DIEL VERTICAL MIGRATION OBSERVED BY ACOUSTIC DOPPLER CURRENT PROFILER

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This paper presents the results of continual 17-week ADCP measurements applied to investigate the migratory behaviour of the Baltic animals. The velocities of vertical migration are determined in different ways and the results are compared. Strict correlation of the moments when downward or upward migration starts with sunrise and sunset times, is confirmed. Additionally, vertical and horizontal movements of water content are examined. Even though quite slow in comparison with horizontal flow, vertical migration exists independently of other factors.

INTRODUCTION

Diel Vertical Migration (DVM) is a worldwide phenomenon, taking place in all oceans, seas and lakes. This 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. 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. Velocities of vertical migration of zooplankton obtained for various basins [3, 5, 6, 7, 10] have rather similar values, from millimetres to several centimetres per second (in the case of krill).

Acoustic Doppler Current Profiler (ADCP) is a device purposed to measure current velocity. It uses four beams that are separated radially by 90° and aimed 20° from the vertical. 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, valuable data on the total backscattering strength of the targets enclosed in the water column [7, 9].

1. DATA COLLECTION AND PRE-PROCESSING

The object of this study is Diel Vertical Migration recorded in the Baltic Sea as a by-product during the hydrodynamic experiment. Continual series of measurements were performed from 12 May to 8 September 2009 in order to study the current field and the surface waves mechanics. In order to increase the precision of the Doppler shift computation, the averaging over depth bins and time intervals is performed. This makes the spatio-temporal resolution of the ADCP data limited. In our case, the ensembles of data averaged in time and depth over 20 minutes and 4 metres were delivered. The data were collected in the Baltic Sea, north to the Hel Peninsula, at the position φ = 55° 28.053' and λ = 018° 14.236' (Fig.1) by use of the bottom-mounted, upward-looking 300 kHz Acoustic Doppler Current Profiler (ADCP, RDInstruments). It was deployed at the depth of 80 m.

Echo intensity data collected by the ADCP were converted to mean volume backscattering strength *Sv* by use of formula giving the dependence of *Sv* on the recorded signal value and emitted power, range, bin length and absorption coefficient α [1]. For the low-saline Baltic, at 10°C and for the frequency 300 kHz α has a value of 0.038 dB/m [2].

For the purpose of migration velocity examination, the depth of the centre of gravity z_{gc} of the squared signal envelope was calculated. It was made on the basis of the determined values of volume backscattreing coefficient $s_v = 10^{Sv/10}$:

$$z_{gc} = \sum_{i=1}^{N} s_{vi} z_i \bigg/ \sum_{i=1}^{N} s_{vi} \tag{1}$$

where:
N – the number of samples in the ping
z_i – the depth related to the ith sample
It was further approximated by hyperbolic function:

$$y = y_0 + B \tanh \frac{x - x_0}{C} \tag{2}$$

and velocity was calculated in the inflection point.

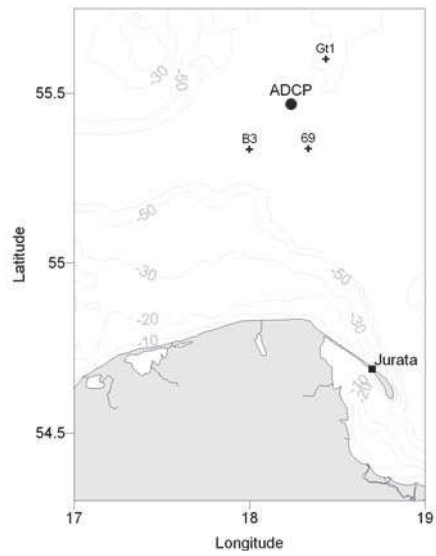

Fig.1. Location of the ADCP and three STD stations

Temperature and salinity profiles were measured by r/v "Oceania" at the ADCP location before its deployment on 11 May and by r/v "Baltica" at the nearby stations Gt1, B3 and 69 on 15-18 August (Fig.1).

2. RESULTS AND DISCUSSION

Temporal variability of echoes

Hydrodynamic experiment performed by use of ADCP has delivered a unique acoustic material concerning the configuration of sound scattering objects in water column and its long-term variability. Experimental series embraced 17 weeks of uninterrupted echosounding (by four differently inclined acoustic beams) – it amounts to the third part of a year. This time is a period of heating the water body and changing the termohaline conditions. Such a long and detailed observation is very pictorial, but difficult to evaluate day by day. For this reason, each consecutive 7 days of our acoustic data recording have been averaged to one mean day, hour by hour, resulting in a mean 24-hour *Sv* matrix representative for a given week. In this way, temporal changes connected with variable temperature and light conditions, can be easily inspected. The result of such operation is illustrated in Fig.2 presenting 4 of 17 averaged 24-hour echograms obtained for the period 11 May till 8 September. The horizontal axis in each echogram embraces the whole day, from midnight to midnight, with the left and right corners of each echogram referring to night-time and the middle part to daytime.

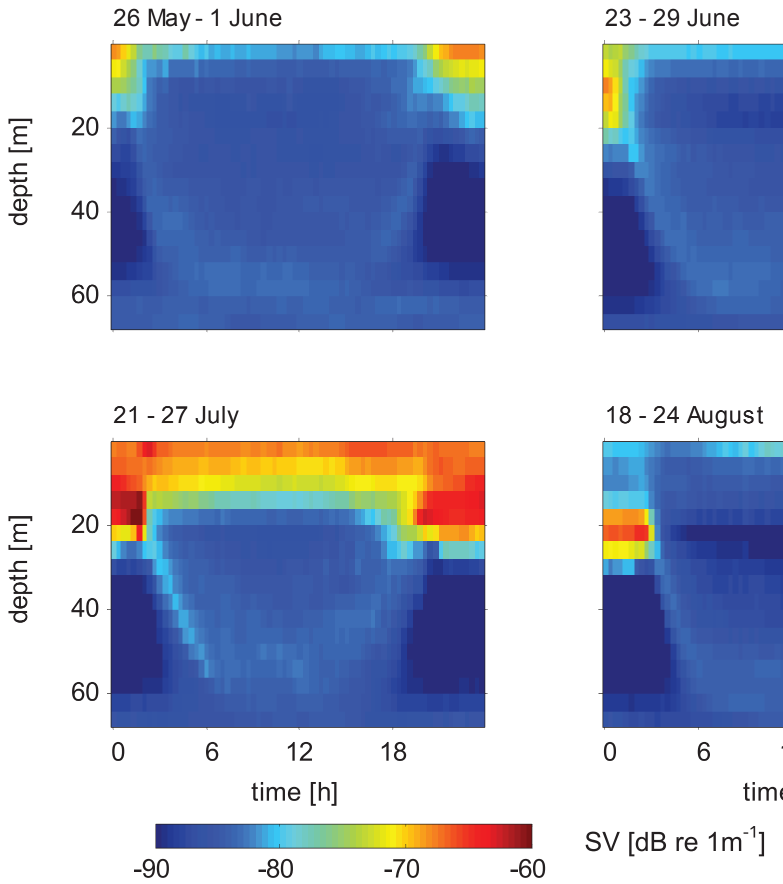

Fig.2. Mean 24-hour echograms for the 3rd, 7th, 11th and 15th week from the period between 12 May and 8 September 2009

Vertical axis describes the depth – from the bottom to the top of the water column. Red patches in the upper corners are reflections from the nocturnal aggregations of zooplankton and fish ascending at night to the sea surface. Vertical redistribution of the scatterers in the morning and in the evening is clearly seen in all pictures. During the first weeks the nocturnal aggregation of organisms appears just below the sea surface and has a width of 4 m (1 bin). Its depth and width increase with time reaching at the end, in September, the values of 25m and 12m, respectively. This fact is strictly connected with seasonal heating of the sea water resulting in the widening of mixed subsurface water layer and the deepening of the summer thermocline (see Fig.3).

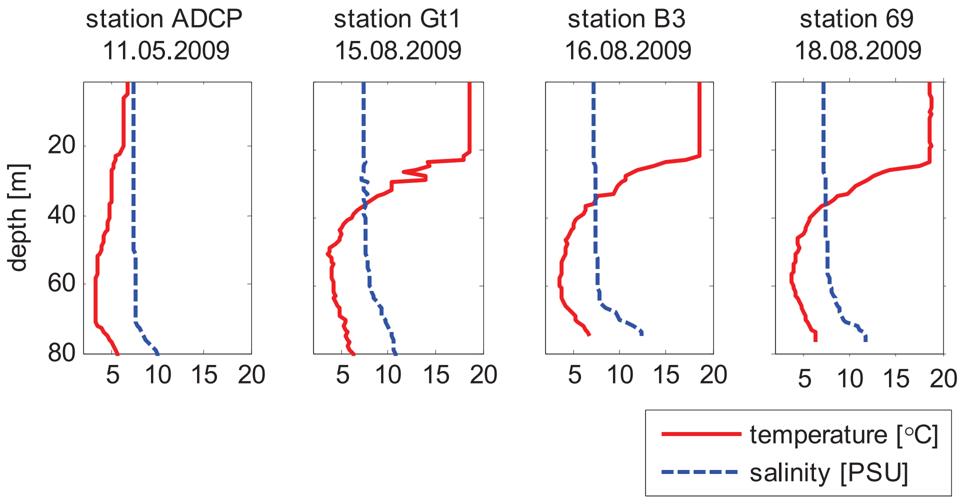

Fig.3. Temperature and salinity profiles taken on 11 May 2009 (r/v "Oceania") and on 15, 16 and 18 August 2009 (r/v "Baltica")

In July, in addition to the change in the depth of the nocturnal scattering layer, also the echo intensity in this layer increases. It can be caused by the rise of the total biomass or/and by phytoplankton bloom.

Furthermore, deeper insight into the shape of migrating layers allows us to observe the changing day length – diurnal break under sea surface increases in consecutive weeks, because days become shorter and shorter.

DVM velocities

The range and speed of upward and downward migration can be determined by various direct and indirect methods [11]. Migration velocity can be determined from the trace on the echogram, from the slope of the hyperbolic curve approximating the gravity centre location in the transition regions or directly from the vertical velocities calculated by ADCP from the Doppler shift of backscattered signals.

The first method calculates the speed from the echogram by finding the trailing edge of migrating organisms. Usually it is clearly seen in the echogram and can be found out by the simple thresholding method. Vertically migrating group of animals causes at a given time the local maximum of *Sv* at a given depth (Fig.4a). The point x_i (on the time axis), in which the difference between the $Sv_{i,j}$ value for a given depth and time cell and the mean value of *Sv* for the whole row exceeds the threshold value, is determined (white points). In the next step, the collection of points x_i is linearly interpolated (black slant lines), indicating the edge of the

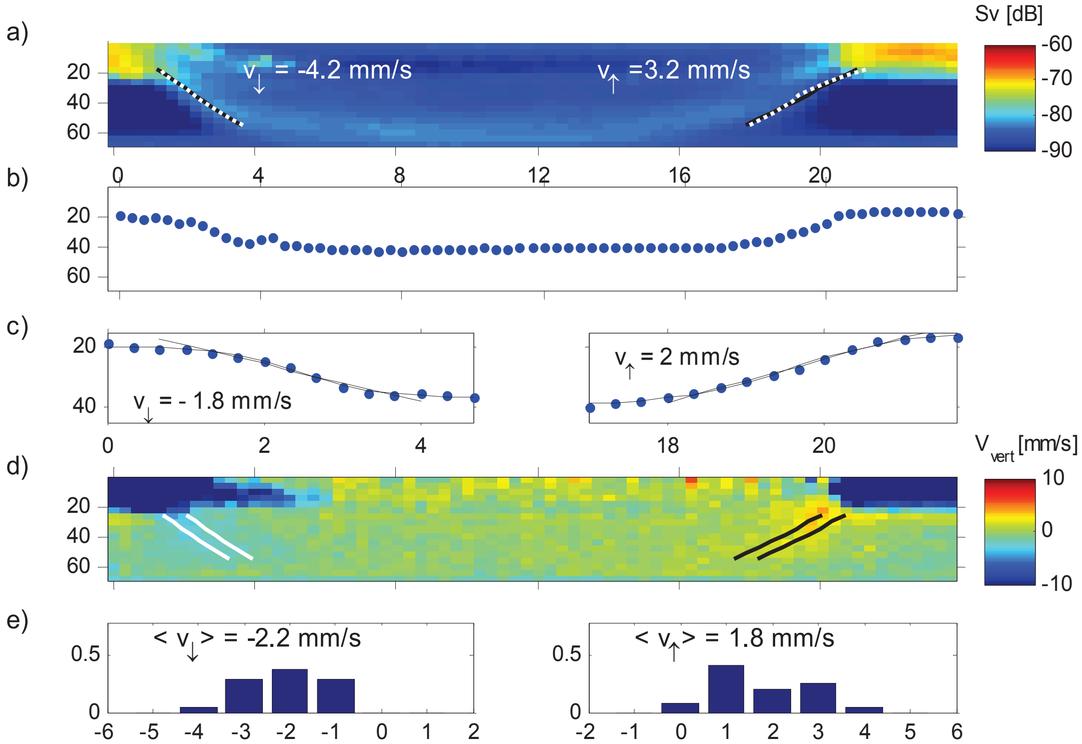

Fig.4. a) 24-h mean echogram representative for the sixth week (16–22 June) with the detected trailing edge of migration (white points) and its linear approximation (black lines); b) gravity centre depth of the echo; c) gravity centre depth at sunrise (left) and sunset (right) approximated by the hyperbolic function; d) vertical component of the water flow with migration paths; e) distributions of vertical velocities at sunrise (left) and sunset (right)

migrating aggregation, ascending at dusk and descending at dawn. The inclination of this line is used as an estimate of the velocity of vertically migrating layer. In the presented case, $v_\downarrow = - 4.2$ mm s^{-1} and $v_\uparrow = 3.2$ mm s^{-1}.

Another way of analysing the temporal variability of a scatterers configuration is based on the computation of the gravity centre depth of the signal envelope (1). Changes in the depth of the gravity centre mirrors vertical displacements of sound scatterers within the water column [10]. Usually we can notice the characteristic shallowing of the depth of the centre of gravity at sunset and its sinking at sunrise (Fig.4b). The speed of migration can be determined from the slope of this curve in the transition phase. The best fitted hyperbolic curves (2) are also shown for the dawn and dusk periods (see Fig.4c). Deduced migration velocities are: $v_\downarrow = - 1.8$ mm s^{-1} for sunset and $v_\uparrow = 2.0$ mm s^{-1} for sunrise. They are lower then those obtained by the first method and, in our opinion, it can be a consequence of the rough averaging in time and space. The method which works excellent in the case of the scientific echosounder, is unfortunately not good in this ADCP case.

As it was already mentioned, ADCP measurement of the components of the current vector is founded on the assumption that scatterers are neutrally buoyant in water and their speed is identical with the speed of medium. Normally, ADCP measures the flow speed, but during dawn and dusk the measured speed is of migrating animals. This is clearly visible on the graph of vertical velocity (Fig.4d). The paths of negative and positive values are discernible during downward and upward migration. If we extend the edge of migration (black slant lines in Fig 4a) to a 1-hour band by adding one sample before $Sv_{i,j-1}$ and one sample after $Sv_{i,j+1}$, we obtain a path of migration. For this path the values of vertical velocity calculated by ADCP can be determined and histograms of such values show the character of their distribution. Fig.4e presents two distributions of vertical velocity values calculated within the migration path. The left one, characteristic for sunrise, is negatively skewed, with a mean value $\langle v_{\downarrow} \rangle = -2.2$ mm s^{-1}. The right histogram (sunset), is positively skewed, $\langle v_{\uparrow} \rangle = 1.8$ mm s^{-1}. Generally, likely because of ensemble averaging, 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.

Sunrise and sunset times

At first sight, the upward and downward movement of marine fauna is synchronous with sunset and sunrise. To check it, the moments of migration initiation were determined by the following method [4, 11]. The consideration of the depth layer where nocturnal aggregations are created, show sharp changes in the *Sv* values during sunrise and sunset. The derivative d*Sv*/dt possess the distinct extremes, minima in the morning and maxima in the evening, and the times of their appearance can be treated as migration moments. Those values calculated for 119 days of the analysed series of measurements are depicted in Fig.5 on the background of dawn and dusk contours determined for the ADCP point. All data obtained by this method seem to be well synchronised with the local times of sunrise and sunset. In most cases the morning migration starts in darkness (red points in the lower part of Fig.5), while the evening events (blue points) are distributed in the twilight zone.

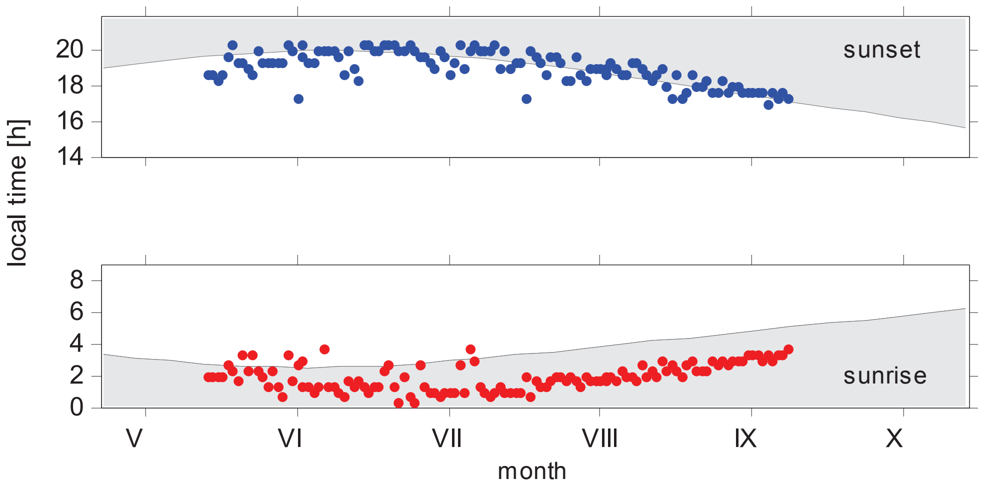

Fig.5. Diagram of sunset and sunrise time at the ADCP point together with times of migration calculated for 119 days of measurements

DVM and inertial currents

An extra information on the current field delivered by ADCP allows us to observe some phenomena not detected by typical echosounders. Analysing the stationary echosounding data we usually assumed that all the time we insonified the same population of vertically migrating animals. But our series of measurements revealed that during about 90% of time very strong horizontal flows were recorded. Fig.6 is an example of a 7-day record of the *Sv* field and three current components: vertical, south-north and east-west. The echogram (upper figure) presents a typical DVM pattern, upward and downward movements in a diel cycle. Vertical velocities (part b) are also typical, with yellow and blue strips in the evening and in the morning, respectively, related to positive (up) and negative (down) velocities of animal movement. The lower two pictures are very interesting. They show inertial currents, which for the Baltic Sea have a period of ca 14 hours (it depends on the basin size). These currents are generated by wind and pressure differences, they create big wires and their absolute speed is large at the surface and decreases with depth due to the friction forces. Halo- and thermocline constitute barriers for the energy transport and the inertial currents very often move in the reverse directions at different depths (for example to the north in the upper layer and to the south close to the sea bottom). Horizontal flow diagrams have such streaked structure. The absolute values of horizontal velocities are of the order of 10 cm s^{-1}, which means that drifters-zooplankters move horizontally with that velocity and our stationary measurement does not concern the same population of animals. Nevertheless, the Baltic fauna still migrate vertically during sunset and sunrise and this movement seems not to be affected by other physical phenomena.

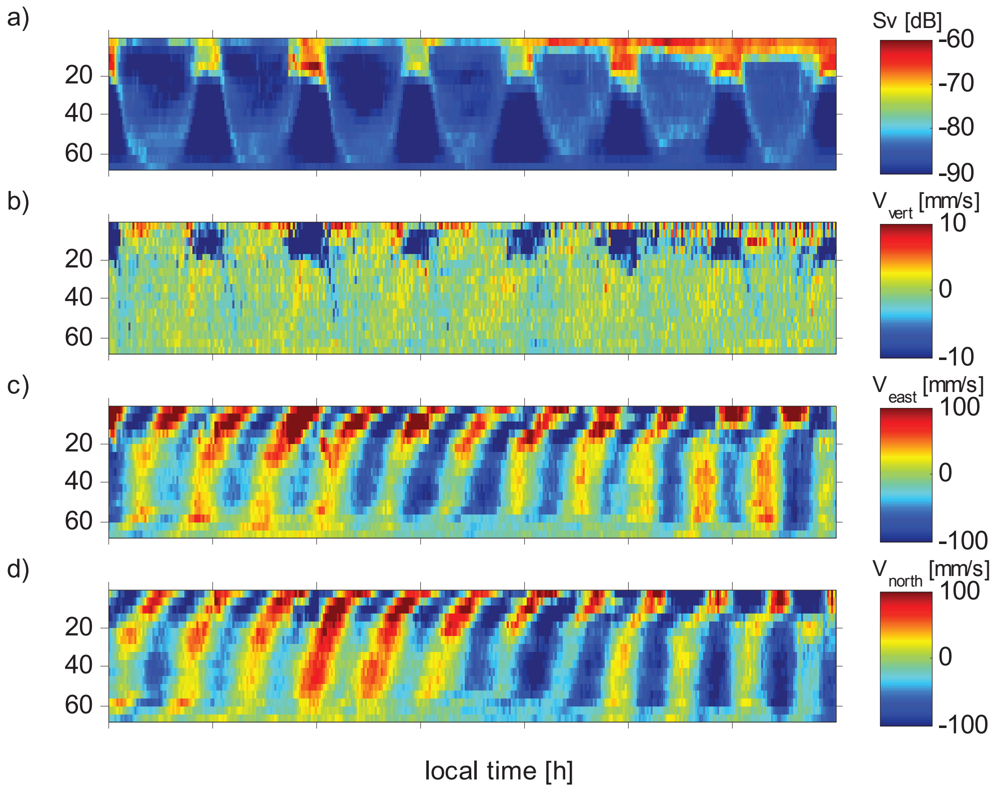

Fig.6. a) 7-day echogram representative for the tenth week (14–20 July); b) vertical current component; c). west-east current component; d) south-north current component. Ticks on the x-axis denote midnights.

3. SUMMARY

This study is a continuation of our Diel Vertical Migration reseach conducted in the Baltic Sea for many years. It is based on the new series of 119-day continuos measurements performed by Acoustic Doppler Current Profiler. The data analysis is focused on temporal echo variability, migration velocities, synchronisation of vertical migrations of organisms with sunrise and sunset times, vertical and horizontal water flow. The main conclusions are the following:

- the time of experiment, from May till September, is the period of heating the water body od the Baltic Sea. This finds its reflection in the increase of the depth of the nocturnal scattering layer and the echo intensity;
- long time of observations allows for the detection of changes in timing of the DVM. Moments of the evening and morning migration are well correlated with the moments of dusk and dawn;
- obtained values of vertical velocity are comparable to those measured by other people in other basins;
- comparison of DVM with horizontal currents reveals a 1 order of magnitude difference in their velocities.

ACKNOWLEDGEMENTS

The authors would like to thank our colleague Waldemar Walczowski from the Ocean Circulation Laboratory IO PAS for providing the ADCP data.

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