A Modeling Study of Behavior and Sampling Bias Introduced by Artificial Light on Marine Organisms During the Polar Night

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Ingvild Marie Krohn Riska

Introductory remarks

I have chosen to use the pronoun "we" during my thesis, as it is more common in scientific writing and as parts of the process has been in collaboration with my supervisors. The written part of the thesis is my own work.

This thesis is a contribution to the project Deep Impact, funded by the Research Council of Norway (NRC #300333), which explores the impact of artificial light on Arctic marine organisms and ecosystems during the polar night. The project partially funded the sample collection and conference participation associated with this thesis.

Abstract

Light structures pelagic communities, as pelagic organisms have adapted to detect small changes in light. However, biological sampling in the dark, such as trawls, plankton nets and acoustic transects often involves some form of artificial deck-light for safety, and the bias introduced is not always accounted for. Here, we explored the impact of artificial light on pelagic organisms, and their change in behavior in three Svalbard fjords during the polar night. By turning deck-lights *on* and *off* while simultaneously conducting acoustic observations, we could then extract individual swimming patterns from the acoustic data, used to inform an individual based model. Trawl samples were also used to ground truth the acoustic observations and parameterize the model. We found that pelagic organisms within a radius of the lit vessel, such as Polar cod and Atlantic herring, immediately responded to the artificial light by swimming away from the light. Across all experiments we observed that there was an increase in backscatter, likely caused by *attraction* to the light, and that the response to *lights on* were faster than the response to *lights off*. Individual swimming patterns extracted from acoustics (target tracking) proved to be a useful tool to get further insight to individual behavior, and modeling provided insight to the mechanisms behind the observed behavior, in addition to generate new hypothesizes. Overall, artificial light from a lit vessel has been shown to alter behavior and vertical distribution of pelagic organisms. Our results confirm the importance of taking artificial light into account when doing biological sampling in the dark.

Keywords: pelagic organisms, artificial light, modeling, acoustics, Arctic

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1 Introduction

1.1 Light structures the pelagic habitat

Light is an important part of how many pelagic organisms get information about the world around them, as many species rely on the ability to detect small changes in light for vital behaviors such as feeding and avoiding predators (Clark and Levy, 1988; Rosland and Giske, 1997). The vertical distribution of pelagic organisms is strongly structured by light, along with other environmental factors such as oceanic variability and seasonality (Urmy and Horne, 2016; Boswell *et al.*, 2020). Sound-scattering layers of mesopelagic fish perform instantaneous light dependent vertical migration, as explained by balancing predation risk and food demand (Giske *et al.*, 2011), where they distribute in depth according to a narrow band of preferred light intensity, their light comfort zone (Røstad, Kaartvedt and Aksnes, 2016). For many species of mesozooplankton, both herbivorous and omnivorous, the ultimate factor behind diel vertical migration, DVM, seems to be minimizing predation risk by seeking daytime refuge in deep, dark waters (Hays, 2003). Predators on higher trophic levels may modify their behavior to optimize forging on the migrating mesozooplankton (Hays, 2003). Vertical migration in response to changes in natural light conditions are found in a variety of species groups, such as with freshwater mysids (Boscarino *et al.*, 2009), arctic marine zooplankton (Berge *et al.*, 2008), freshwater fish (Bohl, 1979), tropical marine fish (Mcfarland, 1986), and arctic marine fish (Benoit *et al.*, 2010a).

1.2 Light during night

Light conditions in the water surface varies greatly between day and night, but there is also a variation in light conditions within the night that depends on water clarity, the monophases and cloud coverage (Ryer and Olla, 1999; De Busserolles *et al.*, 2017). There is a lack of research on teleost communities in darkness, mainly caused by logistical and technical challenges (Hammerschlag *et al.*, 2017). However, pelagic organisms have been shown to react to small changes in ambient light conditions, where lunar vertical migration (LVM) occurs in zooplankton in Svalbard during the polar night, and the cyclic behaviors of zooplankton during the polar night is matching up with the oscillations of light intensity caused by midday twilight, the moon and the aurora (Cohen *et al.*, 2021). Polar cod, *Boreogadus saida*, has also been shown to be sensitive to low light levels, by performing DVM and foraging during the polar night (Benoit *et al.*, 2010b).

1.3 Behavioral responses to artificial light at night

In the last century, there has been a rapid increase in artificial light at night (ALAN), lighting up the marine environment, both from land and also from moving vessels and permanent installations such as rigs, bridges etc. Satellite images have shown that 22.2 % of the worlds coastline, excluding Antarctica, is exposed to light pollution at night (Davies *et al.*, 2014), which has made studying the effect on ALAN in costal systems challenging (Gaston, Visser and Hölker, 2015) because there are almost no coastal zones with pristine light environments left to compare with. For most fish species in both freshwater and marine systems, little is known about the influence artificial light has (Perkin *et al.*, 2011; Davies *et al.*, 2014). However, it is known that light pollution alter the physiology and behavior of individuals, population level processes and echo system- and community interactions in some marine taxa (Gaston *et al.*, 2013). Examples include the Pacific herring *Clupea pallasi* being attracted to a 400 W underwater light (McConnell, Routledge and Connors, 2010), decrease in survival and growth of a coral reef fish after long term exposure to ALAN (Schligler *et al.*, 2021), different Mediterranean fish species being attracted to, or avoiding light in laboratory experiments (Marchesan *et al.*, 2005), Eurasian perch, a freshwater fish, having increased predation success when their habitat was artificially lit (Czarnecka *et al.*, 2019) and *Thysanoessa inermis* and *Meganyctiphanes norvegica* being attracted to light and attracting foraging Atlantic cod, *Gadus morhua* (Humborstad *et al.*, 2018; Utne-Palm *et al.*, 2018). Berge et.al (2020) showed that the response of pelagic organisms to artificial light during the polar night varied between different sampling stations where ambient light levels, latitude, fish community and hydrography varied.

1.4 Biological sampling in the dark

Biological sampling during night time is traditionally performed using some sort of deck-lighting. Interestingly, this artificial light may introduce a bias in biological sampling, acoustic recordings and, therefore, possibly stock assessment (Berge *et al.*, 2020). Acoustic transects or biological sampling in the dark done from vessels might be biased from the on-board light. Vessels lit by normal working lights are shown to disrupt pelagic organisms down to 200 m and within an area bigger than 0,125 km^2 around the ship (Berge *et al.*, 2020). Sameoto et.al (1985) found that there was an instant drop in volume backscattering when euphausiids found on the continental shelf outside Nova Scotia had a sudden change in orientation as they got exposed to light from a vessel. Geoffroy et.al (2021a) demonstrated in Arctic and temperate areas that pelagic organisms strongly avoid artificial light that was lowered down the water column. The organisms also avoided the red light, which is often assumed to not be perceived by pelagic organisms, thus concluding that observations relying on artificial light in the visible spectrum (400-700 nm) is not able to capture the real dynamics of the ecosystem (Geoffroy *et al.*, 2021a). Levenez et.al (1987) found that pelagic fish in the tropics avoided artificial light from moving vessels during the night, thus showing a strong decrease in the upper layers of the echograms in an unpublished report. They found that depending on the speed of the lit vessel, fish dived 5 to 8.5 meters deeper when they were passed by the vessel, and they saw that the fish swam back up to their initial depths after the vessel had passed (Levenez, Gerlotto and Petit, 1987).

1.5 Fundamentals of acoustic observations

As shown in the examples in the previous paragraph, echosounders have previously been used to assess the influence of artificial light on the pelagic community. This noninvasive sampling gear, standard on most research vessels, does not rely on artificial light and is commonly used in marine research for acoustic transects and stock assessment, however, currently with the ships lights turned on. Echosounders can also provide long time series when they are bottom mounted. Split beam echosounders combined with individual target tracking, enable behavioral studies, such as on the individual behavior of mesopelagic fish using stationary upward facing echosounders and individual tracking (Christiansen *et al.*, 2022). Individual target tracking combines sequential pings reflected by individual fishes to reconstruct the swimming patterns trough the acoustic beam (Brede *et al.*, 1990). Acoustic observations are, however, limited to what biomass happens to pass though the acoustic cone-shaped beam during the sampling. Depending on the frequency, the beam has an angle between 7 and 12 degrees, so only a limited part of the water column is sampled, especially close to the surface. Ground truthing by trawl or camera footage is necessary to read the echograms.

1.6 Approaching behavioral questions with modelling

Individual-based modeling (IBM) is a common tool in ecology, where a group-level outcome is produced by individuals. This type of modeling is well suited to investigate individual behaviors, and has been used before to study organismal response to artificial light, such as in seabirds (Troy, Holmes and Green, 2011) and in bird communities in Poland (Kosicki, 2021). A study that used artificial light to control the swimming depth of Atlantic salmon in sea cages, combined an IBM with observational data (Føre *et al.*, 2013). Kaartvedt *et.al* (2019) combined acoustic recordings with an IBM to study the behavior of mesopelagic fish towards light from an ROV in the Red Sea using simple behavioral rules. Using modeling for acoustic experiments allows for full knowledge about the entire water column, and is in contrast to acoustic recordings with the narrow field of the echo beam, not limited by sampling gear. However, some previous knowledge about the modelled system is required. Modeling also allows to run experiments that can test and generate new hypothesizes, without additional fieldwork, and allows to simulate and manipulate parameters.

1.7 Objectives

We aimed to study behavior and sampling bias introduced by artificial light from a vessel on pelagic organisms by setting up light experiments in three fjords in Svalbard during the polar night. Firstly, we analyzed echograms recorded when lights were turned *on* and *off* on a vessel during a period of ambient darkness. Secondly, we combined information about species composition, hydrography, and behavior of individual acoustic targets to further expand our understanding of the study systems. Finally, we utilized individual based modeling to study the mechanisms (behavioral rules) causing the observed behaviors, to generate new hypothesizes, and to simulate how the artificial light alters the distribution of pelagic organisms outside the range of the acoustic beam. As many pelagic organisms are sensitive to natural changes in light, and have been shown to change behavior in response to artificial light, we hypothesized that pelagic organisms would exhibit a clear change in behavior when exposed to artificial light from a lit vessel.

2 Materials and Methods

To study the effect of artificial light on pelagic organisms, we collected data from acoustic light experiments, an individual based model, and additional CTDs and trawls from the sampling sites. We did light experiments in three different fjord systems in Svalbard (Figure 1) during the polar night, a period when the sun is always below the horizon. Data was collected in January 2020 and 2022 on the Polar Night Cruise on bord RV Helmer Hanssen in fjords on the west coast of Spitsbergen, the main island in Svalbard; Billefjorden, Isfjorden and Krossfjorden. We made an individual based model, simulating the acoustic light experiments.

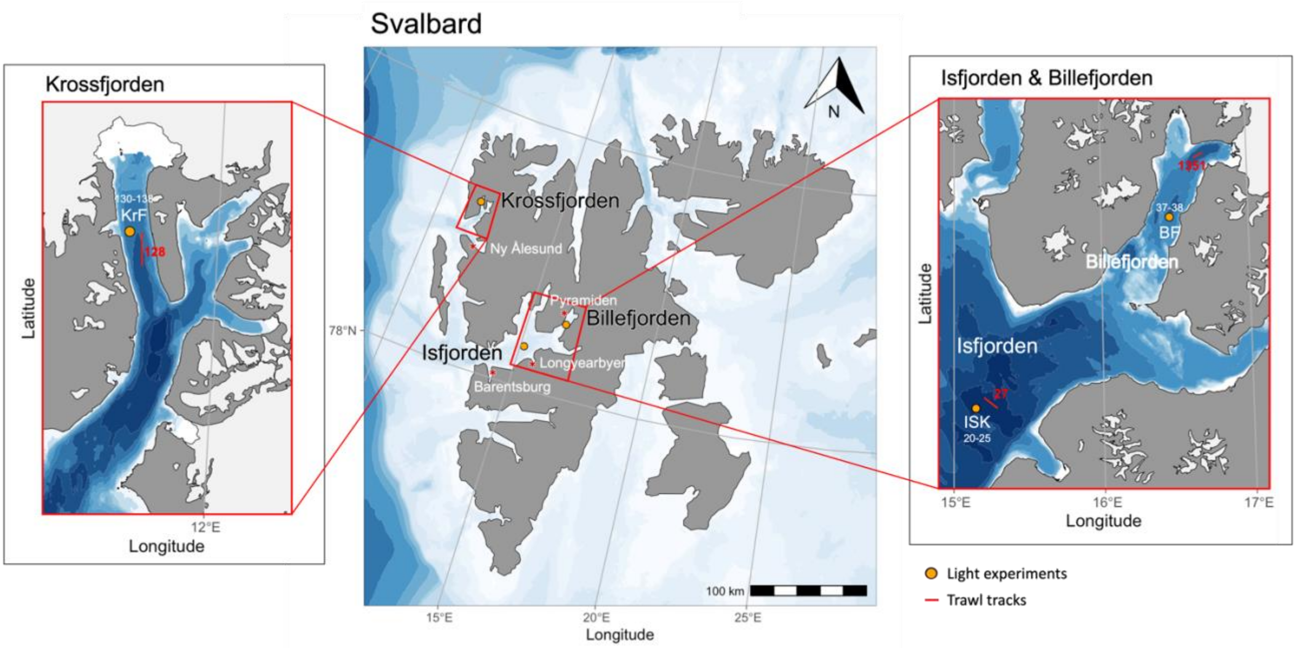

Figure 1: Map of sampling locations in fjords on Spitsbergen in Svalbard from the Polar Night Cruise 2020 and 2022 and August 2022, made using ggOceanMaps (Vihtakari, 2022). Red lines denote trawl tracks with numbers referring to the station numbers. Yellow dots mark the location of the light experiments.

2.1 Sampling locations

We did sampling in three different fjord systems with different proximity to settlements and with different hydrography (Figure 1, Table 1). Billefjorden is a sill-fjord with Arctic water masses and a marine terminating glacier. The fjord is ice covered in winter, and there is little light pollution, with the settlement Pyramiden as the only light source. Billefjorden is a side fjord to Isfjorden, which in contrast is a wide-open fjord influenced by the warm, salty water masses from the West Spitsbergen Current. Longyearbyen and Barentsburg are towns situated in side-fjords to Isfjorden with potential for some light pollution. Krossfjorden is situated at 79 degrees north and has a south facing mouth with several marine terminating glaciers. There are no settlements by the fjord, hence no light pollution.

We collected CTD (conductivity, temperature and depth) measurements (Table 1) to assess the composition of water masses when we did light experiments and took trawls in the fjords.

Table 1: Overview of timing and duration of acoustic light experiments, sampling of water masses (CTD) and pelagic trawling.

					Time (UTC)		
Fjord	**Stnr**	**day**	**month**	**year**	**start**	**stop**	**Duration**
Light experiments							
Billefjorden	37-38	8	Jan.	2020	00:44	10:44	9 h
Isfjorden	20-25	6	Jan.	2022	02:21	08:21	6 h
Krossfjorden	130-138	11	Jan.	2022	10:46	18:45	7 h
CTD							
Billefjorden	28	8	Jan.	2020	-	17:36	-
Billefjorden	1340	31	Aug.	2022	-	22:41	-
Isfjorden	17	7	Jan.	2022	-	00:15	-
Krossfjorden	139	11	Jan.	2022	-	23:02	-
Pelagic trawl							
Billefjorden	1351	31	Aug.	2022	15:40	15:58	18 min
Isfjorden	27	7	Jan.	2022	12:03	12:35	32 min
Krossfjorden	128	11	Jan.	2022	08:48	09:23	35 min

2.2 Light experiments, sampling and processing of hydroacoustic data

We did light experiments turning the ships lights *on* and *off* (Figure 2) in 1- or 1.5-hour intervals and used acoustics to monitor the response of the organisms. The acoustic data from Billefjorden is from 2020, and the data from Krossfjorden and Isfjorden is from January 2022. When the lights were on (Figure 2 A), all deck lights and search lights were lit, and windows let out light from inside the vessel. When the lights were off (Figure 2 B), the search lights were turned off, the deck lights and lights in the CTD hatch were replaced by lower intensity red lights, and windows were blacked out.

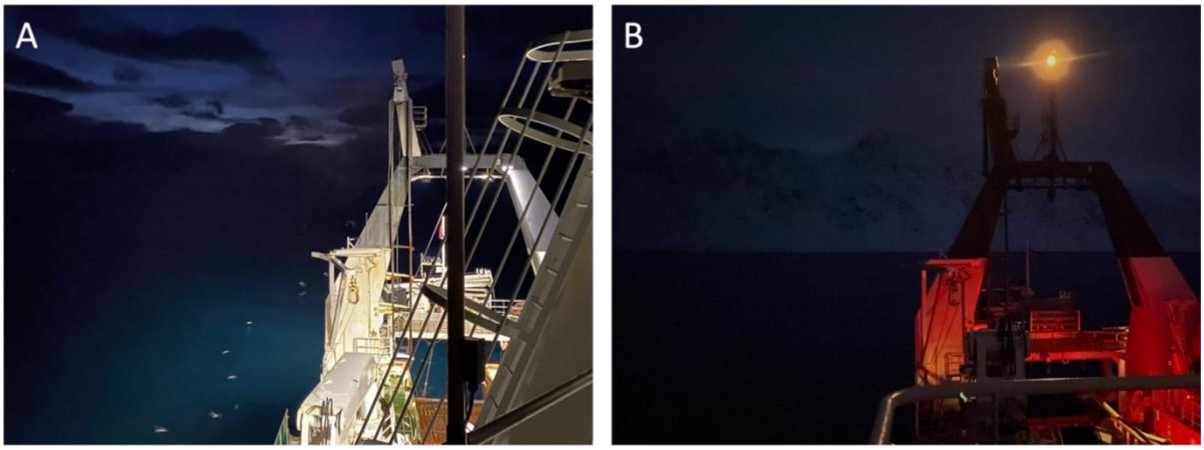

Figure 2: Lights *on* (A) and lights *off* (B) as seen from the bridge on RV Helmer Hanssen in January 2022. Note the illumination in the water around the boat when the lights are *on*. *Photos by Ingvild Riska.*

2.2.1 Setup of light experiments

We conducted the light experiments in three different fjords (Table 1). In Billefjorden, the experiment lasted 9 hours, with 1.5-hour intervals of *lights on* and *lights off*, and a total of three light and three dark periods. In Isfjorden, the experiment lasted 6 hours with 1-hour intervals, also with a total of three light and three dark periods. In Krossfjorden the experiment lasted 8 hours with 1-hour intervals and four light and four dark periods. Each set of *lights on* and *lights off* can be seen as a replicate. In both Billefjorden and Isfjorden, the lights were kept off for some time before starting the experiments, allowing the scattering layers to stabilize before making changes.

We selected sites for the light experiments by scrutinizing the onboard echograms and finding an area where there was sufficient backscatter. To get clear echograms during the experiments, we kept the vessel as stationary as possible in attempt to minimize the effect of wind at the surface moving the vessel in one direction while currents below move in another. Drift was minimized in Isfjorden and Krossfjorden by putting the boat on anchor and using the engine to keep the tension. In Billefjorden the boat was parked in sea ice, keeping it in one place during the entire experiment. There is, however, a possibility that currents caused advection of the community while we did the experiments. Keeping the vessel in one place both before and during the experiments also kept the potential noise disturbance at a relatively constant level as the noise from the engine and propellers were constant and minimized.

2.2.2 Collection of acoustic data

Acoustic data was collected using an EK60 hull-mounted echosounder (Kongsberg Maritime AS, Norway) operating at 18, 38 and 120 kHz. Higher frequencies provide a high spatial resolution, and are advantageous for detecting smaller organisms, but have a limited detection range and are vulnerable to environmental inference. Lower frequencies have a lower spatial resolution, but a higher detection range, and are less vulnerable to environmental inference. As we mainly targeted fish at depths shallower than 300 meters, we here used data from the 38 kHz echosounder for our analysis to balance the trade-offs (Table 2).

Table 2: Settings of the 38kHz EK60 echosounder (Kongsberg Maritime AS, Norway).

	Value	**Unit**
Frequency	38	kHz
Power	2000	W
Pulse length	1.024	ms
Ping rate	1	ping sec^{-1}
Beam width	7	degrees (˚)

2.2.3 Processing of acoustic data and target tracking

Acoustic data was processed to echograms using R (version 4.2.2). We used Target tracking (TT), to get information on the behavior and horizontal- and vertical swimming of individual fish within the echo beam, and to estimate swimming speeds for the modelling. The swimming speed estimated from the tracks is from now on called *target-speed*. This was done using the Echoview R 13.0 software for single-echo detection (SED) algorithm for split-beam echosounder. We selected thresholds in Echoview to isolate targets, where one track had to be made up of a minimum of 5 single targets with minimum 5 pings and a maximum gap between single pings of 5. The thresholds were selected to exclude tracks that were too short, and tracks that were likely made up of several different individuals. We chose a TS-threshold of -60 dB to exclude zooplankton from the tracks. The exported TT dataset was analyzed in R using the package tidyverse (Wickham *et al.*, 2019). A caveat of the Echoview algorithm is that it is unable to separate individual targets in the densest parts of the echograms, thus extracting fewer tracks in denser aggregations as shown with the yellow circles in Figure 6, B and E.

2.3 Sampling and processing of trawl data

2.3.1 Sampling locations and time of trawls

Trawls (Table 1) were taken to ground-truth the acoustic observations, to inform the model on species composition and to estimate swimming speeds, assuming swimming speeds of one body length per second (bl s^{-1}) in cold water (He, 1991; Kessel *et al.*, 2016). The swimming speed estimated from trawl samples is from now on called *length-speed*. Locations for pelagic trawls (Figure 1) were chosen by scrutinizing the echo layers from the EK60 echograms near the locations of the light experiments and targeting the most prominent layers. Each haul lasted between 18 and 35 minutes at target depth with trawl speed of ~3 knots. The pelagic trawl was a Harstad trawl with cod end mesh size of 5.5 mm.

Trawls from Isfjorden and Krossfjorden were taken in January 2022 on the same day, and in close proximity to the light experiments. The Billefjorden trawl was taken 31st of August of 2022 on a UNIS (the University Center in Svalbard) cruise, while the light experiment was done January 8th 2020. We assumed the trawl from August provided good indications of the species composition in Billefjorden in January, as it is a sill-fjord with little connection to the open ocean, and that the composition of water masses in the deeper layers were similar, and as Polar cod, the dominant species, has been found in the fjord at different years and through different seasons (Cusa, 2016).

2.3.2 Processing the trawl catches

The total catch was weighted and sorted to species level or the lowest possible taxonomic level. We recorded total weight, biomass, and total count, abundance, for each species. If the catch contained lots of small individuals of species such as krill, amphipods, small jellyfish, juvenile Lumpeninae (likely Daubed shanny, *Leptoclinus maculatus*), juvenile Atlantic herring, *Clupea harengus*, or Polar cod, *Boreogadus saida*, the large individuals were sorted out first before all the remaining small individuals were weighted, subsampled and sorted to species level. The total abundance and biomass for each subsampled species was then back calculated.

In Isfjorden and Krossfjorden in January 2022, we measured length and weight of a random subsample of 40+ individuals for abundant fish species or measured all individuals for species that were represented with less than 40 individuals. Length was measured in total length to the nearest millimeter for individuals under 10 cm, to the nearest 0.5 cm for individuals between 10 and 20 cm, and to the nearest cm for individuals over 20 cm. Weight was recorded to the nearest 0.1g for small individuals below 10 cm and to the nearest gram for larger individuals.

In Billefjorden in August 2022, we selected 30 Polar cod over 12 cm that we length measured in standard length to the nearest 0.5 cm and weighted to the nearest gram. The length measurements were thus not randomly sampled, and only provided rough indications of the length composition of Polar cod in the fjord.

2.3.4 Length and TS relationship

We used the relationship between the total length of fish and their target strength, TS, as recorded with a 38 kHz echosounder, to better assess the vertical distribution of some of the most prominent species in the echograms, by combining trawl samples with target tracking data.

The relationship between TS and length of Atlantic herring is taken from (Ona and Ona, 2003) and is given by:

$$TS = 20\log(L) - 67.3 \qquad (1)$$

Where L is total length measured in cm.

For Polar cod and Atlantic cod, the TS and length relationship is taken from (Crawford and Jorgenson, 1993) and is given by:

$$TS = 21.8 \log(L) - 72.7 \qquad (2)$$

2.4 Modeling with an individual based model

We built an individual based model (IBM) for simulating light experiments in MATLAB (R2021a), as an extension of a previously published model on light-based herding of mesopelagic fish in the Red Sea (Kaartvedt *et al.*, 2019), and used echograms from light experiments on Svalbard, individuals tracks from the acoustic recordings and length measurements from pelagic trawls as references to parametrize the model. This model description is inspired by the ODD (Overview, Design concepts, Details) protocol for describing an individual based model (Grimm *et al.*, 2006, 2010).

2.4.1 Purpose

The purpose of the model is to better understand how the presence/absence of artificial light from a lit vessel influences the behavior of individuals in the echo layers below, as observed through acoustics, and ultimately further expand the knowledge on what bias this may introduce in scientific data collection during periods of darkness. The modeling is done by simulating a two-dimensional water column with individuals that react to light (Figure 3 A, B).

Using the model allowed us to conduct virtual experiments with different levels of *attraction* and *repulsion* to light, and different swimming speeds based on the light experiments we did in Billefjorden, Isfjorden, and Krossfjorden. In contrast to real sampling with echosounders, the sampling of the modelled water column is not limited by time or by the narrow volume of the acoustic beam.
We were both able to sample the model's predictions in a way that replicates some of the real limitations found in real echograms, and we could also choose to examine the “wider” picture by disregarding the constraints imposed by an echo beam. These experiments can be helpful to build an intuition on what is going on during the real acoustic observations, and help design follow up studies to experimentally test the hypotheses generated from the modelling.

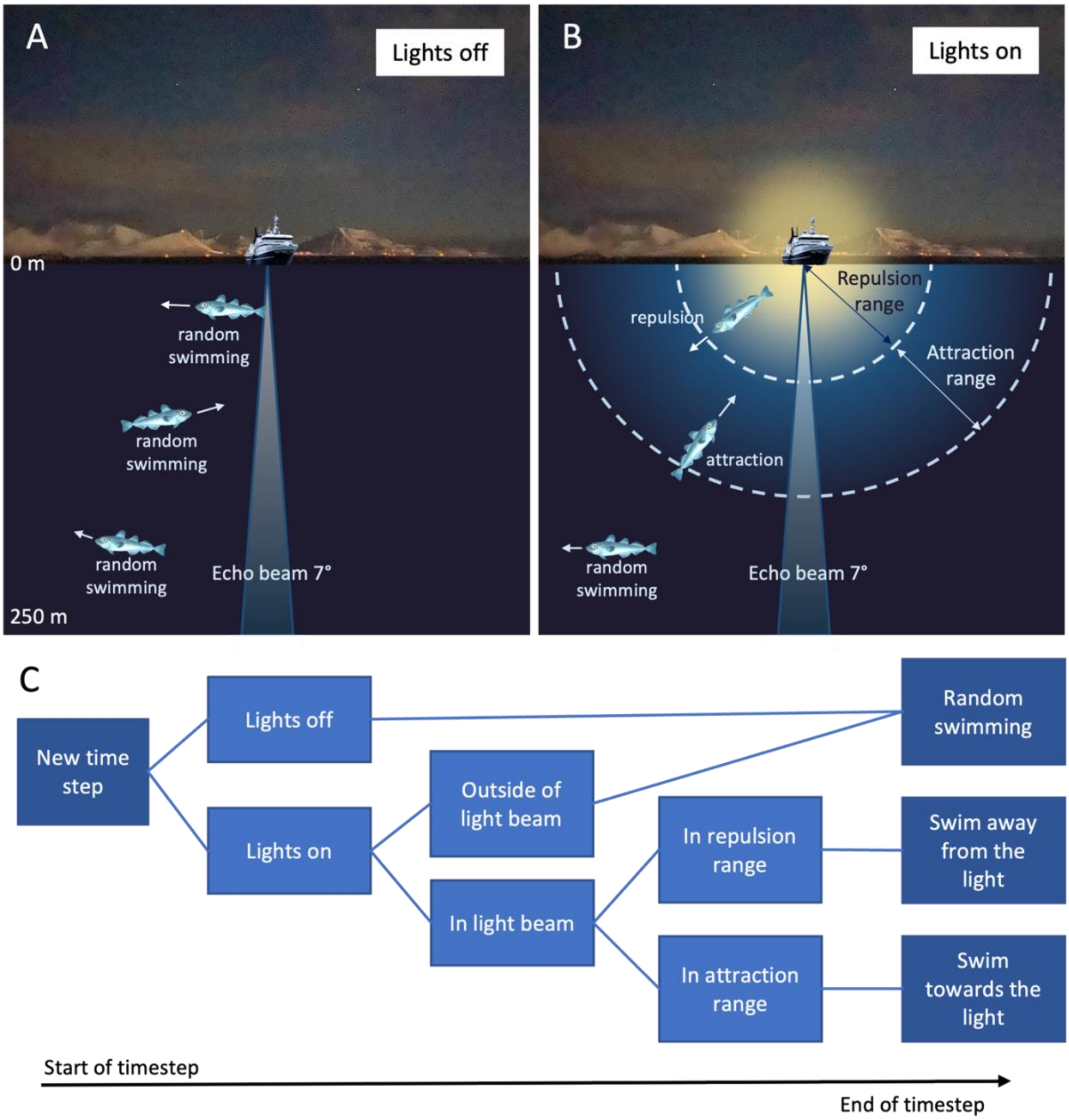

Figure 3: Concept illustration of behavior of modelled individuals, here illustrated with Polar cod, when the lights are *off* (A) and *on* (B). Note the *repulsion* and *attraction* ranges, and the area of the echo beam that was sampled in the model to make the modelled echograms. Model workflow (C).

2.4.2 Entities, variables and scales

The model is individual-based, and the entities in the model are individual organisms distributed in one or two distinct groups within a two-dimensional water column. The spatial and temporal variables (Table 3) were initially selected by looking at the echograms from Svalbard (Figure 6 ABC) and reusing variables from Kaartvedt et al. 2019. Later the model was tweaked by using trawl data on length distribution and species composition, and tracks from individual fish isolated from the echograms to find swimming speeds.

Table 3: Model parameters for the three fjords where both *attraction* and *repulsion* were used. Most values were estimated from trawl data, echograms and individual tracks. The swimming speeds in this table, shows the speeds used in the simulations with both *attraction* and *repulsion*.

Parameters	**Name in script**	**Value**			**Unit**
Fjord		**Billefjorden**	**Isfjorden**	**Krossfjorden**	
Spatial and temporal variables:					
Depth of water column	Z	150	275	227	m
Depth bins	dZ	1	1	1	m
Width of water column	X	700	700	700	m
Width bins	dX	1	1	1	m
Time	T	3600s * 9h	3600s * 6h	3600s *8h	s
Time steps	dT	20	20	20	s
Boat position in X direction	boatX	X/2	X/2	X/2	m
Boat position in depth: at the surface	boatZ	0	0	0	m
Lights on/off	LightOnOff	on/off	on/off	on/off	
Distribution of individuals					
Number of individuals	indNo	20 000	20 000	20 000	
Faction of individuals in echo layers, [gr 1, gr 2]	fishFract	[1, 0]	[0.8, 0.2]	[0.85, 0.15]	
Depth of echo layers, mean, [gr 1, gr 2]	zMn	[105,0]	[75, 160]	[150, 75]	m
Depth of echo layers, SD, [gr 1, gr 2]	zSD	[35, 0]	[15, 70]	[70, 15]	m
Max deviation of individuals preferred depth-range. [gr 1, gr 2]	zIndDev	[10, 0]	[10, 80]	[80, 10]	m
Behavior of individuals					
Swim speed, mean, [gr 1, gr 2]	swimVMn	Table 5 & 6	[0.12, 0.2]	[0.15, 0.1]	m/s
Swim speed, standard deviation, [gr 1, gr 2]	swimVSD	[0.05, 0]	[0.05, 0.1]	[0.1, 0.5]	m/s
Avoidance angle, SD – Deviation from swimming 180 degrees from light source.	angleSD	pi * 0.2	pi * 0.2	pi * 0.2	
Repulsion range, mean [gr 1, gr 2]	repRangeMn	[135, 0]	[120, 138]	[158, 140]	m
Repulsion range, SD [gr 1, gr 2]	repRangeSD	[20, 0]	[20, 35]	[25, 20]	m
Attraction distance from end of repRange, [start of attraction, end of attraction]	attDist	[0, 150]	[0, 100]	[0, 100]	m

Model environment

The two-dimensional water column has a width of 700 meters separated in bins of 1 m, to have enough space so that not all individuals are within the reach of the light (Figure 3 B). Depth is also split into bins of 1 meter, and is chosen after the actual depth of the fjord that is modelled, between 150 and 275 meters. The time horizon of the simulation is 7-9 hours, the same as the acoustic experiments, and time is split in time steps of 20 seconds.

Groups

Individuals in the model move independently without any interactions, and belong to either group one or group two. The group – or groups, of modelled individuals represent the species composition in the scattering layers of the echogram from the fjord that the simulation is based on and are distributed within the two dimensional model water column. Depending on the observations of species composition in the fjord, the distribution of Sv (Volume backscattering strength) in the echogram, and the TS (target strength) of the individual tracks, the different groups represent organisms that are likely to behave in a similar manner. The groups can for instance be a compact layer of juvenile Atlantic herring near the surface, or a mixed assemblage of juvenile Polar cod and larger Atlantic cod distributed randomly throughout the entire water column. The fraction of individuals within each group are chosen based on the echograms, by observing how dense the layers appeared, and by testing how different fractions looked in the modelled echograms. All individuals within a group shares swimming speeds, distribution in depth and light preferences taken from the same normal distributions, which are tuned specially for each group in each fjord. Swimming speed, depth range and light preference stay constant for each individual during the model run.

Horizontal and vertical distribution of groups

The modelled organisms are randomly distributed horizontally (x-axis), whereas their vertical distribution (along the z-axis) was informed by the depth distribution of scattering layers as observed from the echograms when the lights were *off*, assumed to represent the undisturbed state of the system. Distinct, densely packed layers with similar Sv from the echograms are distributed as a group in depth by a normal distribution with a mean and a low standard deviation matching the center and extent of the layer's distribution in the echograms. The individuals also get a narrow depth preference so that they stay within their preferred depths when they are undisturbed. When the scattering layers in the echograms consist of individuals with different Sv, and a homogenous distribution through the water column, the group is given depth preferences from a normal distribution with a wide SD. Their depth preferences are also wide, so that the individuals are free to swim throughout a large part of the water column. When the whole water column in the echograms consist of organisms with similar Sv and a homogenous distribution in depth, they are also given wide depth preferences and depth distributions from a normal distribution with a high SD.

Swimming speed

The groups are assigned swimming speeds from speed estimates based on trawl samples, *length-speed* (Table 5), and acoustic target tracking, *target-speed* (Table 6). Each individual within a group gets assigned a swimming speed from a normal distribution with a mean and a standard deviation special for the group. The standard deviation of the swimming speed distribution is chosen based on how similar the individuals within the layer are, so a layer of individuals of similar size have a smaller SD than a layer where the size varies more. Individuals keep their assigned speed during the entire model run as previously mentioned.

External input: lights *on/off*

The only external input in the model is whether the ship lights are *on* or *off* (Figure 3). We assume that the modeled individuals experience all light as diffuse and not as a direct point source. This is not unreasonable, as the light source is above the water surface on the ship. When the lights are *on*, within a radius from the vessel, the light is too strong and the individuals are *repulsed*, thus calling this range the *repulsion range*. Individuals within the *repulsion range* swim in the opposite direction of the light source with added noise, angleSD (Table 3), as we assume that few individuals swim in an entirely straight line. Individuals that are outside of the *repulsion range*, but still in close enough range to sense the light react by *attraction*, swimming directly towards the light source, and are in *the attraction range*.

2.4.3 Process overview and scheduling

The initial state of the model is when the lights are *off*, and all individuals swim randomly within their preferred depth ranges. For each time step, dT, every individual swim a distance according to their given swimming speed (Figure 3 C). When there is no light, they continue random swimming within their preferred depth range. When the lights are turned on, the individuals within the *repulsion range* swim away from the light (Figure 3 B). If the individuals are within the *attraction range* further away from the vessel, they swim directly towards the vessel until they reach the *repulsion range*. To avoid individuals swimming out of the model boundaries in a given timestep (Z-X plane), predicted movements outside the boundaries are given opposite sign.

2.4.4 Visualization

Visualizing the model as echograms

The model data is visualized as artificial echograms by integrating the number of individuals in each depth bin within an imaginary echo beam. We used a beam angle of 7 degrees, the same angle as the 38 kHz EK60 that was used to record the real echograms. Since the observed echogram is corrected for increasing sampling volume with depth, a similar procedure was done with artificial echo integration, by dividing by beam width in each depth bin.

Visualizing the model in 3D

In addition to constructing the artificial echograms, we can also analyze the whole water column over time, adding each timestep after each other to be able to follow how simulated individuals moved also outside the artificial echo beam. These simulated individuals track can then be visualized as a 3D plot with axis of time (T, sec), distance (X, m) and depth (Z, m).

To visualize what happened outside of the acoustic beam during the light experiments, we visualized a random subset of 1:400 simulated individuals in the modelled water column in three dimensions, as the view of the modelled water column is not limited by the narrow acoustic beam shown in Figure 3 A and B. Hence, the three-dimensional visualizations from the model can be informative of the responses of individuals that are invisible to the on board acoustics.

2.4.5 Simulating *repulsion* and *attraction*

We tested three possible reactions to artificial light by simulating three different versions of each of the acoustic light experiments we did in the three fjords. As *repulsion* and *attraction* were behaviors likely to cause the changes that we observed in the echograms, we ran different simulations by only changing the parameters related to the individual behavior towards the light levels (Table 4).

Table 4: Model parameters for *attraction* and *repulsion ranges* in the different model simulations of the three fjords.

	Billefjorden		**Isfjorden**		**Krossfjorden**	
	gr 1	gr 2	gr 1	gr 2	gr 1	gr 2
Fraction of individuals:	1	0	0.8	0.2	0.85	0.15
Simulation 1: *Attraction* only						
Attraction range, m	285	-	220	238	258	240
Repulsion range (mean), m	0	-	0	0	0	0
Repulsion range (SD), m	0	-	0	0	0	0
Simulation 2: *Repulsion* only						
Attraction range, m	0	-	0	0	0	0
Repulsion range (mean), m	135	-	120	138	158	140
Repulsion range (SD), m	20	-	20	35	25	20
Simulation 3: *Attraction* and *repulsion*						
Attraction range, m	150	-	100	100	100	100
Repulsion range (mean), m	135	-	120	138	158	140
Repulsion range (SD), m	20	-	20	35	25	20

In the first simulation, we modelled echograms where *attraction* was the only response to the artificial light. All individuals within the *attraction range* were set to swim towards the vessel when the lights were on. The radius of the *attraction ranges* in the fjords (Table 4) were selected after testing a range of values based on the real echograms (Figure 6 A-C).

In the second simulation we made echograms where individuals were not *attracted* to the light, and the only reaction to the light was *repulsion*. Individuals within the *repulsion range* were set to swim away from the light.

In the third simulation we combined the *attraction* and *repulsion ranges* from the previous simulations (Table 4). Individuals close to the vessel, within the *repulsion range* were set to swim away from the light, while individuals between the end of the *repulsion range* and the end of the *attraction range* were set to swim towards the light as shown in Figure 3B.

2.4.6 Simulating swimming speeds

A simplifying assumption in our model is that individuals kept the same swimming speed during the simulations, regardless of the light conditions. Therefore, we wanted to see how different swimming speeds influenced the modelled echograms from the light experiments. We simulated the experiments with different swimming speeds based on speed estimates from target tracking, *target-speed*, and from the length, *length-speed*, (Figure 9, Table 5 & 6) and compared them to the actual observations.

We combined our speed estimates with our assumptions of where certain species groups were distributed in the echograms based on species composition from trawls, and from where we knew individual targets of certain TS were located, to assign speeds to the different groups. From our tests based on the speed estimates, we chose swimming speeds for the modelled individuals that were likely to be similar to the real swimming speeds.

We used the light experiment in Billefjorden to visualize three simulations of swimming speeds, as the swimming speeds from the trawls and the tracks were quite different in the fjord (Figure 9). The *target-speed* estimated from the group of individual tracks with TS below -50 dB were used for the first simulation, as they had the lowest speed out of the Billefjorden speed estimates at 0.03 m/s with a SD of 0.02 m/s. For the second simulation, we intermediate swimming speed from comparing both track and trawl estimates at 0.1 m/s with a SD of 0.05 m/s. For the third simulation, we used the highest swimming speed estimate which was the *length-speed* from the trawl, at 0.2 m/s with SD of 0.02 m/s, assuming a swimming speed of 1 bl s^{-1}.

3 Results

3.1 Hydrography

We took CTD measurements to study the hydrography of the fjords while we did the light experiments. Isfjorden and Krossfjorden were mainly composed of Transformed Atlantic Water (TAW), while Billefjorden had a combination of Winter Cooled Water (WCW), Arctic Water (ArW) and Local Water (LW) (Figure 4) (Skogseth *et al.*, 2020).

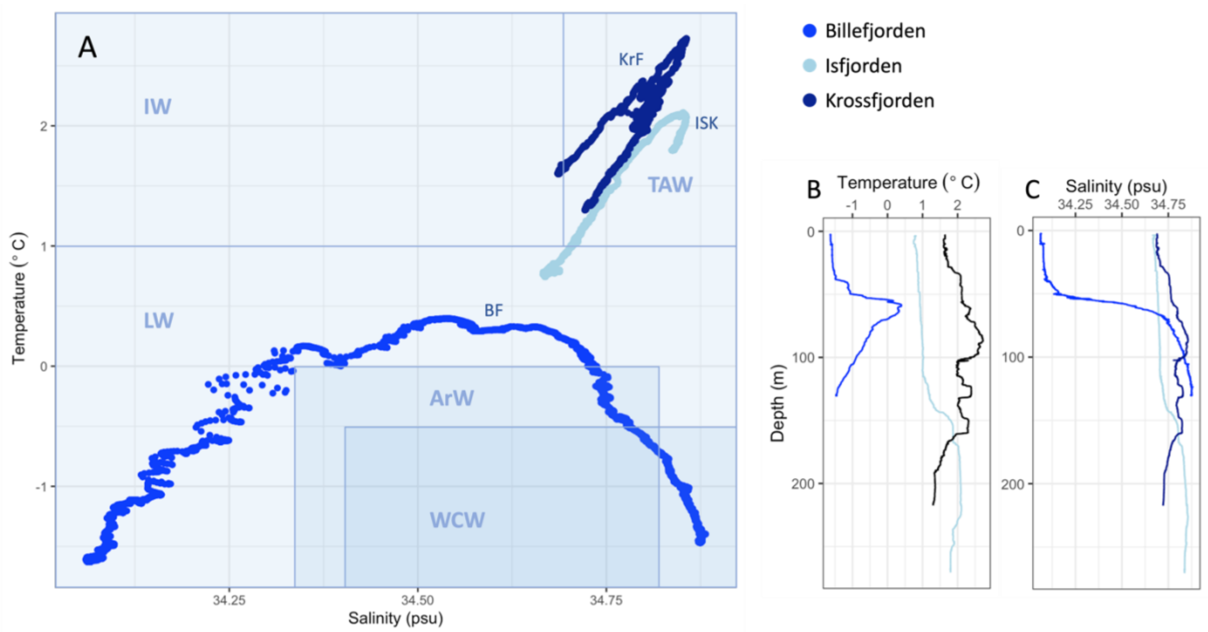

Figure 4: TS diagram from sampling sites (A), Billefjorden in blue from January 2020 and Isfjorden in light blue and Krossfjorden in dark blue from January 2022. Classification of water masses are taken from Skogseth *et.al*, 2020. Abbreviations: IW; Intermediate Water, TAW; Transformed Atlantic Water, LW; Local Water, ArW; Arctic Water and WCW; Winter Cooled Water. Temperature (B), and salinity profiles (C) in the fjords.

Billefjorden (Figure 4) had a shift from cold fresh Local Water above 50 meters, to warm, and saltier Local Water down to ~75 m, to cold and saltier Arctic water and Winter cooled water down to the bottom. As Billefjorden is a sill fjord in the inner part of Isfjorden with little direct exchange to the open ocean, and as the water masses below 60 meters were similar in January 2020 and August 2022 (not shown), we again think it likely that the species composition was similar across the years we sampled.

Isfjorden (Figure 4) had some Local Water at the surface, but mainly Transformed Atlantic water throughout the rest of the water column. Around 150 meters and below, there was a slight shift towards warmer and saltier water in Isfjorden.

Krossfjorden (Figure 4), similar to Isfjorden, had Transformed Atlantic water through the water column, with freshest and coldest water in the upper and lower 20 meters of the water column, and some warmer and saltier peaks around 80, 125 and 150 meters.

In summary Isfjorden and Krossfjorden had a very similar hydrography with more Atlantic influence, while Billefjorden was much colder and more arctic.

3.2 Species composition

The species compositions from the pelagic trawls provided ground truthing for the echograms, and input on swimming speed for the model (Figure 5).

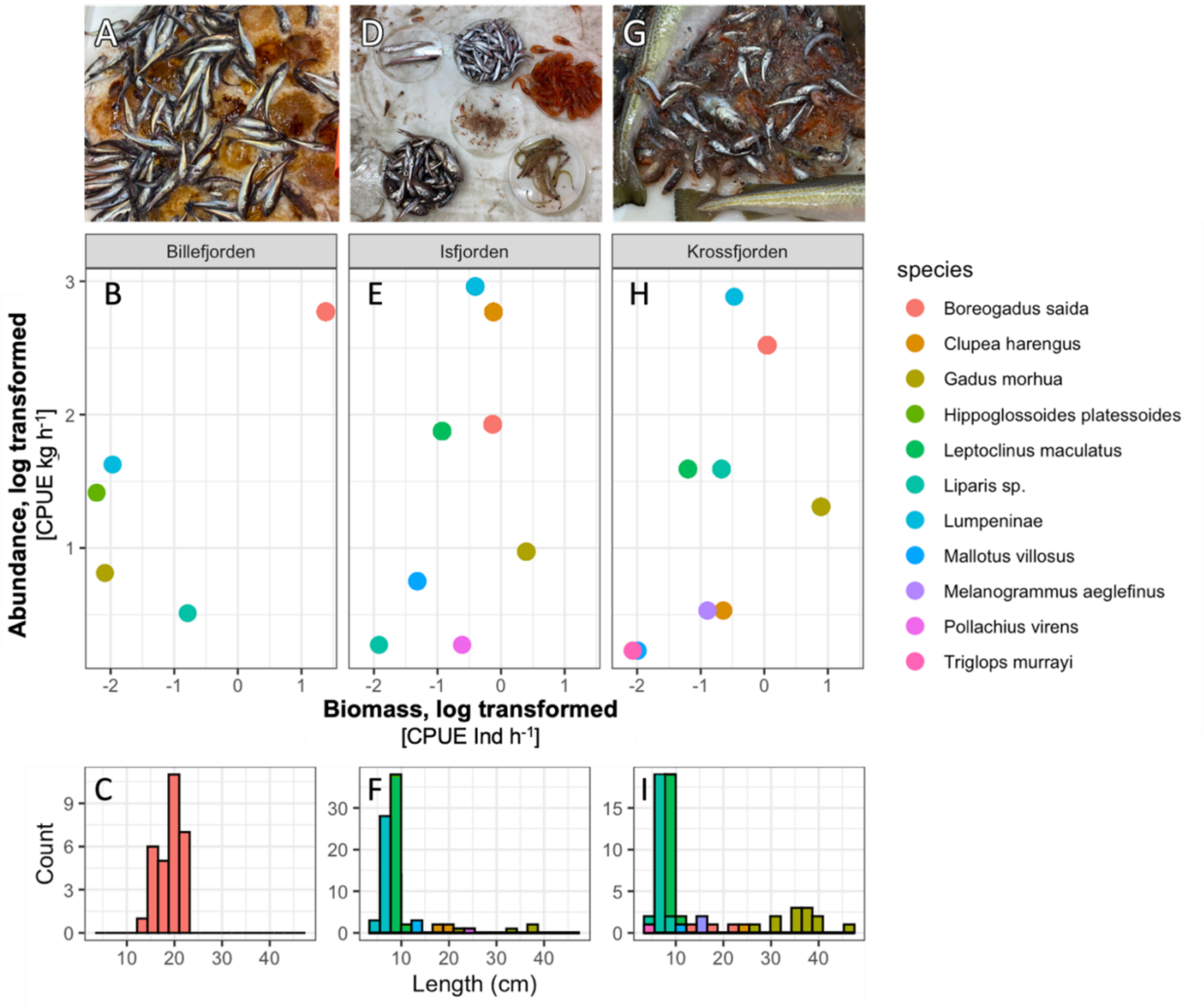

Figure 5: Pelagic trawl catches from Billefjorden(A-C), Isfjorden (D-F) and Krossfjorden (G-I). The upper row shows pictures from the pelagic trawl catches. The middle row shows species composition from pelagic trawls where zooplankton and gelatinous plankton were removed, and biomass, CPUE kg h^{-1}, and abundance, CPUE ind h^{-1}, are log transformed and standardized by trawl time. Species with high abundance and high total biomass are up-right on the plots, while species with few individuals and low total biomass are down to the left. The bottom row shows length frequency distribution of all length measured fish from the trawls.

The pelagic fish community in Billefjorden in August 2022 was dominated by Polar cod, *Boreogadus saida*, both in terms of biomass and abundance, with an individual median length of 19.25 cm and a standard deviation of 2.6 cm (Figure 5 A-C). The part of the zooplankton community that was caught in the trawl had a high biomass of *Cyanea capillata*, and a high abundance of krill of the genus *Thysanoessa* spp., mainly *Thysanoessa inermis*, the Arctic krill species (Appendix 1). The species composition was the most arctic out of the three fjords.

In Isfjorden (Figure 5 D-F), the pelagic fish community had highest abundance of juvenile fish of the subfamily Lumpeninae, mainly *Leptoclinus maculatus* with a median length of 8.5 cm and a SD of 0.71 cm, and second highest abundance of juvenile Atlantic herring, *Clupea harengus,* with a median length of 6.75 cm and a SD of 4.6 cm. Gadoids were also present such as Polar cod with a median length of 7.5 cm and a SD of 0.76 cm and five Atlantic cod with median length 33.5 cm and a SD of 6.7 cm. The Zooplankton community had a high abundance of Euphausiids, mainly *Thysanoessa inermis*, and also some *Pandalus borealis* (Appendix 1). Isfjorden was the fjord with the most Atlantic influenced species composition.

The pelagic fish community in Krossfjorden (Figure 5 G-I) had a high abundance of juvenile Lumpeninae, mainly *Leptoclinus maculatus* with median length of 9 cm and a SD of 0.78 cm, and juvenile Polar cod with median length of 8 cm and a SD of 3.17 cm. The twelve larger Atlantic cod with a median length of 35.75 cm and a SD of 4.9 cm made up over half of the total biomass of the trawl. The zooplankton community was made up of Euphausiids, jellyfish of mainly *Ptychogena lactea,* the shrimp *Pandalus borealis* and hyperiid amphipods *Themisto* spp., mainly *Themisto abyssorum* (Appendix 1).

Table 5: Species composition of fish from pelagic trawls with abundance, biomass, median length measurements and standard deviation for each species. Swimming speed can be estimated from the body length, by assuming swimming speeds of 1 body-length per second, bl s^{-1} (He, 1991; Kessel *et al.*, 2016).

Species	**Abundance** CPUE Ind h^{-1}	**Biomass** CPUE kg h^{-1}	**Median length** cm	**SD length** cm	**Min length** cm	**Max length** cm
Billefjorden - stnr 1351						
Boreogadus saida	592	24.15	19.25	2.62	14.0	23.0
Gadus morhua	7	0.01	-	-	-	-
Hippoglossoides platessoides	26	0.01	-	-	-	-
Liparis sp.	3	0.16	-	-	-	-
Lumpeninae	42	0.01	-	-	-	-
Isfjorden - stnr 27						
Boreogadus saida	85	0.74	7.50	0.76	5.5	9.5
Clupea harengus	590	0.76	6.75	4.60	5.5	21.5

Gadus morhua	9	2.49	33.50	6.68	23.0	37.0
Leptoclinus maculatus	75	0.12	8.50	0.71	7.0	11.5
Liparis sp.	2	0.01	-	-	-	-
Lumpeninae	914	0.39	6.50	0.40	5.5	7.0
Mallotus villosus	6	0.05	12.50	0.58	12.5	13.5
Pollachius virens	2	0.24	25.00	-	25.0	25.0
Krossfjorden - stnr 128						
Boreogadus saida	332	1.11	8.00	3.17	6.0	22.5
Clupea harengus	3	0.23	15.50	13.44	6.0	25.0
Gadus morhua	20	7.81	35.75	4.90	27.0	46.0
Leptoclinus maculatus	39	0.06	9.00	0.78	6.5	10.5
Liparis sp.	39	0.21	7.00	0.71	5.5	8.0
Lumpeninae	766	0.34	-	-	-	-
Mallotus villosus	2	0.01	11.50	-	11.5	11.5
Melanogrammus aeglefinus	3	0.13	16.00	0.71	15.5	16.5
Triglops murrayi	2	0.01	4.00	-	-	-

3.3 Acoustic observations

We combined observations from the echograms and individual tracks to get insight to how the sound scattering layers, and individuals within them, reacted to light. Additionally we got further insight to the vertical species distribution.

3.3.1 Scrutinizing echograms

Lights on

The acoustic observations from the light experiments consistently showed through all replicates in all three fjords that the main scattering layers of pelagic organisms dived when they were exposed to artificial light (Figure 6 A-C). In all replicates, the main scattering layers reacted to the light by diving from around 50 to 100 meters, as indicated with the yellow arrows in Figure 6 A, B and C. We observed the quickest responses to the light in Billefjorden and Krossfjorden (Figure 6 A and C), where the majority of the water column directly below the ship was emptied immediately after the lights were turned *on*. In contrast, the scattering layers in Isfjorden exhibited a slower decent that also started immediately after the lights were turned *on* but lasted 10-15 min before most of the scattering layer had moved below 100 meters.

Lights *off*

When the lights were turned *off* after a period of light, the main scattering layers returned to shallower depths close to 50 meters in all three fjords. The return to previous depths was slower than the sudden descent when the lights were turned *on*, and it took ~15 min in Billefjorden, ~20 min in Isfjorden and less than 10 min in Krossfjorden before the scattering layer stabilized again around 50 meters, as indicated in Figure 6 ABC with yellow horizontal lines.

Gradual increase in Sv

Throughout all three experiments, we observed a gradual increase in backscatter. In Billefjorden, it was shown by the sound scattering layer growing denser with time, where individuals were seen shallower as time passed both when the lights were *on* and *off*. In Isfjorden the increase in backscatter also showed up as gradually denser layers, but in contrast, larger organisms also appeared to become more frequent. In Krossfjorden the scattering layer grew densest around 140 meters, also with larger organisms appearing over time.

Zooplankton layer

We also observed layers of weaker Sv in all fjords, indicated by the turquoise arrows in Figure 6 A-C. The weak Sv layers were observed down to approximately 80 meters in Billefjorden and Isfjorden, and above 25 meters in Krossfjorden. The weak layers showed no clear behavioral patterns in response to the artificial light in Isfjorden or Krossfjorden, however, an even weaker layer in Billefjorden appeared to respond by spreading out when the lights were turned *on*.

Foraging forays

During the period with lights *on*, the main part of the scattering layer stayed at depths below 100 meters in all fjords. However, we observed some individuals in the echograms that swam shallower than 100 meters, into the layers of weaker backscatter. This behavior was particularly visible in Billefjorden, where larger individuals swam up into the weak layer before returning down again as indicated with a yellow arrow in Figure 6 A.

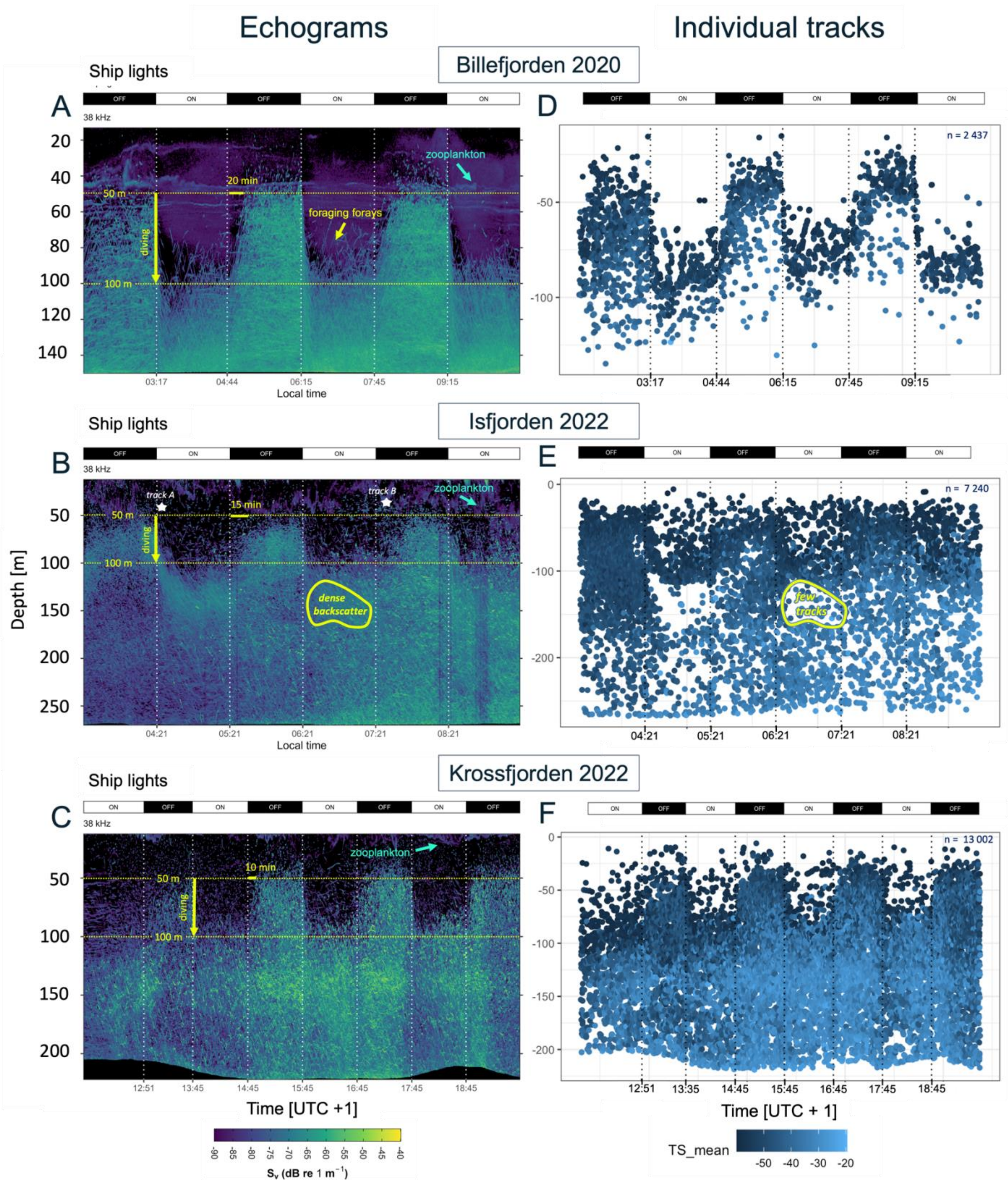

Figure 6: Echograms (A-C) and isolated target tracks (D-F) from the light experiments from Krossfjorden (top), Isfjorden (center) and Billefjorden (bottom). Echograms (left panels) are presented as volume backscatter (Sv, color scale), and show that the scatter layers went ca 50 m deeper when the lights were on. Target tracks (right panels) of all individuals were isolated using Echoview and color scale denote their target strength, TS. The yellow arrow in A indicates the rapid diving and slow decent when light were turned on/off. Turquoise arrows point to layers of low Sv, possibly zooplankton, and the yellow circles are examples of areas of dense backscatter where little target tracking was possible. White stars in B, shows the time and depth of the target tracks visualized in Figure 7.

3.3.2 Target tracking

We extracted tracks using Target tracking to learn more about the behavior of individual organisms during the light experiments (Figure 6 D-F). There were most tracks isolated from Krossfjorden (n = 13 002) (Figure 6 F) second most from Isfjorden (n = 7 240) (Figure 6 E), and the least from Billefjorden (n = 2 437) (Figure 6 D). The tracks from Krossfjorden best represented individuals from the whole water column among the fjords, while Billefjorden and Isfjorden represented mainly the individuals that were shallow enough and/or were in depths with low density of individuals.

3.3.3 Combining trawl and tracks to scrutinize echograms

We combined the echograms with data from the tracks and the trawls to further assess which species likely made up the scattering layers in the echograms. There were several species from the trawls that we did not include, as we focused on the most abundant species, and the species with highest biomass.

In Billefjorden, the distribution of organisms in the echograms looked homogenous from 50 meters to the seafloor at 150 m, without any distinct layers (Figure 6 A). Polar cod likely made up most of the dense sound scattering layer, as it was the most abundant fish from the trawl, with the highest total biomass. The weaker scattering layer towards the surface was likely made up of krill, as krill was most abundant of the zooplankton (Figure 5 B, Figure 6 A). There were few tracks isolated from Billefjorden, but the tracks showed that targets with TS lower than -50 dB were distributed slightly shallower than the targets with higher TS, suggesting that smaller individuals were shallower.

The echogram from Isfjorden had a distinct scattering layer at around 80 meters deep, where the tracks showed that most of the individuals had a TS below -50 dB (Figure 6 BD). As Atlantic herring was the most abundant species of fish with swim bladders from the trawls, with a median length of 6.75 cm corresponding with a TS of -50.7 dB (Equation 1), it is likely that herring made up the shallow layer. In the beginning of the echogram, there was a homogenous distribution of individual with low Sv and low TS below the herring-layer, possibly Polar cod with median length 7.5 cm that has a TS of -49.8 dB (Equation 2). As time went, organisms with stronger backscatter, and TS higher that -40 dB appeared, possibly being Atlantic cod, as the trawl contained Atlantic cod with median size 33.5 cm with a corresponding TS of -36.8 dB (Equation 2). The weak scattering layer towards the surface indicated by turquoise arrows in Figure 6B, possibly consisted of krill or juvenile Lumpeninae (Appendix 1).

The echogram in Krossfjorden (Figure 6 C) showed a vertical distribution where the targets revealed that individuals with low TS were generally distributed shallower than individuals with higher TS (Figure 6 E). Most of the organisms were between 50 m and the sea floor at 200 meters, but here most backscatter was between ~120 and 150 meters, coinciding with the slightly warmer water masses (Figure 4 B). The densest backscatter layer had several individuals with TS higher than – 30 dB according to the tracks (Figure 6 E). The largest Atlantic cod from the pelagic trawl had a length of 46 cm, with a corresponding TS of -36.5 dB (Equation 2), suggesting that larger Atlantic cod made up the layer of high TS. Polar cod was the most abundant swim bladdered fish, with a median length of 8 cm and a corresponding TS of -53 dB (Equation 2), and likely made up much of the rest of the echogram. Also in this fjord, the weak scattering layer towards the surface was likely made up of juvenile Lumpeninae or krill (Appendix 1).

3.3.4 Swimming patterns from individual tracks

Swimming patterns

The tracks revealed the swimming patterns of individual organisms (Figure 7). They showed examples of individuals that were diving immediately after the lights were turned *on*, Figure 7 A, and individuals that swam up after the lights were turned *off*, Figure 7 B.

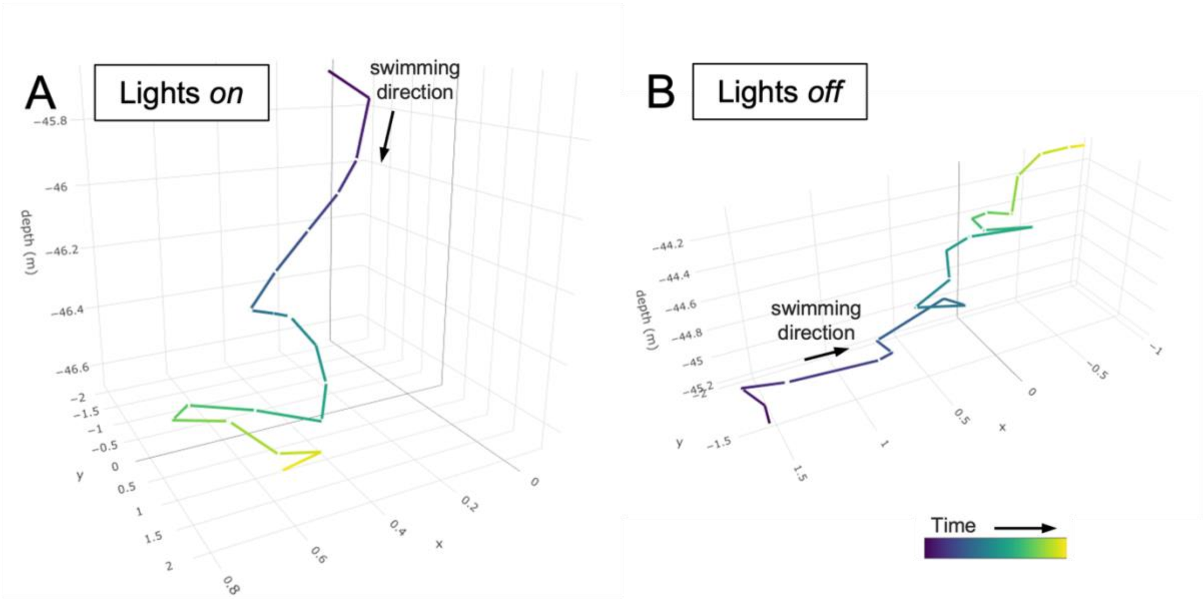

Figure 7: Tracks from Isfjorden showing swimming patterns of acoustic targets relative to the center of the acoustic beam. The x- and y axis (m) show horizontal direction in relation to the center of the echo beam at (0,0), and the depth shows the depth in the water column. A) Shows an individual swimming down when the lights were on at time 04:21, and B) shows an individual swimming up when the lights were off at 07:33. The arrows indicate swimming direction, and the color of the line shows the passing of time, where dark purple indicates the beginning of the track, and yellow indicates the end of the track. The location of the tracks in the echograms are marked in Figure 6 B with white stars.

Vertical swimming direction

The tracks revealed the vertical swimming direction of individuals during the light experiments. Among all tracks across the entire span of the experiments in the upper 150 meters, most individuals had a vertical swimming direction between 10 and – 10 degrees angle, where most individuals had a vertical angle around 0 degrees (Figure 8 A). Within the first three minutes the lights were on during all experiments, we observed that most targets had a negative vertical swimming direction, indicating diving (Figure 8 B). We did not observe the same clear trend in vertical direction when the lights were turned off again. Within the fifteen first minutes after the lights were turned off again, the swimming directions looked very similar to how they looked in Figure 8 A in Isfjorden and Krossfjorden, with no noticeable trend in swimming patterns. In Billefjorden, however, most individuals were swimming upwards within the first fifteen minutes after the lights were off. As the tracks isolated from Billefjorden were mainly the individuals with shallowest distribution, this might indicate that only the shallowest individuals swam actively upwards, while the rest of the water column possibly was refilled by individuals swimming in from the sides in all directions (Figure 8 C).

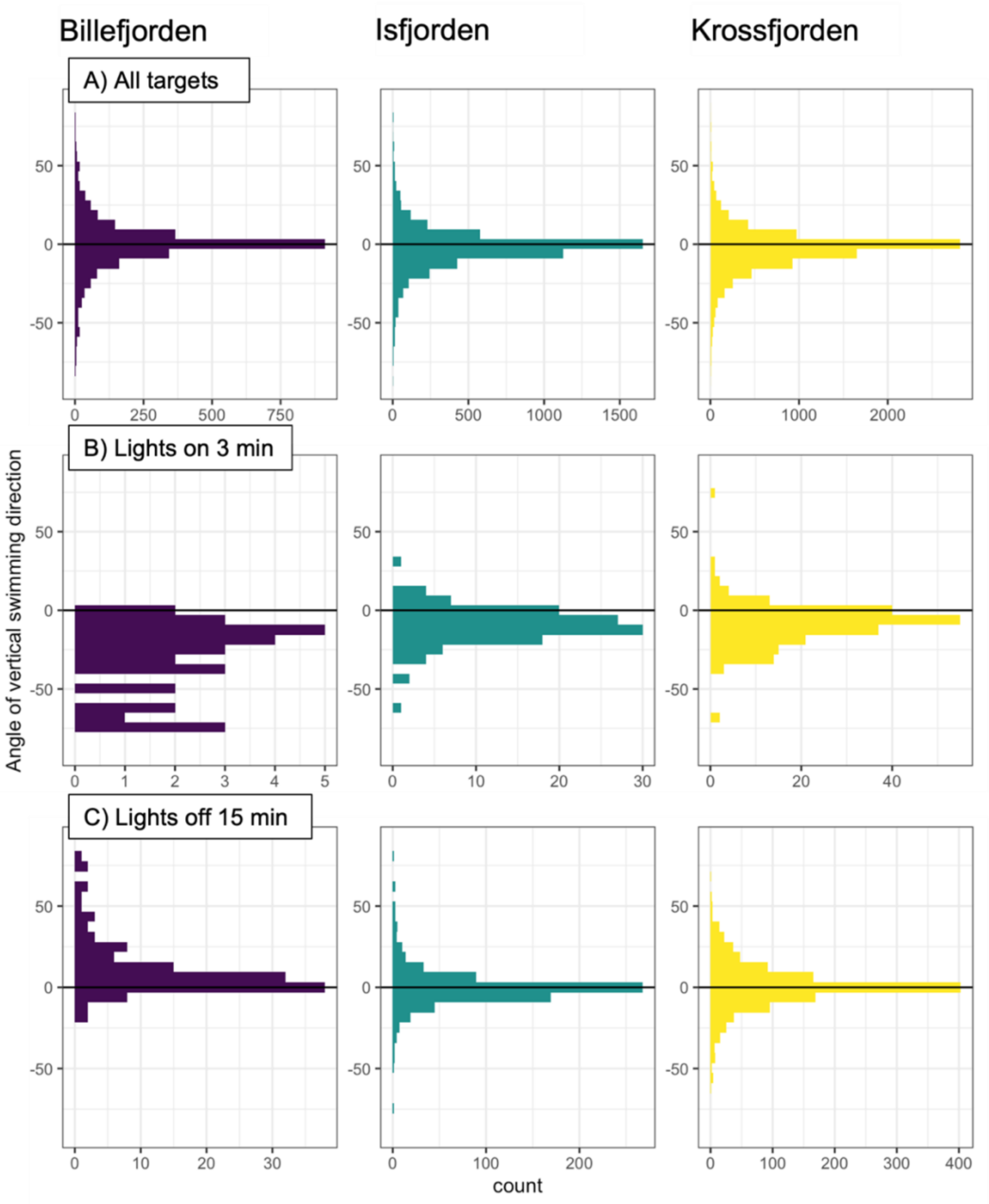

Figure 8: Angle of vertical swimming direction of individual acoustic targets in the upper 150 meters of the water column throughout the entire light experiments (A), in the first three minutes after the lights were on (B), and the first 15 minutes after the lights were turned off (C). The horizontal black line is where there is no change in vertical swimming direction. Individuals below the line swims downwards, and individuals above the line swims upwards.

Horizontal swimming direction

The tracks also revealed the horizontal swimming direction of individuals in relation to the direction of the vessel (not shown). According to the tracks, fish swam randomly in all directions in Billefjorden throughout the entire light experiment as the horizontal swimming direction of individuals tracks was randomly distributed in all directions. Note that the vessel did not move in Billefjorden, as it was stuck in sea ice. In Isfjorden and Krossfjorden, where the vessel drifted slightly, there was some variation in swimming direction trends, where the general trend in swimming direction looked random during some parts of the experiment, but directional during other parts. There were no particular change in horizontal swimming direction in response to the light across all experiments.

3.3.5 Swimming speed from tracks

We estimated swimming speeds using the tracks, *target-speed*, by splitting them into groups of similar TS (Table 6). The tracks from Billefjorden had the lowest speeds, with a mean swimming speed below 0.032 m/s, while tracks from Isfjorden and Krossfjorden had higher and more similar swimming speed with means ranging between 0. 95 and 0.19 m/s.

Table 6: Speed estimates from individual tracks in groups of TS range, where > -50 dB indicates the individuals with lowest TS, often the smallest and -30 dB indicates individuals with higher TS, often the largest.

TS range	n	Mean speed m/s	SD speed m/s	Min speed m/s	Max speed m/s
Billefjorden					
< -50 dB	1 157	0.032	0.023	0.002	0.21
-50 to -40 dB	1 154	0.029	0.021	0.002	0.18
-40 to -30 dB	125	0.031	0.021	0.003	0.10
> -30 dB	1	0.082	-	-	-
Isfjorden					
< -50 dB	2 149	0.16	0.093	0.014	0.39
-50 to -40 dB	2 378	0.19	0.100	0.016	0.39
-40 to -30 dB	1 931	0.12	0.054	0.017	0.38
> -30 dB	782	0.11	0.048	0.017	0.35
Krossfjorden					
< -50 dB	1 681	0.12	0.054	0.006	0.36
-50 to -40 dB	3 372	0.13	0.050	0.009	0.34
-40 to -30 dB	4 076	0.11	0.051	0.003	0.34
> -30 dB	3 873	0.095	0.049	0.005	0.33

Combining swimming speed estimates from the tracks from the light experiments (Table 6) and the pelagic trawl samples (Table 5), provided input to the modelled light experiments (Figure 10). In Figure 9 we compared swimming speed calculated from the tracks in Echoview (A), with a simple approximation that fish swim with 1 body length per second (B). For the latter, average body length is estimated from trawl data. The swimming speed from tracks and from the body length approximation looked similar in Isfjorden and Krossfjorden (Figure 9). However, for Billefjorden the swimming speed estimated from tracks (0.09 m/s) was much lower than that based on the body length approximation (0.3 m/s). The swimming speeds estimated from the different species from the trawls match better up with the swimming speeds from the tracks in Isfjorden and Krossfjorden.

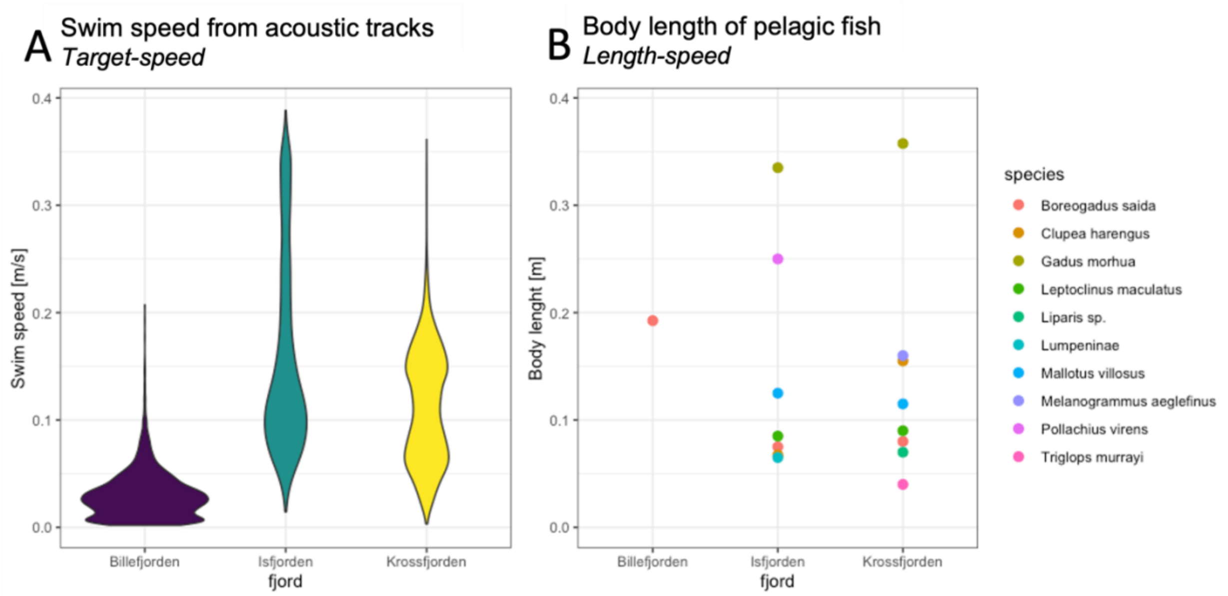

Figure 9: Swimming speeds calculated from Echoview tracks, *target-speed* (A) compared to that approximated from median body length in the trawl samples, *length-speed* (B), where swimming speed can be measured in 1 bl s^{-1} swimming speed from trawl data.

3.5 Modeling acoustic light experiments

3.5.1 Testing *repulsion* and *attraction*

The model revealed that both *repulsion* and *attraction* towards artificial light was necessary to simulate the patterns that were observed in the light experiments (Figure 10).

In the first simulation, where the only reaction to being in the light range was *attraction*, the modeled echograms showed individuals swimming straight to the vessel (Figure 10 B, F, J). This simulation was in great contrast to the real echograms (Figure 10 A, E, I), where individuals kept a distance to the vessel.

The second simulation without *attraction* and only *repulsion* produced echograms where the individuals avoided the light from the vessel (Figure 10, C, G, K), similar to the real observations. However, few individuals returned to their original shallower distributions, leaving the upper layer of the water column emptier than the real observations. This simulation also failed to reproduce the gradual increase in backscatter that we observed in all fjords.

The third simulation that included both *attraction* and *repulsion* towards the light, produced echograms where individuals avoided the area closest to the lit vessel, while organisms further away swam towards the vessel (Figure 10 D, H, L). In this case, that the upper layer of the water column was “refilled” as the lights were turned off again, similar to the real observations, and we observed a slight increase in “backscatter” during the entire simulations. The simulation was however not able to reproduce what happened close to the bottom in the echograms, as there were left “gaps” above the sea floor in the simulated echograms when the lights were turned *on*.

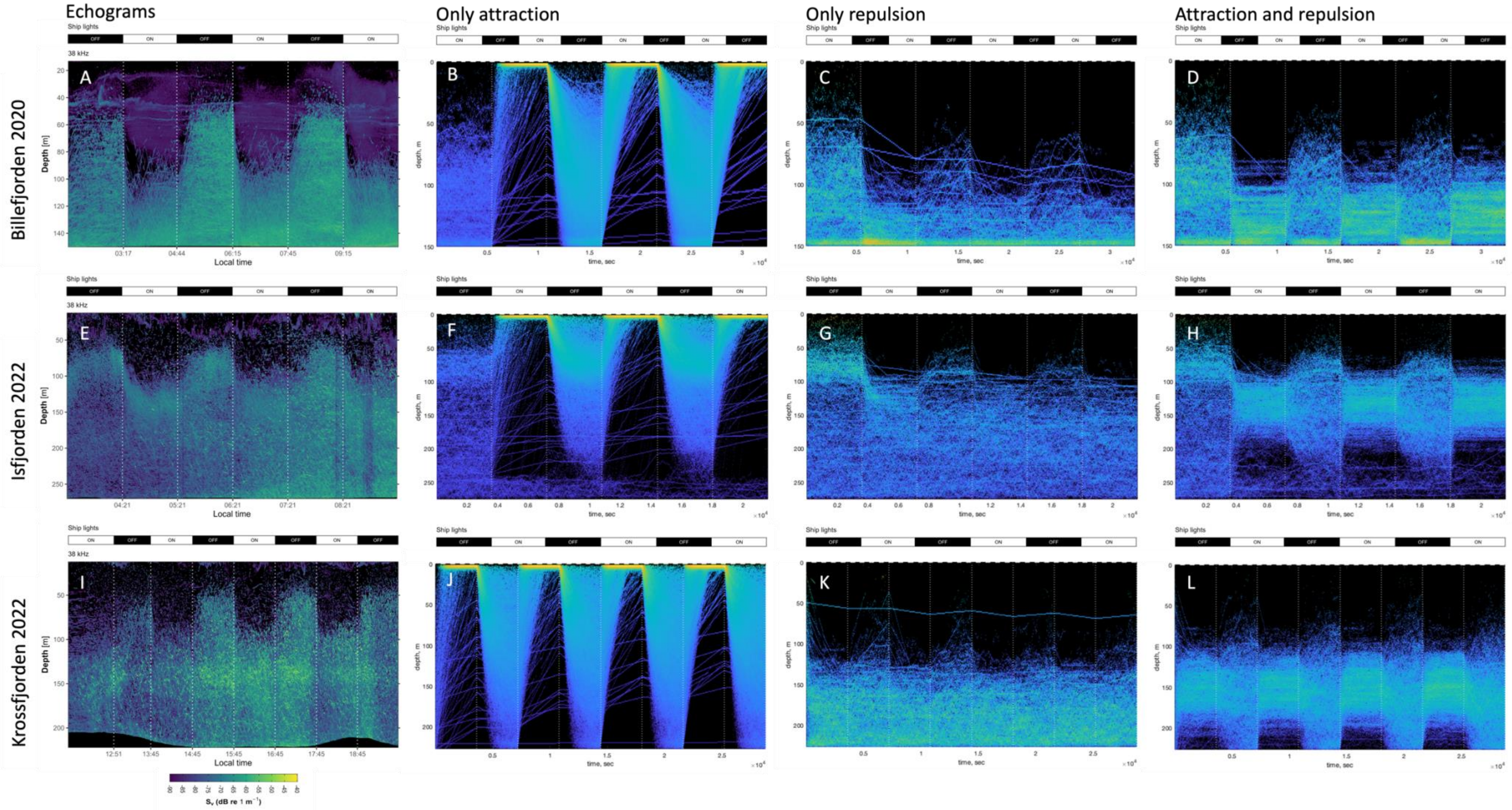

Figure 10: Testing *attraction* and *repulsion* against the acoustic observations in Billefjorden (A-D), Isfjorden (E-H) and Krossfjorden (I-L) using echograms (A, E, I) modelled echograms with only *attraction* (B, F, J), modelled echograms with only *repulsion* (C, G, K) and modelled echograms with both *attraction* and *repulsion* (D, H, L). The colors in the real echograms (A, E, I) show Sv, while the colors in the modeled echograms show density of individuals sampled with an artificial acoustic beam.

3.5.2 Visualizing modeling results in 3D

The model revealed that the swimming behavior of fish outside of the observable volume of the echo beam was changed by the artificial light (Figure 11). It was evident that modelled individuals kept a distance to the lit vessel not only below the vessel, but also to the sides of it (Figure 11 B, C).

When the individuals were only attracted, they stayed close to the vessel during the entire run (Figure 11 A). Few individuals returned to the area close to the vessel during the runs when they were *repulsed* but swam away from the vessel and stayed in their new area (Figure 11 B, C).

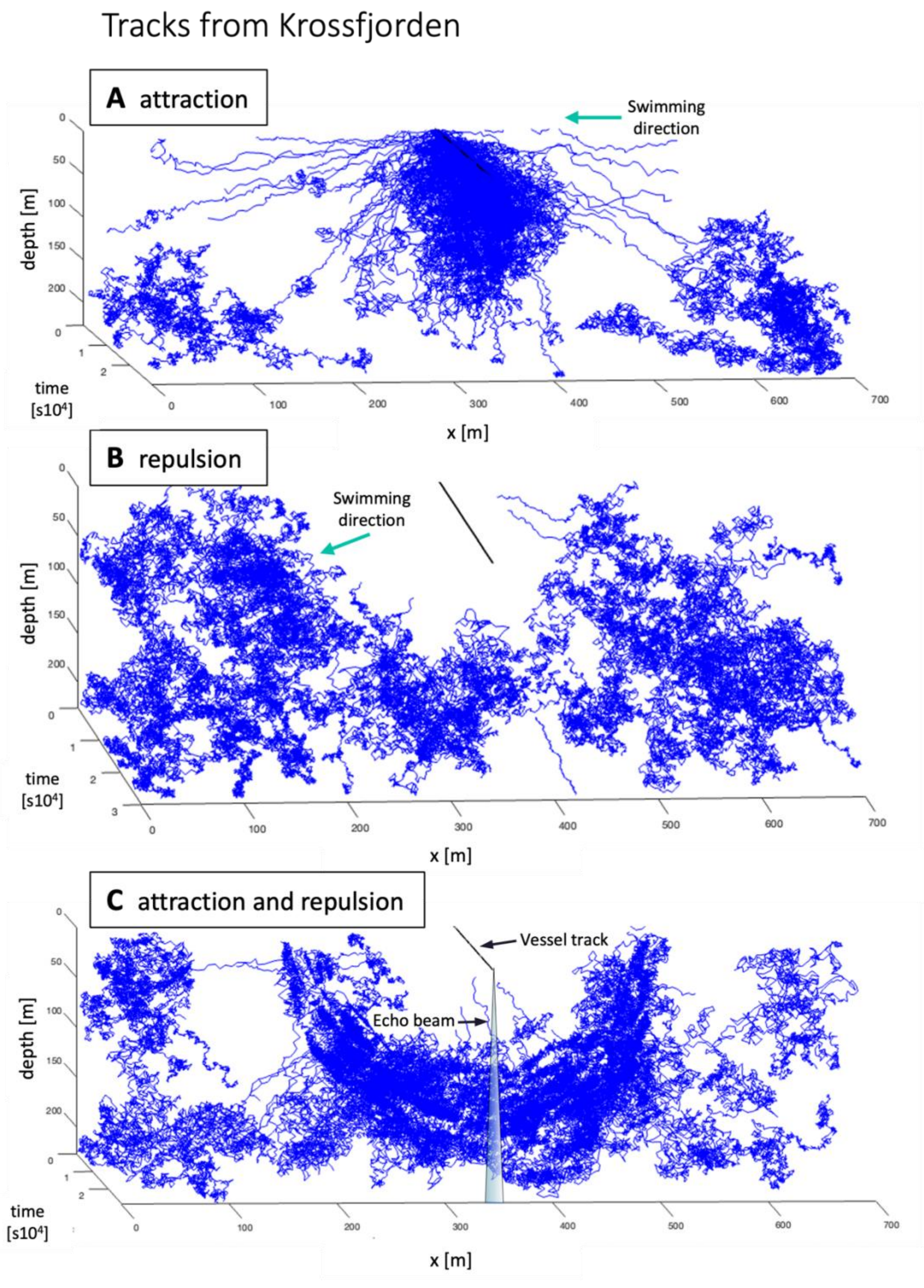

Figure 11: Tracks visualized in 3D from Krossfjorden, showing tracks of every 400th individual in blue, during the modelled runs with lights on and off. Simulation with only *attraction* (A), only *repulsion* (B), and both *attraction* and *repulsion* (C). The x-axis is the width of the modelled water column, the time-axis denotes the passing of time in seconds*10^4 and the depth-axis shows the depth of the modelled water column. The black line at the top of the plots show where the vessel is, and thus, where the light is. Light blue arrows in A and B indicates the swimming direction or individuals at the given placements in the water column. The volume that is sampled by the echo beam is shown in C.

3.5.3 Testing swimming speeds

The different simulations with swimming speeds revealed how different speed estimates looked in the modelled echograms (Figure 12). We observed the same general trends of *attraction* and *repulsion* when we used different swimming speeds. However, the higher speed taken from the highest speed estimate from the trawls (Figure 12 D, Table 5), the quicker the individuals dived when the lights were turned on, and the quicker return to previous depths when the lights were turned off.

The simulation with slower speeds taken from the lowest TS groups in the tracks (Figure 12 B, Table 6) made both the response to *lights on* slow, as well as the return to previous depths when the lights were turned off slow. Neither parts resembled the actual echograms much.

The intermediate swimming speeds taken from both tracks and trawls provided modelled echograms that were similar to the real echogram in terms of reaction to *lights on* and *lights off* (Figure 12 C). The intermediate simulation was also able to recreate the slightly delayed decent after the lights were turned off again, as marked with white arrows in Figure 12 C.

The fast simulation provided the most “refilling” of the water column once the light were turned off out of the three simulations. It was also able to recreate the same slight dip as the lights were turned on as in the echograms, marked by yellow arrows in Figure 12 A and D.

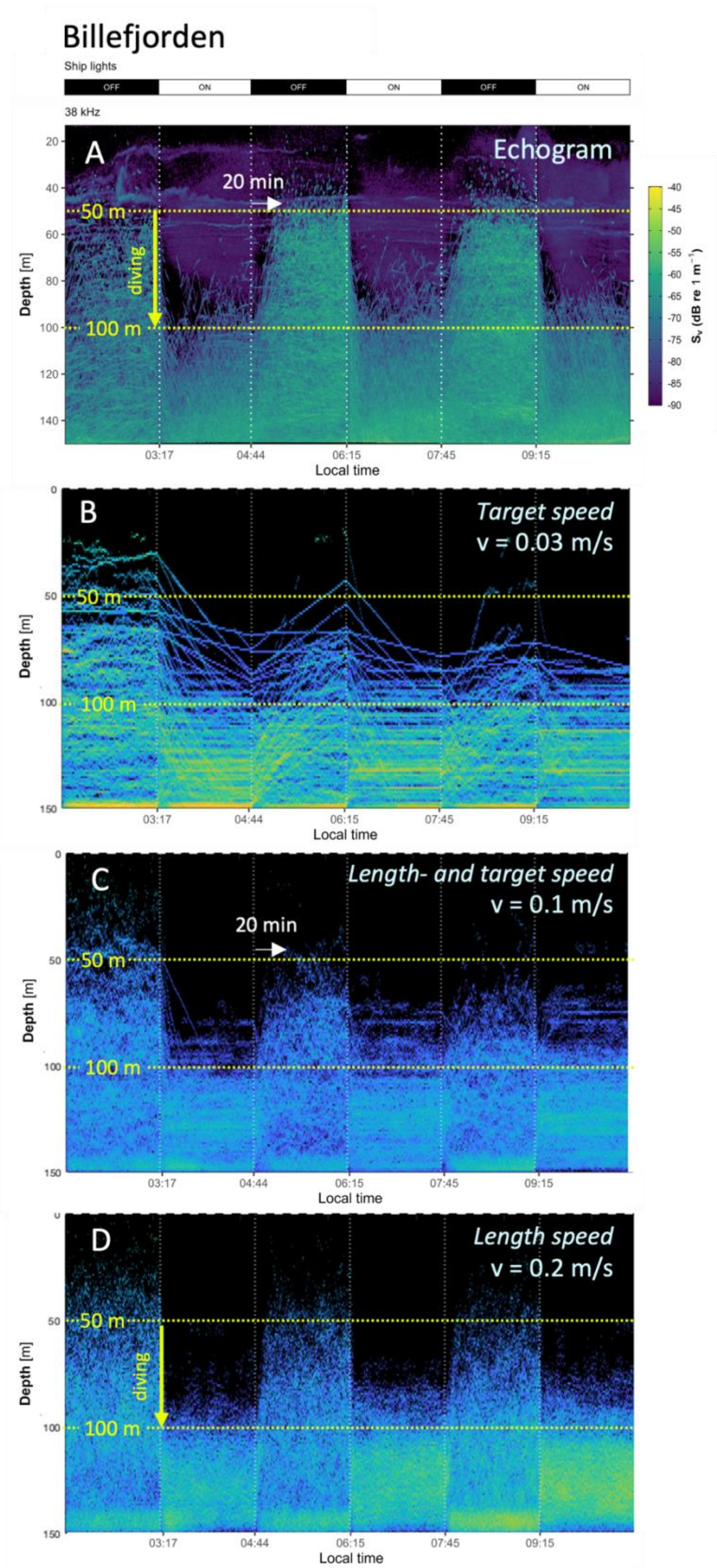

Figure 12: Simulating swimming speeds in Billefjorden based on speed estimates from length measurements from trawl and from individual tracks. White arrows in A and C are examples of the decent after lights were turned off, and yellow arrows in A and D shows immediate diving.

4 Discussion

4.1 Summary of results

This study provides insights into what happens when pelagic organisms are exposed to intermittent periods of artificial light from a vessel during hours of darkness. We hypothesized that pelagic organisms would show a clear change in behavior in response to being exposed to artificial light from a vessel. We found that individuals in the acoustic sound scattering layers in three fjords on Svalbard during the polar night immediately dived and swam away from the light as a response to being within a radius of ~100 meters from the lit vessel, similar to the disturbance Berge *et.al* (2020) observed. The effect was most prominent in the uppermost 100 meters of the water column, but we also observed a gradual increase of backscatter during all experiments, likely explained by *attraction* of individuals further away from the light source.

Our study also utilized modeling to better understand the acoustic recordings, by simulating different versions of the light experiments, to better understand the mechanisms that drove the changes in vertical distribution as response to light. Additionally, the modeling gave insight to what *might* occur outside of the limits of the acoustic echo beam, thus providing a basis to generate new hypotheses that can be tested either by confronting the model with new iterations of the model, or confronting it with new sampling in the field.

4.2 Discussing results

Our findings support that artificial light has the potential to significantly alter the distribution of pelagic organisms in the water column. In contrast to our findings, Gerlotto *et.al* (1990), observed no vertical avoidance from ships lights, but they similarly to us, also observed indications of horizontal avoidance with certain species. However, Levenez et.al (1987) observed vessel avoidance, similar to us, on acoustic surveys in the tropics from a 500 W light on the bridge, but the avoidance did not have effect on the mean echo integral. Both of these studies were done on vessels that were moving, which is common for several sampling methods such as during acoustic transects, which stands in contrast to our stationary experiments. However, our echograms from all three fjords showed an immediate change in vertical distribution from light, and the model revealed that individuals reacted to light at ~200 meters horizontal distance away from the lit vessel. The immediate change, and the large area of influence from light, suggests that we would likely also observe a change in behavior and vertical distribution if our vessel was moving.

We found that the most prominent behavioral responses to artificial light from a lit vessel was *repulsion* and *attraction*, where individuals within range of ~140 meters from the vessel avoided the light, and individuals further away were *attracted*.

We first thought that individuals were *attracted* to light, when we observed an increase in backscatter in the echograms throughout all three light experiments. We checked if it was an artefact of advection, as the boat was on anchor in Krossfjorden and Isfjorden, and movement from wind and currents might have caused it. However, we observed the same increase in Billefjorden as well, while the vessel was standing still in ice, and there being little advection because of the shallow sill. Thus, we found it likely that the explanation for the increase in Sv might be the *attraction* to the diffuse light that we found in the model, as pelagic organisms in Svalbard fjords have been shown to be sensitive to low light levels (Benoit *et al.*, 2010a; Cohen *et al.*, 2021).

Our findings of *repulsion* coincide with Kaartvedt et.al (2019), that also observed that sound scattering layers in the Red Sea avoided artificial light mounted on an ROV when they were within a *repulsion range* of the light. However, Kaartvedt et.al (2019) did not observe that individuals outside of the *repulsion range* were *attracted* to the light, such as we did, but instead that *attraction* occurred within a shorter range from the light source. The short range *attraction* was explained as a behavioral adaption with to observing light as a point source, similar to bioluminescence, and the *repulsion* was a behavioral adaption to light being diffuse, such as daylight from above (Warrant and Locket, 2004). The difference in attraction to light might be an artefact of studying different species groups, as mesopelagic fish and epipelagic fish, such as what we observed, have a different ecology.

As we also assume that all the light from the vessel was experienced as diffuse, the *attraction* response we observed must be explained in a different way than in Kaartvedt et.al (2019). Our modeling results testing *attraction* and *repulsion*, along with the apparent increase in backscatter in all the echograms, pointed towards that individuals were *attracted* to the light when they were further away from the light than the *repulsion range*. We suggest that the attraction response might be caused by the possibility of pelagic fish performing visual foraging. As previously mentioned, Polar cod, that was prominent in trawl catches in both Isfjorden and Krossfjorden, is known to perform diel vertical migration, and foraging during polar night (Benoit *et al.*, 2010b). It is possible that the light conditions within our proposed *attraction range*, provided enough darkness to hide, while being close to potential prey for the pelagic fish. It is not unlikely, as we observed potential zooplankton prey in all three fjords. The foraging hypothesis is further supported by our observations of potential foraging forays in the acoustics from Billefjorden, and that Atlantic cod has been shown to be foraging on krill that had been attracted by light (Humborstad *et al.*, 2018; Utne-Palm *et al.*, 2018).

As our light experiments were executed in fjords on Svalbard during the polar night, in a period where the sun is below the horizon for several months, it is sensible to question if our results were an artefact of adaptations to the special light conditions that only occur at high latitudes. However, we observed similar reactions to artificial light in fjords of both Arctic and more Atlantic species composition, suggesting that the response is not special for arctic species. Additionally, other experiments with artificial light during darkness from both temperate and tropical environments, reported that pelagic organisms reacted to the presence of artificial light during the darkness with avoidance (Levenez, Gerlotto and Petit, 1987; Kaartvedt *et al.*, 2019; Geoffroy *et al.*, 2021b). Thus, it is likely that our findings are not only relevant to high latitudes, but also to other lower latitude systems.

4.3 Limitations

We only tested for the impact of normal deck lights, and did not test the impact of the lower intensity red light that replaced the normal deck lights when the lights were *off* during the experiments. Some acoustic surveys at night try to reduce the impact of artificial light by lowering the light levels, or using red working light instead of bright white, as the red light has been thought to not be detectible by several pelagic organisms (personal communication). New studies suggest that also red light influences the distribution of pelagic organisms, but in a smaller degree, as the light intensities often are lower (Geoffroy *et al.*, 2021b). Our study does not address this potential sampling bias, but light experiments with red light, and the model can be used to predict the potential bias by coupling light measurements of light attenuation from red light, and the visual sensitivity of pelagic organisms.

Our knowledge of species composition is limited to what we caught in the pelagic trawls, and are aware that the catches from the trawls are influenced by different catchability of different species caused by different behaviors towards the sampling gear such as herding by trawl doors, avoidance by diving or ascending, the ability to swim out of the trawl, or escaping the trawl through the mesh. However, we used the sampling gear that best captured the species group we were interested in, the pelagic trawl for pelagic fish. We did not assess the zooplankton community outside of the macrozooplankton that was caught in the trawls, and did not include it in our tests. We did also not include the abundant but small fish of the family Lumpeninae in our tests, as we assumed they did not show up much on the echograms, as they lack swim bladders.

The trawl samples and the isolated tracks from Billefjorden were both of sub-optimal quality. As previously mentioned, the trawl form Billefjorden was sampled 1.5 year after the light experiment, but we assumed it to be representative of the pelagic community composition because of the composition of water masses, the shallow sill of the fjord and previous reports of similar species composition throughout the year (Cusa, 2016). Additionally, the length frequency distribution from Billefjorden was biased, as the sampling was not random, but also here, we assumed that the *length-speed* we calculated still gave an indication of the possible swimming speed in the fjord. In combination with the target tracking data, that was biased towards only the shallowest individuals, both speed estimates together provided some insight to the extremes of the possible swimming speeds that occurred in the fjords, and provided input to the modeling that further gave insight to swimming behavior. The gap between swimming speeds from trawls and tracks, might also be explained by the low water temperature in Billefjorden, as lower temperatures has been associated with lower swimming speeds (He, 1991).

4.4 Further outlook

4.4.1 In situ experiments and observations

For further research, two particular sampling tools have the potential to give much insight to how artificial light from a vessel influence the distribution of pelagic organisms: a bottom mounted echosounder and an autonomous vessel.

Acoustic target tracking proved to be useful to further our understanding of the acoustic observations, by providing information on the target strength, distribution and swimming patterns of organisms that we observed in the echograms. However, we cannot exclude that our tracks are biased from movement of the vessel in Isfjorden and Krossfjorden, as our acoustic recordings were done using the onboard echosounders. To eliminate the bias of vessel movement, upwards facing bottom mounted echosounders have previously been proven helpful in studying individual behavior of mesopelagic fish (Christiansen, Titelman and Kaartvedt, 2019; Christiansen *et al.*, 2022) and pelagic fish (Axenrot *et al.*, 2004). In addition to providing a stable base for target tracking, a bottom mounted echosounder creates opportunities to test new versions of light experiments on artificial light from a vessel, as they do not require any light for sampling. Experiments such as passing the echosounder at different speeds and with red light, all light, and no light, to give more insight to how the combinations of light levels and vessel speeds potentially biases biological sampling. Experiments with passing the bottom mounted echosounder with lights on at different speeds, would provide an important insight in to how data from acoustic surveys done during darkness might be biased. Additionally, passing the echosounder with lights off, would provide an opportunity to control the potential behavioral change introduced by disturbance from the vessel alone. Kaartvedt *et.al* (2019) used both the on board echosounder and a bottom mounted, which together gave a clearer picture of the behavioral changes they observed.

Results from our model when visualized in 3D suggest that a large area around the vessel, outside of the acoustic beam, in all fjords was influenced by the artificial light, where the biggest radius of influence was the highest mean *attraction range* at 258 meters. This is similar to that Berge *et.al* (2020) that found that pelagic organisms were disrupted in an area of more than 0.125 km^2, within a radius of more than 200 meters, when exposed to artificial light. To test our modelled predictions about the change in the area around the vessel, acoustic transects around the lit vessel using an unmanned, autonomous vessel without lights, might give insight. Additionally, an autonomous vessel has the possibility to take measurements of the light characteristics of the area around the vessel.

More information about the light around the vessel would be useful, as we aim to further understand how artificial light from a vessel impacts the pelagic community. Better knowledge of the potential light comfort zones of species in the pelagic community would potentially help explain why the *repulsion* behavior stopped below a certain depth. Light measurements coupled with information of the visual sensitivity of key species in the water column would provide a better insight to what distance from the lit vessel that the organisms are able to detect light, and perhaps what light comfort zones they prefer. It would also be beneficial for further our understanding of what light ranges the organisms are attracted. Further insight to light levels and light detection in different species, in combination with echograms, could also provide input to new iterations of the model to better predict what influence artificial light will have at places with known species compositions.

4.4.2 Future iterations for the model

The model has given further insight to the mechanisms behind what we observed in the echograms. Throughout this study, we have given swimming speed some extra attention to expand our understanding of which behaviors caused the observed reactions to artificial light. By running simulations with different swimming speeds in Billefjorden, we saw that not one swimming speed was able to reproduce the same response to lights going on or off, as the fastest swimming speeds best showed the instantaneous response to lights on, while a slower speed better visualized the delayed response to lights being turned off. It is known that the speed of vertical movement of fish has been correlated with the speed of change in light intensity (Bohl, 1979), and it is possible that the sudden change from light to dark triggers a different behavioral response than dark to light. To further study the behavioral response, variation in speed, from normal swimming speed, to burst speed, could be added to the model.

We also observed that our modelled individuals to a lesser degree than the fish in the echograms, were able to reclaim the water column after the lights were turned off. From our 3D model, we saw that individuals gathered between the *repulsion range*, and the *attraction range*, but that few swam back below the boat when the lights were turned off. By giving the modelled individuals an incentive to keep a certain distance between each other, we could possibly better reproduce the behaviors observed in the echograms.

Other suggestions to further improve the model includes adding more species groups for more specie specific behaviors, including the benthic community, creating more accurate simulated echograms by accounting for species specific TS and length relationships and including hunger, zooplankton and foraging to explore potential foraging forays.

5 Conclusion

Data collected on Svalbard in combination with our model revealed that pelagic organisms responded instantaneously to artificial light from a vessel by *repulsion* when they were within a certain range of the light, and by *attraction* when they were further away from the light. The modeling reveled that a large area around the vessel was influenced by the light. Our findings supports that acoustic and biological sampling done during night, in the presence of artificial light, likely does not show the natural state of the pelagic community.

Appendix

Appendix 1: Species composition and biomass from pelagic trawls.

Species	Abundance [CPUE Ind/h]	Biomass [CPUE kg/h]	Median length cm
Billefjorden - stnr 1351			
Boreogadus saida	592	24.15	19.25
Ctenophora	-	-	-
Cyanea capillata	280	18.21	-
Decapod post larvae	13	0.00	-
Gadus morhua	7	0.01	-
Hippoglossoides platessoides	26	0.01	-
Hyperia galba	13	0.00	-
Liparis sp.	3	0.16	-
Lumpeninae	42	0.01	-
Meganyctiphanes norvegicus	59	0.03	-
Ptychogena lactea	10	0.25	-
Themisto abyssorum	289	0.02	-
Themisto libellula	20	0.00	-
Thysanoessa inermis	335	-	-
Thysanoessa longicaudata	3	-	-
Thysanoessa raschi	65	-	-
Thysanoessa spp.	29437	4.28	-
Isfjorden - stnr 27			
Boreogadus saida	85	0.74	7.50
Clupea harengus	590	0.76	6.75
Euphausiacea	5686	0.72	-
Gadus morhua	9	2.49	33.50
Jellyfish other	-	0.05	-
Leptoclinus maculatus	75	0.12	8.50
Liparis sp.	2	0.01	-
Lumpeninae	914	0.39	6.50
Mallotus villosus	6	0.05	12.50
Pandalus borealis	243	0.49	-
Pollachius virens	2	0.24	25.00
Sclerocrangon spp.	6	0.00	-
Themisto spp.	20	0.02	-
Krossfjorden - stnr 128			
Boreogadus saida	332	1.11	8.00
Clupea harengus	3	0.23	15.50
Euphausiacea	2541	0.33	-
Gadus morhua	20	7.81	35.75

Gonatus fabricii	2	0.08	13.00
Jellyfish other	-	0.52	-
Leptoclinus maculatus	39	0.06	9.00
Liparis sp.	39	0.21	7.00
Lumpeninae	766	0.34	-
Mallotus villosus	2	0.01	11.50
Melanogrammus aeglefinus	3	0.13	16.00
other zooplankton	-	1.11	-
Pandalus borealis	476	0.18	-
Ptychogena lactea	29	0.45	-
Themisto abyssorum	472	0.03	-
Themisto libellula	77	0.01	-
Triglops murrayi	2	0.01	4.00

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