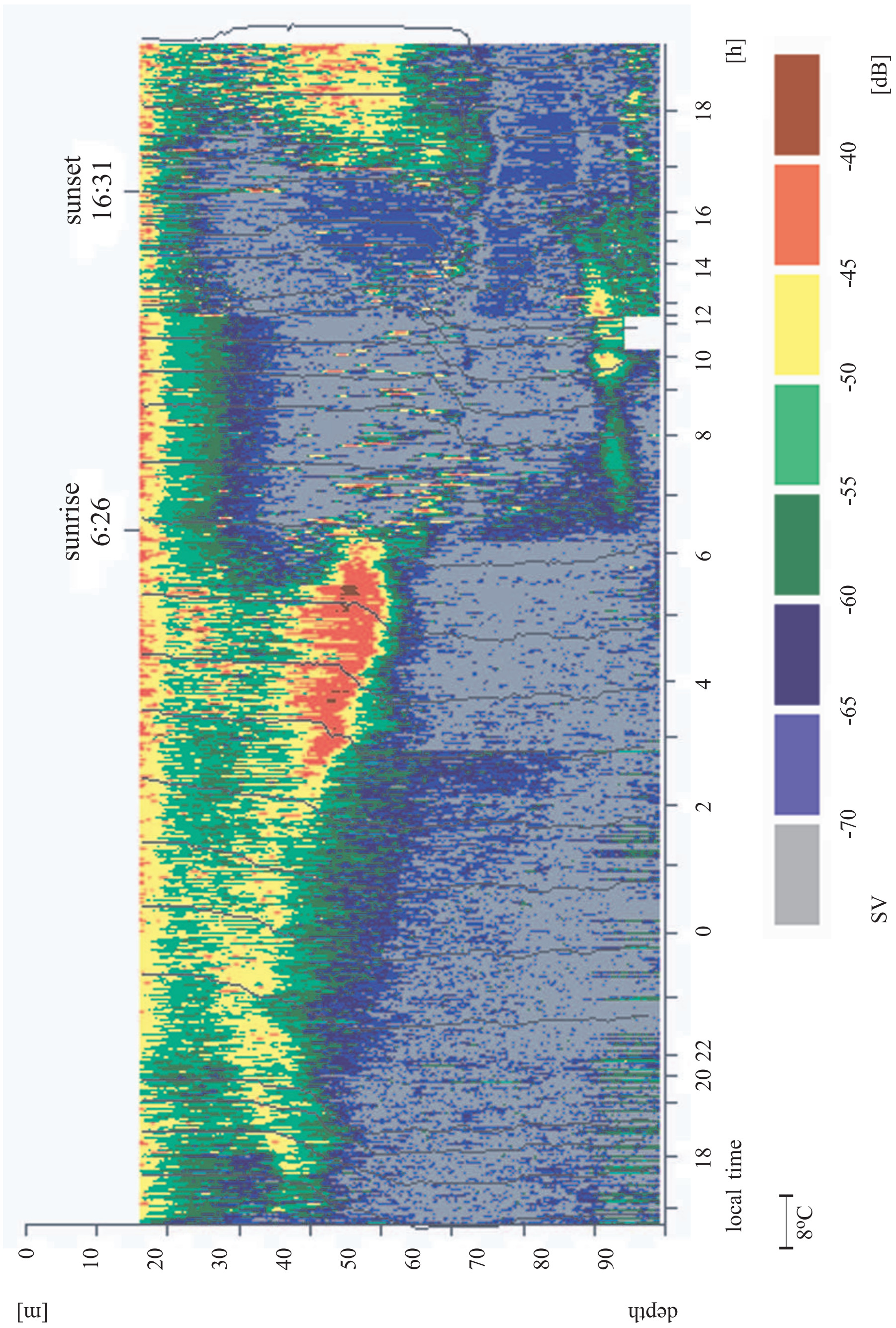

Fig. 11. Echogram recorded in October 1993 compared with vertical temperature profiles measured by CTD

Although the species composition still cannot be acurately determined by acoustic sampling alone, it is possible to discern some fine-scale patterns in the backscattered echoes and relate them to environmental parameters. Apart from diel vertical migration, plankton displacement is caused by movement of the water mass, so zooplankton can serve as tracers in acoustic sounding. This allows for the remote detection of various dynamic phenomena in the sea, like edges, up- and downwelling, internal waves, and mesoscale inhomogeneities (Szczucka *et al.*, 1994; Śliwiński *et al.*, 1993). Biological patches have often been reported at or near physical discontinuities in the water column. In many cases quasi-continuous acoustic sounding can provide complementary information to direct conventional sampling to places and depths of interest.

Frontal zones constitute unique ecosystems where the patchiness of marine populations is generally increased owing to the complex physical environment. The changes in patterns of the scattering layers in a front may be due to differences in water masses and can thus be an extremely useful source of information.

To summarise, it can be said that echosounding makes it possible to obtain useful insight into the spatial and seasonal variability of the sound scattering layers in the Baltic Sea. Closer cooperation between biologists and hydroacousticians is needed in order to improve the interpretation of the acoustic images and to reveal the diurnal migratory habits of different species of zooplankton in this area.

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