ACOUSTIC TRACKING DYNAMIC PHENOMENA IN MARINE ECOSYSTEM

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Acoustic information, collected in the form of measurements of integrated echo energies related to time and 3D space has been applied at the Sea Fisheries Institute since 1981 to examine the rough statistical relationships between clupeoids distribution in the Baltic and the relevant environmental factors. In this paper it is shown that the data collected can be also applied for very detail observation of dynamic phenomena in marine ecosystem. Two differentiated case studies were selected to show new acoustic applications in specific areas of oceanographic research. In the first case spatial characteristics of fish diel vertical migration in the southern Baltic was surveyed and analysed for the period 1994-2007, against the environmental background. In the second case acoustic sounding was applied to quantify ebullition of methane from Baltic sediments. Both phenomena are strongly dependent on climatic variability. For both cases the final characteristics of the phenomenon was given in the form of video frames, expressing the processes in time. Unique method of echo-recording transformation into video frames was described and applied to analyse the process of ebullition of methane from the seabed.

INTRODUCTION

The functioning of the marine ecosystem is consists from many differentiated processes, which are strongly dependent on environmental factors [2]. The ecosystem is based on abiotic and biotic components, which are closely related and involved in circulation chains. Acoustic methods are widely supporting observations of both components [6, 7, 9, 10, 11, 12, 15, 16, 18, 19, 20, 21, 22, 23, 24]. Two different case studies are shown to illustrate particular methods of acoustic tracking dynamic phenomena in the Baltic Sea. One case is dedicated to describe and to analyse diel fish vertical migrations in different geographical zones, characterized by differentiated environment. Dynamics of vertical fish distribution is closely dependent on environmental factors [2, 8]. The second case shows the process of ebullition of the methane from bottom sediments in the Gdańsk Deep, tracked by scientific sounder. The bullition was caused by the CTD sensor landing at the seabed. Ebullition is an important mechanism of gas liberation from bottom sediments to aquatic system and the atmosphere [20, 21]. The scale of this phenomenon corresponds to degree of degradation of the marine ecosystem. Both phenomena are strictly dependent on the state of the environment which is closely correlated with climatic variability.

1. MATERIAL

During the period 1981-2007 ships of Sea Fisheries Institute in Gdynia (RV Profesor Siedlecki and RV BALTICA) carried out series of research cruises, collecting acoustic, biological and environmental data in the southern Baltic. Since 1989 all cruises have been carried out during the autumn (October 1989, 1990, 1994-2007), being the part of international ICES programme of the Baltic pelagic fish stock assessment. Each cruise lasted approximately three weeks, and had a potential to collect data from 1-2 thousands nautical miles of acoustic transect. Samples were collected continuously, and integrated every one nautical mile, 24h a day. The time distribution of samples in relation to the whole period 1981-2007 was quasi-homogeneous what gave a good base to estimate 4D characteristics of clupeoids behaviour in the southern Baltic.
The data applied in this paper were collected in a period 1994-2007 by EY500 scientific system, working at the frequency 38 kHz and with hull-mounted transducer of 7.2˚x 8.0˚ beam. Calibration has been performed with a standard target in Swedish fjords in 1994 to 1997 and in Norway from 1998 to 2007. Cruises were carried out in October and lasted 2 to 3 weeks, giving the possibility of collecting samples over 1 to 1.5 thousands of nmi (approximately 450 transmissions per nmi). Survey tracks of all cruises were on the same grid to obtain high comparability of measurements.

Biological samples were collected over the period from 1994 to 2007 by the same pelagic trawl, on average every 37 nmi. of the transect. Fish observed during all surveys were mostly pelagic, herring and sprat (*Clupeidae*). Hydrologic measurements (temperature-T, salinity-S, and oxygen level-O_2) were made by a Neil-Brown CTD system. The CTD sensor overview is given in the Figure 1. Measurements were made mostly at sample haul positions, with a similar as biological sampling space density. Each hydrological station was characterized by its geographical position and values of measured parameters at 2m depth intervals.

Fig.1. CTD sensor of Neil-Brown hydrologic system of RV BALTICA

In the map in Fig. 2. it is given localization of two acoustic transects L1 (along the parallel 55º15’N) and F1 (along the meridian 16ºE).

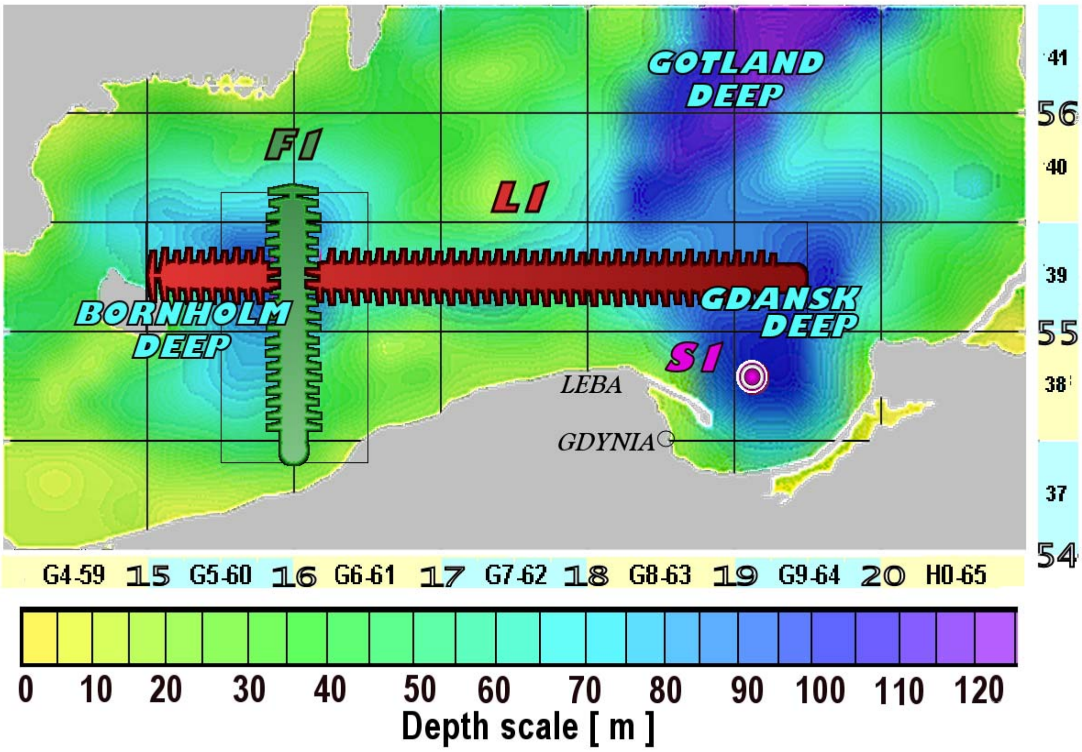

Fig.2. Localization of case studies in southern Baltic area: L1 and F1 – acoustic transects, S1- methane ebullition recording

2. METHODS AND RESULTS

2.1 DYNAMICS OF FISH DIEL MIGRATION IN 4D

The method of extracting inter-disciplinary data from acoustic, biological, and hydrological measurements was described in [15, 18, 19]. Distance of one nautical mile was considered as an elementary unit (record) of the data base. For each record values of remain factors characterizing the biological and hydrological parameters were estimated. Following parameters were measured or calculated for each EDSU:

- date, time, day- night time,
- geographic position,
- bottom depth,
- S_A, S_v values in the layered standard structure,
- depth of the upper (D_u), centre of gravity (D_f), and lower (D_l) limit of fish recordings,
- temperature, salinity, and oxygen level for each 2m depth interval at each nearest CTD station,
- biomass surface density and % of the herring, sprat, and cod.

Dynamics of fish vertical migrations was described for two orthogonal acoustic transects, representing basic configurations of the environment in the southern Baltic (Figure 2). Acoustic, biological and hydrological data were averaged over the whole period of the autumn cruises between 1994 and 2007.

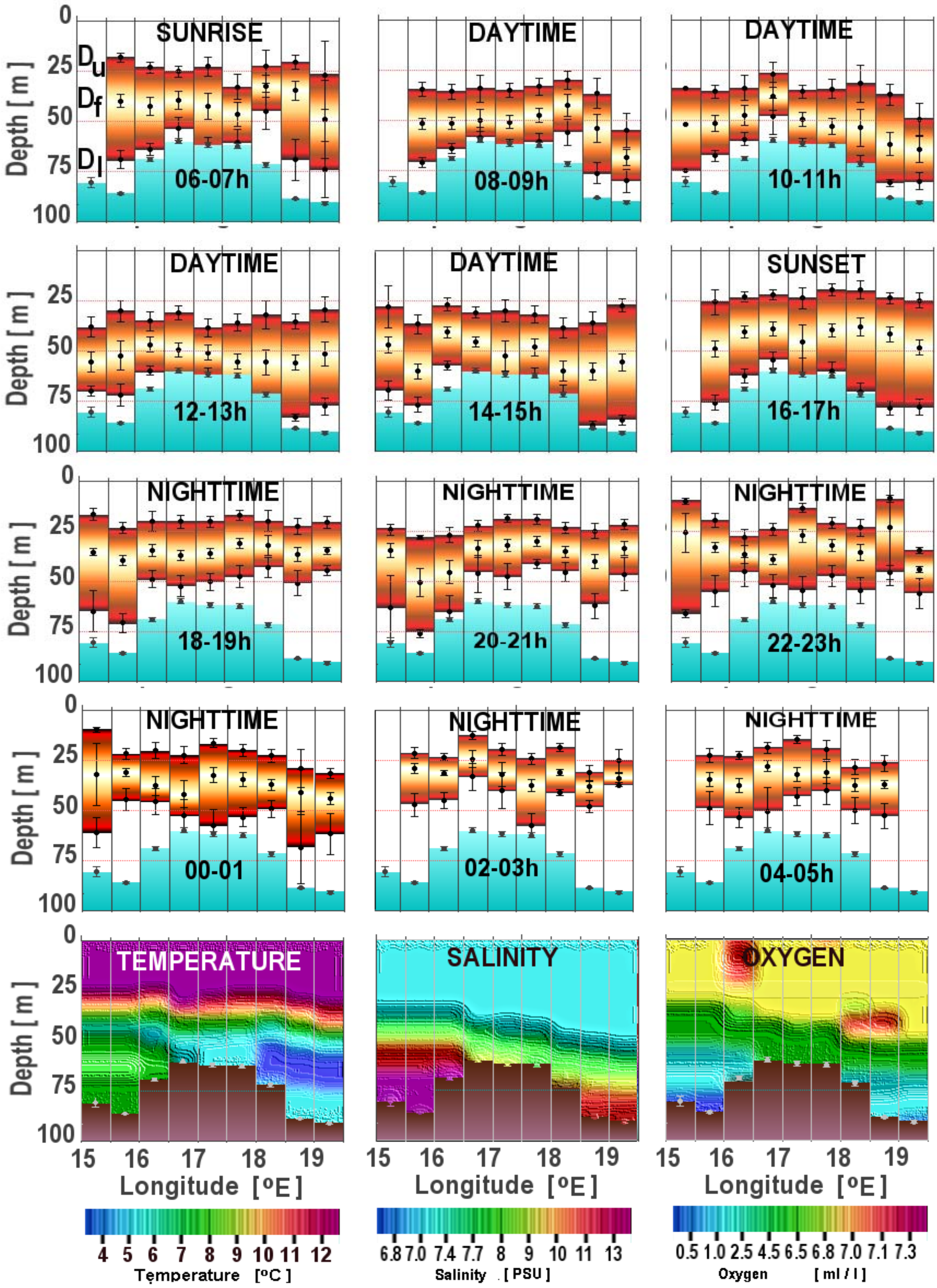

Fig.3. Average (1994-2007) autumn distribution of fish, expressed by upper (D_u), centre of gravity (D_f), and lower (D_l) limit of fish recordings, along transect L1 over 24-h period estimated in selected 1h time periods for 0.5º units of distance along parallel. Lowest panel shows vertical distribution of temperature, salinity and oxygen at the same transect

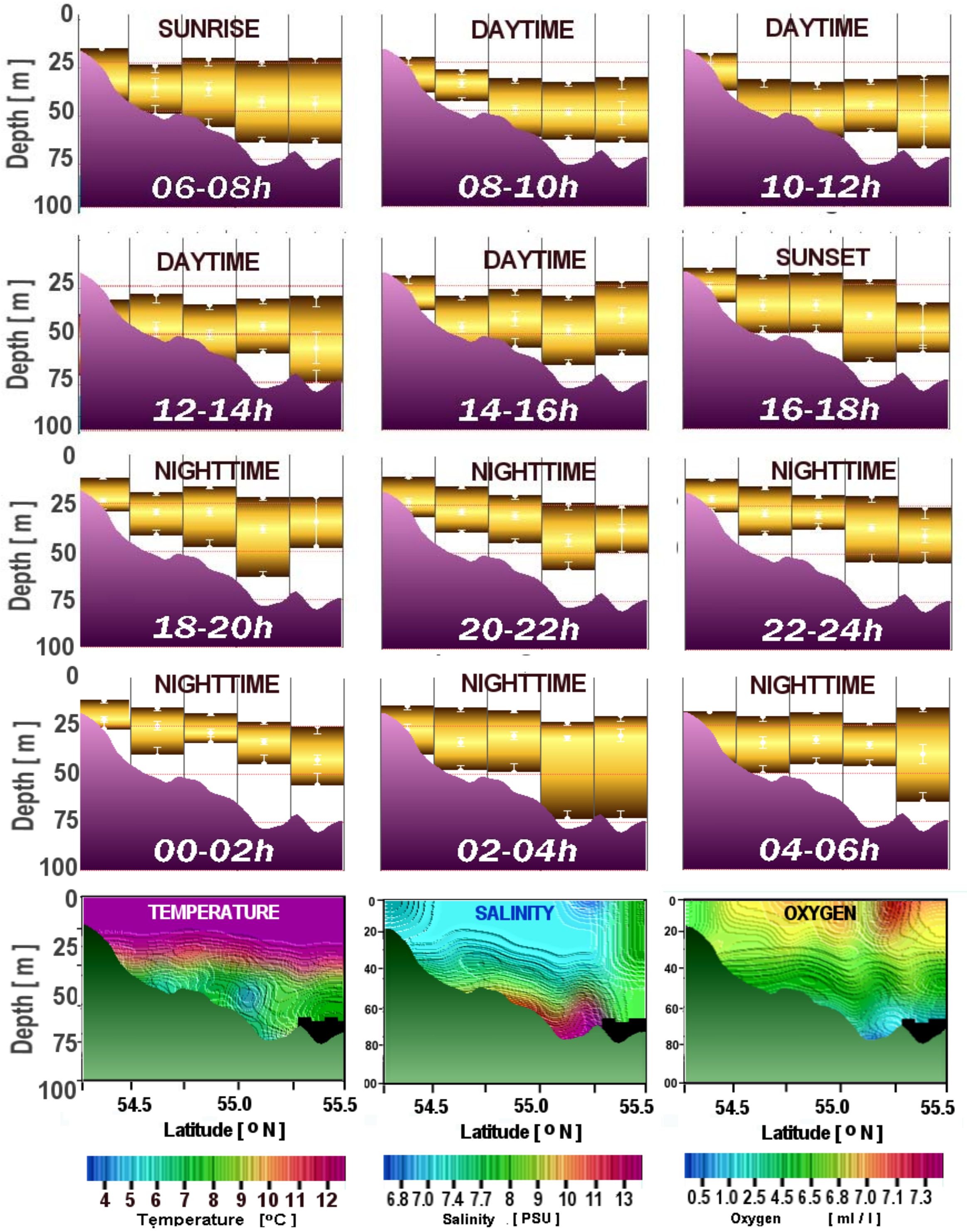

Fig.4. Average (1994-2007) autumn distribution of fish, expressed by upper (D_u), centre of gravity (D_f), and lower (D_l) limit of fish recordings, along transect F1 over 24-h period estimated in selected 1h time periods for 0.25º units of distance along meridian. Lowest panel shows vertical distribution of temperature, salinity and oxygen at the same transect

The first transect L1 (along the parallel 55º15'N – Fig. 3) illustrates the environmental and bathymetric dynamics between the Bornholm and Gdansk Deeps, strongly dependent of inflows of the high salinity water from the North Sea. Both deeps are separated by the bottom shape, what provide a strong limitation of the dynamics of inflow waters. Narrow Slupsk Furrow in the middle produces significant delay in high salinity water expansion.
The distribution of fish is characterized by average values of upper (D_u) centre of gravity (D_f), and lower (D_l) limit of fish recordings, calculated for selected 1h time periods and for 0.5º units of distance. Fish densities at the area of the transect represents close to average values. Percent in weight of three main species are following: 57% herring, 40% sprat, 3% cod.

Results of analysis of fish distribution in different periods of the day can be expressed by following summary:

- configuration of fish vertical distribution is closely correlated to the time of the day,
- three basic configurations (day, night, and transition period) are classified,
- vertical limits of fish migrations are mostly joint with gradients of the environmental factors,
- each factor has differentiated influence on distribution of fish due to the time of the day, geographical localization and bathymetric conditions.

Vertical migration pattern is different in the Bornholm Deep (15-16ºE), in the areas of depth gradients (16-16.5ºE, 18-18.5ºE), Slupsk Furrow (16.5-18 ºE), and Gdansk Deep (18.5-19.5º) The most stable phase is observed during the night time. The biggest instability of the fish distribution appears during the sunrise and the sunset time periods.

The second described transect F1 (along the meridian 16ºE – Fig. 4) illustrates the environmental and bathymetric dynamics between the coast and the middle of the Bornholm Deep, crossing the area from the shallow (20m) to the deeper (>80m) water. The bathymetric profile is monotonic and the depth gradient approximately constant. The halocline appears below 50m depth. The oxygen level is very low in the same range of depth.

The observations noted for the transect L1 are fully valid for the F1 one, but interesting fish behaviour reaction can be observed during the night time in deeper water (over 60m depth) between 55-55.5ºN. Results of catches show higher (10%) percentage of cod in this zone. During the night time (02-04h) the fish recordings appear in demersal zone (60-80m), not usually in comparison to the similar time periods. This phenomenon is quite clearly seen in the Fig. 5, which shows detail variability of volume backscattering strength S_v (t, d) within the period analyzed. The migration of fish from near bottom zone (cod individuals) towards the subsurface layer constituted of pelagic fish is clearly seen (track approximated by line). The fish in pelagic layer responded with escape migrating towards the surface.

Increase of the temperature of sea water joint with the global warming strongly influence the probability of gas ebullition from bottom sediments. There are two basic sources which can substantially influence on methane production in sediments. One source directly is correlated to the earth climate bias, the other corresponds to the anthropogenic factors as: eutrophisation of the reservoirs by intensive agriculture production. In result of the second one increases the percentage of biomass of the underwater flora. This process is negatively correlated with the biomass of the fauna, what in a consequence causes very significant decomposition of the lifeless material. Increase of the temperature in the area of sea bottom accelerates decomposition and decreases solubility of the gases in the same zone.

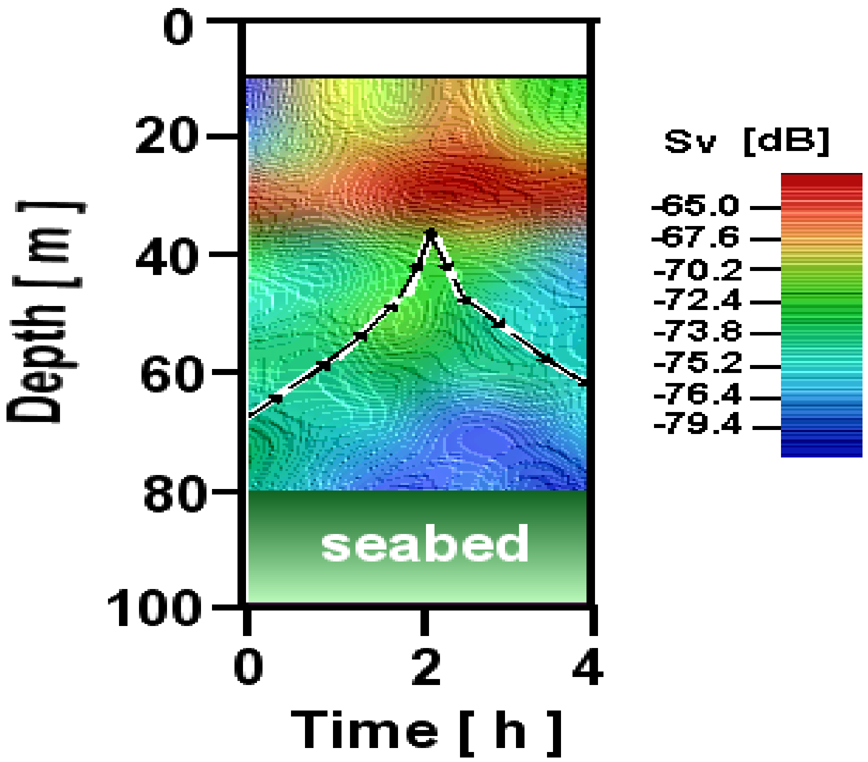

Fig.5. Average (1994-2007) autumn variability of volume backscattering strength S_v (t, d) distribution of fish, along transect F1, indicating cod night feeding migration

2.2 DYNAMICS OF GAS EBULLITION

The most present gas in the bottom sediments is methane, as the product of the anaerobic degradation of organic matter [3, 20, 21]. Due to quickly multiplying favorable circumstances the probability of methane ebullition strongly increases, and the scale of the phenomenon can be incomparable to the level of last hundred years. Acoustics gives us the most effective ways to observe the whole process of production and the ebullition of the methane from the seabed [20]. Due to high difference of the acoustic impedance of the gas and the water the gas bubbles are easily detected by the echo-sounder. The whole process of expulsion of the gas from sediment to the water and rising the bubbles towards the surface can be observed in detail by sonar.

The expulsion of the methane from bottom sediments into water, and rising the bubbles to the sea surface was observed by the author the first time in 1973 aboard RV HYDROMET in the area close to the head of the Hel Peninsula. The echo-recording is presented in Fig. 6. The average velocity of the raise of bubbles was estimated as $0.22ms^{-1}$. The process of bubbling was continuous and was observed during few hours.

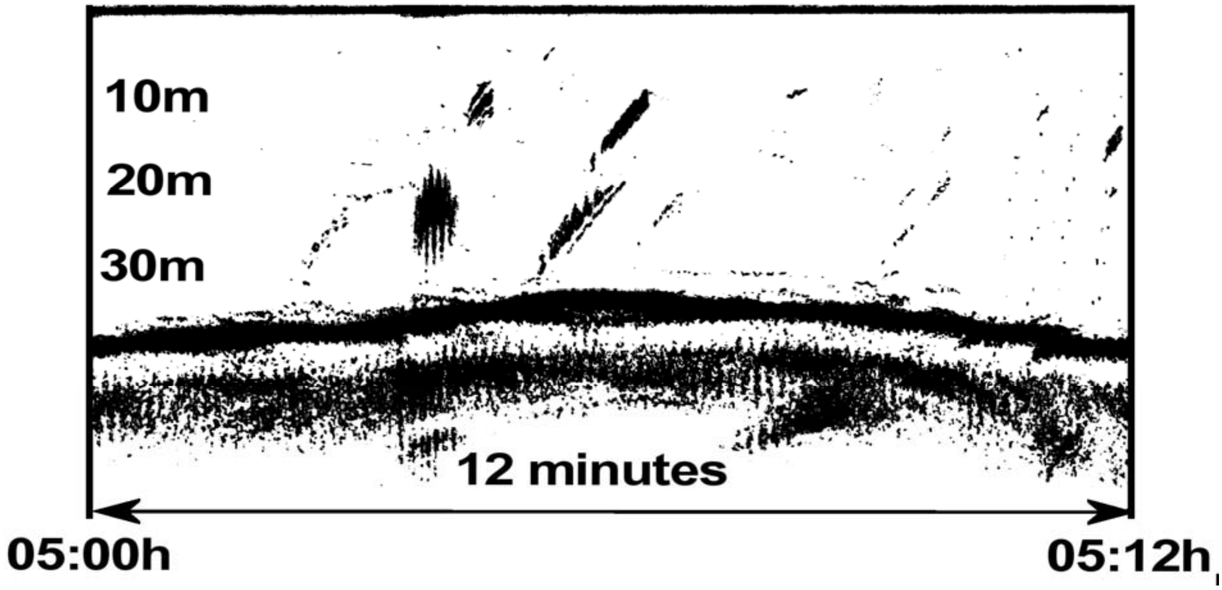

Fig.6. Ebullition of methane from seabed near head of Hel Peninsula observed by ELAC LAZ 17 echo-sounder aboard RV HYDROMET

During analyses of the echograms produced during acoustic survey of pelagic fish resources detail observations of the bottom zone was made since 1981. In 2002 very rare hydrological phenomenon appeared in the southern Baltic. The phenomenon was characterized by very high temperature close to the sea bottom in higher depth. In the Fig. 7 are shown patterns characterizing temperature in a function of depth for one selected station G2(902), being permanently monitored in all RV BALTICA cruises in the autumn. In 2002 the temperature at the bottom over 60m depth was 3ºC higher than during the other years. This fact increased the chemical processes of anaerobic degradation of the organic matter, giving higher probability of the methane ebullition, observed that year at many echo-recordings (Fig. 8.). Detail analysis of echograms collected for the period 1994-2007 in relation to the possible gas ebullition showed some interesting conclusions. In some cases in the moment of impact of CTD sensor (Fig. 1) at the bottom strong gas ebullitions were appearing (Fig. 9.B, C, D) – in the other cases no evidence of this fact was recorded (Fig. 9.A). It can be considered, that the impact of the CTD sensor generates the cloud of the gas ebullition in the area where the sediment is strongly saturated with the gas hydrates. In other cases the impact of the sensor was not producing the ebullition. The phenomenon can be examined in detail by processing the whole package of echoes produced by gas ebullition cause by the CDT sensor impact. Such a model situation, showing this phenomenon was selected (Fig. 10) among many others. The echogram was made in 2004 at the station S1 (Fig. 2), situated close to the station G2(902), described before (Fig.7).

More detail characterization of this area is given in the Table 1, which gives average values of acoustic, biologic and hydrologic magnitudes, and their confidence intervals, maximum, and minimum values, estimated over the period 1994-2007.

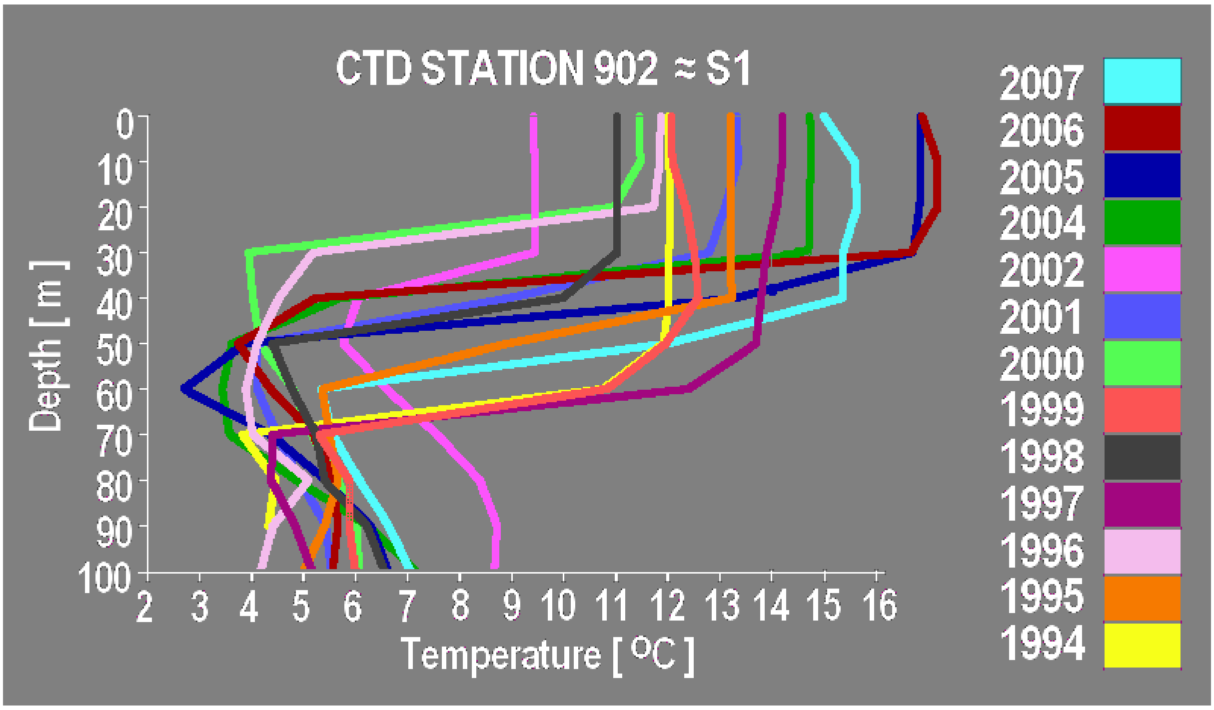

Fig.7. Temperature in a function of water depth at station G2(902) for autumns 1994-2007 (RV BALTICA)

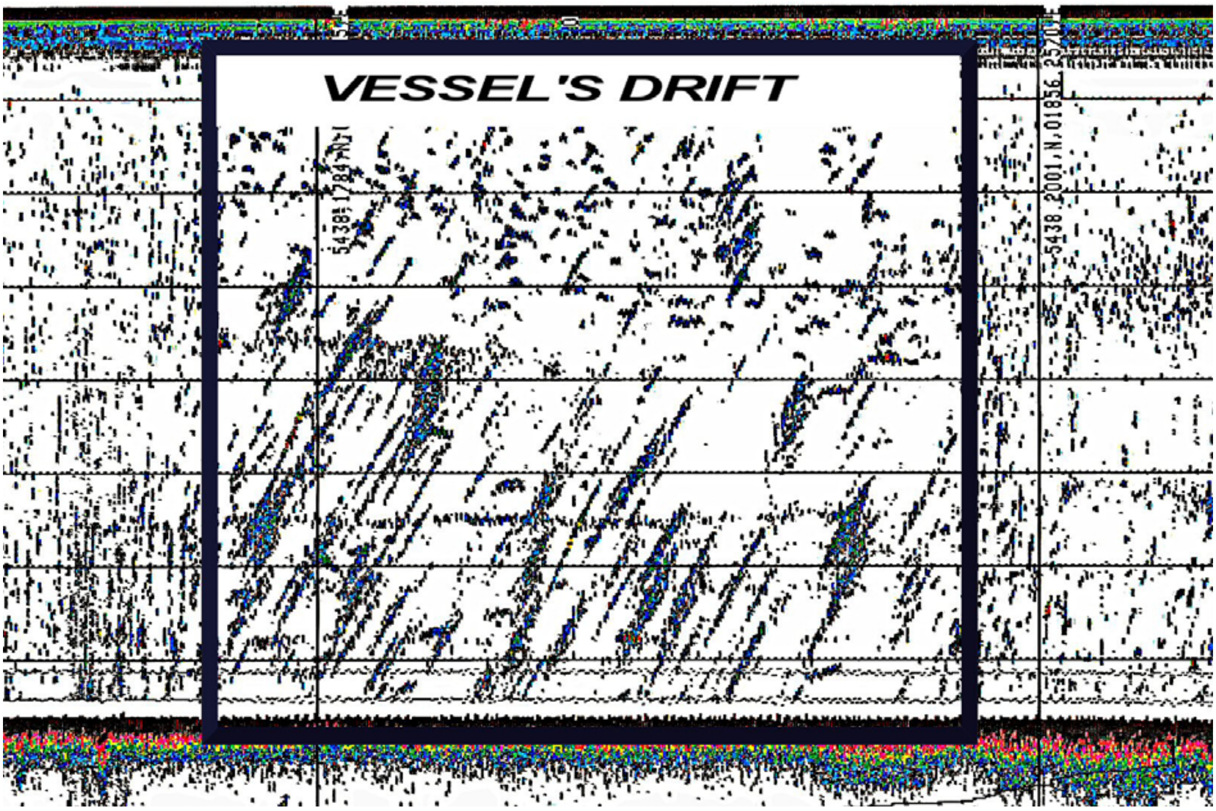

Fig.8. Significant methane ebullitions observed in autumn 2002 (RV BALTICA)

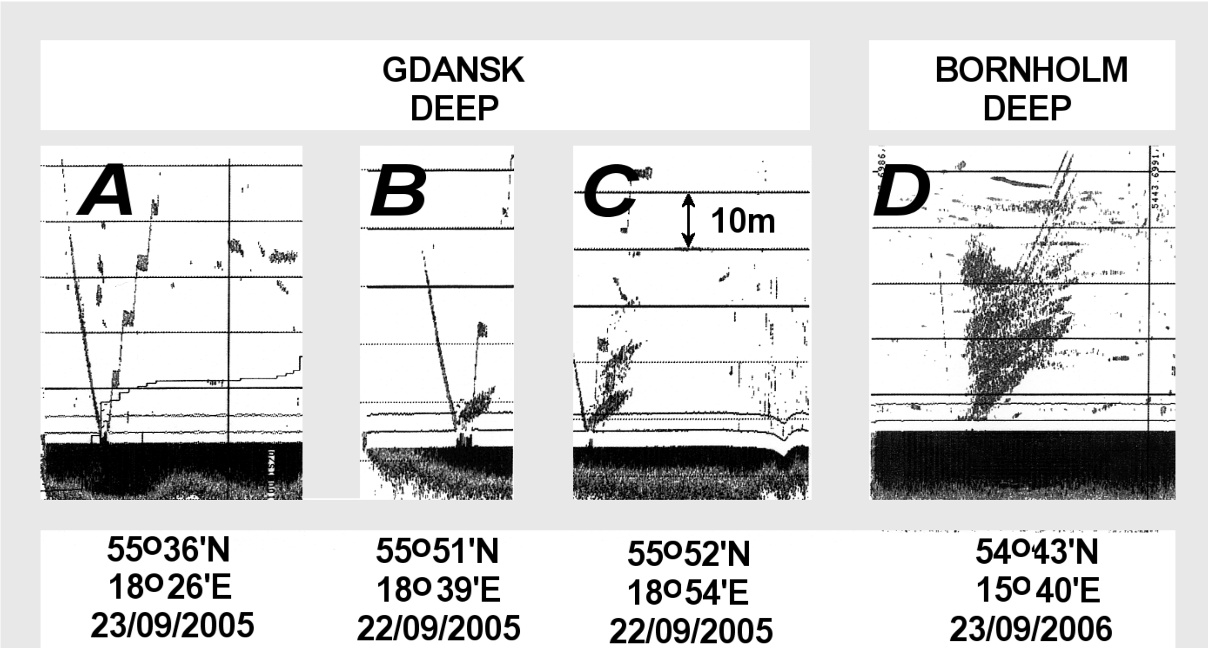

Fig.9. Different forms (A, B, C, D) of response in reaction of impact of CTD sampler to sea bottom sediment (RV BALTICA)

Acoustic data from the station S1 represent:

A. values of scattering of 3m layer over the bottom expressed by S_A,
B. average volume scattering within 3m over the bottom,
C. seabed reflection coefficient calculated with application of multiple echoes measurements [14],
D. value of theta, the parameter characterizing normalized length of bottom echo [19].

Biologic data are calculated by conversion of echoes energy (S_A) integrated over the whole water column into biomass surface density of main fish species, separated by sample hauls results.

Hydrologic data express average values of temperature, salinity and oxygen lavel over a layer 90-100m.

In Fig.10 the traditional echogram is shown in the left side (A). Recording shows launching the CDT sensor (trace marked), which in the moment of touching the seabed generated a huge cloud of the methane. The visualization of the methane ebullition constitutes the main subject of the research. In the first stage an acoustic information on ebullition is filtered according to the depth and time factors. The transformed by this way pattern is shown at the right (B) of Fig. 10. The time is counted from the moment of impact of the sensor on the bottom (T=0s). The whole period of the ebullition lasted approximately 200s. It must be taken into account, that this time period corresponds to acoustic observation of the phenomenon at the frequency 38 kHz. Due to Rayleigh theory the scattering of the gas bubbles is strongly correlated with their diameter and the frequency of the echo-sounder. It
means that variation of the bubble diameter during vertical migration can strongly modulate its echo at fixed frequencies. This element has to be more clearly seen when full animation of the phenomenon is made.

The series of the ebullition echoes (Fig.10.B) is completed with the vertical structure of the water density, calculated on the basis of hydrologic data, measured at the same station.

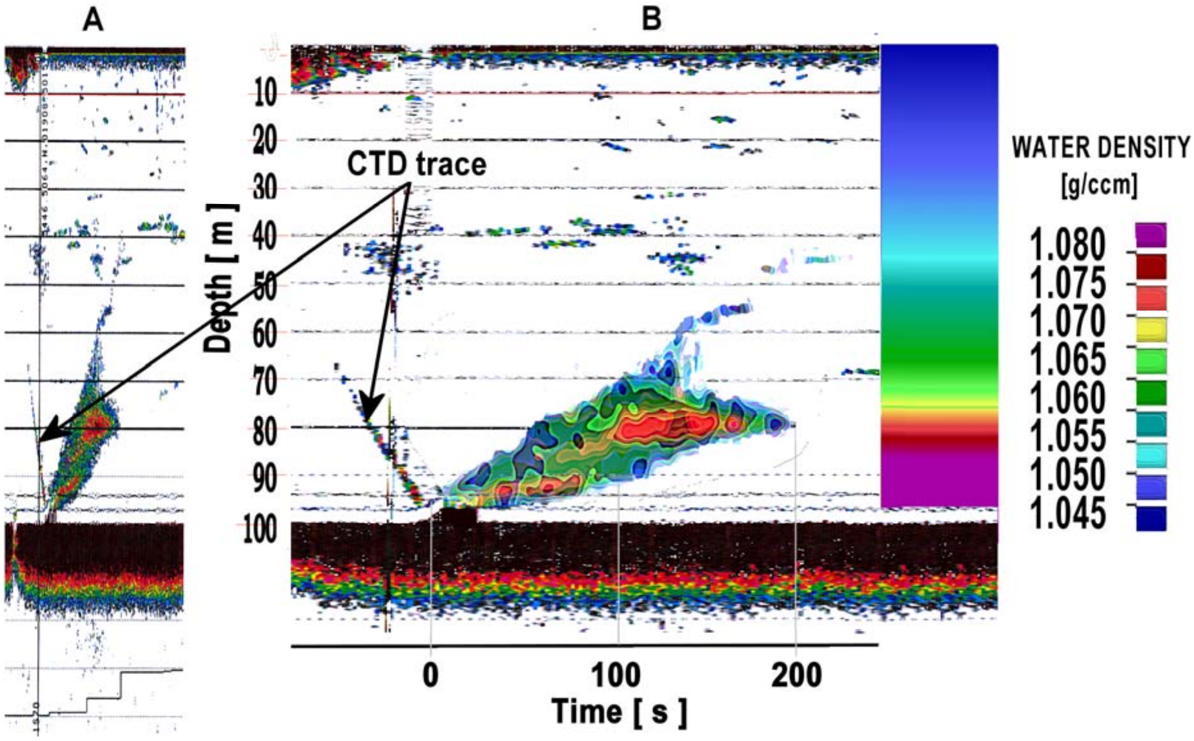

Fig.10. Ebullition of methane at station S1: A – echogram, B – transformed echogram. Water density in function of depth at S1 station area (RV BALTICA, autumn 2004)

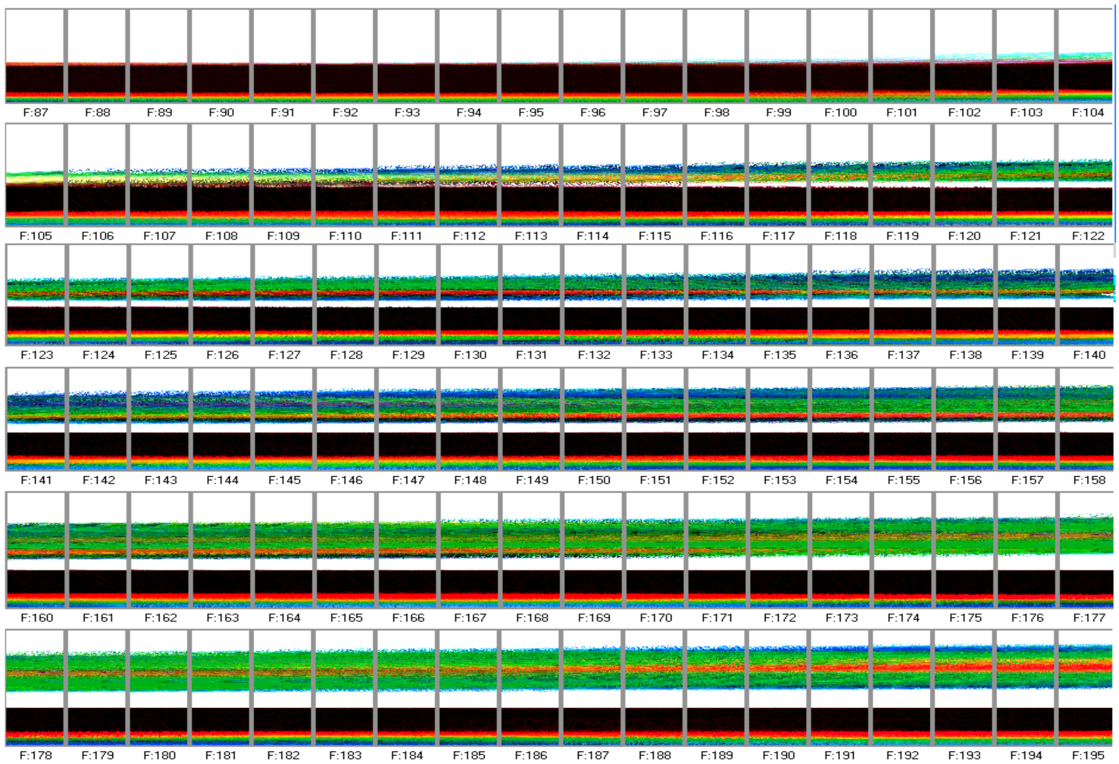

Fig.11. Selected series of frames(108) modeling ebullition of methane at station S1 (RV BALTICA, autumn 2004)

This diagram allows to find correlation between the ebullition process and the gradients of the environment. Approximation of boarders of the acoustic field in a function of time allowed to extrapolate the gas rising speed. In this case the average speed was estimated as 0.24 ms^{-1}, when the lowest was 0.14 ms^{-1} and the highest - 0.4 ms^{-1}.
The final product, the visualization, is based on generating series of single frames from the file corresponding to the recording in Fig. 10.B, and by enhancing the animation with extra frames, interpolated between the original ones. By this method we are able to observe the entire process of ebullition in time and space, comparing all phases with the environmental structure of the media and analyzing the whole process.

Tab.1. Characteristics of acoustic, biologic and hydrologic measurements at station S1 and comparison to whole southern Baltic area

Magnitude, unit	Average value		Conf. int.		Minimum		Maximum	
	S1	South. Baltic	S1	South. Baltic	S1	South. Baltic	S1	South. Baltic
Acoustic measurements								
S_A over 3m demersal layer in m^2 $n.mi^{-2}$	3.54	26.94	1.36	1.15	0.62	0.005	9.54	4889
Sv in 3m demersal layer in dB re m^{-1}	-75.64	-66.84	-79.74	-80.54	-83.14	-104.14	-71.34	-44.24
VD – seabed reflection coeff. in dB [14]	-28.34	-21.25	0.23	1.13	-28.82	-28.58	-27.44	-11.37
Θ'/2 –seabed parameter in º [19]	30.62	23.51	0.80	0.15	29.85	6.93	31.35	46.08
Biologic measurements								
Herring biomass density in t $n.mi^{-2}$	10.59	21.31	8.07	0.65	0	0	69	1962
Sprat biomass density in t. $n.mi^{-2}$	13.53	19.74	13.13	0.56	0	0	113	766
Cod biomass density in t. $n.mi^{-2}$	0.42	1.26	0.28	0.06	0	0	1.72	89
Hydrologic measurements								
Temperature in 90-100m layer in º C	6.03	5.93	0.24	0.12	3.45	3.44	9.20	10.8
Salinity in 90-100m layer in psu	11.51	11.59	0.17	0.15	8.47	8.47	12.88	18.56
Oxygen in 90-100m layer in ml l^{-1}	1.39	1.31	0.25	0.12	0	0	3.77	3.81

3. DISCUSSION AND CONCLUSSIOS

The paper presents results of 2 different case studies in which acoustic methods enabled to observe dynamics of the phenomena typical for the marine ecosystem. The first case was treating on 4D characteristics of fish diel migrations, while the second one was concentrated on detail description of the gas ebullition from the seabed.
Application of acoustic method for evaluation of 4D dynamics of the fish distribution enabled to formulate many new notices, characterizing fish behaviour in relation to the basic abiotic factors of the ecosystem. The method described can significantly enhance previous type of observations [1, 4, 6, 7, 9, 10, 11, 12, 13, 19, 22, 23, 24]. The following conclusions has to be made:

- vertical configuration of the fish is characterized by high diel dynamics,
- diel dynamics of fish configuration is strongly dependent on such environmental factors as: bathymetry, geographical position, vertical and horizontal structure of the main hydrologic factors,
- dynamics is influenced by factors independently but combination of few factors can produce stronger reaction of fish.

Different formulas of filtering and visualization of acoustic data allow to interpret dynamics of fish 4D distribution, producing the information being not possible to obtain by other methods. Animations of time-dependent processes, modeled on the basis of collected data, can significantly enhance biological observations, giving new tool for description of the marine ecosystem.

In the second case acoustic information was transformed to find detail description of the methane ebullition and to correlate it with the environment: the horizontal and vertical structure of hydrology, biology and geology of the area. The phenomenon of generation of the greenhouse gases is directly connected with the climate warming and can accelerate the same process. Evidence and recognition of this phenomena becomes more important year by year. Application of acoustic tracking the phenomenon and modeling its dynamics was fully effective and allowed to formulate the following conclusion:

- in the southern Baltic the probability of methane ebullition is increasing mostly in the areas of Gdansk and Bornholm Deeps, where the bottom sediments are very muddy and contains more organic material,
- those zone are characterized by low level of the oxygen and minimal water currents,
- process of ebullition can be in detail observed by acoustic instruments, but the frequency range of transmitters applied has to be well matched to the bubbles diameters,
- the diameter of the methane bubbles decrease during the raising process (disappearance at 38 kHz in determined period after ebullition),
- diameter of the bubbles is strongly influenced by environmental gradients (maximum was observed at the strongest gradient of the water density).

Taking into consideration the features of the southern Baltic bottom it is possible to estimate the area of potential methane ebullition. In the Polish EEZ such conditions are satisfied by 17% of the total superficies, what corresponds to 4.5 thous km^2.

Basic features of the methane ebullition in the Baltic was clesely comparable with the results obtained in the Lake Kinneret [20, 21].

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