Concurrent acoustical and optical observations in zooplankton studies

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Abstract

Zooplankton is an important component of the marine ecosystem linking primary producers with higher trophic levels. It is characterized by irregular distribution in the water column, forming aggregations called patches. It is difficult to collect complete information on zooplankton distribution with traditional methods (e.g. nets), that provide discrete and low resolution data on distribution of zooplankton biomass and abundance, therefore use of alternative methods is necessary. Acoustic sounding makes environmental studies fast, non-intrusive, and relatively cheap with high temporal and spatial resolution. Laser Optical Plankton Counter (LOPC) delivers real-time information on zooplankton abundance and size spectra. Presented results are based on the data collected in the Gulf of Gdansk, southern Baltic Sea collected during cruises in the years 2013-2014. Data was collected during simultaneous profiling with high frequency (420 kHz) echosounder and LOPC tows along the chosen transects. Zooplankton size spectra obtained by LOPC were used as input parameters in mathematical model of sound scattering on zooplankton individuals. Model output values of acoustic backscattering strength were then compared with values obtained by echosounding. Zooplankton size structure is helpful in validating and refinement of sound scattering model for specific set of scatterers. Acoustical measurements supplemented by optical observations have a great potential to describe zooplankton distribution over large scales.

Keywords: high-frequency acoustics, Baltic zooplankton, LOPC, sound scattering model
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1 Introduction

Zooplankton is a key link between primary producers and higher trophic levels. It is an important component of pelagic ecosystem as the main food for numerous species of fish in the Baltic Sea, e.g. sprat and herring, which are of great economic importance [1]. Our knowledge of zooplankton community structure and abundance provides some information on the pelagic food web and ecosystem state, and enables prediction for the future production and fishing capabilities. Zooplankton organisms respond relatively quickly to environmental changes, so they are good indicators of the ecosystem transformations. Zooplankton community is characterized by sparse distribution throughout water column with sporadic aggregations called patches. Plankton distributions in the sea are patchy due to either environmental factors, such as: temperature and salinity gradients, light intensity, amount of organic matter, or behavioral factors like predator avoidance, reproduction [2]. To understand and analyze resultant processes in the marine ecosystem, it is necessary to collect biological and environmental data with high spatial and temporal resolution. Conventional net sampling provides only discrete and sparse information on biomass, size distribution and community structure of zooplankton [3], therefore use of alternative methods should be taken into consideration. Acoustic sampling methods allow fast, non-intrusive, and relatively cheap environmental studies with high temporal and spatial resolution [4]. Echosounders are widely used to survey and map zooplankton distributions in the World Ocean. Acoustic estimates of zooplankton abundance and distribution have been made earlier using high-frequency echosounding [5]. There are few papers on acoustic scatterers (i.e. zooplankton) diel migration patterns in the southern Baltic Sea, regarding both fish and zooplankton [6; 7]. Ecological studies on Baltic zooplankton, its spatio-temporal variability and taxonomy have been conducted for a number of years [8], mainly with the use of traditional sampling nets [9], but there is a lack of research on acoustical properties of Baltic zooplankton assemblages.

Despite of the wide use of echosounding in biological studies, quantitative relationship between acoustic backscattered signal and zooplankton abundance, its size and taxonomy structure is still an elusive and complicated problem [10]. The acoustic scattering intensity depends on wave frequency, size, shape, orientation, age and total number of plankters in the ensonified water volume. Moreover, scattering strength is a complex function of animal material properties (sound speed and density ratios) [11]. Because of its complexity, evolvement of acoustic models is a great challenge. Many different models, which vary in accuracy and generality, have been developed within the past decades. First scattering models treated zooplankton as a homogeneous fluid sphere [12; 13; 14]. More sophisticated models have been introduced to take into account shape and material properties of animals. Some models treated elongated zooplankton species as a long scattering cylinders or ellipsoids [11; 15; 16]. All these models...
require adjustment and validation for the Baltic Sea conditions with significantly lower salinity and smaller sizes of the same species of zooplankton comparing to the open ocean or adjacent North Sea. Acoustical investigations of biological scattering layers proved that adjustment and implementing of the mentioned models in the Southern Baltic Sea environment is possible [17].

New, complementary instruments for assessing zooplankton abundance have been developed recently, i.e. optical counters [18]. Optical Plankton Counter proved to be well suited to multi-scale studies of zooplankton communities [19]. Concurrent acoustical and optical measurements have a great potential to describe zooplankton assemblages over large temporal and spatial scales [20]. LOPC delivers continuous information on zooplankton size spectra and abundance.

The aim of this work is a comparative zooplankton study, where acoustical measurements are supplemented by LOPC surveys. Research has demonstrated that present knowledge is still not sufficient to provide a complete deterministic model for predicting the zooplankton assemblages size structure and taxonomy [21]. A comparison of different methods is then required to assess more thorough information, as each sampling tool suffers own inefficiencies. This study presents a combined approach to an acoustical assessment of zooplankton abundance and its distribution in the Southern Baltic area. LOPC which delivered abundance and size spectra of zooplankton community was used together with high frequency (420 kHz) acoustic measurements. Information on population structure allowed determination of some crucial acoustical characteristics of the Baltic zooplankton and implementation of the mathematical model of acoustic scattering on the Baltic Sea zooplankton community. Knowledge of the southern Baltic Sea zooplankton acoustic parameters is an important step in refinement of the teledetection methodology of determining the abundance of zooplankton aggregations, assessing its size and species structure in the region, with use of acoustic detection methods. Studies on relationship between acoustic backscattering strength and abundance were made. Study gives the possibility of determining the density and sound speed contrasts of zooplankton tissues and implying them into the mathematical model of sound scattering. The last part is a comparison of backscattered acoustic energy values and model-calculated results, with use of the zooplankton size spectra obtained by LOPC.

2 Study area

Zooplankton acoustical and optical data were collected in the Gulf of Gdansk (southern Baltic Sea), during spring, summer and autumn cruises of r/v Oceania in the years 2013-2014 (Figure 1). Gulf of Gdansk is a south-eastern bay of the Baltic Sea forming separated basin with maximum depth reaching 118 m [22]. It is a Vistula River estuary with hydrography depending strongly on interaction between fresh, river waters and salty, Baltic waters. This study is a part of the ZODIAC (Acoustical estimation of the abundance and spatio-temporal distributions of the Baltic zooplankton) project financed by the Polish National Science Centre.
3 Materials and methods

Echosounding was performed with a high quality DT-X echosounder (BioSonics Inc., Seattle, USA), working at a frequency of 420 kHz, giving acoustic backscatter field in the water column along the ship route. The echosounder has downward-looking acoustic transducer mounted on the ship by a special frame, 1 m below water surface. The construction allows the ship to proceed with speed of approximately 3 knots. The output of the echosounder is a volume backscattering strength $S_v$, which is a logarithmic measure of the volume backscattering coefficient $s_v$, being the sum of the backscattering cross-sections of all zooplankters enclosed in the ensonified unit water volume. The frequency of 420 kHz gives an acoustic signal wavelength of about 3 mm, thus it is capable of detecting individual plankters with the equivalent spherical radius of 0.5 mm. It is based on the criterion of detectability: $2\pi \text{radius}/\text{wavelength} > 1$ [23].

Concurrently with echosounding, Laser Optical Plankton Counter (Brook Ocean Technology Dartmouth, Canada) was towed along the transects. LOPC is the in situ sensor which provides the abundance and community size structure of plankton and particles in water in real-time. The technical specifications allow to obtain particles size spectra in range of 100 µm to 35 mm Equivalent Spherical Diameter (ESD). LOPC measures cross-sectional area of each plankton particle in its beam path in the sampling tunnel, which is 7cm x 7cm. Laser beam is transmitted across the sampling tunnel and then reflected back to photodiode receiver [24]. ESD can easily be transformed into biomass estimates when the zooplankton community under study is composed of similarly shaped organisms. LOPC was working in an undulating mode from the
surface to the maximum of 50 m depth providing comprehensive and continuous description of horizontal distribution of zooplankton sizes at a towing depth.

Zooplankton size spectra obtained by LOPC were divided into 49 size classes (from 100 µm to 35 mm diameter), which were used as input parameters for theoretical model of acoustic backscattering of zooplankton. The “high-pass” sound scattering model by fluid spherical objects [15], which is a good approximate for a collection of zooplankton representatives of different sizes, orientations and shapes [11] was chosen. To validate implemented model, the sum of the modeled values of backscattering cross-sections of all scatterers were transformed into the total $S_v$ and compared with the real $S_v$ values measured by the echosounder in the water layer of the LOPC towing depth. For comparison, the acoustic data were averaged over 1 m depth layers and 10 or 20 transmissions (5 or 10 s). The same applied to the optical data, which were averaged over the same time and depth intervals. As there is lack of information on sound speed and density contrasts for Baltic zooplankton, the contrast were set at $h = 1.027$ and the $g = 1.0$, as proposed for the Arctic copepod species *Calanus finmarchicus* and implemented in previous studies [20].

Comparing acoustic and optical measurements in zooplankton studies can be a tough task. Echogram includes information on all scatterers in water volume. Scattering from subsurface air bubbles, which are very strong acoustical scatterers in the upper layer should be eliminated in further analysis. Strong echoes from fish should also be removed. The fish filtration process was applied to all analyzed echograms before further processing. For each depth interval the backscattering strength measured by the 420 kHz echosounder was compared with the backscattering strength calculated from the model for the zooplankton size and abundance estimations based on the optical measurements at the same time.

Additionally, at chosen points during the survey, environmental parameters such as salinity and temperature, were measured by the SeaBird CTD probe.

The collected data consist of, in total, 5 hours of concurrent acoustical and optical measurements.

### 4 Results

Two exemplary data series were selected to illustrate the results of our study. The first is the distribution of backscattering strength in the 0–50 m layer during the 2 hour long survey along the designated route, collected in the Gulf of Gdansk on 16 May 2014 (Figure 2). Distribution of backscatter reflects the distribution of biomass, most likely of zooplankton. Additionally, strong echoes from fish can be observed at depth of about 25 m and surface layer of strong scattering is seen.

Differences between the modeled and measured values of $S_v$ were plotted against depth (Figure 2). It is clear that model values are underestimated in the upper layers. This is presumably caused by strong scattering from subsurface air bubbles, which are very strong acoustical scatterers. Bubbles are detected by LOPC but their $g, h$ contrasts are much higher
than those of zooplankton. Below 10 meters depth modeled values of volume scattering are overestimated, which should probably be explained by applying too high values of $g, h$ contrasts.

The second set of data is the distribution of backscattering strength in the 0–50 m layer during the 3 hour long survey along the designated line, collected in the Gulf of Gdansk on 23 September 2013 (Figure 3).

Additional temperature and salinity measurements indicate that, there is strong summer termocline visible at the depth of about 45 m. The dense scattering layer is seen just above it. Strong echoes from subsurface bubble layer can be seen, as the sea was rough during the cruise and the model values are underestimated near the surface. The differences in modeled and measured values in the water column suggests that $g, h$ contrasts were set too low.

**Figure 3**: Echogram; distribution of differences between modeled and measured values; temperature plot for a chosen point; 16 May 2014
5 Discussion and conclusions

The Baltic zooplankton acoustical characteristics (i.e. sound speed and density contrasts) are poorly recognized comparing to the ocean and other seas communities. It is very hard to apply exact sound speed and density contrasts to mathematical model of scattering. What is more, they depend on variety of factors. Huge differences in water temperature between spring and autumn have great effect on g, h contrast. Salinity gradients at the mouth of Vistula River and even a phenomena like termocline also influence this characteristics. Moreover, the zooplankton sizes, its taxa composition and abundance varies during summer season. It is known that abundance of Copepoda (which are dominant species) in Gdańsk Bay have two peaks during the season, depending on environmental factors [25]. Analysis of presented data shows that during May cruise zooplankton characteristics applied into the model were set too high, while September study suggests that g, h contrasts were set too low. This can be explained in different species and size composition due to seasonal cycle. Particles size structure data from LOPC suggests that September community consisted of bigger species and was more abundant comparing to May.

Echosounding is capable of providing continuous information on distribution of scatterers in the water column, but exact sizes and abundance remain unknown. LOPC measurements produce data on size spectra of all particles suspended in the water, give estimations of zooplankton abundance but cannot deliver taxonomic structure.

Acoustical estimates of the theoretical backscattering strength calculated by the model are very sensitive to changes in density and sound speed contrasts, even slight change in one parameter can cause huge difference in modeled values, however it is impossible to take properties of each zooplankton individual in the study area into account.
Mathematical model applied in this study assumed homogenous density and sound speed contrasts \( g, h \) for the zooplankton community in the water volume, which is obviously a simplification, but earlier proved to be a good approximate for a collection of zooplankton individuals of different sizes, orientations and shapes in the Arctic.

Analysis of the data shows that scattering strength measured by echosounder and predicted by “high-pass” model using zooplankton size distribution provided by the LOPC differs up to 10 dB. This is caused by lack of knowledge on zooplankton acoustic characteristics, which needs further investigations.

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