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The ecological importance of glacial habitats to high Arctic odontocetes

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LONG-TERM GOALS

The goals of the project were to a) use previously collected data from tagged diving narwhals (*Monodon monoceros*) to fill data gaps on the one-time OMG multi-beam echo sounding survey of sea floor bathymetry in Melville Bay, Greenland, b) combine year-round passive acoustic monitoring (PAM) and remote visual detections of narwhals from land-based cameras to understand how physical properties of glacial fjords (e.g., subsurface Atlantic Water temperature and salinity, surface ice cover) influence narwhal occurrence, relative abundance, and acoustic behavior, c) collaborate with OMG PIs to add oceanographic instrumentation to narwhal moorings (CTDs and standalone temperature sensors) to allow for quantification of the variability of fjord temperature and salinity, and d) use remote camera imagery to quantify glacial ice mélange, glacial velocity, and frontal advance and retreat at three sites in Melville Bay. Our project was coupled to NASA launched the Earth Venture-Suborbital Oceans Melting Greenland (OMG) mission to address existing knowledge gaps surrounding Greenland's glacier dynamics.

OBJECTIVES

This study was focused on answering interdisciplinary questions about what specific physical attributes of Greenland glacial fjord environments attract narwhals (*Monodon monoceros*), which may inform projections about how future changes will impact narwhal subpopulations around the Arctic. We were also interested in using our moored recorders to help understand variability in Greenland's sub surface waters around glacier fronts, providing novel data to the OMG mission to address existing knowledge gaps surrounding Greenland's glacier dynamics. Our objectives were to consider the entire ecosystem component by investigating the connection between a key top predator and the properties of Atlantic water and glaciers, specifically the observed northward intrusion of warm subtropical waters into the subpolar North Atlantic around Greenland.

APPROACH

The project had two components: Part 1) an analytical component based on existing data collected prior to 2016 by the PI and collaborators and, Part 2) a field component in West Greenland collecting new data (2018-2020) on narwhal occurrence and physical properties of the ice-ocean interface in glacier fjords. We report on the approach and results (to date) from the full project below. Contributions are based on work by PI Kristin Laidre (U of Washington), co-I Ian Fenty (NASA Jet

Propulsion Lab), co-I Malene Simon (Greenland Institute of Natural Resources), and unfunded external collaborators Elizabeth Phillips (NOAA Fisheries), Michael Ladegaard and Peter Madsen (University of Aarhus, Denmark), Kate Stafford (U of Oregon), Twila Moon (NSIDC), and U of Washington graduate students Jennifer Stern and Marie Zahn.

In Part 1 we explored the usefulness of narwhal telemetry data to fill in gaps in the OMG bathymetric dataset by looking at depths of dives relative to holes in the bathymetry. In Part 2 we conducted a field component to focus on using year-round passive acoustic monitoring (PAM) and remote visual detections of narwhals from land-based cameras in ice-covered waters of Melville Bay, Greenland to investigate narwhal presence, distribution and ecological associations with glacial and water properties. As described below we deployed moorings at 4 glacial fjords to acoustically detect narwhals. We also collaborated with NASA Earth Venture-Suborbital Oceans Melting Greenland (OMG) mission and added additional instrumentation to moorings to inform NASA's OMG analyses. These included temperature loggers and conductivity-temperature (C-T) sensors that allow quantification of deep fjord temperature and salinity variance driven by external (e.g., propagating coastally-trapped waves) and internal factors (e.g., variability in fresh subglacial meltwater discharge).

In 2015, NASA Earth Venture-Suborbital Oceans Melting Greenland (OMG) mission to address existing knowledge gaps surrounding Greenland's glacier dynamics by collecting observations on the continental shelf. Between 2015–2021, OMG launched several annual surveys: 1) ship-based and airborne expendable conductivity-temperature-depth (CTD and AXCTD) sensors to measure ocean temperature and salinity, 2) ship-based multibeam sonar and airborne gravimetry to map coastal bathymetry on the shelf and within fjords, and 3) airborne interferometric radar to measure surface topography including the extent and height of marine-terminating glaciers (Fenty et al., 2016). OMG's extensive sampling effort was performed principally to examine to what degree are Greenland's glaciers melting from submarine warm water. The OMG campaign obtained oceanographic observations around Greenland at an unprecedented spatial scale and confirmed that the ocean plays an important role in Greenland glacier acceleration and retreat. Yet, ocean observations along Greenland's margins are biased toward summer months with relatively few year-round measurements. Our project coupled with NASA's OMG mission to determine the ecological importance of glacial habitats to narwhals. We combined data from both missions (ONR-funded and NASA OMG) to quantify habitat characteristics for narwhals at Greenland's glacier fronts and supplement our understanding of the NASA mission results with moored observations.

WORK COMPLETED

Field work

2018 Field work

The first cruise was conducted from 21-28 August 2018 (Figure 1). The scientific team on the cruise was Dr. Kristin Laidre (UW), Dr. Malene Simon (GINR), Dr. Ian Fenty (JPL), Peter Hegelund (technician, GINR), Dr. Beth Phillips (fisheries acoustics expert, NOAA), Dr. Twila Moon (glacier expert, NSIDC) and Qaerngaag Nielsen, indigenous hunter from NW Greenland. Three moorings and four remote cameras were deployed at three glacial front sites within Melville Bay, Greenland, including 1) Tuttulupaluk/Sverdrup glacier, 2) Nuussuaq/Kong Oscar glacier, and 3) Rink glacier near the Fisher Islands. Sightings of all marine mammal and seabird species were made during transects

into and out of the glacier fronts. An echosounder EK80 was used to collect acoustic data on prey fields at the glacier fronts and on transects into and out of the study sites. Moorings and cameras were scheduled to be retrieved during August 2019.

2019 Field work

We conducted our second year of successful field work in August 2019. The cruise was conducted from 1-8 August 2019 (Figure 1). The scientific team on the cruise was Dr. Kristin Laidre (UW), Dr. Ian Fenty (JPL), Peter Hegelund (technician, GINR), Dr. Beth Phillips (fisheries acoustics expert, NOAA), Dr. Kate Stafford (UW) and UW graduate student Jennifer Stern. Three moorings and three remote cameras were deployed at three glacial front sites within Melville Bay, Greenland, including 1) Tuttulipaluk/Sverdrup glacier, 2) Nuussuaq/Kong Oscar glacier, and 3) the Fisher Islands. Using external funds, we were able to obtain 3 SoundTrap300s (Ocean Instruments, NZ) to add to the moorings to allow comparison to recordings obtained from the Aurals. Sightings of all marine mammal and seabird species were made during transects into and out of the glacier fronts. An echosounder EK80 was used to collect acoustic data on prey fields at the glacier fronts and on transects into and out of the study sites. Moorings were scheduled to be retrieved during August 2020.

Of note, the 2019 cruise occurred during the week where a massive Greenland heat wave occurred, starting 30 July with T_{max} reaching 25°C in the tundra. The integrated anomaly of melt over the 5 day period (30 July to 4 Aug) was 40Gt which is a ~0.11mm sea level equivalent. The conditions in summer 2019 were what the models project for 2050 using RCP85. It was estimated that eleven billion tons of ice melted across the country on July 30 alone and that day was the biggest daily melt on record for one day. We had to adjust some of our operations due to frequent and large glacier calving which made for dangerous conditions given we were sailing in close proximity to glacier fronts.

In 2019 we discovered that polar bears had visited the cameras in all places, destroying the setup (either by chewing on the electronics or by investigating the camera on their hindlegs and knocking the camera over). We consulted with indigenous hunters on local knowledge methods we might use to try and deter bears from the cameras in 2018 and applied those (e.g., disguising the cameras or coating them with deterrent scents) but did not have success. We decided to end the remote camera deployments given the issues with polar bears on land before freeze-up relative to the cost of the cameras.

2020 Field work (COVID-19 pandemic)

Our field work in 2020 was substantially impacted by the COVID-19 pandemic. We were fortunate to be able to retrieve our 2019-deployed instruments in summer 2020 with the help of local Greenlandic scientists. There was no access to Greenland for US/foreign scientists and it was not possible for PIs to participate. Field work was conducted from 5-12 August 2020 by a small team who sailed from Nuuk to Melville Bay. Two of the three 2019 moorings were recovered, with the third unfortunately lost in the glacier ice presumably sometime earlier that spring. Due to the pandemic, we had to focus on mooring rescue only and forego all other parts of the study, including the sightings of top predators, CTD casts, and all echosounder prey data collection. In total we had three successful Arctic cruises. We deployed six moorings over a two year period in risky areas at the fronts of Greenland's glacial margins and we retrieved five of them, also during a pandemic.

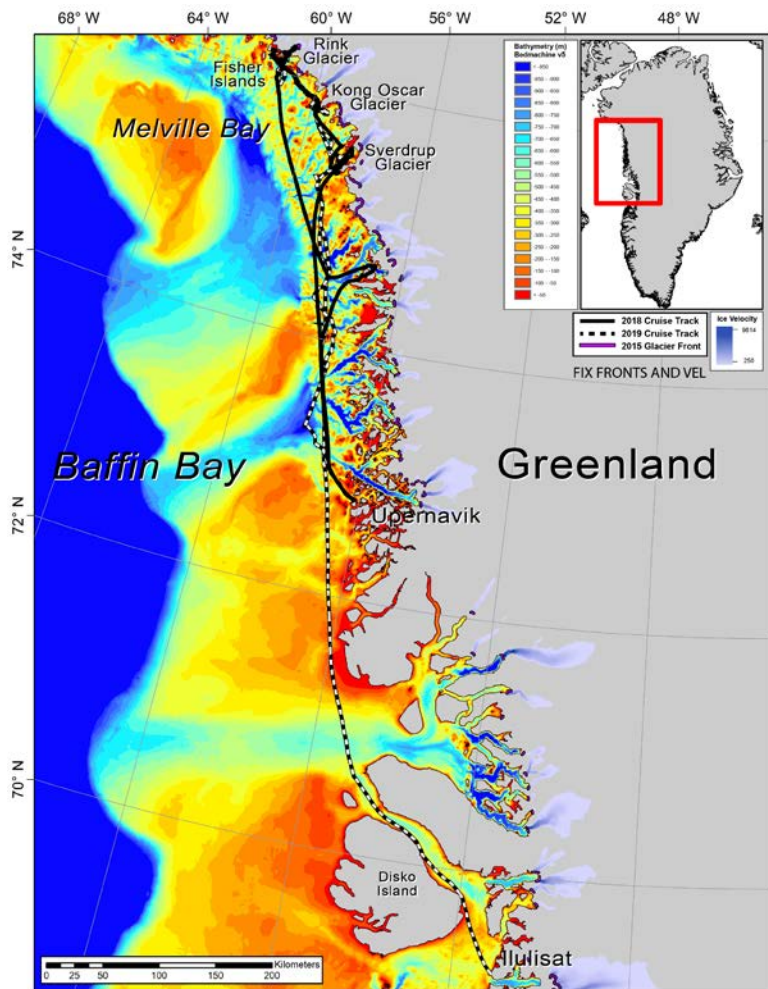


Figure 1. Map of cruise track in 2018 and 2019 along the west coast of Greenland. In 2018 the cruise began in Upernavik where as in 2019 it began in Ilulissat. The three glacier sites are named in Melville Bay.

Sites and mooring configuration

In both 2018 and 2019 seafloor-mounted ocean moorings with marine mammal acoustic recorders and oceanographic instruments were deployed near three glacier fronts with known narwhal presence in Melville Bay, northwest Greenland (Figure 2 & Figure 3). We refer to the ocean mooring locations by the name of the nearest glacier because there are no place names for the fjords/inlets in which they were deployed. A total of six moorings were deployed over two years (2018–2020) and five were successfully recovered (Table 1). The 2019–2020 mooring located near Sverdrup glacier was

destroyed by icebergs and therefore was unrecoverable. The 2019–2020 Rink glacier mooring site had to be shifted to the Fisher Islands due to heavy ice conditions (Figure 2b).

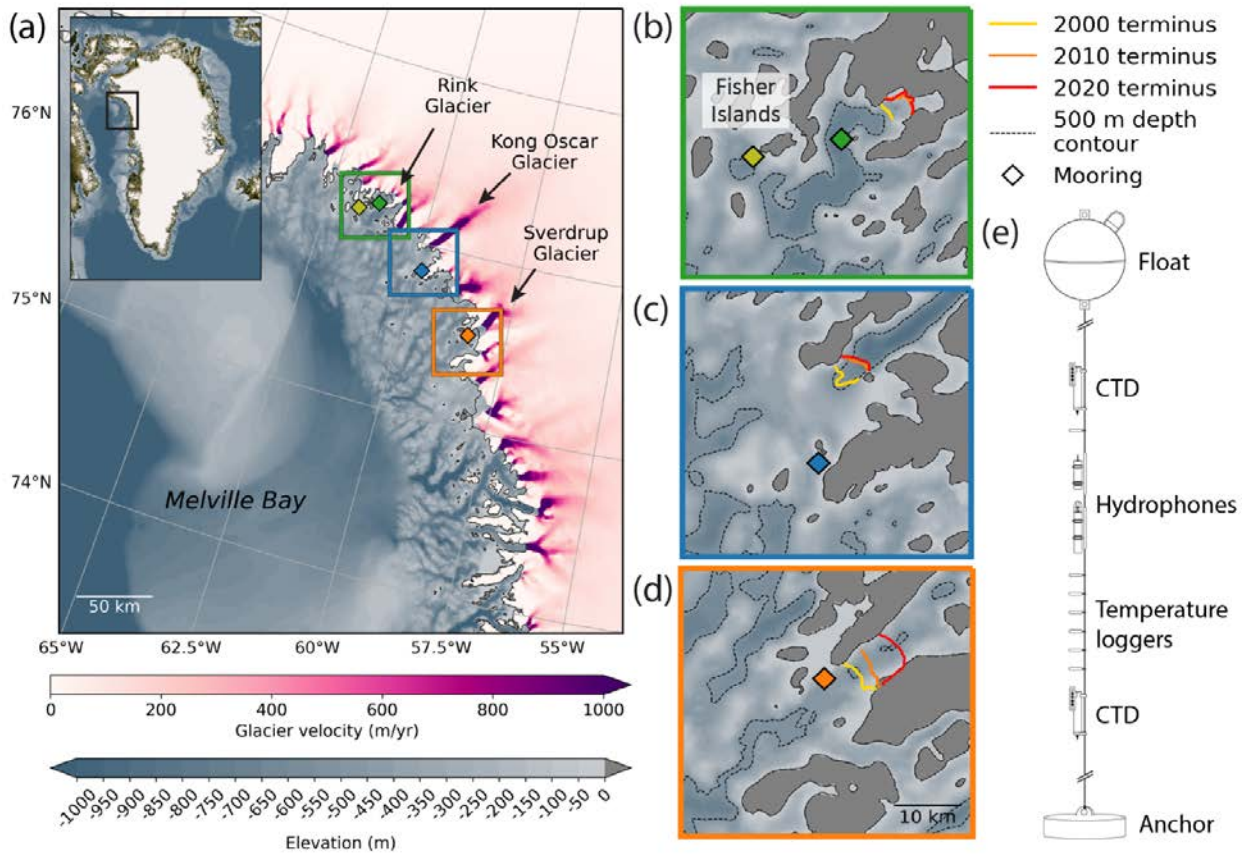


Figure 2. Map showing the study region in Melville Bay, northwest Greenland (a) with inset maps for ocean mooring locations that were positioned in front of three glaciers: Rink glacier (b), Kong Oscar glacier (c), and Sverdrup glacier (d). A schematic of hydrographic and passive acoustic instrumentation included on each mooring is also provided (e). The MEaSUREs Greenland glacier ice velocity 2019 annual mosaic (Joughin, 2022) is overlaid on ocean bathymetry from the International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2012) in (a). Below-ice bed topography from BedMachine version 5 (Morlighem et al., 2017, 2022) is displayed in (b-d) with dashed lines along the 500-meter depth contour and glacier terminus positions for three years (2000, 2010, 2020) from SAR mosaics (Joughin et al., 2021). Colored diamonds indicate locations for each mooring site (green: Rink, light green: Fisher Islands, blue: Kong Oscar, orange: Sverdrup).

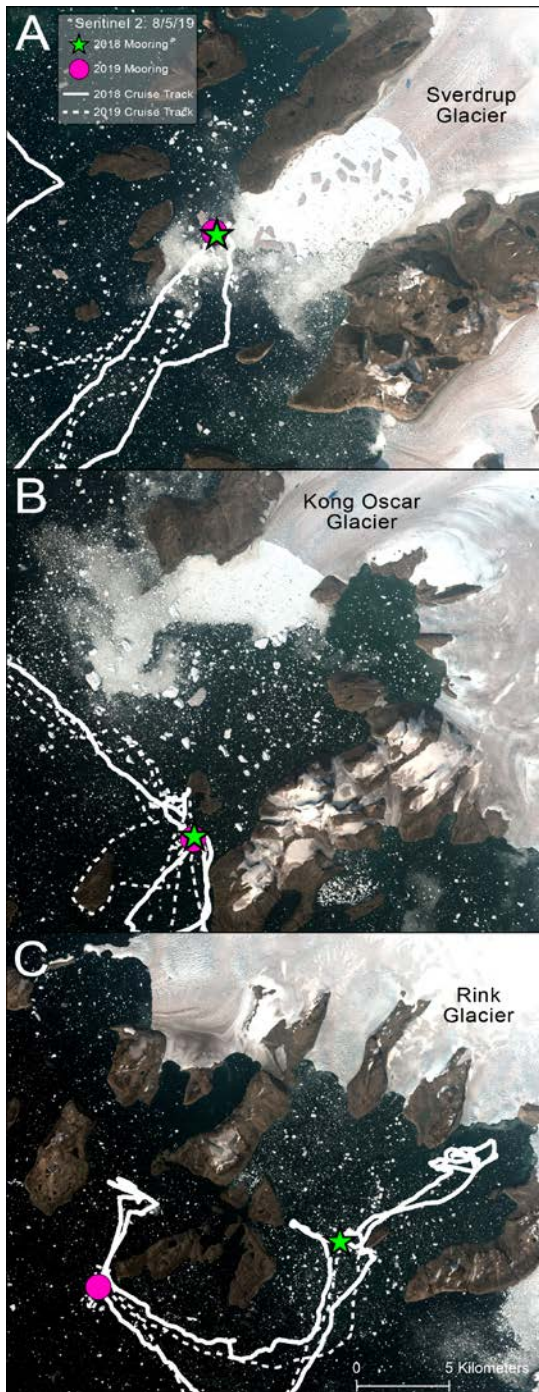


Figure 3. Close-up map of the location of the moorings relative to the glacier front at each site Sverdrup (a), Kong Oscar (b), and Rink (c) glaciers. A Sentinel 2 image is shown at the time of the deployments in 2019.

Methods and analysis

Starting in 2021 we began analyses of the data from the field programs and have continued into 2023 under a no-cost extension. Below we outline the methods and approach for each portion of the study.

Our study sites include three glaciers with different characteristics and thus represent the variety of ice dynamics observed at Melville Bay glacier fronts. Kong Oscar glacier is the largest, fastest-flowing glacier, followed by Sverdrup and Rink. At present, Rink glacier has two termini with shallow grounding depths (mean: 113 m, maximum: 243 m). Kong Oscar is the deepest glacier (mean: 578 m, maximum: 747 m) and produces the most solid ice discharge (i.e., icebergs). Sverdrup has an intermediate grounding depth (mean: 254 m, maximum: 532 m) but has the widest glacier front. Estimates of mean freshwater runoff are smallest for Rink. The runoff arising from Kong Oscar and Sverdrup are similar, but Sverdrup is slightly higher. We selected these sites because they are known areas with narwhal occurrence during summer but also because they were interesting to our NASA collaborators from a physical-science perspective.

Narwhal acoustic analysis

Recordings were made using Aural-M2 loggers (peak clipping levels of 151 dB re. μPa , sampling rate of 32,768 Hz (16 bit), 4 V peak-to-peak input range to ADC, 4-pole Butterworth low-pass filter with 20 kHz cut-off frequency for input voltages ≤ 3.2 V and 15 kHz for voltages ≥ 4.0 V, self-noise ~ 61 dB re 1 μPa , Multi-Électronique (MTE) Inc., Rimouski, Quebec Canada) fitted with HTI-96-Min hydrophones (in-built preamplifier, sensitivity of -165 dB re. V/ μPa , flat frequency response from 2 Hz to 30 kHz, High Tech Inc., Long Beach, MS, USA).

Additional recordings were made using SoundTrap loggers (model ST500 STD, 144 kHz sampling rate, anti-aliasing filter with -3 dB cut-off frequency at 64.8 kHz, clipping level of 173 dB re. μPa (peak), self-noise < 36 dB re 1 μPa above 2 kHz and below sea state 0 at 100 Hz to 2 kHz, Ocean Instruments New Zealand, Auckland New Zealand) that were attached to the same rigs as the Aural-M2 loggers.

Click train detection and classification

The raw data was analyzed using PAMGuard (Gillespie et al., 2008), an open source toolbox for passive acoustic monitoring (version 2.01.06 beta, www.pamguard.org). Transient sounds (such as echolocation clicks) were detected using PAMGuard's "Click Detector" module. This module detects transients based on the amplitude difference between sample by sample moving average measures of signal and noise within a specified filter band (filter settings for Aural-M2 recordings: 4-pole Butterworth filter with 2 kHz high pass; filter settings for SoundTrap recordings: 4-pole Butterworth filter with 20 kHz high pass). The averaging interval of the signal is significantly less than that of the noise and so it rapidly tracks changes in amplitude whilst the noise level changes much more slowly over time. A click was detected and saved if the signal exceeded a 10 dB threshold above the noise.

A large proportion of click detections are likely to stem from transients generated by various noise sources in the environment in part because the time without toothed whales near the acoustic recorders is likely to greatly exceed the time with animals nearby. To identify events where click detections resembled patterns associated with echolocation, the click detector outputs were passed to PAMGuard's "Click Train Detector" module. This module utilizes a multi-hypothesis tracking (MHT) pattern recognition algorithm (Macaulay, 2020). In brief, the MHT algorithm produces numerous sets of tentative click associations, where the number of clicks per hypothetical click train increases over time. To limit the escalating growth of possible click trains, likelihood tests are performed to evaluate if click trains contain clicks with low association, represented by a high χ^2 -value, which are then pruned away to keep only click trains with a high likelihood of being from a single source (Macaulay, 2020).

For this study, where the sampling rates were too low to record the full frequency spectrum of the clicks and hence reliably estimate parameters like peak frequency, the Click Train Detector module was set to detect click trains based on the two variables ICI and click amplitude. For ICI, a maximum limit of 500 ms was set along with an expected standard deviation of 200 ms and a minimum value of 1 ms. For click amplitudes, an expected standard deviation of 20 dB were used.

The SoundTrap recordings contained many click detections (possibly a result of the low self-noise) that it would have taken many weeks for the click train detector processing to finalize if using all detections. It was therefore decided to only run the click train detector for SoundTrap click detections exceeding 120 dB re μPa (peak-to-peak). For Aural-M2 recordings, all click detections were used as input to the click train detector.

Whistle detections

Tonal sounds were detected using PAMGuard's "Whistle and Moan Detector" (WMD) module (Gillespie et al., 2013). The WMD module performs a number of noise reduction and thresholding processes on spectrogram data to effectively generate binary images, which are then processed using a connected component analysis algorithm to detect any long, narrowband tonal signals (Gillespie et al., 2013). The detector searched for tonal sounds across the frequency scaled spectrogram (FFT size 1,024 bins, FFT overlap 512 bins and Hann window using PAMGuard's default settings) from 1,500 Hz up to the Nyquist frequency of each recording (16,384 Hz for Aural-M2 and 72,000 Hz for SoundTrap recordings). This frequency band represented a trade-off between including as much of the communication bandwidth used by animals as possible while ignoring low-frequency tonal sounds from ambient noise, in particular tonals generated by ice. The FFT settings resulted in some rapid click sequences having a tonal appearance in the spectrogram, which thereby made it possible for the WMD module to occasionally detect echolocation buzzes or buzz-like calls that are frequently used for communication by narwhals (REF). The detection threshold for tonal sounds was set to a signal-to-noise ratio of 10 dB, while additional inputs to the WMD module used PAMGuard's default settings.

Manual auditing

For reliable identification of toothed whale events, further processing of the click and whistle detections was necessary. Ambient noise was highly variable over the course of each deployment and strongly depended on conditions such as sea ice concentration, weather, and nearby marine-terminating glaciers. Especially the presence of ice increases the chances of triggering the whistle and click detectors, as well as the click train detector (e.g., if ambient noise results in hundreds or thousands of transients being detected within a few minutes), which may lead to coincidental click patterns being detected as click trains.

To limit the risk of false toothed whale detections, it was decided to manually audit the recordings based on the outputs from the whistle and click train detectors. First, the recordings were divided into non-overlapping 10 min windows, and the sums of click train detections and whistle detections within each time window were computed. Time windows were then selected for manual auditing using MATLAB's *findpeaks* function, which was set to operate at a minimum peak height of 10 detections per time window for click trains and 3 detections for whistles and a minimum peak distance of 6 hours. Thus, up to four time windows could be selected for auditing per day for each of the two selection variables, i.e. the result was a checklist containing up to eight time windows per day. Exploratory analysis suggested that the 6-

hour peak distance criterion combined with the use of the two different types of detector outputs gave a low risk of missing toothed whale events.

Each of the 10-min time windows selected for auditing were manually inspected in PAMGuard using 1) plots of click amplitude versus time with color-coding of click train detections and 2) spectrogram displays (same settings as used for the WMD module) overlaid with plots of whistle time-frequency contours and also including symbols indicating click and click train detections. This work was also conducted in collaboration with Drs. Michael Ladegaard and Peter Madsen (University of Aarhus, Denmark), who assisted with acoustic analysis of narwhal detections when PI Simon was out on family sick leave from 2021-2023.

Opportunistic beluga detections and comparison of narwhal and beluga echolocation

Under the supervision of PI Laidre, Marie Zahn (PhD student at the University of Washington) is using the detections of narwhals and belugas from this study to test the BANTER (Bio-Acoustic event classifier) model, an acoustic classifier which she developed and published in Zahn et al. 2021. This builds off of data collected in Baffin Bay with a vertical array in the ONR-funded project *Behavioral Ecology of Narwhals*, Award Number: N000141110201, PI Laidre. BANTER is composed of two stages of Random Forest classification models, originally built using acoustic recordings from hydrophones with high sampling rates (500 kHz). To accommodate recordings from the SoundTrap hydrophones with lower sampling rates (144 kHz) (this study), Zahn modified the classifier to use a single click detector for the 20-50 kHz range (see Zahn et al. (2021) for description of click detectors). In essence, the updated classifier only uses clicks with peak frequencies in the 20-50 kHz range. The classifier will be tested separately for Kong Oscar and the Fisher Islands SoundTrap data, and species designations (i.e., classification scores) will be compared between locations with different ambient noise levels. The Kong Oscar mooring is positioned closer to the glacier front and has higher ambient noise levels compared to the Fisher Islands mooring. Model diagnostics and tests will be conducted using the *banter* and *rfPermute* packages in R. Species classifications from the BANTER model will be compared to manual identifications completed by a human analyst (M. Ladegaard). Processed acoustic data from Aural-M2 hydrophones attached to the same moorings will also be leveraged for species assignment validation. This is work in progress as part of Zahn's dissertation and results will be complete by the end of 2023.

Echosounder prey analysis

We collected acoustic backscatter using a hull-mounted Simrad EK80 echosounder operating at 38, 120, and 333 kHz in continuous wave (narrowband) mode in 2018 and 2019 (Figure 4). We collected data during transits into and out of each glacier fjord site, as well as during short transits as the vessel moved between oceanographic sampling stations within each site. In total, we surveyed 26 km² in 2018, and 31 km² in 2019. Heavy ice cover at Kong Oscar Glacier in both years limited the research vessel's movements, resulting in less total surveyed area at this site.

Acoustic data were processed using Echoview software to quantify backscatter attributed to fish and zooplankton. Pelagic fish were classified using a minimum mean volume backscattering strength (S_v or MVBS, dB re 1 m⁻¹) threshold of -75 dB and maximum S_v threshold of -35 dB using data from the 38 kHz echosounder, following (Bergström and Vilhjalmarsson 2008). Zooplankton were classified using data from the 120 kHz echosounder, excluding data from below 300 m. We used a threshold approach, with a minimum S_v of -90 dB. Georeferenced integrated area backscatter (nautical-area-backscattering

coefficient, S_A or $NASC, m^2 nmi^{-2}$) attributed to fish or zooplankton were exported in 0.5 nmi horizontal by 10 m vertical bins. All subsequent analyses used integrated $NASC$ values, which is an index of relative abundance and is a proxy for biomass. We focused our analyses on comparisons of $NASC$ between the sites and years, and also examined the vertical distributions of prey by calculating the weighted mean depth of $NASC$ attributed to fish and zooplankton.

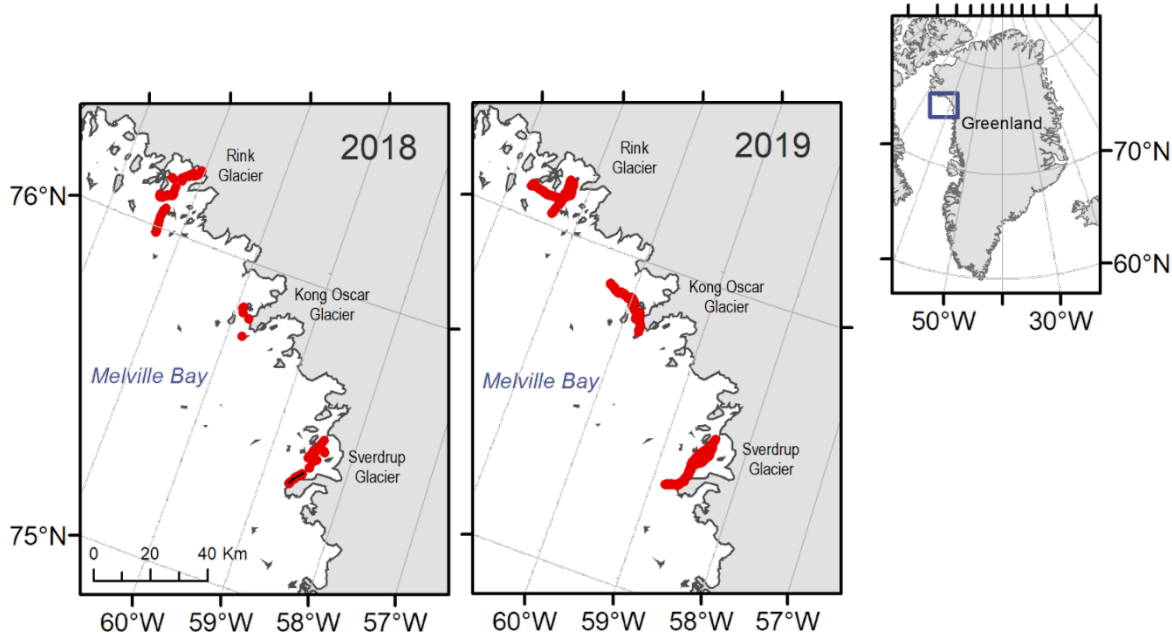


Figure 4. Study area showing the swaths of fjords surveyed with fisheries acoustics using a hull-mounted Simrad EK80 echosounder operating at 38, 120, and 333 kHz in continuous wave (narrowband) mode in 2018 and 2019.

Physical/environmental data analysis

Moored CTDs sampled every 3 minutes and temperature loggers every 20 seconds. CTD pressure data were analyzed to identify anomalous spikes when the mooring was hit by icebergs with deep keels and depressed down the water column. Spikes, typically lasting 1–6 hours and spanning 10–50 m, were flagged and removed. Depth corrections were made for occasions when the mooring was dragged and settled at a new depth. Measurements were averaged into hourly, daily, and weekly datasets. Daily mean temperature and salinity provided a sufficient timescale to examine seasonal patterns and thus was the temporal resolution used in downstream analyses. Temperature and salinity profiles were made by linearly interpolating between observations in the vertical (depth) dimension.

The relationship between temperature and salinity was explored using T-S plots and known water mass densities from previous work (Curry et al., 2014). In T-S space, mixed waters exhibit a positive relationship between temperature and salinity where saltier waters are warmer and fresher waters are cooler. The timing of observations in relation to the T-S mixing line were considered in order to identify which months diverged from this line. Months where observations generally fell along the mixing line were identified and used to fit a linear model. A linear regression was run separately for each mooring as the slope of the mixing line varied slightly between each dataset. In situ temperature

observations from the moorings were then used to predict salinity from the modeled fit. Predicted salinity values were subtracted from the in situ salinity observations to determine when and where (i.e., at what depths) salinity deviated from the mixing line. By plotting profiles of the difference between the observed and predicted salinities, key processes can be identified including evidence of subglacial plumes and upwelling or downwelling events.

The influence of ice and atmosphere dynamics on local ocean variability was examined by relating several key processes to the mooring observations. Year-round timeseries of sea ice cover, vertical velocity (derived from wind stress), air-sea heat fluxes, glacier ice velocity, glacier terminus advance/retreat, and subglacial freshwater runoff were plotted alongside the moored temperature and salinity measurements. Hourly estimates of sea ice cover, wind stress, and air-sea heat fluxes (sum of shortwave radiation, longwave radiation, sensible, and latent heat fluxes) from the ERA5 reanalysis product (Copernicus Climate Change Service, Climate Data Store, 2022; Hersbach et al., 2022) were averaged to a daily resolution. ERA5 estimates are provided on a nominal 0.25° lat-lon grid which corresponds to a $\sim 6.9 \times 27.8$ km grid cell at 76°N . The closest ERA5 grid cell to each mooring location was used.

Ice velocity (m/yr) from Sentinel 2A, 2B, and Landsat 8 imagery were extracted from the NASA MEaSUREs ITS_LIVE project (Gardner et al., 2018, 2022) using a point measured at the glacier centerline and approximately half the glacier width up from the 2019–2020 glacier front. Relative glacier length (km) was normalized and represents the advance (positive) and retreat (negative) of each glacier terminus (Black & Joughin., 2022; Black & Joughin, 2023). Relative length estimates were available at a weekly frequency for Kong Oscar and Sverdrup and monthly for Rink. The freshwater runoff dataset was derived from two regional climate models (RACMO and MAR) and provided as a daily timeseries (Mankoff, 2020; Mankoff et al., 2020). Land and ice basins with runoff outlets in front of Rink, Kong Oscar, and Sverdrup glaciers were considered in our analyses. However, subglacial runoff from each glacier ice basin provided the largest freshwater input.

The work described here on the physical and environmental data analysis is a component of Marie Zahn's PhD dissertation at UW (ongoing) under the direction of PI Laidre and co-I Fenty (NASA).

Narwhal habitat modeling

We used observations from 1 August through 31 October in 2018 and 2019 to standardize the timeframe over the study period. We used Generalized Linear Models (GLMs) to relate environmental conditions to daily narwhal acoustic presence in the three Melville Bay study sites. Given the response was binary (presence/absence), GLMs with a binomial distribution, known as logistic regressions, were developed to explain the probability of detecting a narwhal.

All data were synthesized to a daily resolution and the variables considered built upon covariates used in Laidre et al. (2016). Ocean variables included shallow temperature and salinity (between 120–140 m deep), deep temperature and salinity (between 220–240 m deep), and ambient underwater noise levels from the 4 kHz third-octave level (TOL) band. Each mooring carried a shallow and deep CTD (Table 1), but the depths of these instruments varied across sites and years. To standardize the depths considered in our models, observations from two depth ranges were selected (120–140 and 220–240 m) that were closest to the actual shallow and deep CTD positions. Linearly interpolated values between oceanographic sensors were averaged between the selected depths and used as covariates. For ambient noise levels, the 4 kHz TOL band was selected because low-frequency energy in narwhal click

spectra are found within this frequency band (Stafford et al. 2012) and may have more ecological relevance to narwhals than other TOL bands.

Glacier variables included in our models were glacier ice velocity, terminus position, and freshwater runoff. Since narwhals are ice-associated species (Laidre et al. 2004, 2008), it is possible that they are attracted to glacier calving activity and the extent of ice mélange when visiting glacier fronts. At present, there is no iceberg production or ice mélange dataset available with a sufficient spatial and temporal resolution to include in our models. Therefore, glacier ice velocity and terminus position (i.e., relative length in km indicating glacier advance or retreat) were used as proxies for iceberg production. Sea ice concentration was removed from the covariate list since it was at or near zero for the August–October period. Freshwater runoff that flows into each fjord was included as a variable since it has been linked to biological processes, including prey aggregation and primary productivity (Lydersen et al. 2014). Additionally, previous work showed narwhal presence was negatively associated to runoff where they prefer sites with low silt-laden subglacial runoff (Laidre et al. 2016). Greenland’s freshwater runoff originates from ice sheet melt that is ejected at the base of tidewater glaciers, and to a much lesser degree, from terrestrial sources.

In addition to ocean and glacier variables, day of year (DOY), site, and year were added as fixed effects. DOY reflects the possibility that narwhals respond to environmental cues that are independent of ocean and ice conditions, such as day length. A fixed effect for site was added to examine whether narwhals preferentially visit specific glaciers in response to local fjord conditions. While Aural-M2 hydrophones were deployed in both 2018 and 2019, SoundTraps were only used in 2019. Since the higher sampling rate of the SoundTraps allowed for greater detectability than the Aural-M2 hydrophone, we used narwhal detections from the SoundTraps for 2019. We accounted for the difference in sampling design between 2018 and 2019 by including a fixed effect for year.

Multicollinearity among predictor variables was assessed using Pearson’s correlation coefficients and selected covariates were removed when a positive or negative correlation exceeded 0.6. We found collinearity between DOY and deep salinity and between deep temperature and shallow salinity. The salinity terms (deep and shallow) were removed. Interaction terms were added for DOY and runoff and between DOY and each temperature variable (deep and shallow). Models for all possible covariate combinations were fitted and Akaike’s Information Criterion corrected for small sample sizes (AICc) was used for model selection (Burnham & Anderson 2002). The model with the lowest AICc ($\Delta\text{AICc} = 0$) indicates the best model based on fit and model complexity. Examination of model residuals confirmed independence of observations and no presence of autocorrelation. Models were built using the *MuMIn* (Bartoń 2022) and *stats* packages in R version 4.2.2 (R Core Team 2022).

Contribution to West Greenland-wide detections

The acoustic data recorded in Melville Bay near Rink, King Oscar and Sverdrup Glaciers was included in a separate analysis covering a large geographic area across the entire coast of Northwest Greenland. The aim of this analysis was to describe the presence and seasonality of narwhal and bowhead whales in relation to sea ice coverage between approximately 10 degrees of latitude. The recorders were deployed between 2011-2020 in 8 different locations, with the northernmost location being a mooring from this study (76.1° N) and the southernmost location off Disko Bay (68.6° N), see Figure 1 and 2. The autonomous underwater acoustic recorders (Aural M2, Multi-Electronique, MTE) sampled with 8192 – 32768 Hz, they were deployed for one year at a time. A total of 13 recordings of 4-11 months of recordings were used in the analysis.

Soundscape and ambient noise levels around Greenland

Data from our study were also used in Ladegaard et al. 2021 (*Scientific Reports*), who reported PAM data from 26 deployments in five areas around Greenland across more than 8 years (Oct 2011–Jan 2020) in order to quantify variations in broadband ambient noise levels and obtain baseline estimates for future comparisons. Acoustic data were analysed using generic automated noise type detectors for quantifying broad-scale features of Arctic soundscapes and supplement our analysis with manual auditing to identify the dominant noise sources at each recording location. exist in several areas.

RESULTS

Use of narwhal temperature tag data in ocean models

Narwhals play a crucial role in enhancing our understanding of ocean environments with limited observational data. By diving to the seafloor, instrumented narwhals provide valuable insights into the vertical structure of ocean temperature and the depth of the seafloor. In the context of NASA's OMG mission, the utilization of tagged narwhal data proved to be highly advantageous. Specifically, the mission focused on measuring ocean temperature and seafloor depths on the continental shelf in the northwest region of Greenland, where narwhal data had been collected. The dive depth information obtained from narwhals served as crucial "groundtruth" tie points for the inversion of airborne gravity data and contributed to new, high-resolution bathymetric maps.

The data were used in three unique models, all published: Morlighem et al. 2017. *BedMachine v3: Complete bed topography and ocean bathymetry mapping of Greenland from multibeam echo sounding combined with mass conservation*, *Geophysical research letters* 44 (21), 11,051-11,061, Jakobsson et al., 2020. *The international bathymetric chart of the Arctic Ocean version 4.0*. *Scientific data* 7 (1), 176, and An et al. 2019. *Bathymetry of northwest Greenland using "Ocean Melting Greenland" (OMG) high-resolution airborne gravity and other data*. *Remote Sensing* 11 (2), 131. The IBCAO bathymetry (Jakobsson et al. 2020) is an Arctic-focused dataset within the General Bathymetric Chart of the Oceans (GEBCO) project, which is supported and endorsed by the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

Furthermore, the narwhals' ability to capture ocean temperature data proved valuable in informing the OMG mission plan. These narwhal data offered valuable insights into the locations where warm waters crossed the continental shelf on their way to Greenland's marine-terminating glaciers. By leveraging this information, the OMG mission planners were able to better understand the dynamics of water movement around the Greenland ice sheet.

Narwhal acoustic analysis

Hydrophones recorded for approximately 5–6 months starting in August of each year (2018 and 2019), totaling ~10 months of near-continuous acoustic data (Table 1 and 2). Narwhals were detected 77 days total, 16 of which were days where whales were detected at two locations on the same day. Narwhals were never detected at all three sites on the same day in 2018. In 2018, there were 28 detections

(Rink/Fisher: 13, Kong Oscar: 8, Sverdrup: 7) and in 2019 there were 65 detections (Rink/Fisher: 32, Kong Oscar: 33) (Figure 5). There were no Aural-M2 narwhal detections in 2019 that were not also observed in the SoundTrap recordings.

Table 1. Summary of Mooring instrumentation and deployments. Note. The sampling interval was 180 seconds for the CTD instruments and 20 seconds for the temperature sensors.

Mooring	Date deployed	Date recovered	Seafloor depth (m)	Latitude (°N)	Longitude (°W)	CTD instrument (depths, m)	Temperature sensor (depths, m)
Rink	25 Aug 2018	5 Aug 2019	703	76.1605	61.2791	SBE 37-SM RS-232 (76, 328)	SBE 56 (125, 203, 266, 408, 488, 568, 648, 658)
Fisher	5 Aug 2019	11 Aug 2020	370	76.1038	61.7270	SBE 37-SM RS-232 (137, 377)	SBE 56 (187, 202, 227, 252, 277, 302, 327, 352)
Kong Oscar	24 Aug 2018	4 Aug 2019	251	75.8437	59.8429	SBE 37-SM RS-232 (104, 240)	SBE 56 (123, 143, 162, 182, 201, 220)
Kong Oscar	4 Aug 2019	10 Aug 2020	250	75.8418	59.8431	SBE 37-SM RS-232 (94, 226)	SBE 56 (113, 133, 153, 173, 193, 213)
Sverdrup	22 Aug 2018	3 Aug 2019	385	75.5413	58.4105	SBE 37-SM RS-232 (118, 355)	SBE 56 (153, 188, 223, 258, 293, 311, 337)

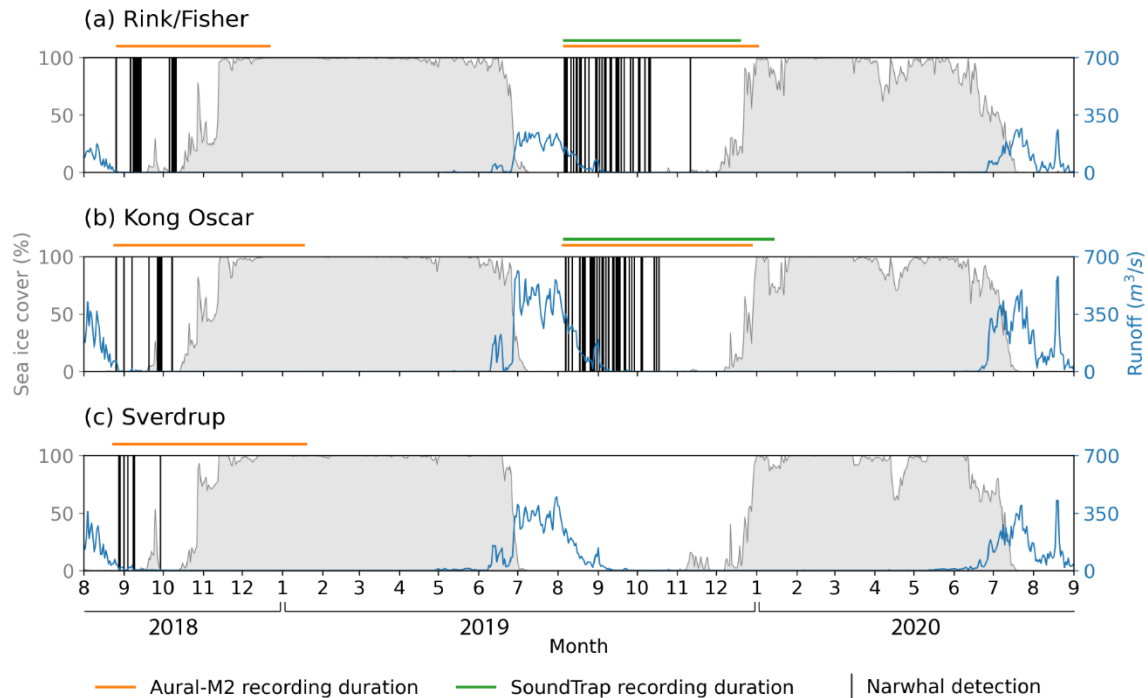


Figure 5. Narwhal detections across all sites and years plotted with percent sea ice cover and subglacial freshwater runoff. These detections have been used in several components of the study.

Table 1. Summary table of the click, click train and whistle detections at each station. Please note that for Aural-M2 recordings (stations 1, 2, 3, 5, 7), the click train detections were based on all click detections, whereas only clicks exceeding a threshold of 120 dB re. μ Pa, were included for click train detections in the SoundTrap recordings due to the higher number of click detections and consequent computer processing time.

Station	Name	Clicks	Click trains (clicks in click trains)	Whistles
1	Rink Glacier 2018-19	31,504,308	697,452 (10,792,884)	19,125
2	Tuttulipaluk 2015-16	7,108,214	127,268 (2,179,193)	838
3	Rink Glacier Fischer	18,698,700	386,157 (4,731,924)	4,552
4	Rink Glacier Fischer_ST	70,745,982	24,589 (511,168)	7,890
5	Nuussuaq Kong Oscar	15,614,587	267,226 (4,165,347)	1,697
6	Nuussuaq Kong Oscar_ST	112,892,215	22,242 (468,342)	77,319
7	Tuttulipaluk 2016-17	2,926,385	53,024 (603,341)	71,406

These data are used in several of the analyses described below, namely comparison of beluga and narwhal echolocation, the narwhal habitat modeling, the West Greenland wide narwhal distribution paper, and the meta-analysis of ambient noise around Greenland using data published by Ladegaard et al., (2021, *Scientific Reports*).

Comparison of narwhal and beluga echolocation

We opportunistically detected belugas during this study as well as a previous ONR grant on narwhal ecology (*Behavioral Ecology of Narwhals*, Award Number: N000141110201), so took the opportunity to conduct an additional component focused on differentiating and classifying belugas and narwhals using their echolocation clicks. Part of this work was published in Zahn et al., 2021, *Scientific Reports* and parts are still in progress. Beluga and narwhal echolocation clicks were observed in recordings from hydrophones on the Fisher Islands mooring in 2018-19, located farther offshore in the Rink glacier drainage basin.

A preliminary test using a subset of the mooring data (~1 hour of recordings for each species) revealed strong model performance with high correct species classification rates (>94%). A complete test of the Fisher Islands dataset showed correct classification for recordings that were not dominated by false positive detections (i.e., noise that was incorrectly detected as a click). Therefore, ongoing work includes adding a category to the acoustic classifier for “noise” in order to identify these false positives. Examination of the Fisher Islands acoustic data confirms that there is a clear difference in energy between beluga and narwhal clicks at the 20 kHz frequency band, where narwhal clicks have higher energy than beluga clicks. Further, visual inspection of narwhal click spectrograms shows a clear edge at the 20 kHz band that is absent in beluga clicks, providing an additional way to distinguish the two species’ clicks from one another. Based on Zahn’s preliminary results, we recommend a minimum sampling rate of 96 kHz for future passive acoustic monitoring studies in order to classify beluga and narwhal echolocation clicks within the 20–50 kHz frequency band. This is work in progress and results will be complete by the end of 2023. This is work in progress as part of Marie Zahn’s dissertation and results will be complete by the end of 2023.

Echosounder prey analysis

Acoustically detected zooplankton abundances were greatest at Rink Glacier in 2018, and similar at Sverdrup and Kong Oscar. Zooplankton abundances were relatively similar at all of the sites in 2019. Zooplankton exhibited bimodal vertical distributions, with high abundances near the surface between 20-50 m, and separate peaks 150 – 200 m (Figure 6). This pattern was particularly evident in 2019. Abundances of pelagic fish were greater in 2018, particularly at Kong Oscar and Rink Glaciers. The vertical distribution of fish differed from zooplankton, and greatest abundances occurred generally between 150-200 m water depth (Figure 7).

These preliminary results on prey abundance were presented at the 3rd World Seabird Conference in October 2021. Analyses are ongoing, and a paper summarizing these findings is in preparation for submission to *Polar Biology*. This work was led by Dr. Elizabeth Phillips of NOAA.

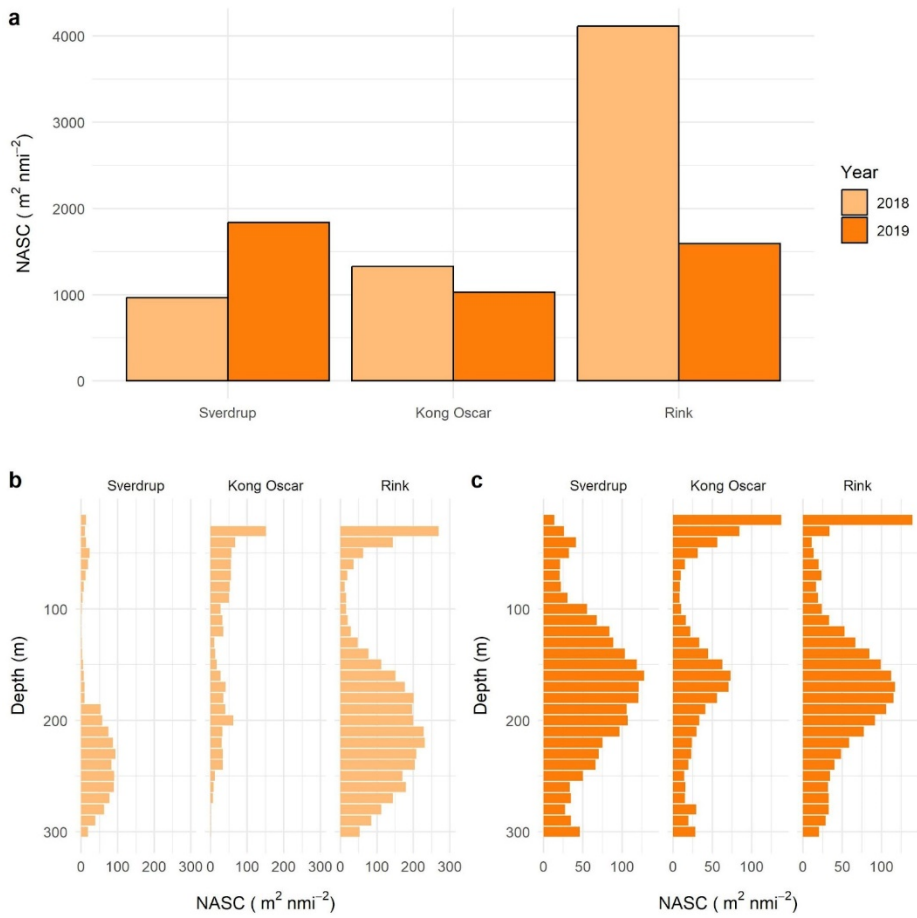


Figure 6. Zooplankton abundance (NASc) observed during surveys at three sites in Melville Bay in 2018 and 2019, including a) overall abundance at each site, and vertical distribution of zooplankton at each site in b) 2018 and c) 2019.

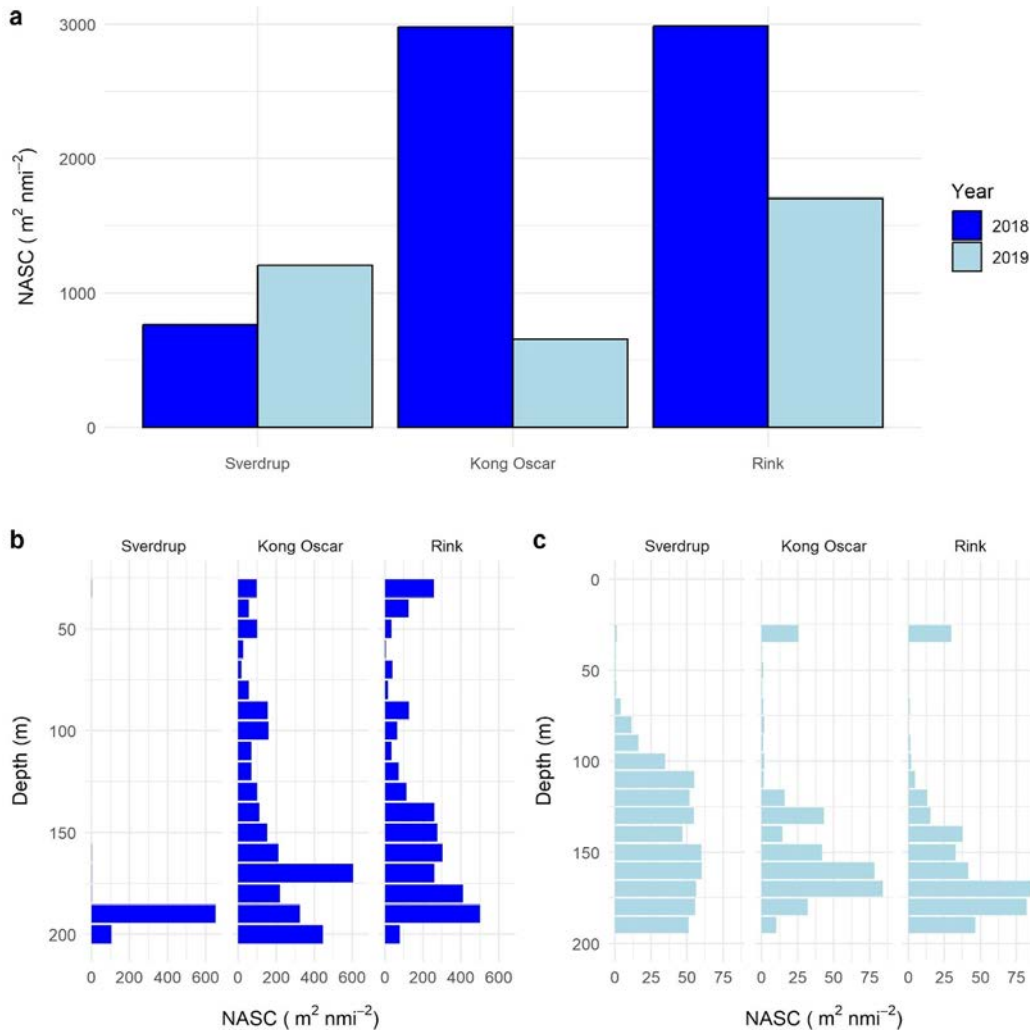


Figure 7. Pelagic fish abundance (NASC) observed during surveys at three sites in Melville Bay in 2018 and 2019, including a) overall abundance at each site, and vertical distribution of fish at each site in b) 2018 and c) 2019.

Physical/environmental data analysis

Results from the mooring oceanographic observations reveal distinct seasonal variation in temperature and salinity at all four locations. Example temperature and salinity profiles along with sea ice concentration are shown from Kong Oscar fjord in Figure 8. While the magnitude differs between each site, the presence of warm, salty water within Melville Bay peaks in spring (April–June). It is known that warm, salty water originating from the North Atlantic—referred to as Atlantic Water (AW)—circulates the continent through currents along the continental shelf. AW is shunted across coastal shelves into drainage basins and fjords where it comes into direct contact with glacier fronts. Consequently, warming of AW results in increased heat transport to glacier termini and accelerated glacier retreat. For Melville Bay, it appears that the greatest warming occurs in spring (April–June) following the ice-covered period. These results are consistent with observations reported farther south in central West Greenland where AW shoals in spring and summer.

During the summer, increased insolation leads to ice melt from glaciers, sea ice, and icebergs. What proceeds is a seasonal freshwater pulse as cold, fresh polar-origin water (PW) is exported from the Arctic and Greenland’s marine-terminating glaciers. This freshwater pulse occurs in late fall/early winter when colder temperatures and lower salinities are visible in the water column (July–February). Thus, the PW layer thickens following the ice-free summer. We expect that the primary source of PW seen in the fjords originates from offshore currents. Ongoing analyses of NASA’s OMG AXCTD and APEX/ALAMO float profiles from the continental shelf and Melville Bay trough will demonstrate whether this hypothesis is true. On a local scale, summertime melt from the ice sheet dives through cracks into a hydrological system below the glacier. This meltwater ultimately exits as runoff under the glacier terminus, forming a subglacial plume in late summer and early fall. The more buoyant freshwater injected at depth rises to neutral buoyancy and in the process mixes the water column. In Kong Oscar fjord, the plume is visible from mid-July to September (Figure 8).

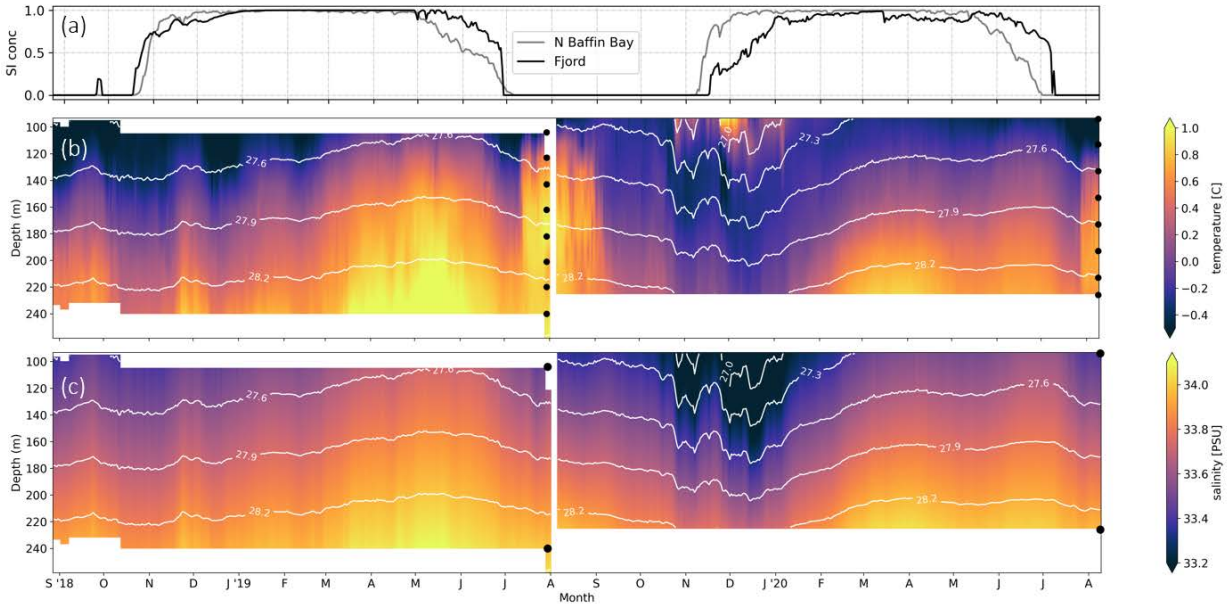


Figure 8. (a) Sea ice concentration within Kong Oscar fjord (gray line) and in northern Baffin Bay (black line). Profiles of ocean temperature (b) and salinity (c) are shown for Kong Oscar fjord from 100–240 meters depth between September 2018 and August 2020. White lines are isopycnals and black dots indicate the locations of temperature and salinity sensors.

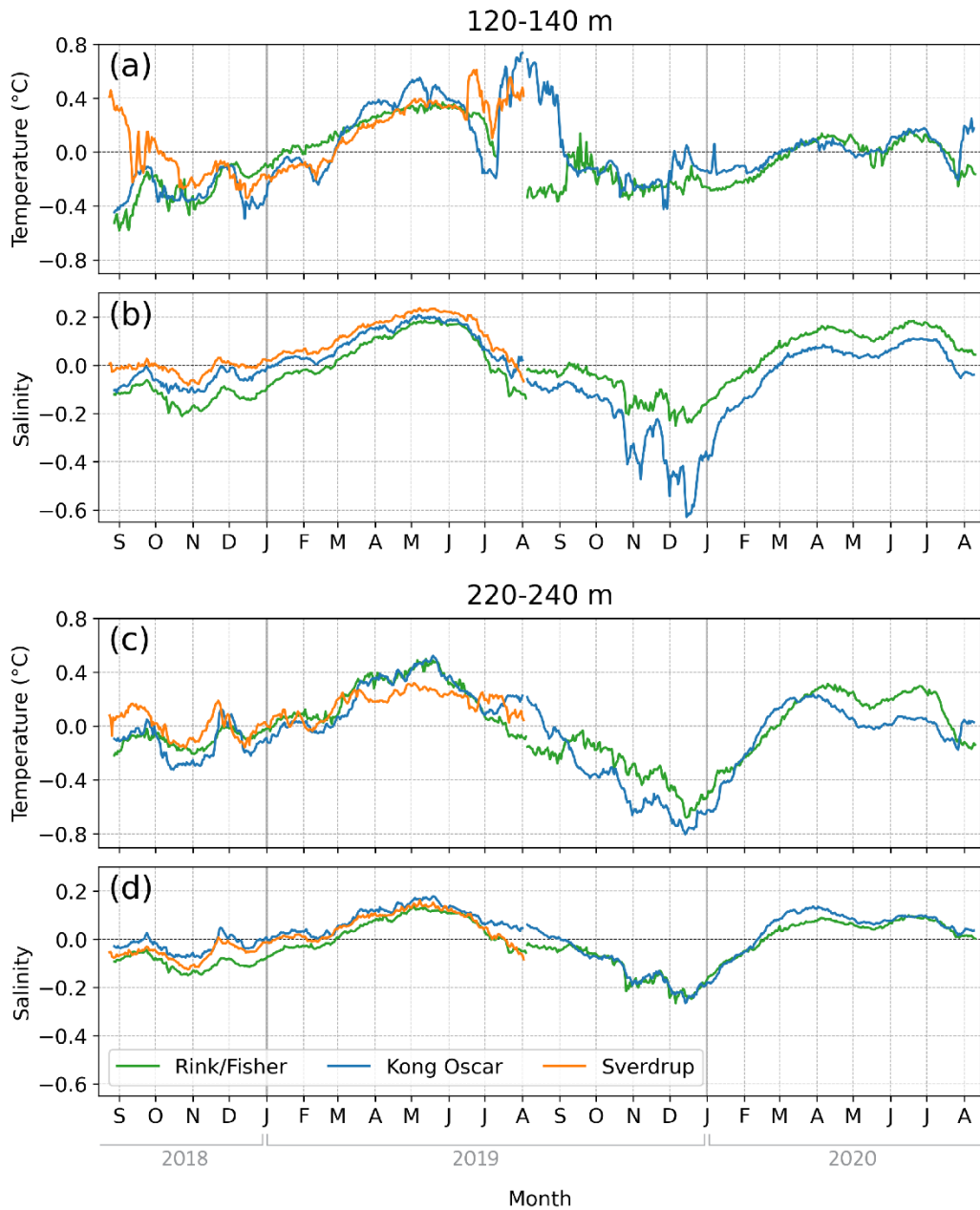


Figure 9. Daily mean temperature and salinity anomalies between 120–140 m (a, b) and 220–240 m (c, d) deep from moored observations at the three sites (green: Rink/Fisher, blue: Kong Oscar, orange: Sverdrup). Mean temperatures in (a) and (c) are -0.07°C and 0.64°C , respectively. Mean salinities in (b) and (d) are 33.60 and 33.91, respectively.

Relating key ice and atmosphere processes to the mooring temperature and salinity profiles revealed their seasonal influence on local hydrography (Figures 8 & Figure 9). Beginning in June, increased insolation causes melting of the ice sheet, glaciers, sea ice, and icebergs. During these summer months, sea ice retreats, glaciers retreat, glacier ice velocity increases, and the ocean absorbs heat (Figure 10). What proceeds is a seasonal nearshore freshwater pulse and deepening of isopycnals from June

through December as meltwater flows into coastal waters. Freshwater runoff increases in June following summer ice sheet melt, reaches a maximum in July/August, and stops in September.

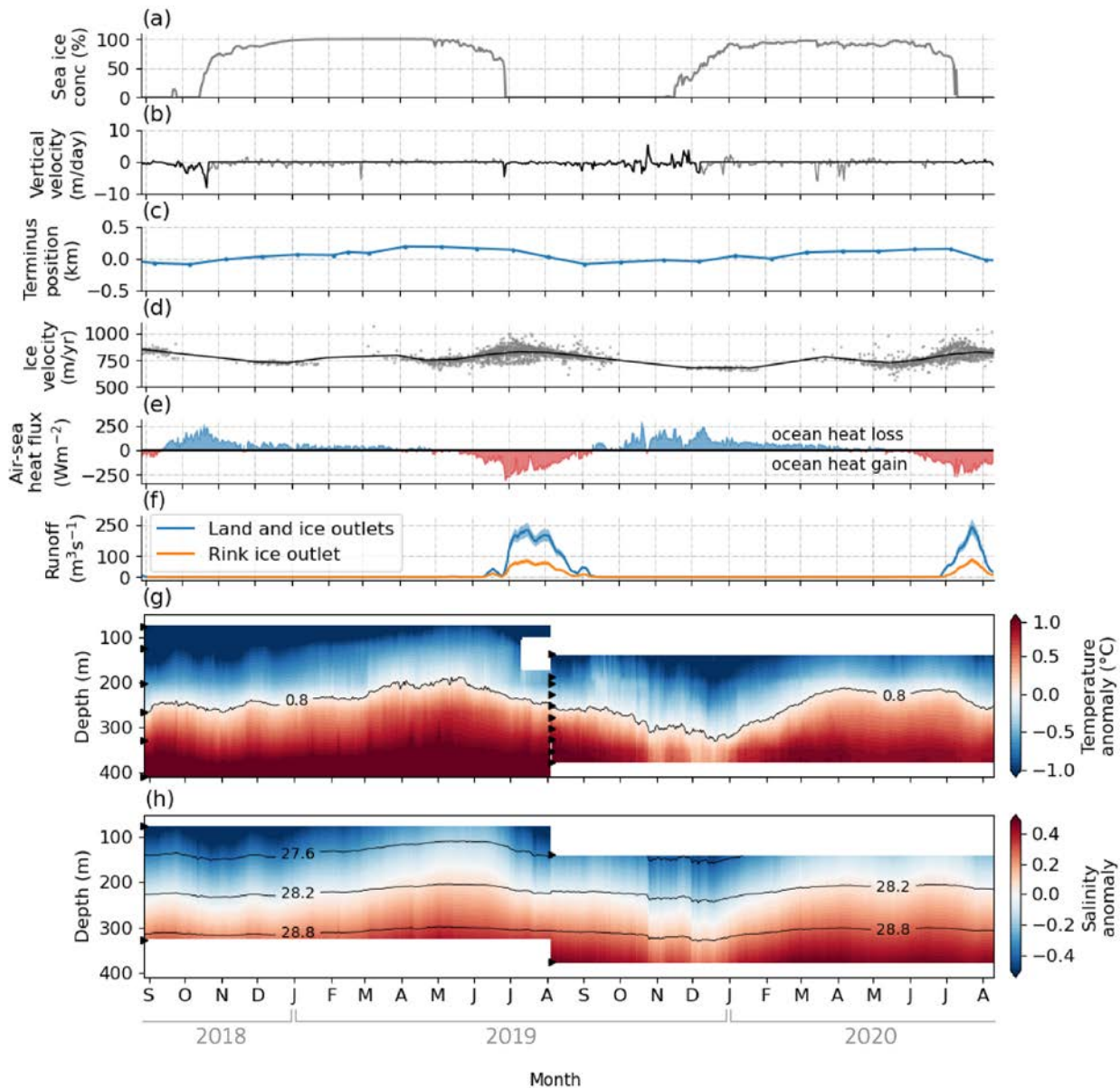


Figure 10. Timeseries of key variables to relate local ice and atmospheric processes to ocean variability shown for the Rink/Fisher mooring site as an example. Sea ice concentration (a), vertical velocity (b), terminus position (c), glacier ice velocity (d), air-sea heat flux (e), freshwater runoff (f), and profiles of temperature (g) and salinity (h) anomalies are shown between September 2018 and August 2020. Although temperature loggers for the 2018–2019 Rink mooring recorded down to 658 m, the upper 400 m are shown here (g) to better match the sampling range in 2019–2020. The black line in (b) shows vertical velocity when sea ice is accounted for (i.e., wind stress is zero when sea ice concentration is above 50%) and the gray line is without considering the presence of sea ice. Increasing values for the relative terminus position (c) indicate glacier advance and decreasing values mean glacier retreat. The black line in (d) is the 30-day running mean of individual ice velocity estimates from satellite imagery (gray points). Air-sea heat flux values (e) are positive for atmosphere

heat gain (ocean heat loss). Runoff (**f**) is shown for all land and ice outlets near the Rink glacier terminus (blue) and only the Rink glacier ice outlet (orange). Runoff is plotted with 15% uncertainty following Mankoff et al. (2020). The mean temperature isotherm (0.8°C) is overlaid in (**g**) and potential density isopycnals are shown in (**h**). Horizontal triangles in (**g**) and (**h**) show the depths where hydrographic sensors were located within each profile.

This work is expected to be submitted to the *Journal of Geophysical Research Oceans* in summer 2023. We are also preparing these data for public distribution so that they can be used by other scientists under the PO.DAAC forum.

Narwhal habitat modeling

With the completion of the hydrographic analysis in early 2023 we were poised integrate the narwhal detections with environmental covariates into a habitat model. This is the final result for grant and the analysis is in final stages of completion. Two primary research questions guided our model development: 1) what environmental conditions are correlated with the seasonal presence of narwhals in Melville Bay fjords, and 2) are there site-specific characteristics that explain why narwhals visit specific glacier fronts? We used observations from 1 August through 31 October in 2018 and 2019 to standardize the timeframe over the study period. We used Generalized Linear Models (GLMs) to relate environmental conditions to daily narwhal acoustic presence in the three Melville Bay study sites.

So far the best model shows that narwhal presence between August–October is best explained by the linear effects of freshwater runoff, day of year (DOY), and year. There was a negative correlation between runoff and narwhal presence where the probability of detecting a narwhal increased as runoff decreased. Although our recordings did not begin until August of each year, it appears that the period when narwhals occupy fjords in Melville Bay is preceded by peak summertime runoff, potentially when biological productivity is high within the fjords. Similar to runoff, the coefficient for DOY was also negative, indicating there is a peak probability of narwhal occurrence and as time progresses (i.e., DOY increases), the probability of narwhal detection decreases. We are still refining the final model as of preparation of this report so we do not present final results here. We plan to adjust the model composition and re-run model selection during summer 2023 and submit a paper by September.

Contribution to West Greenland-wide detections

A large geographic ranges of recorder deployments are being used to assess narwhal and bowhead whale distribution at 8 locations between 2011-2020 (Figure 11). In total of 13 recordings of 4-11 months of recordings are being used in the analysis, which is in progress and led by PI Simon.

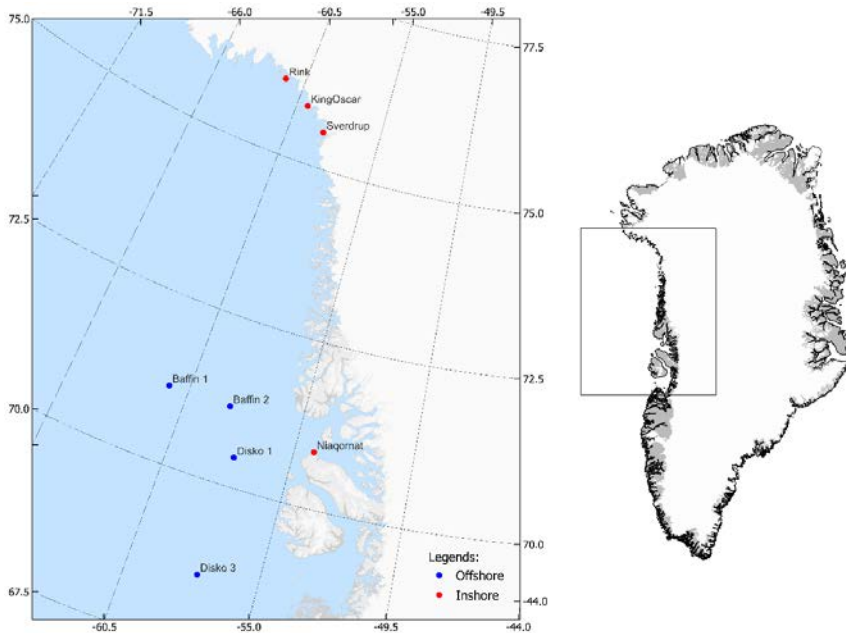


Figure 11. Map of locations of bottom-moored sound recordings included in the Greenland-wide narwhal and bowhead detection analysis. The three northernmost locations are those from this study and reported here.

Soundscape and ambient noise levels around Greenland

Ladegaard et al. 2021 (*Scientific Reports* 11:23360) reported on underwater sound at 26 stations around Greenland, of which three sites in Melville Bay came from this study. In Melville Bay, the recordings collected in late summer 2019 showed considerably elevated noise levels compared to those collected in the same area between 2016 and 2018 with full-deployment median levels in the LF decade band ranging from 108 to 111 and from 87–99 dB re. 1 μ Pa (RMS), respectively. Analysis of seasonal noise variation showed a consistent pattern for Melville Bay, Baffin Bay, and Greenland Sea. From January to June, decade levels were generally lower compared to the rest of the year and often relatively stable, although some stations showed considerable variation. July/August marked an increase in noise levels in all decade bands that generally peaked in September/October. By December, the decade levels had decreased and were comparable to the levels in January to June.

IMPACT/APPLICATIONS

Our study utilizes these key approaches to model and understand the hydrographic variability at four glacial fjords in NW Greenland and novel data on the the distribution of narwhals relative to key environmental properties (biotic and abiotic) in these habitats. Our results provide a baseline context for interpreting narwhal behavioral responses to external stimuli, such as anthropogenic sound. This is critical given the increased use and development in the Arctic, occurring now and expected in the future.

RELATED PROJECTS

There are no related projects.

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