POLISH POLAR RESEARCH
vol. 38, no. 2, pp. 205–229, 2017 doi: 10.1515/popore-2017-0009

Spatial distribution of macroalgae along the shores of Kongsfjorden (West Spitsbergen) using acoustic imaging

Aleksandra KRUSS[1*], Jarosław TĘGOWSKI[2], Agnieszka TATAREK[3], Józef WIKTOR[3] and Philippe BLONDEL[4]

[1] *Istituto di Scienze Marine-Consiglio Nazionale delle Ricerche, Arsenale – Tesa 104, Castello 2737/F, 30122 Venezia, Italy*

[2] *Institute of Oceanography, University of Gdańsk, al. Marszałka Piłsudskiego 46, 81-378 Gdynia, Poland*

[3] *Institute of Oceanology, Polish Academy of Science, ul. Powstańców Warszawy 55, 81-712 Sopot, Poland*

[4] *University of Bath, Department of Physics, Claverton Down, BA2 7AY, Bath, UK*

[*] *corresponding author <aleksandrakruss@gmail.com>*

Abstract: The identification of macroalgal beds is a crucial component for the description of fjord ecosystems. Direct, biological sampling is still the most popular investigation technique but acoustic methods are becoming increasingly recognized as a very efficient tool for the assessment of benthic communities. In 2007 we carried out the first acoustic survey of the littoral areas in Kongsfjorden. A 2.68 km^2 area comprised within a 12.40 km^2 euphotic zone was mapped along the fjord's coast using single- and multi-beam echosounders. The singlebeam echosounder (SBES) proved to be a very efficient and reliable tool for macroalgae detection in Arctic conditions. The multibeam echosounder (MBES) was very useful in extending the SBES survey range, even though it's ability in discriminating benthic communities was limited.

The final result of our investigation is a map of the macroalgae distribution around the fjord, showing 39% macroalgae coverage (1.09 km^2) of investigated area between isobaths -0.70 m and -30 m. Zonation analysis showed that most of the studied macroalgae areas occur up to 15 m depth (93%). These results were confirmed by biological sampling and observation in key areas. The potential of acoustic imaging of macrophytes, and a proposed methodology for the processing of acoustic data, are presented in this paper along with preliminary studies on the acoustic reflectivity of macroalgae, also highlighting differences among species. These results can be applied to future monitoring of the evolution of kelp beds in different areas of the Arctic, and in the rest of the world.

Key words: Arctic, Kongsfjorden, macroalgae, acoustic imaging, habitat mapping.

Introduction

Macroalgal beds are an important part of marine shelf ecosystems, both as primary producers and habitat builders, protecting organisms from predators and currents. They are the dominant species and perennial ones, existing for more than one season. Their role in the carbon cycle and its assimilation is important for coastal and benthic environments. Macroalgae bind organic carbon for a longer time than short-living phytoplankton and remain at the sea bottom (both at the littoral and intertidal) serving as a food source for benthic fauna all year round. Because it is an important environmental component, responsible for up to 20% of primary production in the shallow Arctic (Krause-Jensen *et al*. 2012), it must be taken into account when evaluating the productivity and functioning of fjords (Arrigo and van Dijken 2011). Benthic primary production by macroalgae is difficult to estimate mostly because their biomass and spatial distribution over the coastal areas are poorly quantified (Gattuso *et al*. 2006; Hop *et al*. 2012), whilst known approximations are based on limited studies, mostly from Greenland (Krause-Jensen *et al*. 2007; Krause-Jensen *et al*. 2012). Methods for the evaluation of phytoplankton biomass, productivity and distribution on a wide scale are already well established, but phytobenthos investigations are still a challenging task (Gattuso *et al*. 2006). One has to take into account not only the area and spatial distribution of macroalgae, but also their depth extension that influences benthic net primary production (Gattuso *et al*. 2006; Falkowski and Raven 2007).

Direct biological sampling is still the most popular technique in underwater habitat mapping. It provides detailed information about biomass and species composition. However, despite its accuracy, this method is rather expensive, time-consuming and very localised. Especially in an unknown environment, sampling can be a random process with a blind search for benthic communities and a high probability of not detecting some of them. Conversely, acoustic methods are recognized as a very efficient tool for the assessment of benthic habitats and as an important source of spatial data for the modelling and management of marine environments (Blondel and Murton 1997; Brown *et al*. 2011), particularly when applied to turbid waters. The acoustic approach is very important in polar ecosystems, where intense and dynamic processes require reliable methods for tracking key environmental factors (as macroalgae spatial distribution) (Wiencke *et al*. 2004; Krause-Jensen *et al*. 2007). Aerial photography is also widely applied to the remote monitoring of underwater communities, but the use of this technique in turbid fjord waters is limited (Lehmann and Lachavanne 1997). High-frequency acoustic remote sensing proved to be a better solution for an efficient mapping of benthic habitats in this kind of environment (Anderson *et al*. 2008).

Kongsfjorden is a place where multidisciplinary research on the Arctic environment and climate change has been carried out for many years (*i.e*. Hop *et* *al*. 2002; Gomez *et al*. 2009; Wiencke *et al*. 2011; Hop *et al*. 2012). According to recent biological studies, a climate-driven ecological regime shift was observed there during the last 30 years, seen as a surface temperature increase, glaciers retreating or longer ice-free period, all resulting in spatial and demographic reorganisation of benthic organisms (Węsławski *et al*. 2011; Kortsch *et al*. 2012). Macroalgae are among the indicators of these transformations, being very sensitive especially to water temperature change (Wiencke 2011, Fredriksen *et al*. 2014). Investigations of macroalgae spatial distribution variability in Kongsfjorden between 1980 and 2010 was described by Kortsch *et al*. (2012), showing a significant increase of the seaweeds area along fixed transects (Fig. 1, inside area 1). These observations are in line with registered climate change. Knowledge of macroalgae abundance and spatial distribution along the fjord's coast is essential to draw an exhaustive picture of these environmental transformations.

Our knowledge about the distribution of individual kelp species around the fjord, their habitats and interaction with the marine environment is rather patchy. Most of the information on macroalgae biomass and spatial distribution

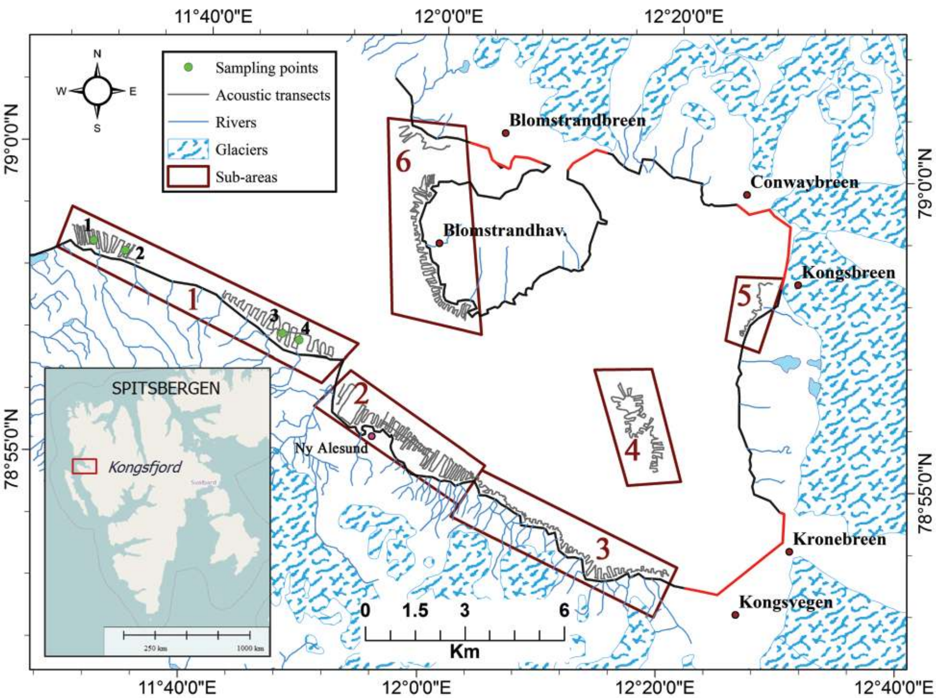

Fig. 1. The map of Svalbard with Kongsfjorden area showing acoustic transects represented as grey lines. SBES measurements are concurrent with the trackline, whereas MBES measurements expand further, their width increasing with depth (for clarity, these swaths ranges are not shown in this map). The shoreline is red in places where there are calving glaciers. The green dots show diving places and the brown borders mark six sub-areas.

in Kongsfjorden comes from samples collected by divers (Włodarska-Kowalczuk *et al*. 1998; Hop *et al*. 2002; Wiencke 2004; Hop *et al*. 2012; Kortsch *et al*. 2012), video data (Beuchel and Gulliksen 2008) or grab samples (Hop *et al*. 2002). These methods provide highly reliable qualitative knowledge about species composition and abundance in one place, but quantitative information is very sparse and implies significant uncertainty when extrapolated to the whole fjord area (Hop *et al*. 2012, Fredriksen *et al*. 2014). Acoustic detection of macroalgae communities around the fjord can be of great help for monitoring their evolution and for planning qualitative, biological sampling.

Studies conducted in Kongsfjorden show that the kelp forests with the highest density occur in the middle sub-littoral zone (5–15 m depth) and that the biomass of dominant species such as *Alaria esculenta* (L.) Greville, *Saccharina latissima* (L.) and *Laminaria digitata* (Huds.) Lamouroux reaches up to 8637 gm^{-2} at 5 m depth (Hop *et al*. 2012). Although the euphotic zone in the fjord rarely exceeds 30 m, only some red algae can be found below this depth (Hop *et al*. 2002; Svendsen 2002; Wiencke 2004; Hop *et al*. 2012). The depth for 1% of photosynthetically active radiation (PAR) during the summer is even limited to 6 m for some of the fjord's areas (Hop *et al*. 2012).

Acoustic studies have shown a significant influence of beds covered by macroalgae on the strength of acoustic backscatter (Carbo and Molero 1997; Sabol *et al*. 2002; Riegl *et al*. 2005; Brown *et al*. 2011; Kruss *et al*. 2012). Models and studies of different substrata acoustic response (Shenderov 1998; Lurton 2002; Jackson and Richardson 2007) show that the distinctive features of echoes received by acoustic instruments (especially SBES) reflect significant differences in benthic structures. The extraction of these signal features, reflecting geomorphological characteristics of benthic habitats, requires a good understanding of the physical interactions between sound waves and the sea bottom (Brown and Blondel 2009). These studies have shown significant influence of macroalgae layers on normal-incidence backscattering, but there are still many doubts about how seaweeds affect scattering over a wide range of angles, and whether they are always clearly distinguishable from the substrata (van Rein *et al*. 2011; http://geohab.org/). Single beam and multibeam echosounders signal analyses have been successfully used in the past for mapping seaweeds and vascular plants (Tęgowski *et al*. 2003; Riegel *et al*. 2005; McGonigle *et al*. 2011; van Rein *et al*. 2011; Parnum unpublished data) but our study is one of the first to be conducted in Arctic fjords (Dunton *et al*. 1982; Kruss *et al*. 2006; Woelfel *et al*. 2010; Tatarek *et al*. 2012). Our team had gained previous experience in Hornsund fjord in 2005 (Kruss *et al*. 2006), where a combination of biological sampling and acoustic imaging (using SBES and a side scan sonar) proved to be efficient and reliable for macroalgae detection.

The main purpose of the present research was to determine the area and spatial variability of macrophytes in Kongsfjorden, and to show the potential of acoustic methods (namely SBES and MBES) for further biological studies and for planning qualitative surveys in that area. To achieve this task, the acoustic reflectivity of benthic vegetation was studied theoretically and experimentally. These steps were used to prepare the methodology and signal analysis techniques for the collection and processing of SBES and MBES data in order to detect macroalgae communities and for further interpretation of collected data. The acoustic habitat mapping techniques we present in this paper offer an efficient solution for holistic and repeatable surveys of the seabed, in this case providing high resolution maps of the bathymetry and of the spatial distribution of macrophytobenthos around a typical Arctic fjord.

Materials and methods

Survey area. — The study was conducted in Kongsfjorden (Fig. 1), a fjord approximately 26 km long and 4–11 km wide, with a total area of ~230 km^2 (Hop *et al*. 2002). The acoustic survey was limited to the euphotic zone (~12.40 km^2). The depth of the bottom area where macroalgae occur is highly variable, due to dynamic changes of water transparency in glacier and river regions, but it rarely exceeds 30 m (Svendsen 2002; Wiencke 2004; Fredriksen *et al*. 2014).

From the west, Kongsfjorden is open to the sea and influenced by the West Spitsbergen Current waters. From the east, it is supplied by freshwater coming from melting glaciers and rivers, carrying a significant amount of suspended matter. The fjord is therefore exposed to dynamic changes in the composition and circulation of water masses. In general, water flows in along the southern coast of Kongsfjorden and flows out through the northern part. There are five main calving glaciers: Kronebreen, Kongsvegen and Kongsbreen in the innermost part of Kongsfjorden, and Conwaybreen and Blomstrandbreen on its northern coast (Fig. 1). The most turbid waters are around the calving glacier fronts on the south-eastern shore, especially next to the Kronebreen glacier, and suspended particle concentrations decrease with depth and distance from the glaciers towards the open fjord (Svendsen 2002). All these factors (*e.g*., water salinity, turbidity or temperature) cause different conditions of macroalgae growth around the fjord, modifying their communities. The presence of glacier ice can cause considerable damage to the brown algae meadows that are torn from the sea bottom or scoured. The other factors having an impact on seaweeds are waves and currents, which do not allow soft sediments to stay on hard substrata over shallow areas in the subtidal zone, and also destroy habitats. In order to stay in place, macroalgae must anchor themselves to rocky bottoms or stones (Svendsen 2002). Due to this environmental variability around the fjord there is a fluctuation in macroalgae abundance and spatial range depending on the region.

To provide a more comprehensive study of the variability of seaweed spatial distribution, the fjord was divided into 6 subareas influenced by different environmental conditions (*e.g.*, glaciers, rivers, and outer and inner parts of the fjord) (Fig. 1) and into 4 depth zones (namely littoral and sublittoral (upper, mid and low), according to Wiencke (2004).

Periods of ice-free days are getting longer in Kongsfjorden, as in other Arctic fjords, during the last few decades (Kortsch *et al.* 2012), which is another important factor for benthic communities growth. When present, sea surface ice stays for the longest in the north-eastern part of Kongsfjorden (until the end of June) (Gerland and Renner 2007).

According to the Norwegian Mapping Authority data from the Ny-Alesund gauge (Hydrographic Service, http://vannstand.no), tides registered for the period of our research range between 19 cm and 150 cm above the Chart datum.

Acoustic data. — The acoustic data were collected in July 2007 in Kongsfjorden, and the overall campaign lasted two weeks. The survey was carried out from an aluminium motorboat, equipped with two transducers mounted on separate poles. The SBES was pole-mounted on the starboard side and the MBES was mounted in parallel on the port side. Due to frequency differences between the two devices, they could collect data simultaneously and without interference. Each device was linked to its own GPS receiver. All acoustic transects were perpendicular to the shore line, spaced every 100–150 m. There were some deviations due to underwater rocks close to the water line and drifting icebergs. Overall, a total distance of 135 km was surveyed and a total area of 2.68 km^2 was investigated (Fig. 1). The shallowest part studied was only 0.70 m deep.

One part of the acoustic dataset was collected with the calibrated SBES, Biosonics DTX. It operates at 420 kHz emitting a narrow, acoustic beam (5.2° wide). The survey was carried out with a constant pulse length of 0.1 ms, yielding a vertical resolution of 0.02 m. The horizontal resolution was ~0.30 m – 0.90 m (depending on depth). The echo signal was recorded as SV values (*i.e.* volume backscattering strengths), measuring the intensity of signal backscattered to the echosounder relative to a particular pulse volume along the signal path (Balk and Lindem 2004). These values were pre-processed by the built-in system, including signal loss compensation.

Data received by SBES were analysed and compared to biological samples and in situ observations in order to confirm its ability to detect macroalgae on the seabed and how they influence the acoustic signal. Fig. 2a shows part of a SBES echogram (from the diving points #1 and #2 area, Fig. 1) with the macroalgae layer clearly visible in the backscatter as clouds of specific SV values (between -20 dB and -40 dB) above the bottom line recognizable as higher signal strength (>-10dB). On the right, inset charts show two representative single-ping SV profiles (Fig. 2b, c). The first (Fig. 2b) indicated by a green arrow on the echogram, comes from the macroalgae growing over a hard bottom area and the second (Fig. 2c, red arrow) is from a bare, hard seabed. A comparison between

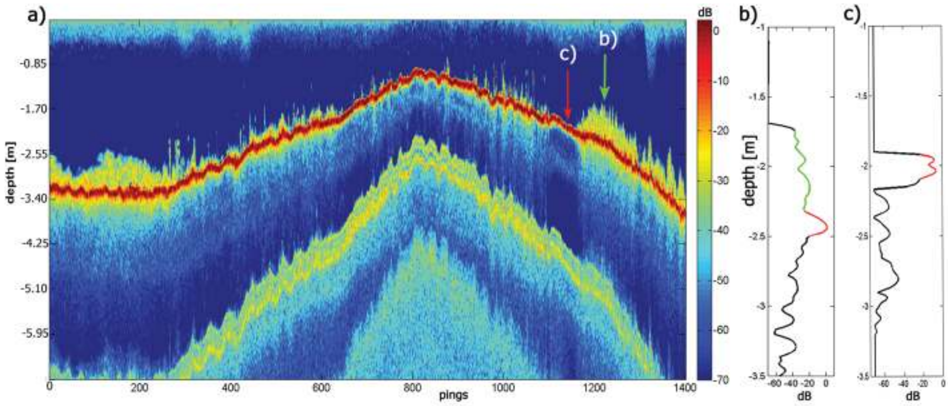

Fig. 2. Single beam echosounder echogram (SV values), showing acoustic measurements as a function of ping number and depths (a). Two examples on the right represent single echo signals (SV in dB) changing with depth: one is related to the bottom with macroalgae (b, green arrow) and the other to the bare bottom (c, red arrow), highlighted in red for the seabed detection area and green for the macroalgae.

these two spots shows an important difference in their respective echo levels and shapes. The backscatter values depend on macroalgae properties such as density, species type or associated benthic fauna (Kruss *et al*. 2008; Kruss *et al*. 2012). Because seaweeds grow mostly on hard, rocky or stony bottoms which strongly reflect the acoustic signal (>-10 dB), the significant contrast between echo intensity values coming from kelps and bottom parts makes macroalgae detection possible.

In contrast to SBES, MBES receives numerous narrow beams combined together into a wide swath. MBES can rapidly cover large areas (even 10 times wider than the water depth). The MBES used here is an Imagenex 837A Delta-T compact device. It creates a swath of 120° x 20° divided into 120 beams, ensonified at a frequency of 260 kHz. The nominal vertical resolution of the MBES is 0.2% of the range selected by the user (*i.e*. 0.02 m at 8 m). Data were acquired for three times the depth range: usually 20 m, 30 m, 40 m and 60 m. MBES data were collected without motion unit support due to cost limits and to the high risk of damage in Arctic conditions. The data were later corrected in post-processing with sound speed profiles collected at the same time around Kongsfjorden by R/V *Oceania*, the research vessel of the Polish Academy of Sciences. The tidal correction was also applied to the bathymetric data.

MBES systems deliver high-resolution co-located bathymetry and acoustic backscatter strength from the bottom surface and from the water column. This provides data from the seabed as well as any scatterers above it (*e.g*. plants, fish, or bubbles). An example of registered echo intensity values in a typical MBES swath is presented in Fig. 3. The track showing bottom detection is represented

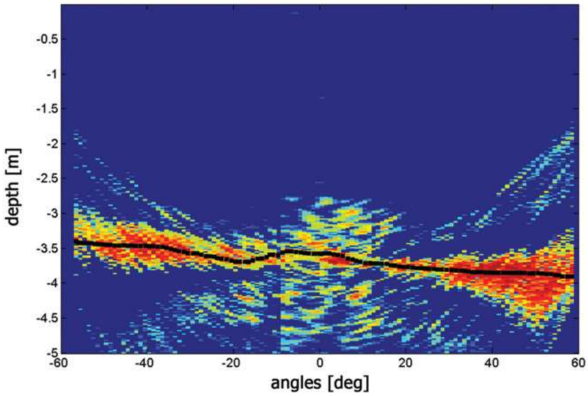

Fig. 3. Typical example of echogram of raw measurement with the multibeam echosounder swath, whose 120 beams cover 120°. Backscatter is not calibrated but represented as a function of the imager's gain. Echo strengths are colour-coded from blue (no or little backscatter) to red (very high backscatter). The seabed (black line) appears relatively flat at 3.5 m depth, sloping slightly to the right. Echoes above the seabed and in the central beams (-16.5° to +16.5°) show targets above the seabed, with lower acoustic reflectivities (yellow-green) and distinct shapes, interpreted here as macrophytes. Water column echoes coming from outer beams are not used in the analyses (see text for details of sidelobe effect).

by a black line inside high echo intensity areas (red); weaker signals from the macroalgae layer (green and yellow) can be observed in the centre of the swath and some noise (light blue) occurs mostly on the side beams. These registered echoes depend not only on the reflectivity of bottom and scatterers but also on the angles of incidence of the signal. One can observe the effect of a sidelobe interference (light blue) in the water column backscatter, an artefact characteristic of MBES systems (Lurton 2002; Hughes Clarke 2006). This effect can mask seaweeds in outer beams and restrict their detection to central beams only, depending on the quality of the MBES system used. The example below (Fig. 3) comes from an area where direct, biological sampling was conducted (Fig. 1, point #1). According to the divers' report, the area comprised a dense macroalgae community, but distinct macroalgae reflection can only be observed in the central beams (Fig. 3).

Biological studies. — During the acoustic survey around shallow, transparent waters south of the fjord, the biologists from our team performed an on-flight visual inspection through aquascope to confirm the occurrence of macroalgae beds and to compare the observation with the real time image from SBES echogram. Thereby we confirmed the significant difference between echo shapes related to bare bottom and vegetation areas. After preparing a preliminary map of macroalgae distribution based on acoustic data for the southern coast of the fjord, we established 4 points for biological sampling to verify our results.

Scuba divers collected seaweeds at each location from a 0.25 m^2 area limited by frames (Fig. 1, green dots). Samples were taxonomically determined using the key book by Wiktor *et al*. (1995). The size and biomass of each taxa in the samples were also evaluated.

Acoustic data processing. — We analysed the acoustic characteristics of seaweeds focusing on SBES data because this approach is more straightforward in order to compare with the literature and does not involve angular response models. Acoustic detection of macroalgae is based on their physical properties, such as the density of the thallus or its size (Carbo and Molero 1997; Shenderov 1998).

The SBES echo envelopes recorded over rocky, sandy or muddy bottom and seafloor covered by macrophytes are considerably different (Shenderov 1998; Jackson and Richardson 2007). When pulses are scattered at the vegetation, echo duration is much longer and the shape of consecutive echo envelopes is much more uneven than for signals scattered at a bare, hard bottom (Sabol *et al*. 2002; Kruss *et al*. 2008; Fig. 3b, c).

The first approach to macroalgae detection was an echogram image analysis that used the industry-standard software Sonar 5 (Balk and Lindem 2004) to apply an edge-detection algorithm. The latter is based on an analysis of intensity in an echogram image to distinguish borders between water, kelps and bottom using SV values characteristic of the reflectivity of these elements. This procedure also provides estimations of macrophyte heights (distance between bare seafloor and top of vegetation, as well as bottom area covered by macrophytes), and mean SV values from inside the layer. This method is especially efficient for large datasets and provides reliable results over flat bottom and average slopes. Nevertheless, parts of the data, usually from deep or sloping areas, were sometimes detected by the Sonar 5 algorithm as macroalgae, although they corresponded in fact to a muddy bottom or to very steep slopes (as confirmed by anchor sampling). Steep slopes (>20%) influence echo shapes (making them last longer) and acoustic backscatter (von Szalay and McConnaughey 2002). To remove such misclassifications, echo envelopes were further processed with our own Matlab algorithms and based on signal data processing procedures presented below (Fig. 4).

Signal processing algorithms comprise parametrical descriptions of echo envelopes and produce data set features whose values reflect the variability of their shapes (Tęgowski *et al*. 2003; van Walree *et al*. 2005; Michaels 2007). In our previous studies we tested a large set of different echo envelope parameters, such as spectral, fractal, statistical and wavelet echo features (*e.g*., Tęgowski and Lubniewski 2002; Kruss *et al*. 2008). However, in the present study, the limited set of parameters proved to be sufficient. The outline of the classification is presented below (Fig. 4).

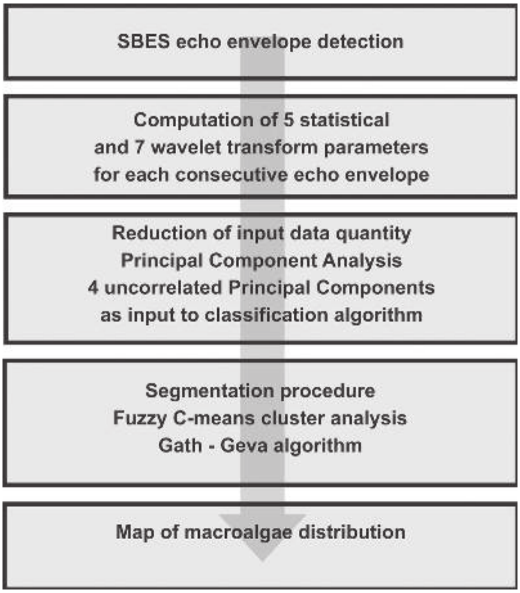

Fig. 4. Processing and classification procedure for single beam echosounder data.

As shown in Fig. 4, the statistical and wavelet transformation echo parameters were first calculated for each consecutive echo envelope, where the second-order central statistical moment m_2 is defined as

$$m_2 = \frac{1}{n-1}\sum_{i}^{n}\left(p_i - \overline{p}\right)^2,$$

in which $i = 1, 2, ..., n$ is the sample number within the echo envelope, p_i is the pressure value of the i-th sample and $\overline{p}$ is the mean pressure of the echo.

The statistical kurtosis γ is:

$$\gamma = \frac{m_3}{\sigma^3},$$

where m_3 is the third-order central statistical moment defined similarly to the second moment and σ is the standard deviation of pressure in the echo envelope. The other calculated statistical parameters of echo envelope were the standard deviation and maximum and mean echo intensity values.

The other parameters included are wavelet features, which are very sensitive to changes in echo shape. The continuous wavelet transformation of echo envelopes was computed for the 7-channel dyadic decomposition (scale $a = 2^j$, $j = 1, ..., 7$) and 3rd-order Coiflet (*Coif3*) wavelets to determine wavelet energies, which are particularly effective in the segmentation and classification procedures (*e.g.* Atallah *et al.* 2002):

$$E_{j,Coif3} = \int_{b_{min}}^{b_{max}} C^2(a,b)\,\mathrm{d}b\,,$$

where $C(a,b)$ are the wavelet transformation coefficients, a is the scaling factor, b_{min} and b_{max} are boundary values of scale b (time).

Some of the echo envelope parameters defined above are linearly dependent. Principal Component Analysis (PCA) was applied to remove this redundancy and to produce a new set of parameters called Principal Components (PC) (Wold 1987). They were ordered by explanatory values. The number of useful PCs is determined by their summed variations, which should ensure above 95% of cumulative variation. In this study, the first four PC were enough for further classification. Finally, a clustering algorithm of fuzzy logic analysis (Gath-Geva) implemented in Matlab was used to divide the data into clusters. The statistical measure of segmentation success is the partition coefficient (PCo). It describes how efficiently the data set was divided into subsets and should have a value above 0.9 (on a 0–1 scale) (Bezdek and Dune 1975). In our case the maximum value was obtained for 3 classes. Parametric analysis of echo signals, compared to backscatter models (Shenderov 1998; Jackson and Richardson 2007) and in situ observations, helped us assign the acoustic signals after segmentation to bottom types. Three seabed classes were defined: bare hard bottom, bare soft bottom, and vegetation.

It was assumed that macroalgae grow on hard bottom or are attached to stones or pebbles (Wiencke 2011; Hop *et al*. 2012), which simplified the classification. The main difficulty was to separate pings coming from soft bottoms or slopes from those related to macroalgae areas according to their echo length. The energy parameter improved discrimination between these classes because a soft bottom has a lower backscatter than a hard bottom covered with macroalgae, although the shapes of the signals are similar.

MBES data are not as straightforward to process as SBES due to the angular dependence of reflected signals and to the noise coming from sidelobe interference visible in the water column backscatter (Fig. 3) (*e.g*., de Moustier and Alexandrou 1991; Hughes Clarke 2006; Kruss *et al*. 2012; http://geohab.org). Due to the limited number of biological samples in Kongsfjorden, it was necessary to study more comprehensively the acoustic properties of macroalgae and the Imagenex Delta-T multibeam performance. A tank experiment was conducted at the University of Bath after the field campaign, using the same MBES as in the Arctic research and exactly the same macroalgae species as in Kongsfjorden, but collected along the English coast, including S*accharina latissima* and *Laminaria digitata*. These specimens were bound in groups with a biomass of ca. 2 kg and moved below the transducer over different substrata and across the swath. The results showed that only the central beams, with angles ranging from -16.5° to +16.5°, can be used to obtain reliable results for macroalgae detection with this MBES (Kruss *et al*. 2012), registering their characteristic echo shape. In outer beams (more than 17° from nadir), there is a strong influence of the sidelobe effect on water column data, which prevents correct macroalgae detection.

The values of the backscattering intensity were recorded by the Imagenex software and represented as numbers within a 0–255 range. They were already scaled in terms of beam insonification area and transmission loss. The data were processed in Matlab with our own algorithms for slant range correction, bottom detection and macroalgae identification using water column backscatter data (Kruss *et al*. 2012). Each survey line range was limited to between -16.5° and +16.5° angles and saved as slices of SBES-like echograms corresponding to all pings at a certain angle every 1°, along the survey track. MBES echograms were log-transformed and each slice was processed using mathematical morphology tools (namely closing operators) to remove noisy, high-intensity small spikes from the water column (Haralick *et al*. 1987). In each slice, bottom detection was achieved using a maximum-amplitude approach, and macroalgae tops were detected based on an edge-detection algorithm in Matlab. This procedure detects sharp changes in image brightness (pixel values related to backscatter intensity), resulting in edge lines (Nilback 1986) separating the reflection of macroalgae from that of the water and bottom.

The abundance and spatial distribution of macroalgae were first calculated for single beam data, then compared to multibeam data to check their correlation when they overlapped. The two kinds of results created a database with points (including Easting, Northing, and depth with macroalgae height). This outcome was gridded using the Kriging method with a linear variogram (Isaaks and Srivastava 1989; Cressie 1993) to create a map layer showing macroalgae distribution over the investigated areas. The threshold value for seaweed detection was set to 0.05 m for both devices.

The classification results were compared to biological samples data and to visual inspection over the shallow bottom areas.

Results

Biological studies. — In the 4 areas sampled directly (Fig. 1, green dots), 6 macroalgae species were found. Four of them belong to Phaeophyta – *Alaria esculenta* (L.) Greville, *Desmarestia aculeata* (L.) J.V. Lamouroux, *Saccharina latissima* and *Saccorhiza dermatodea* (Bachelot de la Pylaie) J. Agardh. The other 2 belong to the Rhodophyta – *Palmaria palmata* F. Weber *et* D. Mohr and *Ptilota gunneri* P.C. Silva, Maggs *et* L.M. Irvine in Maggs *et* Hommersand. The species which occurred in all 4 stations was *Saccharina latissima*. The biggest biomass of macroalgae in the sampling areas was at Station #2, it was

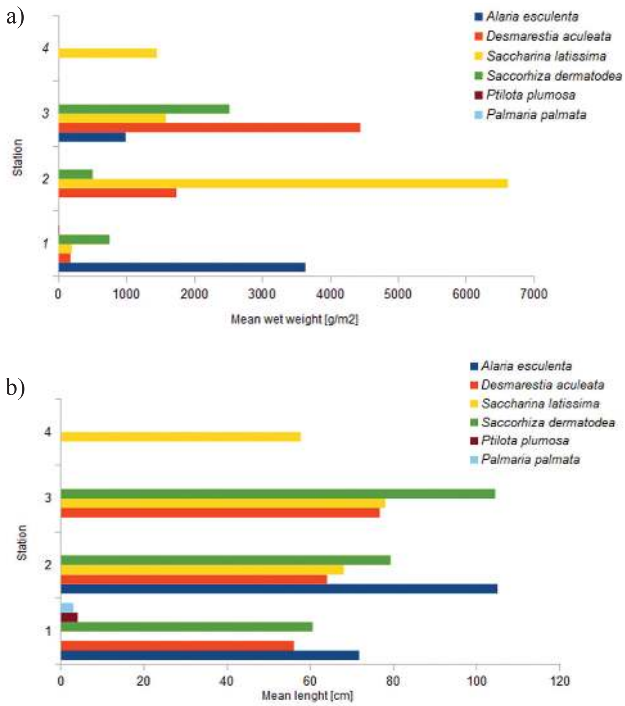

Fig. 5. The mean wet weight of macroalgae collected at sampling stations (1 g accuracy) (a). The average lengths of particular taxa of seaweeds collected at four sampling stations (1 cm accuracy) (b).

Saccharina latissima (Fig. 5a) with 6612 gm^{-2} of wet weight. The smallest biomass was that of two Rhodophyta species found at Station #4 (8 gm^{-2} each). The results show that the examined areas were covered mostly by brown algae, the dominant group in this region. Scuba divers observed hard substrate (*e.g.*, rock, stones or gravel) in all the locations.

The size of kelps varied between the sampled locations (Fig. 5b, the average length). The longest specimen, a *Saccorhiza dermatodea* kelp, was found at Station #3 and was 190 cm long. It was also the longest of all the species sampled in all locations. The overview of average macroalgae lengths for each taxa (Fig. 5b) shows that 2 stations (#2 and #3) had longer seaweeds than the other two (#1 and #4). At Station #2 the longest species was *Alaria esculenta*, while at Station #3 the mean longest taxa was *Saccorhiza dermatodea*.

Observations from aquascope were used not only to verify the acoustic signal but also to compare it with species type on the bottom (Fig. 2). The species observed around pings 900–1100 were thin and long *Halosiphon tomentosus* (Lyngbye) Jaasund and around pings 1–350 were large brown, algae (*Alaria esculenta*, *Saccharina latissima*, *Saccorhiza dermatodea*).

Estimation of macroalgae spatial distribution. — During the final segmentation process we used as input features 4 Principal Components with 97% explanatory value. The subsets were assigned to 3 bottom classes according to their clustering centres. Each centre represented the values of features characteristic of the echo shapes of hard or soft bottoms and of bottoms covered by macroalgae. Evaluation of the clustering procedure shown a partition coefficient PCo=0.96, which is recognized in the literature as a good result for the statistical division of the data set (Bezdek and Dunn 1975). The classification procedure described here does not give information about macroalgae heights, so we used the data obtained from image analysis and only modified them with classification results, thus removing false detections.

To better understand the morphology of the very shallow area of the fjord (<30 m depth), we created a bathymetry map (Fig. 6) based on SBES data, also using the Kriging algorithm for a 20 m neighbourhood and a 2 m resolution. We could not incorporate all the MBES data because of the lack of a motion reference unit, so only central beams were used not to introduce large positioning errors.

Overall, SBES amounts covered a 0.13 km² area, whereas the MBES dataset, limited to ±16° beams, covered a 0.78 km² (summed acoustic footprint area). Detected macroalgae cover 39% of the investigated region (0.30 km²). To present

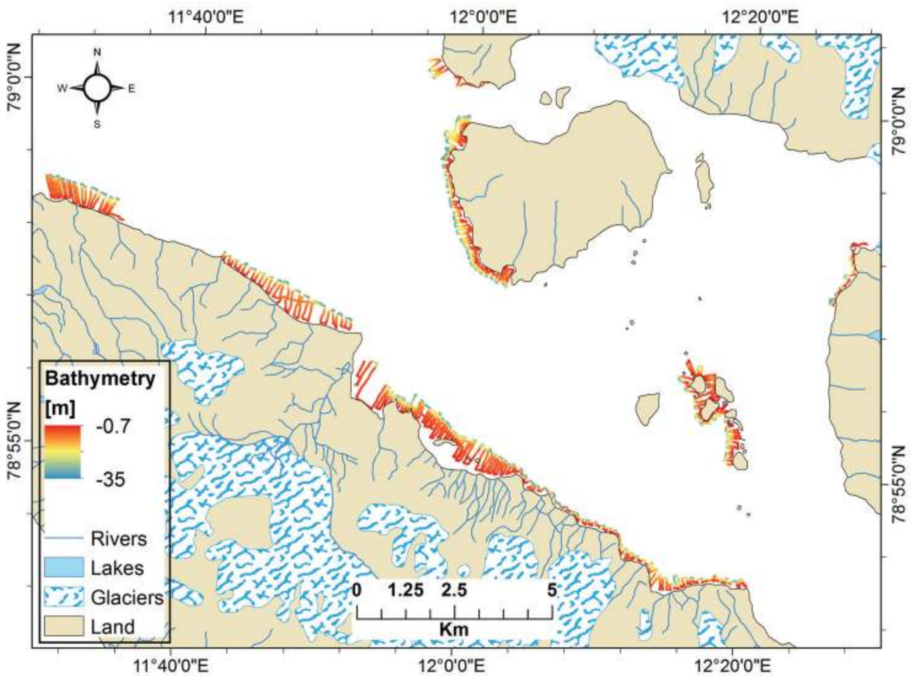

Fig. 6. Kongsfjorden coastal zone bathymetry, in UTM33X map projection. Data based on collected SBES data with a 2 m grid resolution.

results as a continuous data layer, heights were gridded to 1 m resolution (using an ordinary Kriging interpolation with 20 m neighbourhood). It resulted in the map of a 2.68 km² bottom area around the fjord's shore, with 1.09 km² of macroalgae layer and with a Kriging standard deviation error of 0.11 m and of 41% the seabed coverage. In other words, we obtained information about the macroalgae distribution around the fjord (Fig. 7), covering 20% of its euphotic bottom area and having 2% error of macroalgae detection spatial interpolation, while keeping high spatial resolution. Fig. 7 also shows macroalgae height variability, with maximum values up to 1.30 m.

The mean macroalgae heights and spatial distribution related to the subareas and zones are presented in Table 1. All results, except the last row of table 1, are based on direct detections from acoustic data and related to areas of acoustic footprints. The last row is derived from gridded layers of bathymetry and macroalgae heights, compared in ArcGIS. The values illustrate the percentage of bottom covered by seaweeds for each depth zone (Table 1).

According to ArcGIS comparison of bathymetry and macroalgae distribution layers, it occurred that most of the investigated macroalgae appear in the first 15 meters of depth (93%). The results in Table 1 show the biggest bottom coverage by kelps in the upper sublittoral belt (66%). We found the biggest

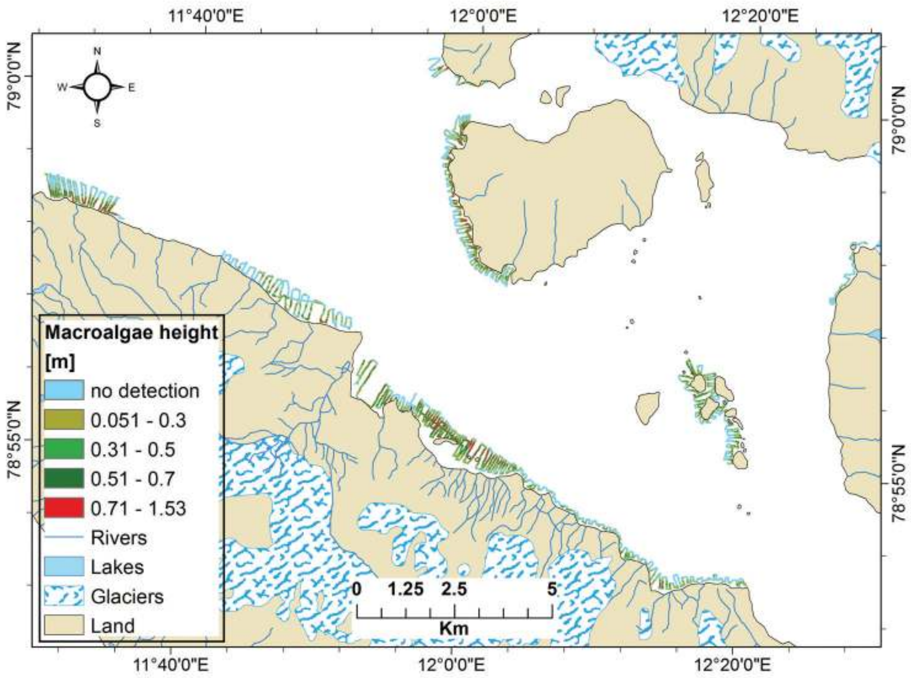

Fig. 7. Map of macroalgae spatial distribution and their layer height variability in Kongsfjorden, in UTM33X coordinates, 1 m grid. The vertical colour bar represents the macroalgae heights (in meters).

Table 1

Mean heights of macroalgae layers [m] and bottom coverage [%] over subareas and according to depths. All the values are taken from the direct acoustic detections and estimations except the last row based on gridded data comparison. Accuracy of acoustic detection is 0.05 m.

Littoral (0.7–2.5 m)	Upper sublittoral (2.5–5 m)	Mid sublittoral (5–15 m)	Low sublittoral (15–30 m)	Coverage (%)	Area no
0.44	0.60	0.43	0.31	28	1
0.38	0.50	0.54	0.40	62	2
0.27	0.39	0.38	0.38	35	3
0.34	0.41	0.39	0.33	49	4
0.27	0.28	0.29	0.39	17	5
0.47	0.60	0.46	0.26	45	6
0.36	0.46	0.42	0.35	39	Mean
47%	66%	44%	7%	41	Mean Gridded Coverage (%)

seaweed communities in the bay next to the base of Ny-Alesund (62%, area #2) whilst the smallest one was near the Kongsbreen glacier (17%, area #5). One can observe that macroalgae were detected even in area #5 and east of area #3, close to the calving glaciers where they were not expected due to the very turbid water (Fig. 7, Table 1).

The largest mean height of the kelp layer was recorded in the upper sublittoral zone, especially in the outer part of the fjord (Table 1, area #1) and around Blomstrandhanvoya (area #6), both around 0.6 m.

The heights of macroalgae layers are not equal to the real length of each kelp, because the thalli are not rigid and are often bent or twisted by current influences. Usually the macroalgae are more horizontally oriented. This was confirmed by the divers while collecting samples. The macroalgae layer they observed was similar to the one on the echogram, but smaller than the maximum lengths of the macroalgae species. Data from divers' observations and measurements are 100% in agreement with acoustic detection and estimations of seaweed layers height (Table 2), considering that both measurements are with 0.05 m accuracy. Due to diurnal current conditions, the height of the kelp layer may vary, but we did not have enough samples to calculate the exact variation.

Macroalgae acoustic characteristic and detection. — Examination of the SBES data mean backscatter strength for seaweed layers in Kongsfjorden shows that 90% of the intensity values vary between -35 dB and -21 dB (SV values measured by the Biosonics echosounder). This proves that kelps are distinguishable from the underlying flat, hard bottom, whose SV values are higher than -10 dB.

Table 2

Comparison of macroalgae lengths collected over 4 sampling stations with estimation of the heights of their layers (*N/A*=not available). The data come from divers' reports and echogram estimations (both measurements with accuracy of 0.05 m).

Station number	Depth [m]	Layer height according to divers [m]	Layer height according to echograms [m]	Range of single macroalgae lengths collected on the spot [m]
1	3.90	1	0.90	0.04–1.40
2	7.90	0.30–0.50	0.45	0.25–1.47
3	7.50	N/A	0.38	0.22–1.90
4	6.60	N/A	0.49	0.11–1.60

We also noticed various distributions of mean SV values (Fig. 8) when comparing the seaweed areas of different sites. One such example can be found in Fig. 8 (next to sampling points #3 and #4, Fig. 1). The SBES echogram was divided into two parts: on the left, mean intensities of the macroalgae layer are lower (Fig. 8b, green) than on the right (Fig. 8b, red). The histogram of related mean SV values (Fig. 8b) shows two maxima, different by 9 dB.

Discussion

As far as the authors know, this 2007 survey is the first estimation of macroalgae area over Kongsfjorden at such a large scale and using underwater acoustics. Recent biological studies reveal that quantitative data on macroalgae in Kongsfjorden is still a poorly known element of the fjord's description (Hop *et al*. 2012). Only a few locations around Kongsfjorden were examined, mostly for species composition. We think that such an extensive study, comprising the entire fjord and presenting macrophytobenthos distribution around it, is an important contribution to existing knowledge. At the same time, acoustic detection of seaweeds has shown its full potential as a powerful tool for further monitoring of macrobenthic communities.

The result of 39% coverage of the bottom by seaweeds is related to the area surveyed, which excluded some glacier sites and the northern part of the outer fjord (Fig. 7). Moreover, this value is only slightly different from the gridded result (41%), meaning that we can represent 20% of the euphotic zone area with only 2% interpolation error. Overall, we present the map of 2.68 km^2 of the bottom around the euphotic zone, finding 1.09 km^2 was covered by macroalgae (Fig. 7). The results based on acoustic detection of macrophytobenthos showed a very good agreement with the results of biological data analysis, observations from the survey boat and some anchor samplings, even though only 4 biological

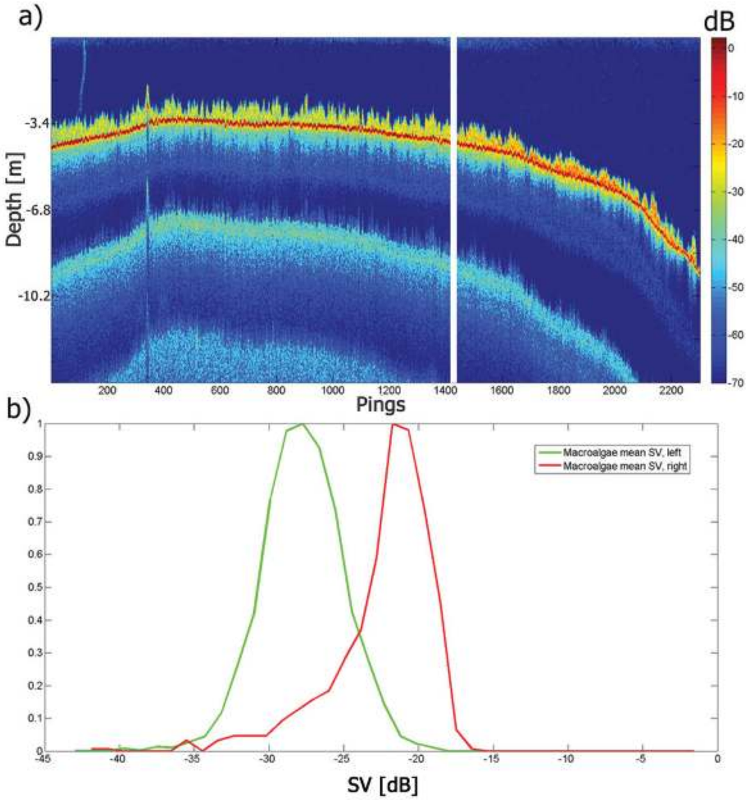

Fig. 8. SBES echogram (a) with macroalgae layers showing two maxima in the mean SV histogram (b). Species on the right side of the echogram (divided by a white stripe) reflect the acoustic signal more strongly (red line) than those on the left side (green line). Macroalgae layer mean intensity values are represented in dB (a), histogram curves are normalized to 1 (b).

sampling stations could be accessed by divers. Comparison with ground-truth data and macroalgae acoustic characteristic investigations confirmed that macroalgae can be detected using acoustic devices, especially SBES and to some extent MBES.

Using SBES for underwater vegetation detection is already a popular method in acoustic habitat mapping. Its usability was already proven in the Arctic by members of our team (Kruss *et al*. 2006). The new achievement of the present study was to show the changeability of macroalgae acoustic response in the fjord and a potential of this phenomenon for future developments in qualitative detection. We assume that the variability of backscatter of macroalgae layer visible in Fig. 8 is due to different species content and their acoustic characteristic. The conclusion is that body shape and density of macroalgae directly influence their acoustic response that was confirmed by aquascope observations related to echogram from Fig. 2. These phenomena could lead in the future to the acoustical detection of different groups of species if they grow in homogeneous meadows. However, this hypothesis requires further comparative studies with more ground truth data.

Frequency differences between the devices do not influence their performance and macroalgae detection, but along with the pulse lengths they might affect the estimation of their heights, because of different vertical resolutions. Nevertheless, the estimation results are comparable and highly correlated (0.8), as can be seen in Fig. 9. The data show region from the south part of Kongsfjorden, nearby diving stations #3 and #4 (Fig. 1). Layer heights were measured over the same areas and imaged at the same time. Echograms for both acoustic devices show detected heights from SBES data and MBES central beam data slices (-3.5°). Multibeam measurements have smaller vertical resolutions (depending on range used) and smaller backscatter ranges than the SBES used, which complicates the detection of smaller macroalgae layers (Fig. 9b). SBES can also reflect more accurately the variations in the seaweeds' layer shape (Fig. 9a).

The technical development and accessibility of compact MBES such as the Imagenex allows them to be used also in the demanding polar environment. Macroalgae detection using MBES devices has some limitations and is not much in use to date, especially considering water column data processing (McGonigle *et al*. 2011, http://geohab.org). Their backscatter curves are more difficult to interpret than SBES ones, but by limiting the extent to ±16° we managed to obtain information

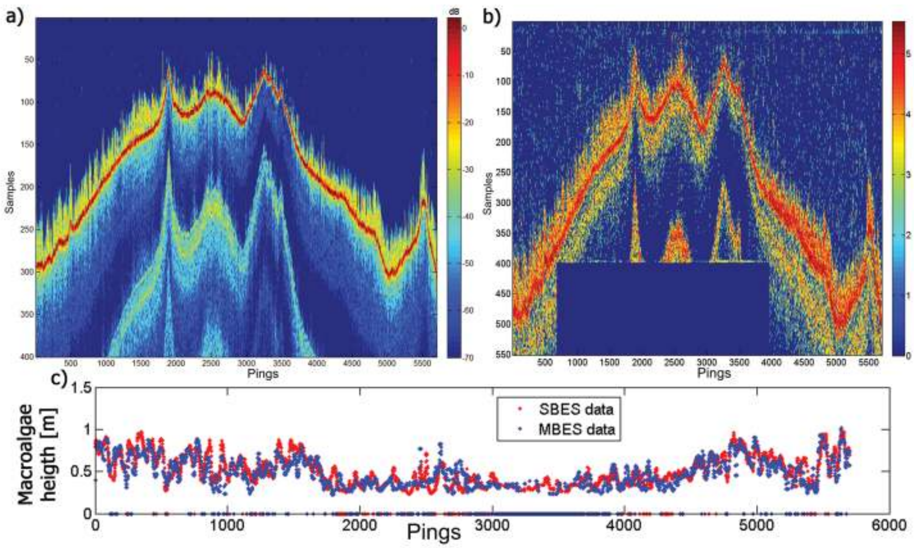

Fig. 9. Comparison of a SBES echogram (a) with a MBES echogram from central beam (-3.5º, b) presenting data from the same region covered by macroalgae (visible depth range is 1–5 m). The chart (c) shows estimated seaweed heights layer according to analyses of both types of echograms (blue dots: MBES results and red dots: SBES).

about macroalgae detection and their height distribution with more than 80% agreement with SBES results. Tank experiments helped us to better understand the Imagenex Delta-T performance reducing the operational swath width to ±16°, and confirming that, within this range, the dominant Arctic species of macroalgae give a very characteristic acoustic response. The other beams could not be used for kelp detection at this stage because the sidelobe interference noise generated in the water column is relatively stronger than seaweeds' response. One should note that more advanced devices can already overcome this problem and might have the capability to use effectively more or even all beams. Although limited by the beam range, MBES gives much wider coverage of the bottom and better data resolution than SBES. Angular dependence of MBES backscatter does not allow for qualitative analysis of intensity levels from different macroalgae groups (as we did for SBES), in part because of the absence of a motion reference unit.

Table 1 and Fig. 7 show seaweed distribution on the seabed and provide less accurate yet significant information about their depths and heights. Most of the seaweed area (93%) occurs down to 15 m depth, which can be explained by limited light penetration during the summer (due to suspension coming from melting glaciers), narrowing the euphotic zone (Hop *et al.* 2012). Recent biological sampling from the Hansneset area (Fig. 1, zone #6) confirms this zonation, showing that most of the macroalgae biomass occurs down to 15 m with a maximum at 5 m (Hop *et al.* 2012). Following our results (Table 1), one can see the maximum value of macroalgae covering 66% of the bottom in the upper sublittoral (2.5 m – 5 m depth range). This result might be explained by the study of Hop *et al.* (2012), identifying 5 m depth as a limit of destructive impact by ultraviolet radiation. During our investigations, a large seaweed area was also detected in the very shallow littoral zone belt (47%). This phenomenon can be justified by very good light conditions and limited ice scouring, while due to climate warming, Kongsfjorden has had only a very small sea ice area since 2007 (Fredriksen *et al.* 2014) and whose range was limited only to the north-eastern part, close to the glaciers (Gerland and Renner 2007).

Our assessment also varies for different fjord areas, depending on dominant environmental factors. The increasing influence of the Atlantic current carrying relatively transparent, warm and saline waters, creates good conditions for macroalgae growth, leading to their higher abundance. Data from Kortsch *et al.* (2012) monitoring the Kongsfjordneset zone (Fig. 1, inside area #1) show variability of macroalgae coverage from 10% in the 1980s to around 45% at the time of our measurements, 2007, decreasing again to 10% in 2008. Even though this investigation was related only to a small bottom spot, it shows how much seaweed communities can change under strong environmental pressure. We obtained 28% of the coverage for that area (#1), but our survey was much more extensive.

Increasing temperature also influences glacier melting. Waters running off from the glaciers (especially Kronebreen the east and Kongsvegen the south-east) are turbid due to sediment suspension, and also colder and fresher than elsewhere in the fjord. These factors limit the occurrence of macroalgae, as reflected by their low coverage at the bottom of these sites (Table 1, areas #5 and #3). The presence of macroalgae very close to the glacier (zone #5) was not expected, but may be explained on the one hand by the glaciers' retreat, which uncover new areas for macroalgae (Węsławski *et al*. 2011; Krause-Jensen *et al*. 2012), and on the other hand, by the currents which influence sediment transfer. It is known that brown algae are capable of living partly buried in the sediments, as long as they remain partly exposed to the light from time to time (Roleda *et al*. 2008).

The differences in height distribution of the macroalgae layer might be explained not only by the influence of water properties but also by the geomorphology of the fjord. In area #6, the seaweed layer was the highest (Table 1, area #6), and that part of the bottom is shaded by Blomstrandhanvoya (Voronkov *et al*. 2013) and therefore has good conditions for macroalgae to expand. In the outer part of the fjord seaweeds are also relatively high (mean value up to 0.6 m, Table 1) but more patchy, which might be explained by their exposition to more severe conditions at the mouth of the fjord. However, wave action can also support their growth by removing soft sediments, improving light penetration and reducing herbivory (Hop *et al*. 2012).

Preliminary results of macroalgae abundance based on this research were published in Woelfel *et al*. (2010), with a large interpolation factor resulting in a value of 5.1 km^2 of bottom area covered by seaweeds in the whole euphotic zone. Similar data were included in a preliminary map presented in Kruss *et al*. (2008). The first published estimations were limited to SBES data and interpolated to the fjord's entire euphotic zone with a potentially large error. The purpose of these papers was to give a continuous substrata layer for microphytobentos analysis and optimising classification algorithms, without any further interpretation. In the present study, our main goal was instead to focus on macroalgae communities and to give their detailed description using the full data set, including both SBES and MBES data, increasing the accuracy of calculations, and avoid large interpolations.

The acoustic methods for benthic habitat mapping presented in this paper proved to be highly efficient and reliable in a difficult, Arctic environment where devices must withstand hard weather conditions and be easily mounted on different research platforms, some of which need to be small enough to access the shallower parts and navigate between emerging rocks and drifting icebergs. The acoustic approach also limits the time spent for surveying in very unfavourable conditions. The SBES and MBES used in the investigations performed very well. The MBES, with its wide range, proved a very good solution for future benthic habitat mapping, even though in this case the quality of the signal limited its use to a very narrow swath. To use full performance of MBES it is suggested to have a motion unit and a very precise positioning system, at least DGPS with 0.1–0.2 m accuracy. The GPS solution we had was ten times less accurate, so we could not use full swath to create bathymetry and high resolution grid for macroalgae layer. SBES is a very good solution for low-cost measurements and gives more precise results but with lower spatial resolution.

Large amounts of data demand a simple and efficient processing approach, which we achieved using mostly image analysis algorithms (especially for MBES), completed with signal analysis.

The survey might seem to be out of date (2007) but both acoustic data and signal processing methods are still very current and valid. Presented maps of macroalgae spatial distribution and bathymetry are filling a gap in monitoring of Kongsfjorden environment evolution due to climate change.

Although the composition or biomass of species cannot yet be detected using only echosounder measurements, it is however possible to detect macroalgae and to map their spatial distribution in an efficient and cost-effective way, giving a broad but fine resolution image of the bottom. This kind of approach is useful especially for monitoring macroalgae beds and their evolution. Combined with the classical methods of direct samples collection, underwater acoustic scan help to better understand how macroalgae communities in Arctic fjords are modified by climate change. This approach can also be used in other climatic zones.

Acknowledgments. — Field measurements were part of project ARCFAC-026129-70 (PI: Jarosław Tęgowski). The research leading to these results was conducted at the University of Bath, with funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° PIEF-GA-2009-251832 to A. Kruss and Ph.Blondel, and during Marie Curie Bandiera Cofund ARMSC with CNR ISMAR Venice (Italy), supervisors Fabio Trincardi and Fantina Madricardo. The SBES research was supported by the Institute of Oceanology of the Polish Academy of Science (IOPAS) and the Ministry of Education and Science of Poland (#N306-425034). The Biosonics DTX sonar was made available by Biosonics Inc. and Janusz Burczyński, whereas the Imagenex sonar was kindly provided by Don MacKay (Hydro Products UK Ltd.). We would also like to thank Prof. Christian Wiencke for the help of his diving team in collecting the biological samples that proved essential for validation of these results.

References

Anderson J.T., Holliday D.V., Kloser R., Reid D.G. and Simard Y. 2008. Acoustic seabed classification: current practice and future directions. *ICES Journal of Marine Science* 65: 1004–1011.

Arrigo K.R. and van Dijken G.L. 2011. Secular trends in Arctic Ocean net primary production. *Journal of Geophysical Research* 116: C09011.

Atallah L., Smith P.J. and Bates C.R. 2002. Wavelet analysis of bathymetric sidescan sonar data for the classification of seafloor sediments in Hopvågen Bay – Norway. *Marine Geophysical Researches* 23: 431–442.

BALK H. and LINDEM T. 2004. *Sonar4 and Sonar5-Pro. Post processing system. Operator manual v5.9.4*. Lindem Data Acquisition, Norway: 485 pp.

BEUCHEL F. and GULLIKSEN B. 2008. Temporal patterns of benthic community development in an Arctic fjord (Kongsfjorden, Svalbard): results of a 24-year manipulation study. *Polar Biology* 31: 913–924.

BEZDEK J.C. and DUNN J.C. 1975. Optimal fuzzy partitions: A heuristic for estimating the parameters in a mixture of normal distributions. *IEEE Transactions on Computers* 24: 835–838.

BLONDEL PH. and MURTON B.J. 1997. *Handbook of Seafloor Sonar Imagery*. PRAXIS-Wiley & Sons, Chichester, UK: 336 pp.

BROWN C. and BLONDEL PH. 2009. Developments in the application of multibeam sonar backscatter data for seafloor habitat mapping. *Applied Acoustics* 70: 1242–1247.

BROWN C.J., SMITH S.J., LAWTON P. and ANDERSON J.T. 2011. Benthic habitat mapping: A review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. *Estuarine, Coastal and Shelf Science* 92: 502–520.

CARBO R. and MOLERO A.C. 1997. Scattering strength of a Gelidium biomass bottom. *Applied Acoustics* 51: 343–351.

COTTIER F., TVERBERG V., INALL M., SVENDSEN H., NILSEN F. and GRIFFITHS C. 2005. Water mass modification in an Arctic fjord through cross-shelf exchange: The seasonal hydrography of Kongsfjorden, Svalbard. *Journal of Geophysical Research*: 110(C12).

CRESSIE N.A.C. 1993. *Statistics for Spatial Data*. Wiley Series in Probability and Mathematical Statistics, Iowa State University, New York, USA: 928 pp.

DE MOUSTIER C. and ALEXANDROU D. 1991. Angular dependence of 12-kHz seafloor acoustic backscatter. *The Journal of the Acoustical Society of America* 90: 522–531.

DUNTON K.H., REIMNITZ E. and SCHONBERG S. 1982. An Arctic Kelp Community in the Alaskan Beaufort Sea. *Arctic* 35: 465–484.

FALKOWSKI P.G. and RAVEN J.A. 2007. *Aquatic Photosynthesis: Second Edition*. Princeton University Press, Princeton: 488 pp.

FREDRIKSEN S., BARTSCH I. and WIENCKE C. 2014. New additions to the benthic marine flora of Kongsfjorden, western Svalbard, and comparison between 1996/1998 and 2012/2013. *Botanica Marina* 57: 203–216.

GATTUSO J.P., GENTILI B., DUARTE C.M., KLEYPAS J.A., MIDDELBURG J.J. and ANTOINE D. 2006. Light availability in the coastal ocean: Impact on the distribution of benthic photosynthetic organisms and their contribution to primary production. *Biogeosciences* 3: 489–513.

GERLAND S. and RENNER A.H.H. 2007. Sea-ice mass-balance monitoring in an Arctic fjord. *Annals of Glaciology* 46: 435–442.

GOMEZ I., WULFF A., ROLEDA M.Y., HUOVINEN P., KARSTEN U., QUARTINO M.L., DUNTON K. and WIENCKE C. 2009. Light and temperature demands of marine benthic microalgae and seaweeds in polar regions. *Botanica Marina* 52: 593–608.

HARALICK R.M., STERNBERG S.R. and ZHUANG X. 1987. Image analysis using mathematical morphology. *IEEE transactions on pattern analysis and machine intelligence* 9: 532–550.

HOP H., PEARSON T., HEGSETH E.N., KOVACS K.M., WIENCKE CH., KWAŚNIEWSKI S., EIANE K., MEHLUM F., GULLIKSEN B. WŁODARSKA-KOWALCZUK M., LYDERSEN CH., WĘSŁAWSKI J.M., COCHRANE S., GABRIELSEN G.W., LEAKEY R.J.G., LØNNE O.J., ZAJACZKOWSKI M., FALK-PETERSEN S., KENDALL M., WÄNGBERG S.-Å., BISCHOF K., VORONKOV A.Y., KOVALTCHOUK N.A., WIKTOR J., POLTERMANN M., DI PRISCO G., PAPUCCI C. and GERLAND S. 2002. The Marine Ecosystem of Kongsfjorden, Svalbard. *Polar Research* 21: 167–208.

HOP H., WIENCKE C., VÖGELE B. and KOVALTCHOUK N. 2012. Species composition, zonation, and biomass of marine benthic macroalgae in Kongsfjorden, Svalbard. *Botanica Marina* 55: 399–414.

HUGHES CLARKE J.E. 2006. Applications of multibeam water column imaging for hydrographic survey. *The Hydrographic Journal* 120: 3–14.

ISAAKS E.H. and SRIVASTAVA R.M. 1989. *An Introduction to Applied Geostatistics*. Oxford University Press, New York: 561 pp.

JACKSON D.R. and RICHARDSON M.D. 2007. *High-Frequency Seafloor Acoustics*, Springer, New York: 616 pp.

KORTSCH S., PRIMICERIO R., BEUCHEL F., RENAUD P.E., RODRIGUES J., LONNE O.J. and GULLIKSEN B. 2012. Climate-driven regime shifts in Arctic marine benthos. *Proceedings of the National Academy of Sciences of the United States of America* 109: 14052–14057.

KRAUSE-JENSEN D., KÜHL M., CHRISTENSEN P.B. and BORUM J. 2007. Benthic primary production in Young Sound, Northeast Greenland. *Bioscience* 58: 160–173.

KRAUSE-JENSEN D., MARBÀ N., OLESEN B., SEJR M.K., CHRISTENSEN P.B., RODRIGUES J., RENAUD P.E., BALSBY T.J.S. and RYSGAARD S. 2012. Seasonal sea ice cover as principal driver of spatial and temporal variation in depth extension and annual production of kelp in Greenland. *Global Change Biology* 18: 2981–2994.

KRUSS A., TĘGOWSKI J., WIKTOR J. and TATAREK A. 2006. Acoustic estimation of macrophytes in the Hornsund fjord, the Svalbard Archipelago. *Hydroacoustics* 9: 89–96.

KRUSS A., BLONDEL P., TĘGOWSKI J., WIKTOR J. and TATAREK A. 2008. Estimation of macrophytes using single-beam and multibeam echosounding for environmental monitoring of Arctic fjords (Kongsfjord, West Svalbard Island). *Journal of Acoustics Society of America* 123: 3213.

KRUSS A., BLONDEL PH. and TĘGOWSKI J. 2012. Acoustic properties of macrophytes: Comparison of single-beam and multibeam imaging with modeling results. *11th European Conference on Underwater Acoustics 2012. ECUA 2012, Institute of Acoustics, St. Albans*: 168–175.

LEHMANN A. and LACHAVANNE J.B. 1997. GIS and remote sensing in Aquatic Botany: Introduction. *Aquatic Botany* 58: 195–207.

LURTON X. 2002. *An introduction to underwater acoustics: Principles and applications*. Springer-PRAXIS, Chichester: 680 pp.

MCGONIGLE CH., GRABOWSKI J.H., BROWN C.J., WEBER T.C. and QUINN R. 2011. Detection of deep water benthic macroalgae using image-based classification techniques on multibeam backscatter at Cashes Ledge, Gulf of Maine, USA. *Estuarine, Coastal and Shelf Science* 91: 87–101.

MICHAELS W.L. 2007. *Review of acoustic seabed classification systems*. *In*: J.T. Anderson, D.V. Holliday, R. Kloser, D. Reid, Y. Simard, C.J. Brown, R. Chapman, R. Coggan, R. Kieser, W.L. Michaels, A. Orlowski, J. Preston, J. Simmonds, A. Stepnowski (eds), *Acoustic seabed classification of marine physical and biological landscapes*. ICES Cooperative Research Report 286, ICES, Copenhagen: 94–115.

NIBLACK W. 1986. *An introduction to digital image processing*. Prentice-Hall International Ltd, New Jersey: 215 pp.

RIEGL B., MOYER R., MORRIS L., VIRNSTEIN R. and PURKIS S.J. 2005. Distribution and seasonal biomass of drift macroalgae in the Indian River Lagoon (Florida, USA) estimated with acoustic seafloor classification (QTCView, Echo). *Journal of Experimental Marine Biology and Ecology* 326: 89–104.

ROLEDA M.Y., DETHLEFF D. and WIENCKE C. 2008. Transient sediment load on blades of Arctic *Saccharina latissima* can mitigate UV radiation effect on photosynthesis. *Polar Biology* 31: 765–769.

SABOL B.M., MELTON R.E., CHAMBERLAIN R., DOERING P. and HAUNERT K. 2002. Evaluation of a digital echo sounder system for detection of seagrass. *Estuaries* 25: 133–141.

SHENDEROV E.L. 1998. Some physical models for estimating scattering of underwater sound by algae. *Journal of Acoustic Society of America* 104: 791–800.

SVENDSEN H. 2002. The physical environment of Kongsfjorden–Krossfjorden, an Arctic fjord system in Svalbard. *Polar Research* 21: 133–166.

TATAREK A., WIKTOR J. and KENDALL M.A. 2012. The sublittoral macroflora of Hornsund. *Polar Research* 31: 18900.

TĘGOWSKI J. and ŁUBNIEWSKI Z. 2002. Seabed characterisation using spectral moments of the echo signal. *Acta Acustica/Acustica* 88: 623–626.

TĘGOWSKI J., GÓRSKA N. and KLUSEK Z. 2003. Statistical analysis of acoustic echoes from underwater meadows in the eutrophic Puck Bay (southern Baltic Sea). *Aquatic Living Resources* 16: 215–221.

VAN REIN H., BROWN C.J., QUINN R., BREEN J. and SCHOEMAN D. 2011. An evaluation of acoustic seabed classification techniques for marine biotope monitoring over broad-scales (>1 km^2) and meso-scales (10 m^2>1 km^2). *Estuarine, Coastal and Shelf Science* 93: 336–349.

VAN WALREE P.A., TĘGOWSKI J., LABAN C. and SIMONS D.G. 2005. Acoustic seafloor discrimination with echo shape parameters: a comparison with the ground truth. *Continental Shelf Research* 25: 2273–2293.

VON SZALAY P.G. and MCCONNAUGHEY R.A. 2002. The effect of slope and vessel speed on the performance of a single beam acoustic seabed classification system. *Fisheries Research* 54: 181–194.

VORONKOV A., HOP H. and GILLIKSEN B. 2013. Diversity of hard-bottom fauna relative to environmental gradients in Kongsfjorden, Svalbard. *Polar Research* 32: 11208.

WĘSŁAWSKI J.M., KENDALL M.A., WŁODARSKA-KOWALCZUK M., IKEN K., KĘDRA M., LEGEŻYNSKA J. and SEJR M.K. 2011. Climate change effects on Arctic fjord and coastal macrobenthic diversity – observations and predictions. *Marine Biodiversity* 41: 71–85.

WIENCKE CH., VOGELE B., KOVALTCHOUK A. and HOP H. 2004. Species composition and zonation of marine benthic macroalgae at Hansneset in Kongsfjorden, Svalbard. *Berichte zur Polar und Meeresforschung* 492: 55–62.

WIENCKE C. (ed.) 2011. *Biology of polar benthic algae*. *Marine and Freshwater Botany*. Walter de Gruyter GmbH & Co. KG, New York: 342 pp.

WIKTOR J.M., OKOLODKOV J. and VINOGRADOVA K. 1995. *Atlas of the marine flora of southern Spitsbergen*. Institute of Oceanology Polish Academy of Sciences, Gdańsk: 515 pp.

WŁODARSKA-KOWALCZUK M., KUKLIŃSKI P., RONOWICZ M., LEGEŻYNSKA J. and GROMISZ S. 2009. Assessing species richness of macrofauna associated with macroalgae in Arctic kelp forests (Hornsund, Svalbard). *Polar Biology* 32: 897–905.

WOELFEL J., SCHUMANN R., PEINE F., FLOHR A., KRUSS A., TĘGOWSKI J., BLONDEL Ph., WIENCKE CH. and KARSTEN U. 2010. Microphytobenthos of Arctic Kongsfjorden (Svalbard, Norway): biomass and potential primary production along the shore line. *Polar Biology* 33: 1239–1253.

WOLD S. 1987. Principal Component Analysis. *Chemometrics and Intelligent Laboratory Systems* 2: 37–52.

Received 17 November 2016
Accepted 23 February 2017