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Acoustic scattering layers reveal a faunal connection across the Fram Strait

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ABSTRACT

Acoustic scattering layers (SL) at various depths are common phenomena in most oceans, but the organisms that make up these layers vary and so does their density, and hence the backscattered energy. During two crossings of the deep Fram Strait between the shelves at Svalbard and Northeast Greenland at latitudes 77°N and 79°N, we registered epipelagic and mesopelagic SL across the entire Fram Strait and quantified their acoustic backscattered energy. In addition, one pelagic trawl haul was made at each crossing together with a CTD cast at the northern crossing. The epipelagic SL was present at 0–200 m depth, whereas the mesopelagic SL was located at 300–500 m depth during day and at shallower depths during night indicating diel vertical migrations. The epipelagic SL consisted of young-of-the-year fishes, mostly redfish *Sebastes* sp. No trawl hauls were made in the mesopelagic SL, and the identity of organisms is unknown. Few strong echoes from single targets at mesopelagic depths stood out from the rest of the targets and were interpreted as adult Atlantic cod *Gadus morhua*. This is the first report of scattering layers covering the whole distance of the deep parts of the Fram Strait, and strengthen the assumption about an east–west connection of organisms and young-of-the-year fishes originating from the spawning grounds along the Norwegian coast and the western Barents Sea towards Northeast Greenland.

1. Introduction

Marine organisms like zooplankton and fishes often aggregate in the water column and are detected by echo sounders as scattering layers at given depths. Layers at epipelagic depths (0–200 m) often consist of zooplankton feeding on phytoplankton in the photic zone where photosynthetic production takes place and fishes feed on the zooplankton (i.e. Eriksen et al., 2017). Layers at mesopelagic depths (200–1000 m) may consist of a mixture of mesopelagic fishes, crustaceans, cephalopods and gelatinous plankton (Irigoien et al., 2014). The depth of such scattering layers is most often determined by the light regime, but hydrographic features may also play a role (Kaartvedt, 2008; Klevjer et al., 2016). In high latitude areas, epipelagic scattering layers are often ephemeral in nature, occurring only at the time of the year when primary and secondary production is taking place, and both zooplankton and fish larvae may leave the epipelagic layer during winter (Knutsen et al., 2017; Hobbs et al., 2018). Mesopelagic layers are more permanent but some of the organisms may undertake diurnal vertical migrations (DVM), hiding from predators in darker depths at day-time and ascend towards the surface to feed during night-time (Kaartvedt, 2008).

While scattering layers are well studied at lower latitudes, the existence and behaviour of such layers in the high Arctic are less known (Hobbs et al., 2018), although several articles have dealt with scattering layers in northern areas during the last decade. Some of these papers focus on particular fish species like polar cod (Benoit et al., 2010; Geoffroy et al., 2011, 2015; Bouchard et al., 2017) while others, for instance Geoffroy et al. (2016, 2019), Berge et al. (2020) uses hydroacoustic methods to study scattering layers containing both fish and invertebrate plankton. Studies on the Atlantic side have been confined to the Svalbard shelf and coastal areas, while a few have also described sound scattering layers at mesopelagic depths. During the SI_ARCTIC project 2014–2017 (Ingvaldsen et al., 2016a, 2016b, 2017a, 2017b) acoustic transects were made from the west coast of Svalbard across the shelf and into the deep water of the Fram Strait as well as in the area northwest of Svalbard. Knutsen et al. (2017) described both epipelagic and mesopelagic scattering layers in the eastern Fram Strait transects, and Gjøsæter et al. (2017) demonstrated that the deep scattering layer in these areas displayed DVM, albeit less pronounced than further south in the north-eastern Atlantic. Siegelman-Charbit and Planque (2016) compared deep scattering layers in the north-eastern Fram Strait with similar layers at lower latitudes in the Northeast Atlantic and concluded that the further north, the less backscatter energy was reflected from the layer, indicating decreasing biomass and/or a changed composition

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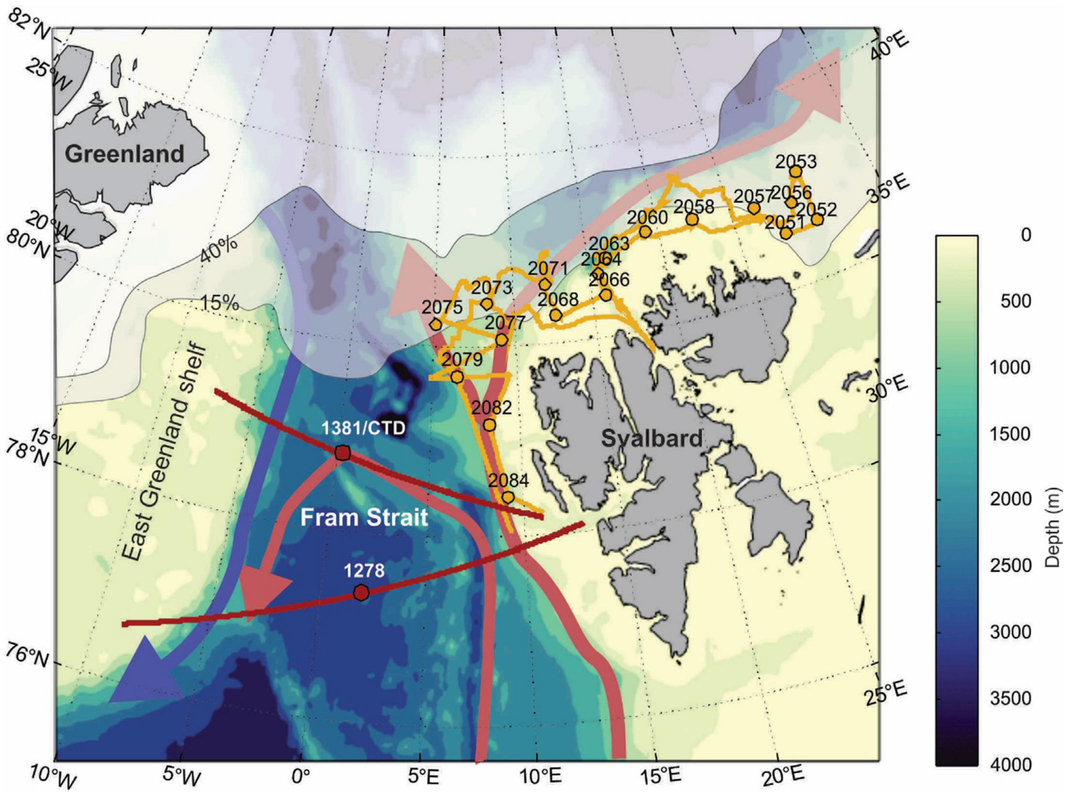

Fig. 1. Fram Strait bathymetry, general circulation, sea ice conditions and the observations used in this study. Light red and blue arrows show West Spitsbergen Current and East Greenland Current respectively. Average sea ice conditions during the period of the surveys are shown with white shading. The acoustic transects of R/V Helmer Hanssen during 14 September-25 September 2017 (TUNU) are shown with dark red lines and the location of the pelagic trawl stations and the CTD are indicated with dark red circles. The acoustic cruise track and the pelagic trawl stations sampled with R/V Helmer Hanssen during 21 August-7 September 2017 (SI_ARCTIC) are shown in orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of scatterers with increasing latitude. However, the transects conducted during the SI_ARCTIC project only covered the eastern part of the Fram Strait (Knutsen et al., 2017), and so did the survey in the Fram Strait reported by Siegelman-Charbit and Planque (2016). The recent comprehensive study by Geoffroy et al. (2019) from deep waters north of Svalbard covering both the winter (January) and summer (August) situation, revealed that a sound scattering layer found at 50–500 m during winter and 200–700 m during summer, comprised both zooplankton and pelagic fishes of boreal and arctic origin.

1.1. Study area

The Fram Strait separates Svalbard and Northeast Greenland (NEG) at latitudes 77°–81°N, and it is the only deep-sea connection between the Atlantic and the Arctic Oceans (Fig. 1). The sill depth is almost 2600 m, and the bathymetry is complex due to a combination of ridges, fracture zones and deeper basins. The strait is confined by a wide (~300 km) shelf in NEG and a narrow (~70 km) shelf at Svalbard. The NEG shelf is covered by sea ice for about 10 months a year, while the Svalbard shelf currently has open water also during winter. The width of the deep part of the Fram Strait is about 360 km in the south and it narrows to about 170 km in the north.

The environmental conditions in Fram Strait are strongly influenced by the warm West Spitsbergen Current (WSC) carrying Atlantic Water northwards on the eastern side. The WSC has two branches; an eastern branch following the continental shelf break west of Svalbard (Beszczynska-Möller et al., 2012), and a western branch flowing along the slope of the Knipovich Ridge and continuing offshore into the Fram Strait (Orvik and Niiler, 2002). The eastern branch constitutes the main source of the Atlantic inflow to the Arctic Ocean. This water crosses and possibly also partly flow along the Yermak Plateau, before the branches re-join north of Svalbard continuing northeastwards along the continental slope towards the Arctic Ocean (Aagaard et al., 1987; Koenig et al., 2017; Menze et al., 2019).

The western branch of WSC recirculates in the Fram Strait between latitudes 78°N and 79°N, providing a direct pathway for Atlantic Water across the strait (Marnela et al., 2013; Håvik et al., 2017). This branch is often named the Return Atlantic Current (RAC). Previous studies have shown that Atlantic Water is also transported westward in the northern part of the Fram Strait by extensive eddy activity (Hattermann et al., 2016; von Appen et al., 2016).

In the western Fram Strait, the cold East Greenland Current (EGC) flows along the NEG shelf-break. In the northern parts, at least two distinct branches are known, i.e.; one along the shelf-break and one separate outer branch further to the east (Håvik et al., 2017). The shelf-break EGC carries cold and fresh Polar Surface Water in the upper 150–200 m and Atlantic-origin Water below. The shelf-break EGC is characterized by a strong surface-intensified flow close to the shelf-break with core speeds ranging between 0.2 and 0.4 m/s (Marnela et al., 2013; Håvik et al., 2017).

Here, we describe the presence of scattering layers and some of their organisms observed during acoustic transects crossing the deep Fram Strait at latitudes 77–79°N in September 2017 (Fig. 1). We compare these findings with those from a similar survey conducted northeast in the Fram Strait and north of Svalbard at 80–81°30′N approximately half a month earlier (Ingvaldsen et al., 2017b).

We address the following research questions: do the scattering layers and the corresponding organisms such as young-of-the-year fishes previously observed close to Svalbard extend across the deep Fram Strait westwards to the NEG shelf? And if so, do the same organisms make up the layers near the Svalbard coast and over deep water? Does the distribution of organisms give evidence for a transport

Table 1
Catch on trawl stations no 1278 and 1381 at the TUNU-VII Expedition 2017. All fishes were Young-of-the-year.

Trawl station	Date	Position	Depth m	Species	Total catch kg	Numbers	Body size
1278	15 Sept.	77°22.6′N 2°14.7′E	31–46	Beaked redfish *Sebastes mentella*	25.42	~43800	36–50 mm
				Haddock *Melanogrammus aeglefinus*	0.012	1	115 mm
1381	25 Sept.	78°51.8′N 0°38.0′W	20–33	Capelin *Mallotus villosus*	0.004	5	0.8 g
				Atlantic cod *Gadus morhua*	0.016	2	8 g
				Beaked redfish *Sebastes mentella*	0.554	~615	0.9 g

of organisms across the Fram Strait from east to west? Do adult Atlantic cod (*Gadus morhua*) swim further west than previously observed by Ingvaldsen et al. (2017c)?

2. Materials and methods

The study is based on a survey of the TUNU Programme (Christiansen, 2012) conducted with R/V Helmer Hanssen (UiT The Arctic University of Norway) 14–25 September 2017; i.e. TUNU-VII Expedition (Christiansen, 2018).

Two transects were made across the deep Fram Strait i.e. from Longyearbyen (LYR) in Svalbard to the NEG shelf, and vice versa on the return. Acoustics and near-surface temperature were sampled continuously along a southern (LYR-NEG, latitude ~77 °N) and a northern (NEG-LYR, latitude ~79 °N) transects (Fig. 1). Moreover, two pelagic trawl hauls were made over the deep Fram Strait with one haul at each crossing (Fig. 1, Table 1). During the northern crossing, one CTD profile was obtained from the same location as the trawl haul.

The TUNU data were compared to similar data sampled from the SI_ARCTIC/The Barents Sea Ecosystem Survey west and north of Svalbard (Fig. 1). This survey was conducted with the same vessel (R/V Helmer Hanssen) during the period 21 August-7 September 2017, thus slightly earlier than the TUNU survey. During the survey, numerous pelagic trawl hauls were taken (Ingvaldsen et al., 2017b).

2.1. Acoustic data collection

Acoustic data for estimation of the distribution and magnitude of backscatter from organisms in the water column down to 1000 m were collected with calibrated EK60 split beam echo sounder systems at the acoustic frequencies 18, 38, and 120 kHz all operated at 1 ms pulse duration. The transducers were mounted on a drop keel instrumented with transducer faces ~3 m below the hull, usually ~8.5 m below the sea surface.

The area scattering (s_A) was recorded as Nautical Area Scattering Coefficients (NASC, m^2 nmi^{-2}, MacLennan et al., 2002). The s_A values were then grouped in 10-m depth bins from below the hull mounted 38 kHz transducer at ~15 m to 700 m depth.

Target strength distributions were extracted at 38 KHz. A maximum gain compensation of 6 dB was applied to calculate TS for targets off centre axis of the beam. Criteria for single target detection was echo lengths of 0.8 to 1.2 relative to the transmitted pulse.

The vessel's EK60 systems were calibrated at the beginning of the SI_ARCTIC survey on 21 August using standard methods and spheres (Foote et al., 1983). The systems have proven to be stable over time, and at this calibration the correction factor for s_A was less than 0.4 dB for 38 and 120 KHz and about 0.7 dB for the 18 KHz system.

The noise level at the various echo sounder frequencies was not measured during the TUNU survey. However, in 2015 Helmer Hanssen's noise level was measured in the same area, in deep water and at several cruise speeds (Gjøsæter et al., 2017) and should be relevant for the present survey. The recorded noise level at 10.8 knots (cruise speed used during the two crossings) were −137, −161, and −152 dB re 1 W, as directly measured by the Simrad EK60 in passive mode at 18, 38, and 120 kHz. These noise levels enable measurements of a weak scattering, corresponding to $S_V = -80$ dB re 1 m^{-1}, with 10 dB signal to noise ratio at about 700 m range at 18 kHz, 800 m range at 38 kHz, and 200 m range at 120 kHz. Since most of the deepest scattering layers were observed at depths less than 600 m, and as weak scatterers approaching the lower integrator threshold would be observable much deeper (750–800 m), we concluded that the observed noise level was acceptable.

2.2. Scrutinizing of acoustic data

Multi-frequency scrutinization and target strength analysis were conducted with the Large Scale Survey System (LSSS) post-processing software (Korneliussen et al., 2006; Korneliussen et al., 2016), which also was used for exporting files for subsequent analysis. The interpretations were made per standard procedures where the total backscatter was split into target categories (see ICES, 2015; Korneliussen et al., 2016). The processing involved manual removal of unwanted acoustic signals from wind-generated bubbles etc. The weather conditions were variable during the two crossings, with some heavy wind especially during the first crossing but bubble attenuation and bubble drop-outs were mostly absent.

The allocation of total s_A to species or groups of organisms was difficult, because only one trawl haul was made (upper 20–45 m) during each crossing. We therefore made an allocation of s_A based on the information from the trawl haul, backscattering strength from layers and single targets, depth of the organisms, appearance on the echograms, and frequency response. The lower threshold in terms of volume backscattering strength (S_V) was set to −82 dB re 1 m^{-1}, and we restricted the number of species/groups to the following: Young-of-the-year (YOY) fishes, zooplankton, pelagic scatterers, Atlantic cod (*Gadus morhua*), and other scatterers. The criteria for discrimination are given in Table 2.

We then compared the acoustic data from the TUNU survey with those obtained from the SI_ARCTIC 2017 survey (Ingvaldsen et al., 2017b), although the scrutinizing of acoustic data at that survey was performed slightly different from what we have done here. In particular, the allocation of acoustic backscatter to species or groups

Table 2
Criteria for allocation of s_A into various species or groups of organisms.

Species or group	SV lower threshold	SV upper threshold	Comment
YOY fishes	−70 dB	No upper limit	Upper 100 m
Zooplankton	−82 dB	−70 dB	Upper 100 m
Pelagic scatterers	−82 dB	−65 dB	Below 100 m
Cod	−65 dB	No upper limit	Below 100 m, TS > −40 dB
Other scatterers	–	–	Dense concentrations at the NEG shelf break and other signals not fitting into the groups defined above.

Table 3
Catch on trawl stations 2079, 2082, 2084 in the Fram Strait “FS”, and on trawl stations 2051, 2052, 2053, 2057, 2058, 2060, 2063, 2064, 2066, 2068, 2071, 2073, 2075 North of Svalbard “NS” at the SI_ARCTIC survey 2017. FS: Dates of trawling 5-6th September. Positions: Fram Strait. Depth of trawling 0–60 m. NS: Positions: North of Svalbard. Depth of trawling 0–60 m. All fishes but lump suckers were Young-of-the-year.

Trawl stations	Species/Genus	Total catch, kg	Numbers	Body size, cm
FS	Capelin *Mallotus villosus*	2.43	4567	5.0 – 6.8
FS	Cod *Gadus morhua*	4.196	966	6.1–11.0
FS	Beaked redfish *Sebastes mentella*	115.00	197,561	3.1–5.4
FS	Herring *Clupea harengus*	0.06	109	5.1–8.3
FS	Haddock *Melanogrammus ageglefinus*	5.80	511	7.8–13.4
FS	Lump sucker *Cyclopterus lumpus*	9.776	23	6.5–30.5
FS	Wolffish *Anarchicas* sp	0.06	1	8.0
FS	Arctic rockling *Gaidropsarus argentatus*	0.01	6	5.6–6.9
NS	Capelin *Mallotus villosus*	1.05	2025	4.9–6.5
NS	Atlantic cod *Gadus morhua*	2.03	575	6.3–9.4
NS	Beaked redfish *Sebastes mentella*	0.748	737	2.6–4.8
NS	Haddock *Melanogrammus ageglefinus*	0.348	85	6.2–12.0
NS	Wolffish *Anarchicas sp*	0.004	4	3.1–7.1
NS	Greenland halibut *Reinhardtius hippoglossoides*	0.012	4	6.0–7.5
NS	Long rough dab *Hippoglossoides platessoides*	0.007	4	3.3–4.2
NS	Daubed shanny *Leptoclinus maculatus*	0.001	2	4.8–6.2
NS	Sculpin *Triglops* sp.	0.001	2	4.8–6.2

included more groups since frequent trawl sampling made it easier to identify the organisms contributing to the backscatter.

2.3. Biological data

During the TUNU survey, two epipelagic hauls were made with a Harstad trawl (Godø et al., 1993), having an opening of about 20 × 20 m, and a small meshed (4 mm) net in the cod end. Sample sites and catches are given in Table 1. Epipelagic trawl data obtained during the SI_ARCTIC survey west and north of Svalbard (Table 3) were then compared with those of the TUNU survey. Both surveys used the same vessel and trawl, but the Svalbard hauls were performed according to protocol used by the Institute of Marine Research for sampling of YOY fishes. That is, the trawl is hauled in three steps with the headline of the trawl at 0, 20 and 40 m for 10 min thus effectively covering a depth interval from surface to 60 m (Eriksen et al., 2010).

2.4. Environmental data

The temperature was measured continuously from the cooling water intake under the hull at 4 m depth. Temperature data from both crossings of the Fram Strait are shown in Fig. 2. In addition, one CTD cast was made during the northern crossing (latitude ~79°N).

3. Results

Fig. 1 shows the survey area, the main hydrographic features, and the transects and trawl stations made during the SI_ARCTIC and TUNU surveys in August-September 2017.

3.1. Hydrographic features

For both TUNU-crossings, the WSC was evident with near-surface temperatures above 6 °C east of about longitude 6°E (Fig. 2A). Further west, the southern crossing (latitude 77°N) showed a weak, gradual temperature decrease across the deep part of the Fram Strait, but with near-surface temperatures above 4 °C until encountering the NEG shelf break at longitude 3–4°W. Here, the near-surface temperature gradient was stronger, and the temperature dropped rapidly towards 0 °C.

The northern crossing (latitude 79°N) showed a somewhat different pattern with a strong near-surface temperature decline just west of the WSC at about longitude 5°E (Fig. 2A). Enhanced near-surface temperatures were visible between longitudes 1°W–4°E, indicating that the transect crossed a recirculation branch of Atlantic Water. This was confirmed by the CTD data obtained from the westernmost part of the recirculation (Fig. 2B), showing a prominent layer of higher temperatures (mean 4.3 °C and maximum 5.5 °C) and high-salinity (mean 34.9 and maximum 35.0) Atlantic Water at about 25–110 m depth. Atlantic-origin Water also occupied the water column between about 100–700 m depth. West of the RAC (i.e. west of approx. 2°W), the near-surface temperatures rapidly decreased towards −1 °C at the shelf-break at 3–4°W (Fig. 2A).

Both crossings showed a strong temperature variability over short distances, indicating presence of meso-scale eddies commonly found in this region (Hattermann et al., 2016).

3.2. Overall description of the TUNU-echograms

Backscatter was present from near surface to bottom (at 100–250 m depth) at the Svalbard shelf, while only a very weak scatter was detected at the NEG shelf (Fig. 3). In the Fram Strait, some prominent acoustic features included: 1) high backscatter in the upper 100 m, from just outside the Svalbard shelf (approx. longitude 9.5°E), to approximately the middle of the Fram Strait (approx. longitude 1°E), and very low acoustic backscatter from the upper layer further west towards NEG. 2) a mesopelagic scattering layer, being at 300–500 m depth at daytime, and at shallower depths at night.

The northern return crossing, from NEG to Svalbard (Fig. 3), showed similar acoustic patterns but in reversed order. The backscatter from the upper 100 m, however, was less pronounced than during the southern crossing ten days earlier.

During both crossings, an area of increased backscatter at 250–550 m depth at the NEG shelf break, interpreted as dense aggregations of organisms were seen (Fig. 3).

3.3. Target strength

Target Strength (TS) data were extracted, and the TS-values are grouped and plotted as −70 to −50 dB, −50 to −40 dB, −40 to −30 dB, and > −30 dB (Fig. 4). Strong scatterers (TS > −40 dB) were mostly confined to the shelf and shelf-break areas, although a few also occurred in the mesopelagic and epipelagic layers. Both the mesopelagic and the epipelagic layer were dominated by scatterers with TS < −50 dB, followed by scatterers with TS between −50 and −40 dB.

The scatterers at the NEG shelf-break showed TS-values in the span −50 dB to −40 dB. However, due to dense aggregations of organisms very few single-target echoes and hence TS-measurements could be

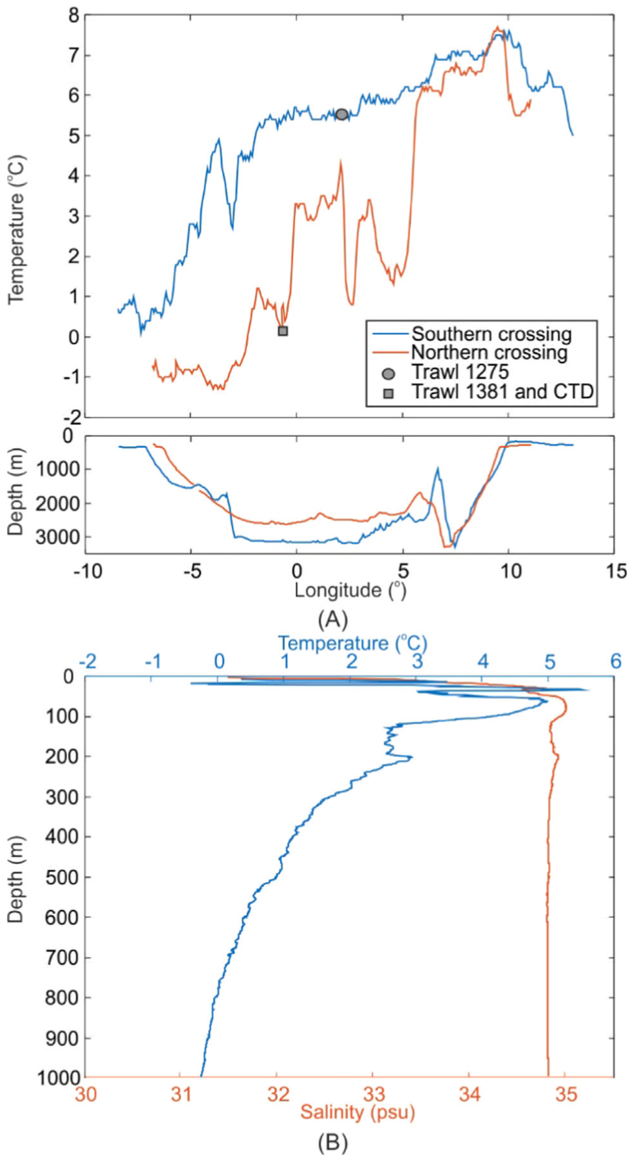

Fig. 2. Near-surface (4 m depth) temperature and bottom depth measured at the two crossings of Fram Strait (A). Vertical profile of temperature and salinity in the upper 1000 m from the CTD cast (B). The location of the trawl stations and the CTD are shown in the upper panel of A and in Fig. 1.

extracted. Some TS measurements just above the main concentration of organisms (marked by black dots in Fig. 3C) gave TS-values centred around −45 dB.

3.4. *Scattering organisms from scrutinized acoustic data*

Based on the acoustic characteristics of the backscatter (see Table 2), most of the scattering in the upper 100 m could be assigned to YOY fishes, and the remaining scatter probably to zooplankton (Fig. 5). This is supported by the trawl hauls taken during the crossings at 25–50 m depth in positions 77.37°N, 2.19°E and 78.85°N, 0.63°E (Table 1), where the catches consisted almost entirely of various YOY fishes, mainly beaked redfish (*Sebastes mentella*). The identity of zooplankton organisms is not known but their absence in the trawl hauls may indicate that they were small-sized and thus avoided the net mesh. The zooplankton in the epipelagic layer extended across the entire Fram Strait during both crossings, but the s_A-values were mainly less than 100 m^2nmi^{-2}. Scattering of YOY fishes was found throughout the southern crossing, while at the northern crossing it was absent over the NEG shelf and 60 nautical miles offshore (corresponding to approx. longitude 2°W). The s_A-values were much higher for YOY fishes than for zooplankton, peaking to 930 at the northern crossing and 3860 m^2nmi^{-2} at the southern crossing near Svalbard.

There is no ground-truthing of the composition of the mesopelagic layer during TUNU-VII Expedition, but based on studies at the Svalbard side of the Fram Strait (Gjøsæter et al., 2017; Knutsen et al., 2017) this layer probably consists of various mesopelagic fishes, pelagic crustaceans, gelatinous plankton, etc. Interestingly, this is also where Ingvaldsen et al. (2017c) caught 26 adult cod. Consistent with that, we tentatively assigned to adult cod targets with similar characteristics to those interpreted as cod in Ingvaldsen et al. (2017c). The mesopelagic layer was most prominent on the Svalbard side (Fig. 5) but extends almost over the entire Fram Strait. The s_A-values were modest with a maximum of about 300 m^2nmi^{-2} for both crossings. Interestingly, a characteristic shift in scattering depth between day (~100 m) and night (300–500 m) indicated the presence of diel vertical migration (Figs. 3 and 5). The s_A-values for cod were low, and mostly confined to the Svalbard side of the Fram Strait (Fig. 5), but very low values of s_A: (0.1–1.0 m^2nmi^{-2}, corresponding to 1–10 detections per 5 nautical mile) were recorded from both crossings far west into the Fram Strait.

The epipelagic layer had a much stronger backscatter than the mesopelagic layer. The s_A from the epipelagic zone (zooplankton and YOY fishes) occasionally were above 350–400 m^2nmi^{-2}, while the s_A-values of the mesopelagic zone rarely exceeded 20 m^2nmi^{-2}.

The aggregations of organisms (Fig. 3) at the NEG shelf-break could not be assigned to taxonomic groups, because no pelagic trawl hauls were made, and no specific TS-values could be extracted from scatterers. The few TS-values obtained from the outskirts of the aggregation were in the span −50 dB to −40 dB. The frequency response was rather flat at 18–38 KHz (the signal to noise ratio of the 120 KHz is too low at this depth to include in the frequency response).

4. Discussion

While the topographic and oceanographic features of the Fram Strait are well known (e.g. Rudels et al. (2005) and Håvik et al. (2017) and references therein), this is the first published data on the acoustic scattering along transects crossing the Fram Strait. Although the identity of scattering organisms is scarce, the information obtained from the acoustic systems is nonetheless valuable. The Fram Strait is the only deep connection between the Atlantic Ocean and the Central Arctic Ocean, and it is the main gateway for the exchange of water and biota between the two oceans. In this respect, the Fram Strait is an area of great scientific interest, especially in a period where ocean warming pushes boreal organisms poleward on an unprecedented scale (Christiansen et al., 2016; Christiansen, 2017; Andrews et al., 2019).

4.1. *Does the mesopelagic scattering layer cross the Fram Strait?*

The answer to this question is yes; there is a continuous mesopelagic SL spanning, if not the entire stretch over the strait, at least almost so. The density of organisms over the deep parts of the Fram Strait seemed to decrease from east (Svalbard) to west (NEG) (Fig. 6). Backscattering from the mesopelagic SL was at the same level as found during the SI_ARCTIC surveys (Knutsen et al., 2017), and that reported by Siegelman-Charbit and Planque (2016). Knutsen et al. (2017) grouped the mesopelagic SL-organisms into “strong” (YoY, cod, capelin, redfish, and other fishes) and “weak” (including micronekton, krill, amphipods, and mesopelagic fish) scatterers, and concluded that the strong scatterers dominated the SL near the shelf break while the weak scatterers gradually took over farther offshore. This indicates that the composition of mesopelagic SL-organisms changed from being fish-dominated to zooplankton-dominated toward the open sea. However, the acoustic transects into the Fram Strait were still close to Svalbard with an end point at longitude ~5°E. We have not made a corresponding grouping

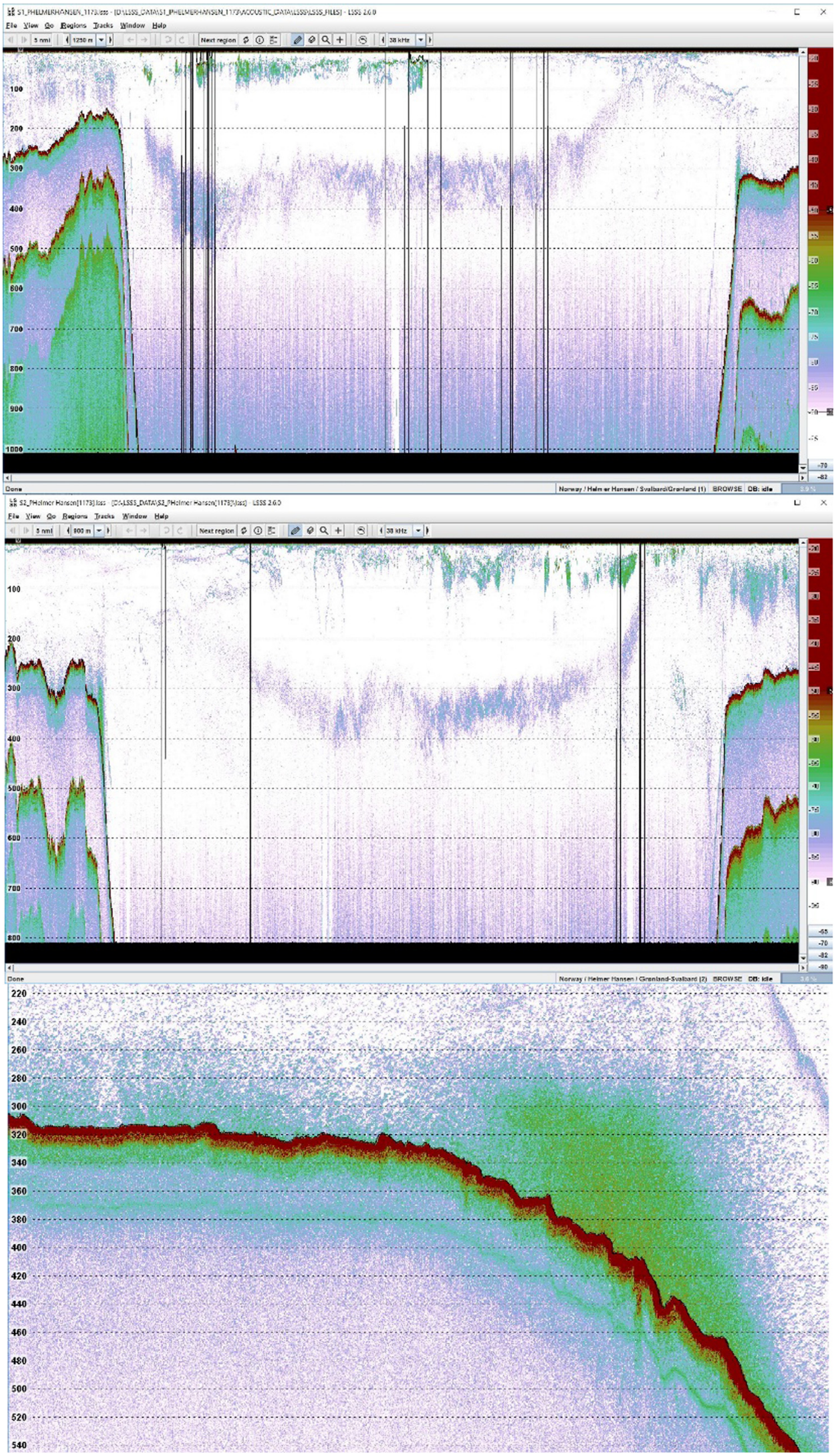

Fig. 3. Fig. 3 Echograms (38 KHz) with Sv threshold at −90 dB. Upper panel: Southern crossing, from Svalbard to NEG. Svalbard shelf to the left, NEG shelf to the right. Middle panel: Northern crossing, from NEG to Svalbard. NEG shelf to the left, Svalbard shelf to the right. The vertical scale is 0–1000 m depth. The horizontal distance from shelf brake to shelf brake is approximately 240 and 250 nautical miles respectively, for the two crossings. Note that when the threshold is set as low as −90 dB, the noise (increasing with depth because of the time-varied gain (TVG) of the echosounder) becomes prominent at depths deeper than 500 m. Lower panel: Close-up echogram of the aggregation of scatterers at the NEG shelf break. Vertical scale is 220–540 m depth.

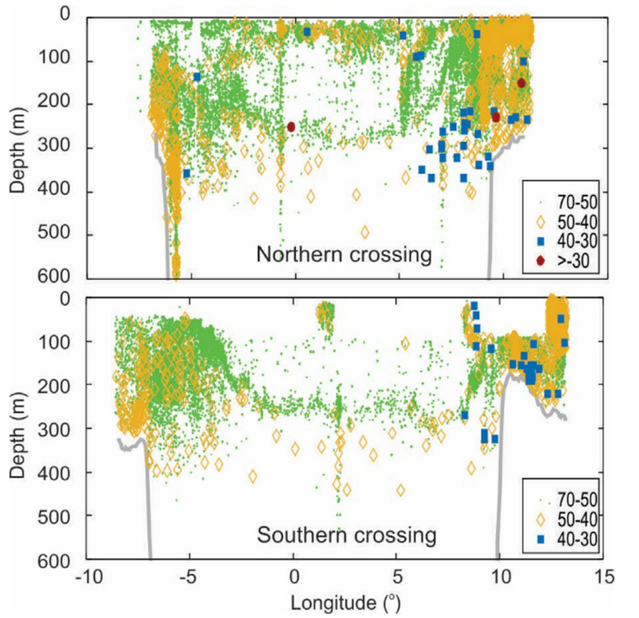

Fig. 4. Spatial distribution of TS of the scattering organisms at 38 kHz during the two crossings of the Fram Strait. The grey line indicates the bottom contour.

of scatterers here, but our data indicate a similar pattern going from dominance of fish scatterers near the coast to smaller pelagic scatterers like zooplankton offshore (Fig. 5).

4.2. Do young-of-the-year fishes cross the Fram Strait?

The epipelagic layer extended over the entire Fram Strait during the southern crossing from Svalbard to the NEG shelf at latitude 77°N, and from about 60 nautical miles off the NEG shelf break toward Svalbard during the northern crossing at latitude 79°N (Fig. 5). The acoustic backscatter was relatively high (> 350 m^2nmi^{-2}) on the Svalbard side of the Fram Strait and decreased to less than 100 m^2nmi^{-2} towards the NEG shelf. Previous investigations along the west coast of Svalbard have shown a layer rich in YOY fishes, which probably had been advected from the spawning areas further south (Knutsen et al., 2017). The acoustic registrations of YOY fishes from the Fram Strait (TUNU) were compared with those obtained west and north of Svalbard conducted in August-September 2017 (SI_ARCTIC) and revealed that the acoustic backscatter was similar in the entire eastern Fram Strait (Fig. 7). The acoustic backscatter was lower north of Svalbard than on the western side of Svalbard, but still higher than in western Fram Strait.

The two trawl hauls conducted during the Fram Strait crossings (TUNU) showed that the epipelagic layer consisted almost solely of YOY redfish in addition to one haddock and a few Atlantic cod and capelin (Table 1). However, none of the trawl hauls were taken west of longitude 1°W, and the species composition further towards the NEG shelf is unknown. We compared the composition of the trawl catches in the epipelagic layer at the present survey (Table 2) with that found in the northeastern Fram Strait and north of Svalbard (Table 3) from the preceding SI_ARCTIC survey. The catches from the group of stations in the Fram Strait and that north of Svalbard were much in line and were dominated by YOY redfish, capelin, cod, and haddock. The Fram Strait stations also contained some YOY herring and lump sucker (both YOY and older specimens) that lacked in the northern samples, while the stations north of Svalbard contained a few specimens of Greenland halibut. Long rough dab and daubed shanny were absent from the Fram Strait samples. The absence of these rarer species in the two trawl hauls during the TUNU survey could be caused by chance alone, and do not allow us to conclude that they are absent from the more offshore waters of the Fram Strait. Since most of the above fish species spawn in spring, the layer of YOY fishes is a seasonal phenomenon, with peak biomass during the months August and September. Siegelman-Charbit and Planque (2016) reported that during a survey in May further north in the Fram Strait, the nautical area backscattering coefficient from the epipelagic layer was on average 18 m^2nmi^{-2} which is substantially less than that recorded during the TUNU survey in September (average 213 and 129 m^2nmi^{-2} on the southern and northern crossings respectively).

The epipelagic concentration of YOY fishes seems to extend across the entire Fram Strait, and this opens up for a putative transport of various YOY fishes originating from the spawning sites along the Norwegian coast, and along the shelf break between the western Barents Sea and the Norwegian Sea, to the NEG shelf.

The RAC crosses the Fram Strait between latitudes 78–79°N and is a direct pathway for warm Atlantic Water across the Fram Strait (Marnela et al., 2013; Christiansen et al., 2016; Håvik et al., 2017). Our two acoustic transects were situated in the southern and northern rim of this recirculation (Figs. 1 and 7). This is also consistent with the near-surface temperatures where the southern crossing showed near-surface temperatures above 4 °C until encountering the NEG shelf break at longitude 3–4°W, while the northern crossing showed rapidly decreasing near-surface temperatures west of longitude 2°W, reaching almost −1 °C at the NEG shelf break (Fig. 2A).

Strand et al. (2017) modelled the spreading of YOY Atlantic cod in years 1978–1991 and showed that up to 1/3 of a cohort may disperse off the continental shelf and into the deep Norwegian Sea during their drift from spawning areas along the Norwegian coast to the nursery areas in the Barents Sea. According to their drift model, most of the offspring transported into the open ocean were either transported back onto the shelf and into the Barents Sea, or were circulating within the Lofoten Basin. However, 2.4% of the offspring were carried northwest toward the NEG shelf. Christiansen et al. (2016) discovered Atlantic cod (*Gadus morhua*), beaked redfish (*Sebastes mentella*), capelin (*Mallotus villosus*) and deep-sea shrimp (*Pandalus borealis*) on the NEG shelf and shelf-break (latitudes 74–77°N). These authors hypothesised that plankton and offspring of fishes may advect from the Barents Sea to the NEG shelf by RAC. Moreover, recent genetic analyses assigned the cod, redfish and shrimp from NEG to their respective populations in the Barents Sea (Andrews et al., 2019).

The existence of faunal connections between the Barents Sea and the NEG shelf is therefore supported by several independent studies such as direct field observations (Christiansen et al., 2016), modelling of advection routes (Strand et al., 2017), genetic assignments (Andrews et al., 2019), and now acoustic registrations of epipelagic scattering layers extending toward NEG across the deep Fram Strait (our study).

Considering ocean warming and subsequent changes in species distribution, more species of boreal origin are expected to reach NEG. The advection of meroplankton from the Barents Sea is of particular interest. For example, snow crab (*Chionoecetes opilio*) is omnipresent in the Arctic and sub-arctic shelf seas and has become highly abundant in the eastern and central Barents Sea and was recently observed even northwest of Svalbard (Ingvaldsen et al., 2017b). On the other hand, snow crab and other brachyuran crabs are apparently absent in NEG (Fredriksen, 2018). As snow crab spreads further west in the Barents Sea one might expect that the meroplanktonic larvae may reach also the NEG shelf via WSC and RAC as may the larvae of the invasive red king crab (*Paralithodes camtschaticus*) of the Barents Sea (Christiansen et al., 2015).

4.3. Do adult Atlantic cod cross the Fram Strait?

During both crossings, we observed acoustic targets at mesopelagic depths (ca 200–600 m) with stronger target strengths (TS −40 to −30 dB) than those scattered by typical mesopelagic organisms. The presence of such echoes was extremely rare, but somewhat more

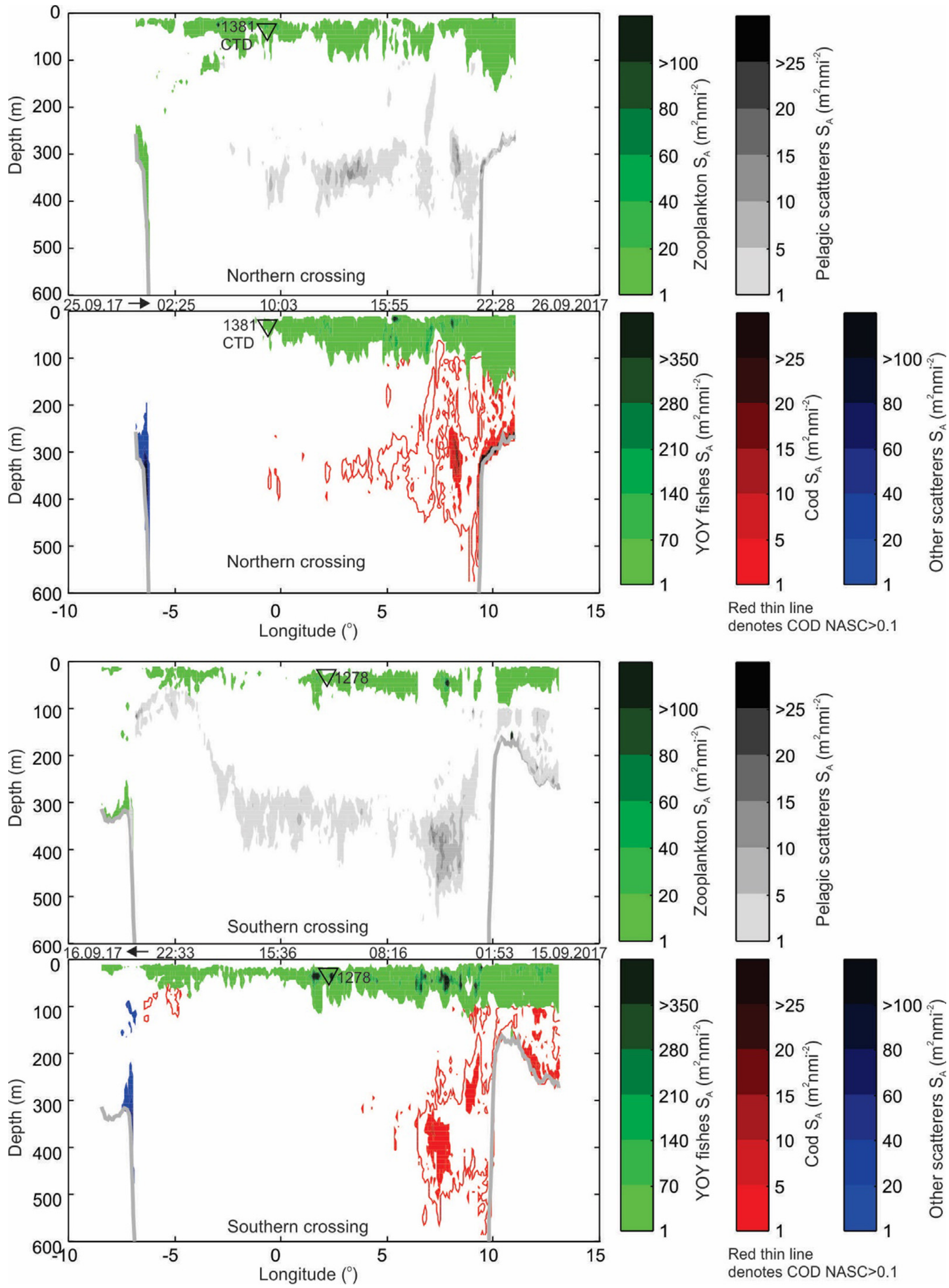

Fig. 5. Scrutinized data (s_A) for the acoustic group's zooplankton and pelagic scatterers (1st and 3rd panels), and YOY fish, cod and other scatterers (2nd and 4th panels) from the northern and southern crossings. The grey line indicates the bottom contour. Note that Greenland is to the left and Svalbard to the right in both panels.

common on the northern than on the southern crossing, and most common at the Svalbard side of the Fram Strait.

No trawl hauls were made at mesopelagic depths during the TUNU survey and we have no ground-truthing of the acoustic signals. The TS values of −40 to −30 dB would correspond to cod sizes of 25–80 cm. No organisms normally considered part of the mesopelagic scattering layer have as strong echoes as this, except possibly large Greenland sharks (*Somniosus microcephalus*) that could have TS in this range (Ona and Nielsen, in submission) and this species is known to be present in the area. Sharks have no gas bladders and their TS is less affected by frequency than the TS signal of Atlantic cod, which is stronger at 18 than at 38 KHz. This is not necessarily detectable for single targets, because the directivity of the echo differs with frequency, and the tilt angle may differ from target to target. The frequency response from a scattering layer will, however, reflect whether the layer consists of organisms with or without gas bladders. By tuning the S_V threshold upwards to a level where only strong scattering objects in the DSL remained visible (~ −75 dB), the frequency response showed a drop from 18 to 38 kHz ($S_{V18} \sim 1.5\ S_{V38}$). We cannot conclude that the TUNU-data we interpret as adult cod is in fact cod, but it is highly likely.

The westward migration of adult cod over deep water in the eastern Fram Strait is consistent with Ingvaldsen et al. (2017c). The present

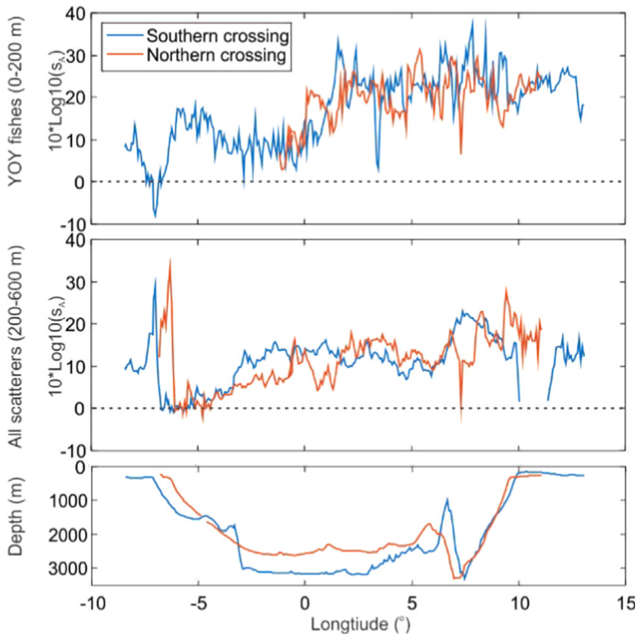

Fig. 6. Total (vertical integrated) s_A across Fram Strait. Det upper panel show young-of-the-year fish in the epipelagic layer, while the middle panel show all scatterers in the mesopelagic layer. The lower panel show bottom depth.

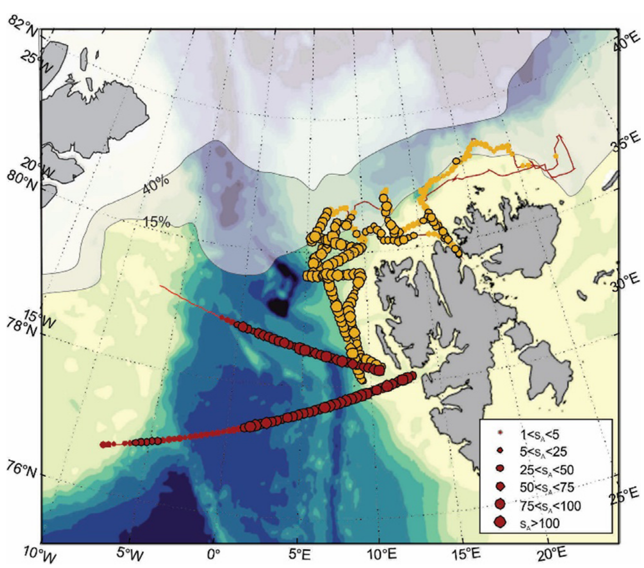

Fig. 7. Vertical integrated s_A of juveniles in the upper 100 m depth layer during the TUNU (dark red) and SI_ARCTIC (orange) surveys in 2017. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

acoustic observations showed targets interpreted as cod to be present rather continuously to about longitude 1°W (Northern crossing) and about 4°E (Southern crossing) with single observations extending to about 6°W (Fig. 5). The acoustic observations from TUNU are further south from where Ingvaldsen et al. (2017c) found a maximum westward migration (latitude 79°40′N). Atlantic cod are considered mainly demersal as adults and reach their north-westernmost feeding grounds on the Svalbard shelf north in the Fram Strait. Therefore, the cod's "willingness" to undertake a pelagic westward turn across the deep Fram Strait would perhaps be larger further north. Another issue is that the horizontal width of the deep parts of the Fram Strait decreases northwards and the minimum deep-water distance to cross from the Barents Sea toward NEG is in these northern parts. Therefore, if Barents Sea cod migrate westwards exploring new habitats, the northern route appears most likely for a successful crossing of the Fram Strait.

An exchange of cod belonging to the Icelandic stock across the deep Denmark Strait between Iceland and Southwest Greenland have been described (e.g. Storr-Paulsen et al., 2004), where a westward transport of fry spawned near Iceland and an eastward active migration of adult cod back from Greenland has been hypothesized. Recently, concentrations of cod were detected near the Jan Mayen Island northeast of Iceland, an area where cod has only been found occasionally previously (ICES, 2020). Jan Mayen Island is separated both from Iceland, Greenland and Svalbard/Barents Sea by deep water. In summer/autumn 2018, a Norwegian vessel caught 450 t of cod in the Jan Mayen Island EEZ and otolith readings and genetics both indicated this cod to be a mix of Northeast Arctic and Icelandic cod. In 2019, Norway carried out an experimental fishery during four different periods in order to investigate further the occurrence of cod in this area in space and time as well as stock identity. The size distribution and genetic composition of the cod was similar to that in 2018. Most of the cod caught in April-May 2019 was spawning or spent. Cod spawning in this area has not been observed previously. Similar investigations will continue in 2020 (ICES, 2020). It is unknown whether cod of Icelandic and North East Arctic origin came to Jan Mayen waters as larvae/juveniles, or whether they may have migrated to this area as adults.

In light of these observations the possibility that cod over deep parts of the Fram Strait could in fact be a sign of adult cod moving back from Greenland to Svalbard cannot be ruled out. However, since only juveniles have so far been sampled from the NEG this possibility seems very unlikely.

To reach a firm conclusion on adult cod crossing the Fram Strait, further studies combining acoustics and pelagic hauls are warranted for the northern parts of the Fram Strait.

4.4. Aggregations of organisms in the East Greenland Current

The few TS measurements from single targets obtained in the periphery of the areas of increased backscatter at the NEG shelf break with range from about −36 dB to −56 dB indicate that gas bladder fishes could be present. The most likely candidates would be polar cod (*Boreogadus saida*) and ice cod (*Arctogadus glacialis*), which have been detected together with juvenile Atlantic cod in one and the same trawl hauls at the NEG shelf break during the TUNU-VI Expedition in 2015 (Christiansen et al., 2016). Given that the scattering stem from these fishes, their body size would span 10–30 cm. The backscatter from the whole aggregation was slightly stronger at 18 kHz than on 38 kHz when the S_V threshold was set at −82 dB, and this did not change significantly at higher thresholds. If the entire aggregation consisted of gas bladder fishes only, we would anticipate a stronger backscatter at 18 kHz than at 38 kHz. On the other hand, a mixture of fishes and for instance crustacean zooplankton would probably give more equal backscattering strength at these two frequencies, since the plankton would give a stronger echo at 38 kHz than at 18 kHz.

Similar registrations were made at the NEG shelf break during both crossings, but the aggregations were more pronounced and the vertical range wider in the northern (250–550 m depth) as compared to the southern crossing (Fig. 3).

The EGC temperature at the NEG shelf-break at these latitudes and depths (250–550 m) are 1–3 °C (Marnela et al., 2013; Håvik et al., 2017), and the thermal habitat would be suitable also for fishes and zooplankton common in Svalbard waters.

During a survey of the east Greenland shelf and the Greenland Sea in 2017 (Bouchard, 2020) trawl hauls at similar depths (300–550 m) caught both *Boreogadus saida*, *Arctogadus glacialis* and *Gadus morhua*, together with myctophids, jellyfish, squids, krill and amphipods. It is unknown whether any of those trawl hauls were set in an acoustic registration similar to the one we observed off the shelf edge.

5. Conclusions

We show that the epipelagic and mesopelagic scattering layers previously observed at Svalbard cross the Fram Strait to the NEG shelf, but with lower backscattered energy indicating lower biomass and/or a change in composition of scatterers on the western side of the Fram Strait.

The composition of organisms in the epipelagic layer is seemingly similar across the Fram Strait with YOY (mainly *Sebastes* sp.) dominating.

Stray specimens of targets interpreted to be Atlantic cod, previously shown to occur in the mesopelagic layer over deep water on the Svalbard side of the Fram Strait, were also found (however, in low concentrations) further west in the Fram Strait, and there are indications of single individuals near the NEG shelf.

Given the continuous distribution of epipelagic and mesopelagic scattering layers across the Fram Strait, and what is known about the circulation patterns in the area, it is highly likely that there is a regular connection of organisms between the eastern side and the western side of the Fram Strait, although with a high variability between individual years (Strand et al., 2017).

Author contributions

HG and RBI conceived the idea, and prepared and analysed the acoustic data. JSC conducted the field sampling of acoustic and biological data. HG drafted the first version of the manuscript and all co-authors took part in subsequent review. RBI prepared the figures.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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