Application of underwater imagery for the description of upper sublittoral benthic communities in glaciated and ice-free Arctic fjords

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Abstract
Complex bottom topography and the presence of floating ice significantly complicate the use of traditional sampling methods in Arctic coastal waters, forcing to look for alternative approaches. One such technique is underwater imagery, which has grown in popularity in recent decades based on its effectiveness in hard-to-reach places. We demonstrate that an underwater video mosaic can be a reliable method for comparative analysis of Arctic habitats under the glacier influence and glacier influence-free habitats. The filming was carried out in the upper sublittoral (2–65 m) of Hornsund and Isfjorden areas, representing two ice-free and two glaciated bays. Video footage was obtained using an ROV mounted and “drop-down” video cameras and transformed into 148 video mosaics. Based on the lowest possible taxonomic level, 31 biological features (morphospecies) were identified and ascribed to benthic functional groups based on their feeding and mobility type. The morphospecies and functional groups were used for the comparative analysis to reveal the ecologically meaningful differences in benthic community structure in different Arctic benthic habitats. We discovered greater abundances of motile scavengers in glacier-influenced bays whereas glacier influence-free bay had more sessile suspension filters and glacier influence-free riverine bay was dominated by discreetly motile and deposit feeders. Underwater imagery mosaics have proven to be a fairly reliable tool for fieldwork-efficient quantitative characterization of benthic communities in the hard-to-reach Arctic’s upper sublittoral.

Keywords Seabed · Video mosaics · Morphospecies · Functional groups · Svalbard

Introduction
Svalbard is warming four times faster than the worldwide average (Wei et al. 2016) and shown the largest temperature increase in Europe, with linear trend of ~ 2.6 °C per 100 years (Nordli et al. 2014). Increased seawater temperature in Spitsbergen fjords (Pavlov et al. 2013) following meltwater discharge from the glaciers results in an increase of suspended sediment in West Svalbard during summer and early autumn months (Moskalik et al. 2018). Warming of water and ice conditions of Svalbard are strongly influenced by the West Spitsbergen Current (WSC), especially during winter (Walczowski and Piechura 2011).

Atlantic water intrusion during summer transforms Arctic water-dominant Isfjorden into Atlantic-dominant Isfjorden, while Hornsund is less affected likely due to Sørkapp Current influence (Promińska et al. 2018). In addition, Muckenhuber et al. (2016) hypothesized that the interannual variability of sea ice cover in Hornsund is less affected by WSC than in Isfjorden: in the first case, the ice cover affected by WSC recovers after a year, while in the second case, it takes several years. In general, fjords affected by glacier melting are characterized by increasing shallows, lower salinity, higher temperatures, and sedimentation rates (Drewnik et al. 2016). Increased freshwater inflow and suspended solids from melting glaciers and warmer saltier WSCs have an impact on the benthic environment in the bays and fjords of West Svalbard (Wlodarska-Kowalczuk and Pearson 2004). Presumably, this impact is different in glaciated and glacier influence-free fjords, as well as in areas that differ in the
degree of impact of WSC. Thus, differences in the structure of benthic communities can be determined by large-scale regional (i.e., hydrographic settings of a fjord/magnitude of Atlantic water masses advection) and local differences (e.g., presence of a glacier or nearby river runoff in a fjord basin). Multiple studies analysis indicated that glaciers have a negative impact on fjords’ natural populations and communities (Cauvy-Fraunié and Dangles 2019). Under the influence of melting glaciers, benthic organisms are as follows: (1) dominated by small, motile, scavengers (Meyer et al. 2015), or surface-detritus feeders (Włodarska-Kowalczyk et al. 2005), (2) species richness, evenness, biomass, and organism size decrease (Włodarska-Kowalczyk et al. 2005; Mazurkiewicz et al. 2021) while (3) generalist/invasive taxa tend to dominate rather than “local” specialist species (Cauvy-Fraunié and Dangles 2019), and (4) due to the warming climate, northward expansion of boreal species was noticed (Berge et al. 2005; Wassmann et al. 2010).

In recent decades, benthic studies in Arctic regions have used a variety of sampling strategies dependent on the depth at which they operate. Sublittoral zone was mostly analyzed by using traditional sampling techniques from large ships limited by shallow depths. These techniques, including dredge (Kaczmarek et al. 2005; Kędra et al. 2013; Jørgensen et al. 2015) and Van Veen grab (Kendall et al. 2003; Włodarska-Kowalczyk et al. 2005; Renaud et al. 2007), revealed that physical properties (depth, temperature, salinity, presence of ice and glaciers, predominating water masses, and glacier sedimentation) are the primarily factors shaping structural and functional attributes of benthic communities along the large Spitsbergen fjords. In the upper sublittoral (0–40 m), SCUBA diving techniques were used and observed local small-scale changes in species composition, diversity, and successional patterns (Jørgensen and Gulliksen 2001; Beuchel et al. 2006; Wessels et al. 2006; Beuchel and Gulliksen 2008; Ronowicz et al. 2018; Al-Hababeh et al. 2020). The remote underwater video technique has the potential to be used at a wide range of depths and has recently been conducted in Svalbard in conjunction with conventional sampling techniques (Kędra et al. 2013; Sswat et al. 2015) or as a stand-alone tool (Laudien and Orchard 2012; Mazurkiewicz et al. 2021). The use of remote video assisted to detect benthic community structure and megafauna differences between the assemblages along the bathymetric gradient or bottom water temperature. However, to the best of our knowledge, none of the research carried out in Svalbard used the underwater video mosaics technique.

Underwater mosaic (UWM) is a set of images compiled from the co-registration of adjacent frames from video in a single high-resolution image (Rzhanov et al. 2000). This method requires more preprocessing time before being used for biological analysis; however, it creates a wide-area view of a scene and provides the more convenient way to quantify visible organisms than raw video. As any digital image, an UWM may be zoomed, moved forward and backward, as well as used for semi-automatic (Šaškov et al. 2015) and automatic (Buškus et al. 2021) methods. Recently, UWM was used for seabed surface mapping (Rzhanov et al. 2000; Li et al. 2019), benthos monitoring (Gintert et al. 2012; Li et al. 2019; Rende et al. 2015; Šaškov et al. 2015), benthic population estimates (Lim et al. 2018; Corrigan et al. 2019), or benthic habitat identification and mapping (Gintert et al. 2012; Lim et al. 2018).

The main limitation of the UWM method is that it does not provide the same taxonomic resolution for identifying different benthic groups; some of them (e.g., crabs and starfish) can be identified to the species or genus level, while others (nemertins, sponges) can be identified only to the class or phylum level. In order to avoid this problem, the concept of morphospecies was applied, where “Morphospecies are defined as taxa distinguished solely on the basis of morphological differences easily identified by nonexperts” (Brind’Amour et al. 2014). This concept was used extensively in the mid-90 s in the terrestrial realm (on plants and insects) and stimulated great debate at the time (Oliver and Beattie 1996; Goldstein, 1999, cit. by Brind’Amour et al. 2014). More recently, benthologists are using the “morphospecies” approach to evaluate the importance of wrack to habitats (Chapman and Robert 2004), colonization and successional change on artificial substrates (Underwood and Chapman 2006) and in bottom trawl surveys (Brind’Amour et al. 2014). Also to describe the distribution, abundance, and diversity of sessile invertebrate fauna (Meyer et al. 2014), and to monitor long-term changes in megafaunal seafloor assemblages (Kuhnz et al. 2020), etc.

In this study, we use an UWM to investigate the structure of the benthos in the upper sublittoral in two areas of western Spitsbergen, Isfjorden and Hornsund, under various conditions: from ice melting and turbid river bays to glacier influence-free areas. During the Little Ice Age, the majority of Svalbard bays were covered with glacial ice (Martín-Moreno et al. 2017). The seabed shallower than 100 m depth was almost unified and now gets diverse following the deglaciation and climate warming. The coastal benthic habitats are exposed to the change of principal drivers: iceberg scouring, intensive sedimentation, turbidity currents, salinity, and temperature change. Having the sequence of seabed habitats of the present-day deglaciation history, we attempt to find out whether the video mosaic method in combination with the morphospecies approach and functional group concept reflects ecologically meaningful differences in benthic community structure in different Arctic habitats.
Materials and methods

Study area

Svalbard, the largest island of Norway’s Svalbard Archipelago, lies on the edge of the Barents Sea shelf, between the Norwegian mainland and the North Pole. The coastal waters of the western Spitsbergen are strongly affected by the WSC and the runoff of freshwater from rivers and melting glaciers (Walczowski and Piechura 2011). The WSC brings warmer and more saline Atlantic water from the Norwegian Sea, thus contributing to the warming climate of Svalbard. The inner Hornsund basin has cooler and lower salinity water since it is isolated by the sill which creates a natural barrier preventing the WSC from mixing with the bay water and probably due to the strong influence of the Sørkapp Current (Promińska et al. 2018), thus creating the conditions for seasonal glacier growth in the bays. Occasionally, though, the WSC extends into the fjords, bringing warm water and melting the seasonal ice formed in the bays, as has been the case in Isfjorden over the last decades (Skogseth et al. 2020). The study was carried out in two fjords of Western Spitsbergen: Hornsund, which represents typical Arctic environment, and Isfjorden, where the climate is milder due to the greater influence of WSC.

Data collection was done in four bays that represent combinations of two factors: location in ‘warm’/‘cold’ fjord and proximity to active tidal glacier. Adriabukta and Gipsvika, represented glacier influence-free areas, Burgerbukta, and Borebukta are in the vicinity of melting glaciers; the first in each pair is located in Hornsund (‘cold fjord’) and the second in Isfjorden (‘warm fjord’) (Fig. 1).

In each study area (Hornsund, Isfjorden), two bays were selected, and at each bay, 5 to 7 video transects were performed, covering a depth range of 2 to 65 m. Transects were recorded at increasing depths in order to cover as much depth variation as possible, resulting in different transect lengths and therefore an uneven number of mosaics (Table 1). In total, 2.8 h of video material was filmed along 23 transects. Video recordings along each transect were transformed into 148 video mosaics, which were used further for visual analysis as samples.

Underwater video data collection

Underwater video data during different sampling seasons were collected with a remotely operated vehicle (ROV) and a drop-down video system. ROV camera was equipped with a high-resolution analogue camera navigation system and a primary camera. The primary camera was mounted vertically, had 3 CCD, Full HD (1920 x 1080) resolution, high-quality Leica Dicomar lenses and 10 x optical zoom. The

![Fig. 1 Underwater video sampling sites in Svalbard, 2018–2019. Borebukta (1) and Gipsvika (2) in Isfjorden and Burgerbukta (3) and Adriabukta (4) in Hornsund. Glacier's boundaries were manually defined using satellite imagery from Landsat 5, Landsat 7–8 acquired from USGS website to show approximate direction of glacier retreat.](image-url)
primary camera lighting system consists of 16 bright LED in 4×4 stations. The ROV camera set was used in Isfjorden surveys. For surveys in Hornsund, a drop-down camera was used. It was equipped with an analogue camera of 700 TV lines (TVL) resolution for live view and a digital camera (Panasonic HX-A500) that recorded the seabed at high resolution (1280×720 px) on a memory card. During the filming, camera angle was set perpendicular to the seabed, the speed was approx. 0.5 knot, and the altitude over the seabed was 0.4–0.5 m ensuring optimal lighting conditions and consistent field of view. Laser points indicating scale were fixed only on drop-down camera system and not always visible; however, approximate length of 30 s video mosaic was estimated to be from 4.4 to 5.1 m².

**Underwater video mosaics creation and processing**

As the exact lengths of the filmed transects were not clear and the duration of the video footage also varied between transects, it was decided to divide the footage into 30-s segments in order to compensate for these discrepancies. For the analysis, 30-s segments with a stable field of view, a constant speed of 0.5 knots, and an altitude of 0.4–0.5 m ensuring optimal lighting conditions and consistent field of view. Laser points indicating scale were fixed only on drop-down camera system and not always visible; however, approximate length of 30 s video mosaic was estimated to be from 4.4 to 5.1 m².

### Identification of morphospecies

A total of 31 morphospecies were identified to the lowest possible taxonomic level from UWM (Fig. 2). The catalogue of identified morphospecies was created and consulted with taxonomic experts. In the catalogue taxonomical hierarchy, sampling date, bay, transect, depth, and suggested identification features were provided. We assume that each morphospecies belongs to one species based on its unique appearance. The set of morphospecies included not only zoobenthos as such, but also organisms that live near the bottom (nektobenthos, demersal fish) and are closely associated with benthic habitats (sensu Levinton 2001). All morphospecies were marked in the video mosaics using the data labeling platform Labelbox (Labelbox, 2022).

### Ascribing morphospecies to functional groups

Morphospecies were classified into two functional group categories: mobility and feeding mode (Macdonald et al. 2010). Morphospecies were considered as motile if having active movement required for feeding (usually with visual movement traces observed on camera), discreetly motile if able to move, but movement isn’t necessary for feeding, sessile if not moving (e.g., attached to the hard substrate).

Four feeding modes were distinguished: deposit feeder, suspension/filter feeder, predator, and scavenger (Online Resource 1). Morphospecies that had two feeding modes (e.g., predator and detritus feeder or predator and scavenger) were classified under scavenger feeding mode for simplicity. Information on feeding habits and mobility was composed based on (Macdonald et al. 2010) and Arctic Traits Database (Degen and Faulwetter 2019).
Data analysis

Uneven transect lengths at different depth zones were corrected by either randomly eliminating mosaics or manually generating pseudo-mosaics from video frames when the sample size was insufficient. Three bathymetric zones were used to analyze depth-related differences in benthic structure: lower salinity layer and euphotic zone 10–20 m, wave action on the seafloor at 20–40 m, and colder and saltier water at < 40 m depth (based on Beszczynska-Moller et al. 1997; Drewnik et al. 2016). Differences in the number of morphospecies and individuals between the depth intervals were assessed using nonparametric Kruskal–Wallis test. Dunn’s post hoc test was performed to determine which depth intervals differed significantly.

Relative abundance was analyzed with or without the most numerically abundant morphospecies (Sabellidae) in order to reveal the contribution of less abundant morphospecies and to depict other patterns in morphospecies composition possibly related with the presence of ice and riverine input. Indicator-species analysis index (De Cáceres et al. 2010) was used to identify morphospecies associated with a particular depth interval or multiple depth intervals in a specific bay. This index consists of two measures: fidelity (the probability of finding a morphospecies in a particular depth interval of a given bay) and specificity (the probability a depth interval belongs to a particular bay given that the morphospecies is there) into a single index with a maximum value of 1. Nonmetric multidimensional scaling (MDS) analysis was performed for grouping of transects in different bays based on morphospecies presence/absence data using Bray Curtis similarity coefficient. One-way ANOSIM (analysis of similarities) was used to test for differences between bays and two-way ANOSIM was performed with two factors (warm/cold fjord and glacier-influenced/glacier influence-free bay) to determine which factor contributed most to these differences. Statistical significance of the ANOSIM global R statistic was assessed by a permutation (999 times) test (at α < 0.05 level). ANOSIM R statistic varies between -1 and 1, with values close to 1 indicating high dissimilarity. Morphospecies contribution accounting to the similarities between bays was determined using similarity percentage (SIMPER) analysis.

MDS, ANOSIM, and SIMPER analyses were performed using PRIMER 6 software (Clarke and Gorley 2006). Robust nonparametric statistical analysis was done using “WRS2” and “dunn.test” packages available in R (R Development Core Team 2020). Indicator-species analysis index (IndVal) was performed using “indicspecies” package in R (R Development Core Team 2020). Graph plots were created using “ggplot2” and “patchwork” packages in R (R Development Core Team 2020).
Results

Diversity of morphospecies and feeding-mobility groups

A total of 31 morphospecies were identified in 148 samples. Samples contained from 0 to 589 visual features; in total, 10,308 of such objects have been identified and counted. The taxonomic accuracy of identification varied from phylum up to species level for different morphospecies, with majority of cases being characteristic genus and species levels (Table 2). Annelida and Mollusca had the most distinct features which allowed to identify 6 morphospecies each, followed by Arthropoda (5) and Chordata (5). Porifera and Nemertea were the most difficult to identify as they were not identified to lower taxonomic levels. Seven morphospecies belonging to five phyla were identified to the species level: Ptychogastria polaris (Cnidaria), Similipecten greenlandicus (Mollusca), Chone infundibuliformis and Bispira fabricii (Annelida), Urasterias lineki (Echinodermata), Pagurus pubescens, and Hyas araneus (Arthropoda).

In the whole study area, individuals of Annelida (5531 individuals, 54% of total abundance) and Echinodermata (3141 individuals, 30% of total abundance) dominated. Among annelids Sabellidae and A. marina morphospecies were the most abundant (4155 and 1134 individuals, respectively), while Ophiuridae family were the most abundant morphospecies among echinoderms (3137 individuals). Six morphospecies were counted in hundreds (Ceriantharia, Bivalvia Ch. infundibuliformis, Alcyonidium sp., Bryozoa), 10—in dozens, the rest 16 morphospecies occurred only in few individuals.

The most frequent morphospecies in the research area was Sabellidae, which occurred in 83% of transects, followed by Liparidae (54%), Bryozoa (46%), Bivalvia (42%), Pleuronectiformes (38%), and Ch. infundibuliformis (33%). Eleven morphospecies occurred in more than 25% of transects, while 7 and 9 morphospecies occurred only in two and one transect, respectively (Fig. 3).

Most morphospecies were ascribed to motile (15), 8—discretely motile, and 8 to sessile. Regarding feeding mode, the majority of morphospecies were predators and suspension filters (12 each), 5—scavengers, and 2—deposit feeders. The majority of motile individuals belonged to Arthropoda and Pisces phyla with 4 morphospecies each, which is 80% of all Arthropoda and Pisces morphospecies, while Annelida morphospecies comprised 44% of all sessile morphospecies in the study area. One morphospecies from Annelida phylum comprised 97% of all sessile species in the study area, and all deposit feeders (2) were also Annelids. All morphospecies belonging to Bryozoa, Porifera, and majority of Annelida and Mollusca morphospecies were suspension filters. All Cnidarians and Nemertea phyla in the study area were predators, 33% of predators belong to Chordata phylum. Majority of scavengers (60%) belonged to Arthropoda phylum. The most common were sessile suspension filters (ocurred in 96% of transects), followed by motile predators and motile scavengers (74%), and discretely motile suspension filters (57%) (Online Resource 2). The least frequent were discretely motile predators (35%) and discretely motile deposit feeders (26%). Sessile predators, sessile deposit feeders, sessile scavengers, motile suspension filters, motile deposit feeders, and discretely motile scavengers were not present.

Vertical distribution of benthic assemblages within the bays

Borebukta (glacier/“warm fjord”)

In total, 20 morphospecies were found (5 annelids, 4 arthropods, 4 molluscs, and others). Majority of morphospecies were motile (9), discretely motile (8), and suspension filters (9). Morphospecies richness was similar at different depth intervals on average 4 ± 1 morphospecies per sample (Kruskal–Wallis test $H = 1.4, p > 0.05$); however, it...
Fig. 3 Occurrence of all morphospecies in stations from the entire study area

Fig. 4 An infographic showing relative morphospecies distribution of total abundance in bays along the depth intervals (N—mean abundance ± standard deviation and S—morphospecies richness at a given depth interval). Some symbols used in the infographic were provided by Integration and Application Network (ian.umces.edu/media-library)
was lowest at shallowest depth (8) and highest in 20–40 m depth zones (11–12) (Fig. 4). Abundance did not differ significantly among bathymetric zones (Kruskal–Wallis test $H = 0.64, p > 0.05$) due to high variation at > 40 m depth (the abundance ranged from 3 to 589 ind. sample$^{-1}$), the average number of individuals at 40 m depths where noticeably higher (289 ± 158 ind. sample$^{-1}$) than in more shallow areas (42 ± 16 and 40 ± 30 ind. sample$^{-1}$, respectively). Discretely motile predator Ceriantharia and sessile suspension filter Sabellidae were the most abundant morphospecies at shallowest depth zone (43% and 36%, respectively), while at 20–40 m and > 40 m depths, it was Ophiurida (80% and 96%, respectively, 2–550 ind. sample$^{-1}$). Motile scavengers increased with depth and were the most abundant at the deepest depth interval (96%). Indicator-species analysis identified 6 morphospecies strongly associated with separate depth zones. Ceriantharia was uniquely associated with shallowest depths, *Urasterias lineki* with 20–40 m depth zone. Ophiurida and Lumpeninae were uniquely associated with 20–40 and < 40 m depth zones, while *Psychogastria polaris* and *Similipecten greenlandicus* were uniquely associated with the shallowest (< 40 m) zone.

**Burgerbukta (glacier/"cold fjord")**

In total, 9 morphospecies were found, most of them belonged to Chordata (3) and Bryozoa (2). Majority of morphospecies were motile (4) and sessile (3), predators (5), and suspension filters (3). The diversity of morphospecies in bathymetric zones varied from 6 to 7 and was similar at different depth intervals (Kruskal–Wallis test $H = 5.41, p > 0.05$). On average, 3 ± 1 morphospecies per sample. Highest abundance was observed in 20–40 m depth (101 ± 119 ind. sample$^{-1}$) but did not differ significantly (Kruskal–Wallis test $H = 2.53, p > 0.05$) from shallowest (8 ± 7 ind. sample$^{-1}$) and deepest (24 ± 15 ind. sample$^{-1}$) depth zones. Highly abundant sessile suspension filter Sabellidae was dominant in all depth zones (67 to 92% of total abundance in a zone) and reached up to 295 ind. per sample. The highest Sabellidae abundance was observed in 20–40 m zone (93 ± 117 ind. sample$^{-1}$); however, it was not significantly different (Kruskal–Wallis test $H = 3.93, p > 0.05$) from 20–40 m depth zones (6 ± 7 and 17 ± 14 ind. sample$^{-1}$, respectively). Indicator-species analysis identified shrimps as morphospecies strongly associated with 20–40 and < 40 m depth zones, while Lumpeninae strongly associated with 10–20 and 20–40 m depth zones.

**Gipsvika (glacier influence-free/"warm fjord"/riverine bay)**

In Gipsvika, 14 morphospecies were found in total, most of them belonged to Mollusca (4), Annelida (4), and Chordata (3); the majority of them were motile (9), predators (7), and suspension filters (4). The lowest diversity of morphospecies (5) was at shallowest depth, the highest (11)—at 20–40 m, while 8 morphospecies were found at > 40 m depth. However, the average number of morphospecies in samples in all depth intervals did not differ significantly (Kruskal–Wallis test $H = 0.23, p > 0.05$) and it was on average 2 ± 1 morphospecies per sample. The abundance of individuals was significantly higher (Kruskal–Wallis test $H = 13.17, p < 0.05$) at 20–40 m depth zone (90 ± 29 ind. sample$^{-1}$) than in zones above 20 m and below 40 m (43 ± 39 and 16 ± 9 ind. sample$^{-1}$, respectively). Discretely motile deposit feeder *A. marina* was the most abundant at the shallowest depth interval comprising 76% of total abundance (up to 69 ind. sample$^{-1}$). Sabellidae morphospecies dominated in deeper zones, comprising 99% and 91% of total abundance at 20–40 m and > 40 m depths, respectively. Indicator-species analysis showed that only *A. marina* morphospecies was strongly associated with the shallowest depth.

**Adriabukta (glacier influence-free/"cold fjord")**

In total, 12 morphospecies were found, most of them belonged to Chordata (3), Annelida (2), and Bryozoa (2); the majority of morphospecies were sessile (5), motile (4), and suspension filters (6). The highest morphospecies diversity was observed in deepest zone (11), while at < 20 m and 20–40 m zones, 8 and 7 morphospecies were found, respectively. The number of morphospecies was similar at different depth intervals (Kruskal–Wallis test $H = 3.03, p < 0.05$, on average 5 ± 1 morphospecies per sample). The highest abundance was observed in < 40 m zone (138 ± 78 ind. sample$^{-1}$) while at 20–40 m depth, it was significantly lower (Kruskal–Wallis test $H = 8.55, p < 0.05$) with 44 ± 35 ind. sample$^{-1}$ on average. Sabellidae dominated in deepest zone, comprising 75% of total abundance and reached up to 316 ind. per sample. Highly abundant sessile suspension filter Bryozoa was dominant in all depth zones (49 to 81% of total abundance in a zone) and reached up to 215 ind. per sample. Sessile suspension filters Bryozoa sub-dominated above < 40 m depth zone: at < 20 m and at 20–40 m depth comprising 81 and 56% of total abundance (up to 215 ind. sample$^{-1}$). Indicator-species analysis identified Sabellidae morphospecies strongly associated with the deepest depth interval.

**Peculiarities of benthic structure in different bays**

**Morphospecies**

Sabellidae was the most common morphospecies in all four bays (frequency in Gipsvika -100%, Burgerbukta -95%, Borebukta -75%, Adriabukta -46%). Lumpeninae were
also frequent in the following three sites: Adriabukta -63%, Burgerbukta -33%, and Borebukta -36%. Ophiurida was frequent in majority of Borebukta samples (96%) and Ceriantharia (39%) were also very frequent there. *A. marina* were apparent in Gipsvika (21%) only. Shrimps were present in only Borebukta and Burgerbukta but were more prevalent in the later (86%). Bryozoa were very common in Hornsund (Adriabukta -92%, Burgerbukta -29%). Bryozoans *Alcyonidium* sp., Bivalves, and *Ch. infundibuliformis* were highly frequent only in Adriabukta samples (63%, 67%, and 54%, respectively).

Sabellidae were dominant in majority of the sites. In Adriabukta, they constituted 51% (0–91% trans.\(^{-1}\)) of abundance; in Burgerbukta, 88% (61–95% trans.\(^{-1}\); and in Gipsvika, 65% (21–99% trans.\(^{-1}\)) (Fig. 5a). Nine morphospecies were the next most abundant: bryozoans *Alcyonidium* sp. and Bryozoa, bivalves, Ceriantharia, Halcampa, *Ch. infundibuliformis*, bioturbating worms, shrimps, Lumpeniniae, Pisces, and Pleonectiformes. Each site was distinguished by the sub-dominance of one of the morphospecies: Bryozoa in Adriabukta, shrimps in Burgerbukta, Ophiurida in Borebukta, and *A. marina* in Gipsvika (Fig. 5b).

In Adriabukta, Bryozoa constituted 29% (2–83% trans.\(^{-1}\)) of total abundance, in Burgerbukta shrimps constituted—8% (4–28% trans.\(^{-1}\)), in Gipsvika *A. marina* constituted 32% (0–78% trans.\(^{-1}\)) of total abundance. In Borebukta, Ophiurida comprised 75% (1–96% trans.\(^{-1}\)) of total abundance, while Ceriantharia comprised 9% (0–68% trans.\(^{-1}\)). Bivalvia were the second most abundant morphospecies in Adriabukta, comprising 9% of total abundance, while in Burgerbukta, it was Bryozoa and Lumpeniniae which comprised 1% each of total abundance.

Overall, the number of individuals was higher in Burgerbukta (102 ± 168 ind. trans.\(^{-1}\)) and Adriabukta (96 ± 51 ind. trans.\(^{-1}\)) than in Burgerbukta (58 ± 88 ind. trans.\(^{-1}\)) and Gipsvika (46 ± 57 ind. trans.\(^{-1}\)) (Fig. 6). The dominant morphospecies Sabellidae was the most abundant in Burgerbukta (51 ± 86 ind. trans.\(^{-1}\)) and Adriabukta (49 ± 67 ind. trans.\(^{-1}\)), less abundant in Gipsvika (30 ± 39 ind. trans.\(^{-1}\)) and Borebukta (12 ± 15 ind. trans.\(^{-1}\)). In Borebukta, Ophiurida (not present in other bays) was the most abundant (76 ± 170 ind. trans.\(^{-1}\)). The sub-dominant Ceriantharia were tenfold lower in numbers (9 ± 11 ind. trans.\(^{-1}\)), but significantly more abundant in Borebukta than in Adriabukta and Gipsvika (Kruskal–Wallis test \(H = 8.5, p < 0.05\)). Bryozoans *Alcyonidium* sp., Bryozoa, and Bivalvia were the most abundant in Adriabukta (4 ± 6, 28 ± 27, 9 ± 9 ind. trans.\(^{-1}\), respectively); in other bays, only single individuals of these morphospecies were recorded. *A. marina* was the most abundant in Gipsvika (15 ± 30 ind. trans.\(^{-1}\)) and not present in other bays, while shrimps was the second most abundant morphospecies in Burgerbukta (5 ± 4 ind. trans.\(^{-1}\)) and not present in glacier influence-free bays Adriabukta and Gipsvika.

**Mobility and feeding mode**

Most of the individuals in the study area were sessile (42 ± 23 ind. trans.\(^{-1}\)) constituting 56% of relative abundance, followed by motile (24 ± 43 ind. trans.\(^{-1}\), 32%) and discretely motile individuals (9 ± 6 ind. trans.\(^{-1}\), 12%). The highest number of sessile organisms was in Adriabukta
(69 ± 65 ind. trans.−1), Burgerbukta (51 ± 86 ind. trans.−1), and Gipsvika (30 ± 39 ind. trans.−1), where they dominated (86%, 89% and 66%, respectively), while in Borebukta, they constituted 15% (17 ± 20 ind. trans.−1) (Fig. 7a). Under feeding mode category, suspension filters composed the majority of feeding mode in the study area (63%), scavengers—27%, while predators and deposit feeders—5% each. Suspension filters where the most abundant and dominant in Adriabukta (94 ± 51 ind. trans.−1, 98%), Burgerbukta (51 ± 89 ind. trans.−1, 89%), and Gipsvika (31 ± 39 ind. trans.−1, 66%).

Functional group composition of sub-dominant morphospecies revealed similarities between bays with similar glacier history (Fig. 7b). This was supported by one-way ANOSIM where highest functional group similarity between glacier-influenced bays (associated with a nonsignificant difference) and the lowest similarities between Adriabukta and Burgerbukta bays with different glacier history (associated significant difference). In glacier-influenced Borebukta, motile individuals were the most dominant (76%, 89 ± 171 ind. trans.−1) and in Burgerbukta, they sub-dominated (10%). In contrast, motile individuals reached up to 2% in glacier influence-free bays (Adriabukta, Gipsvika), while discretely motile organisms were sub-dominant there (11% and 33%, respectively). As for feeding mode, scavengers were the most abundant and dominant in glacier-influenced Borebukta (76 ± 170 ind. trans.−1, 75%) and in Burgerbukta, they sub-dominated constituting 8% of relative abundance. Controversially, the highest amounts of deposit feeders were found in Gipsvika (15 ± 30 ind. trans.−1, 32%), while in Adriabukta, they were the second highest, yet constituting only 2% of relative abundance in that bay.

**What defines differences of benthic assemblages: geographical location of bays or the presence of glaciers?**

There is a clear distinction between the structure of benthic communities in four bays. According to nMDS and Cluster analysis (Fig. 8, Online Resource 3), all bays are separated based on the presence/absence data. The most distinct community is in Borebukta (Isfjorden), while other

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**Fig. 6** Number of individuals per transect of the dominant and all morphospecies in the bays (mean ± standard deviation)

**Fig. 7** Relative abundance of morphospecies in bays categorized by feeding mode and mobility type (a) dominant morphospecies (b) same assemblages without the most abundant Sabellidae in order to showcase the contribution of less abundant morphospecies. HA—Hornsund Adriabukta, HB—Hornsund Burgerbukta, IB—Isfjorden Borebukta, IG—Isfjorden Gipsvika.
three are relatively more similar; however, bays within different glacial impact are not overlapping. This is supported by ANOSIM, which indicated statistically significant differences between the structure of benthic communities in four bays (R: 0.71; \( p = 0.001 \)). The pairwise test showed that the strongest differences were between Borebukta and Adriabukta (R = 0.87, \( p = 0.001 \)), Adriabukta, and Burgerbukta (R = 0.81, \( p = 0.002 \)). The only pair with moderate differences was glacier influence-free bays Gispvika and Adriabukta (R = 0.62, \( p = 0.005 \)). The pairwise test showed that there are more differences between glacier influence-free and glacier-influenced bays (R = 0.77; \( p = 0.001 \)) than between geographical areas (R = 0.69; \( p = 0.001 \)).

SIMPER analysis revealed that the differences between bays in benthic communities were primarily driven by 13 morphospecies with cumulative contribution from 81 to 84% in each bay (Table 3). In Gispvika, Sabellidae had the highest contribution, followed by Bivalvia, Ch. infundibuliformis, A. marina, and Buccinum sp. In Borebukta, Ophiurida, Sabellidae, and Ceriantharia contributed the most while in Adriabukta, Bryozoa, Bivalvia, Ch. infundibuliformis, Alcyonidium sp., Lumeninae, and H. araneus contributed the most. In Burgerbukta, Sabellidae, shrimps, Lumpeninae, and Pisces were among highest contributors. Isfjorden bays were more heterogeneous than bays in Hornsund as SIMPER analysis showed that the within-group similarity in Gispvika and Borebukta was 36 and 46%, respectively, compared to Adriabukta (69%) and Burgerbukta (64%) in Hornsund. In

| Bay          | Av. Sim. (%) | Contrib. (%) | Cum. (%) |
|--------------|--------------|--------------|----------|
| Gispvika     | 16.93        | 46.7         | 46.7     |
|              | Bivalvia     | 4.8          | 13.1     | 59.8     |
|              | Ch. infundibuliformis | 3.0 | 8.4 | 68.2 |
|              | A. marina    | 2.8          | 7.7      | 75.9     |
|              | Buccinum sp. | 1.8          | 4.8      | 80.7     |
| Borebukta    | 18.0         | 38.9         | 38.9     |
|              | Sabellidae   | 12.6         | 27.2     | 66.1     |
|              | Ceriantharia | 8.1          | 17.6     | 83.7     |
| Adriabukta   | 14.4         | 20.3         | 20.3     |
|              | Bivalvia     | 9.4          | 13.5     | 33.8     |
|              | Ch. infundibuliformis | 9.4 | 13.5 | 47.3 |
|              | Alcyonidium sp. | 9.1 | 13.1 | 60.4 |
|              | Lumeninae    | 9.1          | 13.1     | 73.5     |
|              | H. araneus   | 5.7          | 8.3      | 81.8     |
| Burgerbukta  | 23.6         | 32.5         | 32.5     |
|              | Shrimps      | 23.6         | 32.5     | 65.0     |
|              | Lumeninae    | 6.0          | 9.5      | 74.5     |
|              | Pisces       | 5.8          | 9.1      | 83.6     |
general, similarities of particular morphospecies at each bay were relatively low (2–21%) indicating that there was a high level of variation in morphospecies between transects within each bay. Two-way SIMPER analysis also showed that average dissimilarity between morphospecies was slightly higher in glacier-influenced/glacier influence-free bays (68%) than between bays located at warm/cold fjord (67%).

**Discussion**

**Underwater imagery in studies of upper sublittoral in Svalbard**

The target area of this study was the upper sublittoral (depth range from 3 to 65 m), which had not been surveyed much with underwater video techniques in Svalbard (Table 4). The majority of benthic studies at these depths were done by SCUBA divers (Gulliksen et al. 1999) which nowadays is commonly used in the conjunction with underwater imagery (Jørgensen and Gulliksen 2001; Beuchel et al. 2006; Al-Habahbeh et al. 2020), while underwater video systems were deployed at depths deeper than 50 m and open waters.

### Table 4 Benthic studies using underwater imagery (UI) in Svalbard waters with indication of the number of various features identified (named as “species,” “morphospecies,” or “taxa” in various studies)

| Authors                  | Method                                      | Object                | Depth    | Location            | Features |
|--------------------------|---------------------------------------------|-----------------------|----------|---------------------|----------|
| Jørgensen and Gulliksen  | UW photography, SCUBA suction sampling      | Rocky bottom fauna    | 16–32    | Kongsfjorden        | 34–73    |
| (2001)                   | SCUBA photo transects                       | Macroepibenthos       | 15–30    | Kongsfjorden        | 47       |
| Beuchel et al. (2006)    | SCUBA photo quadrats                        | Macrobenthos          | 15       | Kongsfjorden        | 23       |
| Beuchel and Gulliksen    | SCUBA UW photography                        | Rocky bottom fauna    | 15       | Kongsfjorden        | 23       |
| Tatarek et al. (2012)    | UW video transects and SCUBA sampling       | Macroflora            | 3–40     | Hornsund            | 17*      |
| Voronkov et al. (2013)   | SCUBA frame sampling and UW video transects | Hard-bottom fauna     | 0–30     | Kongsfjorden        | 403*     |
| Hop et al. (2016)        | SCUBA frame sampling and UW video transects | Macroalgae            | 0–30     | Kongsfjorden        | 27*      |
| Brand and Fischer (2016)| Fishing net, SCUBA head-mounted video camera| Fish community        | 3–12     | Kongsfjorden        | 12**     |
| Al-Habahbeh et al. 2020  | SCUBA photo quadrats                        | Hard-bottom benthos   | 15       | Smeerenburgfjorden and Kongsfjorden | 53 |
| Bergmann et al. (2011)   | Photo transects, Agassiz trawl and a box corer| Megabenthos          | 223–291  | Kongsfjorden        | 28*      |
| Laudien and Orchard (2012)| ROV                                          | Macroepibenthos       | 30–200   | Kongsfjorden        | 25       |
| Meyer et al. (2014)      | UW video photo transect                     | Megabenthos, macrozoobenthos | 2084–2332 | W. Svalbard, Fram Strait | 60 |
| Meyer et al. (2015)      | UW photographs                              | Megabenthos           | 77–360   | N. Svalbard, Raudfjorden, Rijpfjorden | ~14 |
| Dunlop et al. (2021)     | Time-lapse images                           | Scavengers            | 145–360  | Isfjorden, Billefjorden, Kongsfjorden, Raudfjorden, Smeerenburgfjorden and Rijpfjorden | 32 |
| Mazurkiewicz et al. (2021)| UW photographs                              | Megabenthos           | 33–350   | N. Svalbard fjords  | 33       |
| Schimani et al. (2022)   | ROV                                          | Macroalgae            | 2–138    | Kongsfjorden        | 13       |
| Fleischer et al. (2007)  | UW photographs, video transects, dredge     | Atlantic snake pipefish | 50–100   | Hornsund, Kongsfjorden, Mittragrunnen | 1 |
| Kędra et al. (2013)      | UW video, Veen grab and dredge              | Benthos, epifauna, infauna | 40–150   | Svalbard Bank       | ~7–80    |
| Sswat et al. (2015)      | UW video, Agassiz trawl                     | Epibenthic megafauna  | 50–450   | N. Svalbard        | 141      |
| Deja et al. (2016)       | UW video and Tucker trawl                   | krill                 | 25–180   | Hornsund, Kongsfjorden | ~12 |

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Laudien and Orchard (2012) used the term “taxa” instead of species approach in a hard-to-reach places, such as deep seas. For example, using quantitative morphospecies approach, we found that the bays we studied differed in their unique fauna (Fig. 6): numerous brittle stars (most likely Ophiocten sericeum or Ophiura robusta (Deja et al. 2016)) were unique to Borebukta, high numbers of shrimps were characteristic for Burgerbukta, bryozoans Alcyonidium sp. were specific for Adriabukta, while A. marina were specific for Gipsvika.

In addition, the morphospecies approach, combined with the analysis of functional groups, helped to notice another large-scale pattern. Włodarska-Kowalczyk et al. (2005), while using a traditional grab sampling method, have found that the tube-dwelling polychaetes dominate in the transition zone, but were absent in the areas disturbed by glaciers. This could be due to intensive sedimentation near melting glaciers burying sessile fauna and impeding tube-dwelling organism irrigation, resulting in their suffocation. Using UI method in our study, we noticed a similar pattern: the tube-dwelling Sabellidae were dominant (relative abundance 51%—88%) in all bays excluding Borebukta. It may be assumed that our sampling areas in three bays were situated in the transition zone (sensu Włodarska-Kowalczyk et al. 2005), while in Borebukta, the benthic environment was more impacted by the glacier, what reflected in decline of tube-dwelling polychaetes. Although we do not have enough environmental data to support this assumption, we can nonetheless formulate a working hypothesis for future research, including sampling covering the entire gradient from glacier proximity to fjord margins as well as parameters needed to quantify glacier impact.

In order to reveal distribution patterns of other, less numerous morphospecies in benthic community, we excluded Sabellidae from the analysis (Fig. 5). These results showed that bays under the glacier influence deviated from glacier influence-free bays with higher numbers of motile scavengers. Similarly, Meyer et al. (2015) found that small, mobile, scavengers were most common near heavily sedimented inner fjord stations affected by warmer Atlantic water masses. Meanwhile, areas less effected by melting glacier had higher numbers of discretely motile or sedentary individuals and suspension filters as this was also seen in Adriabukta, that is glacier impact-free for over 100 years. Higher abundance of suspension filters in Adriabukta can be explained by lower sedimentation rates and sediment stability as these are known to be important factors shaping benthic community structure (Włodarska-Kowalczyk and Pearson 2004).

ANOSIM showed that bays defined by presence/absence of a glacier were more similar than when grouped by the location in the same fjord. Similarly, Włodarska-Kowalczyk et al. (2012) study and Cuauy-Fraunié and Dangles (2019) meta-analysis demonstrated glacier proximity importance for faunal composition over the regional factors. In our study, Hornsund is a shallow fjord with little inflow from the warm Atlantic waters but affected by East Spitsbergen
Current which brings colder waters, in contrast to the large, open, and Atlantic water-dominated Isfjorden. Both glacial bays (Burgerbukta and Borebukta), despite the hydrological and biological difference between the two fjords, were quite similar in functional groups composition (higher numbers of motile scavengers), which suggests the important role of glacier for shaping the seabed biota.

Our method allowed to detect mesoscale differences in benthic communities within the bays along the depth gradient (Fig. 4). For example, discretely motile deposit feeder, the lugworm *A. marina*, was dominant at Gipsvika shallowest depths, where benthic life was presumably most affected by the nearby Gipsdalselva river outflow. It should be noted that here we also observed the gypsum deposits in our underwater videos. *A. marina* is known to be able to tolerate unfavorable conditions such as low salinity (up to 10 PSU), temperature (−1°C), and lack of oxygen; moreover, their population density even increases in the areas with higher hydrogen sulfide concentrations (Petrovskaya 1953 and Sveshnikov 1963 in Alyakrinskaya 2003). Freshwater input from rivers was studied in sub-Arctic fjords which also revealed a positive relationship between river output and mobile deposit feeders (McGovern et al. 2020). Further, down the slope at Gipsvika, the gypsum deposits disappear (below 19 m) and the lugworm is gradually substituted by Sabellidae (from 40 m and deeper), which probably indicates the diminishing impact of the river outflow.

In some cases, our observed pattern did not correspond to those found in previous studies. For example, Włodarska-Kowalczuk and Pearson (2004) have found that within their studied depth gradient (38–380 m) in Kongsfjorden fjord, the brittle star *Ophiura robusta* was associated with the deeper depths at the entrance (200–300 m), while in our study the morphospecies Ophiurida was dominant at much lower depths in Borebukta, from 23 to 54 m, the deepest sample in our study.

**Directions for future research**

Changes in benthic communities caused by climate change are anticipated to be more pronounced and quicker to notice in shallower Arctic bays where retreating glaciers creates new unoccupied areas. These newly formed habitats likely increase the colonization processes of a “new species” demonstrating the need for further research in the Svalbard upper sublittoral. Climate change may lead to a complete transformation of Arctic coastal ecosystems, with an increase in smaller and shorter-lived invertebrates and a decrease in long-lived organisms (Al-Habahbeh et al. 2020). Our study showed that UWM can provide a novel nondestructive tool to assess and monitor the Arctic ecosystem status and trends in the era of global warming.

**Conclusions**

We demonstrate that the underwater video mosaic method in combination with morphospecies and functional group approaches works at mesoscale (depth gradient) and large scale (different fjords and bays), allowing to observe differences in benthic composition. We discovered greater abundances of motile scavengers in glacier-influenced bays with Ophiuroidea being the most prevalent, whereas glacier influence-free bay had more sessile suspension filters (e.g.,
Bryozoa, _Acytonidium_ sp.) and glacier influence-free riverine bay was dominated by discreetly motile and deposit feeders ( _Arenicola marina_). Mosaics are good for efficient manual analysis of video material which gives a high-resolution wide-area view of a scene. It is also an excellent tool for effective annotation of UW visual features and it can be used for automatic morphospecies identification through Artificial Intelligence.

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**Author contributions** SO, AŠ, SM, and DD contributed to the study conception and design. AŠ and DD collected the data. Material preparation and analysis were performed by SM with a support of AŠ. The first draft of the manuscript was written by SM and AŠ and all authors commented on previous versions of the manuscript, with especially important feedback from MWK, SO, and AŠ. SO and JMW supervised the research project. All authors read and approved the final manuscript.

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**Declarations**

**Competing interests** The authors declare no competing interests.

**Ethical approval** No approval of research ethics committees was required to accomplish the goals of this study because the work was conducted with an underwater imagery.

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