1. Introduction

The narwhal (Monodon monoceros) is a relatively small whale, measuring 4–5 m long and weighting up to 0.9–1.6 tonnes, that is classified as an endemic Arctic cetacean. It is famous for its unique spiral tusk, which is up to 3 m long and erupts asymmetrically through its upper lip. Narwhals remain an understudied cetacean, despite several hundred years of hunting by the Inuit (or Inughuit) and Europeans (Ahonen et al., 2019; Blackwell et al., 2018; Marcoux, 2008; Marcoux et al., 2012). For example, it was only recently suggested that additionally to the popular theory about the use of narwhal’s extraordinary tusk organ in intrasexual selection (e.g., Graham et al., 2020), the tusk could sense changes in salinity, temperature, and pressure (Nweeia et al., 2014), whereas its influence on sound production remains unclear (Ford & Fisher, 1978).

One of the main narwhal habitats is in the Arctic waters between Canada and Greenland in Baffin Bay. The sizes of narwhal populations, and their spatial and temporal dynamics, are generally poorly known due to difficulties in observing these animals in the icy polar waters. An effort has been made by the Greenland Institute of Natural Resources to estimate the approximate numbers of animals in the coastal hunting areas of Greenland via visual aircraft-based observations and direct observations from the coast (Heide-Jørgensen, 2004; Heide-Jørgensen et al., 2010). These studies have confirmed that Inglefield Bredning Fjord (IBF) in Northwest Greenland is one of the key summering grounds for narwhals in June–September, before their regular outward migration to offshore wintering grounds, which are poorly known, but it is likely that some part of the IBF narwhal stock winters in the North Water polynya in Baffin Bay (NAMMCO, 2018). It is possible that IBF hosts approximately 5% of the total narwhal population west of Greenland (see Heide-Jørgensen et al., 2010; NAMMCO, 2018).

Estimates of narwhal numbers in certain areas are essential for general biodiversity assessments and also the Canada/Greenland Joint Commission on the Conservation and Management of Narwhal and Beluga, which...
issues annual hunting quotas for narwhals. For example, hunters from Qaanaaq—the largest settlement in Northwest Greenland, with about 650 inhabitants—are catching 118 narwhals every year (the average multiyear harvest from data by NAMMCO, 2018), which is equivalent to approximately 1–2% of the individual abundance estimate in IBF for August 2007 (Heide-Jørgensen et al., 2010). However, the population size estimates used for these presumably sustainable hunting practices remain extremely uncertain (8,368; 95% confidence interval: 5,209–13,442) (Heide-Jørgensen et al., 2010), do not take into account the local hunting experience (Hastrup, 2019), and there are no available data on the short- and long-term changes in narwhal abundance and presence.

Narwhals are recognized as “one of the most vulnerable Arctic species to climate change” due to their narrow ecological niche (Ahonen et al., 2019). Therefore, the potential impacts of the ongoing dramatic warming and the associated changes in the environment around Greenland (including the increased presence of narwhal predators, such as the Arctic killer whale) on the narwhals must be understood (Breed et al., 2017; Koblitz et al., 2016; Laidre et al., 2016). Several recent studies have also highlighted the need to study the potentially harmful effects of increasing anthropogenic noise on narwhals (Heide-Jørgensen et al., 2013; Kyhn et al., 2019) and other marine mammals (Jones, 2019). For example, it has been suggested that seismic air-gun surveys for hydrocarbon exploration in Baffin Bay may have disruptive effects on the migration behavior of narwhals and even lead to the freeze-in of hundreds to thousands of animals in sea ice because they hesitate to return southward through the seismic survey areas in the autumn (Heide-Jørgensen et al., 2013).

The above-mentioned issues and practical concerns, together with fundamental scientific questions about the behavior, foraging, reproduction, communication, migration, and adaptation of narwhals to ice-filled environments, make further narwhal research both crucial and urgent. Several methods have been used to monitor and study these animals, including visual observations via coast- and aircraft-based surveys (Heide-Jørgensen et al., 2010), animal-borne recorders (Blackwell et al., 2018), and passive acoustic monitoring (Ahonen et al., 2019). The latter, noninvasive practice is becoming an important tool in the comprehensive documentation of natural and artificial noise in the ocean, changes in physical processes, animal acoustic presence, species classification (e.g., Merchant et al., 2015; Mikhailovsky et al., 2015; Risch & Parks, 2017), and estimations of the absolute and relative numbers of individual animals (e.g., Castro et al., 2015; Marcoux et al., 2011). Passive hydroacoustic recordings of underwater environments (or “soundscapes”) provide the most objective, continuous, long-term time series (Lin et al., 2017; Merchant et al., 2015) and have important advantages over episodic and more bias-prone aerial and human observations (Heide-Jørgensen, 2004; Heide-Jørgensen et al., 2010). Furthermore, unlike direct bio-logging, these observations are not stressful for the animals (Blackwell et al., 2018). For a review of the current knowledge on underwater noise in the Arctic, the reader is referred to PAME (2019).

Narwhals appear to be very skittish animals and are difficult to approach with motorized boats, especially large research vehicles (Blackwell et al., 2018; Miller et al., 1995; Möhl et al., 1990). However, it is possible to overcome this challenge by acquiring hydroacoustic measurements using moored sensors or sensors attached to buoys. For example, the long-term acoustic presence of narwhals and other acoustic mammals has recently been monitored in the Fram Strait close to East Greenland (Ahonen et al., 2019; De Vreese et al., 2018). Furthermore, near real-time streaming of underwater sound coupled to machine learning recognition is now available for the East Greenland coast (“Statoil Greenland I” observatory at N79.05°, W12.53°; http://listentothedeep.com). However, the visual confirmation of the animal’s presence, or the documentation of small and local concurrent anthropogenic or geophysical events, such as iceberg collapse, glacier calving, or sea ice dynamics, is difficult with this kind of unsupervised monitoring.

Here, we analyzed measurements acquired from either a whale hunter boat or from a small boat piloted by a local guide. This data acquisition approach was chosen since local Inuit hunters are generally knowledgeable about the area and the narwhal’s behavior and are usually able to detect the presence of an animal much faster than a nonlocal. They first spotted the narwhal with binoculars or the naked eye, then shut down the engine, waited, and quietly moved off in a kayak, hoping to get close enough to the occasionally resurfacing whale to harpoon it in the traditional way. This approach provided the unique opportunity to make hydroacoustic measurements within ~25 m of the animal. We specifically analyzed these acoustic observations to characterize the soundscape of a major Greenlandic glacier fjord, IBF, and its tributary, Bowdoin
Figure 1. (a) Map of Inglefield Bredning and Bowdoin fjords in Northwest Greenland (inset). Black circles show the recording sites (listed in Tables 3 and 4). Red circles highlight the locations where narwhals were observed. Thin lines show the main search effort (usually starting from Qaanaaq). The background satellite image was acquired by the Copernicus Sentinel-2A satellite on 27 July 2019. (b–e) Photographs illustrating specific features of the historical narwhal hunting grounds and local environment: (b) narwhal right next to hunter’s boat, (c) kayaking hunter, (d) male narwhal caught near Bowdoin Glacier (Kangerluarsuup Sermia), and (e) calving front of Bowdoin Glacier visited by narwhals.
Fjord, to identify the key biological and environmental acoustic sources and also explore the potential for future long-term hydroacoustic observations in glacier fjord areas.

2. Methods

2.1. Study Site

The study site is located near Qaanaaq settlement in Northwest Greenland (Figure 1). IBF spans ∼100 km, is ∼15–20 km wide, and extends to >900 m depth (Willis et al., 2018), and contains ∼20 ocean- or land-terminating glaciers. One of the tidewater glaciers, known as Kangerluarsuup Sermia in Greenlandic (Bjørk et al., 2015) or Bowdoin Glacier in foreign languages (Sugiyama et al., 2015), discharges ice and subglacial runoff into the Bowdoin Fjord, a tributary of IBF, which is 18 km long and up to 500 m deep (Kanna et al., 2018). Any of the depths in this area can be easily reached by narwhals (Blackwell et al., 2018). Bowdoin Glacier is known to have several pronounced subglacial meltwater plumes with strong silt-laden discharge (Kanna et al., 2018) and sediment-laden river runoff (seen as reddish plumes on the west side of Bowdoin Fjord; shown in Figure 1).

Early accounts of the area in the scientific literature, particularly, Bowdoin Fjord and Bowdoin Glacier, were made during expeditions by the American polar explorer Robert Peary (e.g., Baldwin, 1896; Chamberlin, 1897). His memoirs frequently mentioned the ice conditions, glaciers, kayakers, and narwhals and described an encounter with a school of narwhals (at least six tusks) near the entrance to Bowdoin Fjord at the end of the Arctic summer in 1894 (Peary, 1898). Both the main IBF and smaller Bowdoin Fjord have recently become the subjects of comprehensive studies (e.g., Kanna et al., 2018; Podolskiy et al., 2016, 2017; Sugiyama et al., 2015). An exhaustive literature search indicates that the only hydroacoustic observations to date were made in IBF by Møhl et al. (1990) and Miller et al. (1995) from boats specifically used for narwhal recordings.

2.2. Observations

Our measurements were made with two hydrophones suspended in the water from a small motorized boat (less than 1.5 tonnes). The first hydrophone, AQH-020 (AquaSound Inc., Kobe, Japan), was deployed on a rope to 6.6 m depth, which was maintained with a small weight. The setup had headphones to listen directly from the boat in real time and was mainly used as a monitor. The second hydrophone, SoundTrap STD300 (Ocean Instruments, Auckland, New Zealand), was suspended on the second rope at 11 m depth under its own weight. The technical details and sampling parameters of the instruments are given in Table 1.

Hydroacoustic data, GPS records, and visual observations were acquired across the two fjords (see map in Figure 1). Each hydroacoustic measurement was made after the engine was shut down, and all efforts were made to avoid the production of noise by the people on board. Anthropogenic noise was inevitable on several occasions because simultaneous oceanographic observations were made with a small electric winch and “messenger” deployment (i.e., a weight attached to a hydrocable and released for closing a Niskin water sampler) or transponder use. These operations were duly noted by the observer on the boat. Measurements were made during the hunting search effort. No kayaker succeeded in getting within harpooning distance of the narwhals, so no strong human-whale interactions potentially affected the data set, although this would have been an interesting response study.

The data were collected over several days in the second half of July 2019, after complete disappearance of the sea ice, although abundant icebergs and smaller pieces of ice were still present. The sea conditions indicated winds of ∼1–2 on the Beaufort scale, which reached 3 in the evening of 19 July 2019.

### Table 1

<table>
<thead>
<tr>
<th>Instrument Used in This Study</th>
<th>Setup 1 (monitor)</th>
<th>Setup 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrophone</td>
<td>AQH-020 by AquaSound Inc.</td>
<td>SoundTrap SD3000 by Ocean Instruments NZ</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>20 Hz to 20 kHz</td>
<td>20 Hz to 60 kHz</td>
</tr>
<tr>
<td>Amplifier</td>
<td>Aquafeeler III (SQE-1001B) by AquaSound Inc.</td>
<td>—</td>
</tr>
<tr>
<td>Recorder</td>
<td>PCM-M10 by Sony</td>
<td>—</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>44.1 kHz, 16 bit</td>
<td>96 kHz, 16 bit</td>
</tr>
<tr>
<td>Gain</td>
<td>50 dB</td>
<td>176.2 dB</td>
</tr>
<tr>
<td>Deployment depth</td>
<td>6.6 m</td>
<td>10.8 m</td>
</tr>
</tbody>
</table>
2.3. Signal Processing and Classification

The audio recordings were analyzed via listening and visual inspection of the corresponding filtered waveforms and spectrograms (created using a short-time fast Fourier transform [FFT]). The signals were enhanced via band-pass filtering, such that the corresponding waveforms became the most prominent, and any noise was canceled prior to characterizing the signals. The audio data from the SoundTrap instrument were converted into pascal units, and the data from the Sony/AquaSound setup were shown as relative, normalized pressures (due to unknown conversion factors in the overall system).

2.4. Vocalizations and Terminology

We first describe the terms most frequently used in the literature as a reference for our narwhal acoustic phonation classification. Specifically, three classes of signals are usually identified (Table 2): (1) clicks, (2) pure tones (whistles), and (3) pulsed tones (or tonal-pulsed signals or pulsed calls) (Blackwell et al., 2018; Ford & Fisher, 1978; Miller et al., 1995; Rasmussen et al., 2015).

The click class has two subclasses: (1a) click trains, with repetition rates of less than $<30–50$ clicks per second, and (1b) click bursts (or buzz), with higher repetition rates. Whistles (2) are continuous pure-tone signals with overtones. Pulsed tones are the most contentious signals because there is no consistent analysis in the literature, as different sampling rates and spectrogram window lengths are used, which make their classification difficult. One of the earliest studies based on encounters with a herd of 100–150 narwhals in Koluktoo Bay, Canada, described pulsed tones as highly variable: “from high pitched ‘screams’ and...”

Table 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Class</th>
<th>Subclass</th>
<th>Behavioral context</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Click series</td>
<td>Train</td>
<td>Echolocation</td>
</tr>
<tr>
<td>1b</td>
<td>—</td>
<td>Burst</td>
<td>Feeding</td>
</tr>
<tr>
<td>2</td>
<td>Whistles</td>
<td>—</td>
<td>Communication</td>
</tr>
<tr>
<td>3a</td>
<td>Pulsed tones</td>
<td>Irregular $\frac{dR}{dt}$</td>
<td>Communication</td>
</tr>
<tr>
<td>3b</td>
<td>—</td>
<td>Regular $\frac{dR}{dt}$</td>
<td>Communication</td>
</tr>
</tbody>
</table>

Table 3

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
<th>Duration (min)</th>
<th>Location, ° (N, W)</th>
<th>Sensors deployed</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 July</td>
<td>12:55:17</td>
<td>19.2</td>
<td>77.474752, −68.660610</td>
<td>S, A</td>
<td>Narwhal respiration; strong current-inclined sensor cables</td>
</tr>
<tr>
<td>19 July</td>
<td>13:19:53</td>
<td>60</td>
<td>77.488215, −68.597227</td>
<td>S, A</td>
<td>Narwhal respiration; closest encounter with a narwhal at ~25 m; second seen ~200 m away; kayak in water; strong current-inclined sensor cables</td>
</tr>
<tr>
<td>19 July</td>
<td>14:19:53</td>
<td>3.6</td>
<td>77.485103, −68.574985</td>
<td>S, A</td>
<td>Kayak in water</td>
</tr>
<tr>
<td>19 July</td>
<td>16:19:41</td>
<td>60</td>
<td>77.523033, −68.403958</td>
<td>S, A</td>
<td>Narwhal respiration; see narwhal group (3–4) ~1.1 km away; kayak in water</td>
</tr>
<tr>
<td>19 July</td>
<td>19:06:57</td>
<td>22</td>
<td>77.618543, −68.564536</td>
<td>S, A</td>
<td>Iceberg capsize at 100 m</td>
</tr>
<tr>
<td>20 July</td>
<td>00:44:47</td>
<td>60 × 8</td>
<td>77.548649, −68.550752</td>
<td>S, A</td>
<td>1 m depth; unsupervised overnight deployment (retrieved from water at 06:39:06)</td>
</tr>
<tr>
<td>20 July</td>
<td>13:02:59</td>
<td>28</td>
<td>77.527026, −68.534285</td>
<td>S, A</td>
<td>See narwhal ~100 m away, noisy piece of ice at 20 m; kayak in water; engine start at the end</td>
</tr>
<tr>
<td>20 July</td>
<td>14:01:42</td>
<td>2.3</td>
<td>77.505033, −68.553648</td>
<td>A</td>
<td>Engine start at the end</td>
</tr>
<tr>
<td>20 July</td>
<td>14:30:26</td>
<td>3</td>
<td>77.487211, −68.483834</td>
<td>S, A</td>
<td>Surrounded by icebergs</td>
</tr>
<tr>
<td>20 July</td>
<td>15:10:13</td>
<td>13</td>
<td>77.495954, −68.658084</td>
<td>S, A</td>
<td>Meet another boat, engine restart</td>
</tr>
<tr>
<td>21 July</td>
<td>22:17:04</td>
<td>3</td>
<td>77.675334, −68.636040</td>
<td>A</td>
<td>Transponder; close to ice—strong melt noise at the end</td>
</tr>
<tr>
<td>21 July</td>
<td>22:19:53</td>
<td>15</td>
<td>77.671904, −68.639090</td>
<td>A</td>
<td>Transponder; close to ice—strong melt noise at the end</td>
</tr>
<tr>
<td>22 July</td>
<td>00:12:34</td>
<td>5.4</td>
<td>77.525553, −68.442136</td>
<td>A</td>
<td></td>
</tr>
</tbody>
</table>

Note. “S” and “A” correspond to hydrophones by SoundTrap and AquaSound, respectively.
Table 4
Hydroacoustic Records Made at Bowdoin Fjord on 27–28 July 2019

<table>
<thead>
<tr>
<th>Date</th>
<th>Time (UTC)</th>
<th>Duration (min)</th>
<th>Location, ° (N, W)</th>
<th>Sensors deployed</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 July</td>
<td>13:28:58</td>
<td>30</td>
<td>77.617588, −68.597946</td>
<td>A</td>
<td>Winch</td>
</tr>
<tr>
<td>27 July</td>
<td>14:13:59</td>
<td>10</td>
<td>77.667788, −68.643976</td>
<td>A</td>
<td>Bowdoin Glacier calving front; winch</td>
</tr>
<tr>
<td>27 July</td>
<td>15:56:33</td>
<td>4.5</td>
<td>77.66487, −68.78195</td>
<td>A</td>
<td>Near Gnom Glacier river, shallow deployment at 0.5 m</td>
</tr>
<tr>
<td>27 July</td>
<td>17:03:04</td>
<td>15</td>
<td>77.672426, −68.658150</td>
<td>A</td>
<td>Bowdoin Glacier calving front; hunters spotted a young narwhal, parked near a small iceberg</td>
</tr>
<tr>
<td>27 July</td>
<td>17:22:16</td>
<td>5.7</td>
<td>77.669874, −68.657587</td>
<td>A</td>
<td>Bowdoin Glacier calving front; hunters spotted a young narwhal, moved away from a small iceberg</td>
</tr>
<tr>
<td>27 July</td>
<td>17:59:39</td>
<td>6.3</td>
<td>77.676941, −68.664817</td>
<td>A</td>
<td>A narwhal at 50–60 m; hear respirations (engine on till 18:01:35)</td>
</tr>
<tr>
<td>27 July</td>
<td>19:44:32</td>
<td>89.5</td>
<td>77.668669, −68.656365</td>
<td>A</td>
<td>CTD measurements, winch</td>
</tr>
<tr>
<td>27 July</td>
<td>21:57:07</td>
<td>67</td>
<td>77.628218, −68.637347</td>
<td>A</td>
<td>CTD measurements, winch</td>
</tr>
<tr>
<td>27 July</td>
<td>23:07:12</td>
<td>42</td>
<td>77.625571, −68.616875</td>
<td>A</td>
<td>“Messenger”, winch</td>
</tr>
<tr>
<td>28 July</td>
<td>00:02:41</td>
<td>55.3</td>
<td>77.619299, −68.595757</td>
<td>A</td>
<td>Narwhal group (3–5) seen ~1 km away to the east; “messenger”, winch; kayak in water</td>
</tr>
</tbody>
</table>

Note. “A” corresponds to a hydrophone by AquaSound.

‘screeches’ to lower ‘growls’ and ‘roars’” (Ford & Fisher, 1978). That study arbitrarily distinguished two subclasses of pulsed tones based on the pulse repetition rate \( R_r \), specifically (3a) a pulse series with an irregular variation in \( R_r \) with time and (3b) a pulse series with a regular variation in \( R_r \) with time that was often repeated at regular intervals (1.2–10 s). However, the differentiation between the buzz, which also exhibited regular variations in \( R_r \) and might appear at semiregular intervals, and the pulsed tone was not explained. Blackwell et al. (2018) recently analyzed the vocalizations of tag-bearing narwhals and classified all of the pulsed tones and whistles in a single “call” category. The authors distinguished pulsed calls from terminal click buzz with two criteria: (1) a lack of echo clicks before and after the series and (2) the calls had high amplitudes, in contrast to the decreasing amplitude and interclick interval (ICI) of a terminal click burst. However, both of these criteria are difficult to use in passive hydroacoustic experiments due to continuous changes in the source-receiver configuration.

3. Results

Approximately 9.3 hr of supervised and 8 hr of unsupervised boat-based hydroacoustic measurements were collected and analyzed. The majority of the observational sites were located in Bowdoin Fjord or nearby (Figure 1). The details of each individual observation are given in Tables 3 and 4. Narwhals were encountered 6–7 times during the survey period, as close as ~25 m to the hydroacoustic sensors. The narwhals were continuously traveling and diving. Therefore, they were only sighted several times during each recording session, depending on the observer (i.e., kayakers usually followed the same whale and therefore could confirm its visual presence for the full period of a recording). Blowhole respiration could be clearly heard on four occasions. However, we never heard any other airborne sounds, such as the “wheezing, moaning, and gurgling” described by Ford and Fisher (1978). We first describe the key manually identified biological sound sources and then present the environmental and anthropogenic signals.

3.1. Clicks and Buzz

Click sounds were the most common type of recorded signal. Similarly to previous studies, we identified two different types of clicks (Ford & Fisher, 1978; Miller et al., 1995; Rasmussen et al., 2015):

1. click trains (or echo clicks), ≤30 clicks per second;
2. click bursts (or buzz), >30 clicks per second.

Some of the literature on narwhals has designated click bursts of a similar duration (≤2 s) as either “pulsed signals” or “pulsed calls” (Ahonen et al., 2019; Marcoux et al., 2012). The way such signals look depends strongly on the window length used to construct the spectrogram. For example, it is difficult to recognize the signal as an actual typical click burst using a relatively long 0.1 s window.
Figure 2. (a) Band-pass-filtered time series (10–47 kHz) of clicks recorded at Inglefield Bredning Fjord (IBF) on 19 July 2019 (time is relative to 13:19:53 UTC). The corresponding spectrogram was generated using a 1,024-point FFT with a 0.0104 s Hamming window and 50% overlap. The high amplitudes are due to the close distance to the narwhal (<25 m).
(b) Zoomed view of a double click (marked with a triangle in panel a) (5–47 kHz; spectrogram was generated with a 0.000104 s Hamming window and 90% overlap). (c) Power spectral density (PSD) of the first (red) and the second (blue) clicks (Konno–Ohmachi spectral smoothing with a coefficient 40 was applied and is shown as thick curves). The clicks are separated by a Δt of 0.0037 s. The second click has ∼5 dB less energy than the first click and lacks a high-frequency onset (>30 kHz).

The click train rates were ∼7–10 clicks per second (Figure 2), whereas the click burst rates were as high as 330 clicks per second (Figure 3). The two most prominent features of the ultrasonic click trains were (i) a high-frequency onset (>30 kHz) of small amplitudes, followed by higher amplitudes, and (ii) double clicks (Figure 2b). Specifically, the first and most energetic broadband click with a high-frequency onset was followed by a second less energetic click ∼3.5–3.7 ms later. The second click also lacked a high-frequency onset (Figure 2c). This feature was observed for all of the clicks that were recorded at the closest distance to the narwhal (∼25 m). Furthermore, the consistent spacing between the primary and secondary clicks indicated that these click trains could not simply be attributed to vocalizations by a second animal nearby. The second hydrophone (Sony/AquaSound), which was suspended on a shorter cable, also showed double...
Figure 3. (a) Band-pass-filtered time series (1–47 kHz in black and 10–47 kHz in red) of irregular click bursts recorded in Bowdoin Fjord on 19 July 2019 (time is relative to 16:19:41 UTC). (b) Band-pass-filtered time series (1–47 kHz in black and 15–25 kHz in red) of regular click bursts recorded in IBF (time is relative to 13:19:53 UTC). Note the elevated low-frequency tone at 2.8 kHz. The corresponding spectrograms were generated using a 1,024-point FFT with a 0.00104 s Hamming window and 50% overlap.
Band-pass-filtered time series (18–30 kHz) of a click burst with a semiregular interclick interval (ICI) of 3.8 ms and a basal tone at 2.7 kHz recorded in IBF on 19 July 2019 (time is relative to 13:19:53 UTC). The corresponding spectrogram was generated using a band-pass-filtered (1–47 kHz) time series (1,024-point FFT with a 0.0052 s Hamming window and 90% overlap).

For the same sequence, but with a shorter time separation between the clicks (~2.3–2.5 ms). The clicks comprising the bursts did not have this double-click feature.

The amplitude of the clicks in the click train events increased toward the end of a sequence (Figure 2a), whereas the amplitude of the burst events increased in the beginning and then decreased at the end of the burst. The buzz spectra had a base tone centered at ~2.75 kHz in all of the shown cases, which lasted for the full buzz duration or longer (Figures 3 and 4).

The ICI decreased in a step-like manner from ~210 to 95 ms in several of the observed click train events (Figure 5a). The click bursts had an irregular (gradually increasing or decreasing intervals between clicks) or quasiregular spacing (Figures 5b–5d). For example, Figure 5b shows an ICI decreasing from ~40 to 4.6 ms, whereas Figures 5c and 5d show nearly constant click rates that are spaced at 2.6–3.8 ms.

### 3.2. Whistles

Here, we refer to “whistles” as pure-tone signals. Examples of frequency-modulated whistles are provided in Figure 6. Figure 6a shows the clearest record, with 0.75-s-long down-sweeping harmonics. Approximately half of its duration has flat, regularly spaced overtones (repeated every 4.5 ± 0.1 kHz between 4.5 and 31.6 kHz). Figure 6b shows a similar whistle but with a lower signal-to-noise ratio. Both events overlap click trains. Another type of down-sweeping whistle, which is repeated every 0.66 ± 0.11 kHz between 10 and 20 kHz, is shown in Figure 6c. The whistle duration ranged between 0.4 and 0.75 s.

### 3.3. Train of Reverberating Clicks

A special type of a click train with a 7 s duration is shown in Figure 7. It was possible to audibly distinguish this click train, which was reminiscent of a hybrid between a click train and whistle. Specifically, the energy was contained between 12 and 21 kHz, and the train was composed of reverberating amplitude-modulated clicks. The amplitude of the equally spaced clicks (Δt = 0.185 s) gradually increased and then decreased over ~7 s. Each click in this sequence had a resonating spectrum, with 6–9 spectral peaks spaced every 0.56 ± 0.08 kHz (Figure 7b). Furthermore, every subsequent click exhibited a downshift in its spectrum relative to the previous click. This resulted in down-sweeping harmonic lines, which could be manually traced on the spectrogram.
Figure 5. Automatically detected peaks with the corresponding ICIs for different click sequences. (a) Three consecutive click trains with a decreasing ICI from \(\sim 210\) to \(\sim 95\) ms (band-pass-filtered signal, 10–47 kHz, from Figure 2a). (b) Decreasing ICI from 40 to 4.6 ms, with a jump-like return to higher interval of 11 ms (band-pass-filtered signal, 10–47 kHz, from Figure 3a). (c) Semiconstant ICI of 2.6–3.7 ms (band-pass-filtered signal, 15–25 kHz, from Figure 3b). (d) Semiconstant ICI of 3.8 ms (band-pass-filtered signal, 18–30 kHz, from Figure 4). Note that the y axis limits are 10 times wider for the echo clicks (a) than for the burst clicks (b–d).

3.4. Iceberg Tremors

Iceberg “booms,” cannon shot-like sounds, and rumblings were the strongest low-frequency transient sources (below \(\sim 5\) kHz) in the underwater soundscape at IBF (Figure 8a). Such events were first heard underwater as a thunder-like sound and were then followed a few seconds later by an air phase that was attributed to the more than fourfold difference in sound speeds. Only the underwater phase was recognizable in some instances because the sound was more effectively propagated in water.

3.5. Ice Melt and Cracking Noises

One of the most obvious sources of audible noise was produced by iceberg melt, which was attributed to the bursting of pressurized air bubbles within the ice and the associated cracking (Urick, 1971). This noise source was clearly audible at distances of up to several meters from some icebergs (see supporting information Video S1). Elevated noise levels were noted by observers each time when measurements were made close to floating ice chunks (Figure 8b), icebergs, or, most notably, within a few hundred meters of the calving front of Bowdoin Glacier.

To identify how noise changes in close proximity to the glacier front, Figure 9 shows the median amplitude of noise in the 20–5000 Hz frequency range (Merchant et al., 2015) at a particular point versus distance to the calving front of Bowdoin Glacier. The absolute sound pressure level (SPL) measurements via SoundTrap were not made close enough to the calving front and therefore appeared to be flat. However, the relative levels of the pressure amplitude measurements with the Sony/AquaSound setup suggested elevated acoustic noise near the glacier (0.6–1.5 km away). The corresponding variation in the frequency spectrum with
distance is shown in Figure 10, which demonstrates that there are spectral peaks between 1 and 4 kHz at six locations near the calving front of Bowdoin Glacier.

### 3.6. Anthropogenic Noise

Several types of anthropogenic noise sources were recorded: those produced by the boat engine, transponder, or concurrent oceanographic operations, such as the “messenger” deployment for deep-water sampling (Figure 11).

A spectrogram of engine ignition (Figure 11a) shows a somewhat similar frequency content to that of iceberg rumbling (Figure 8a). However, it contains distinct low- and high-frequency harmonics and does not show the exponential-like decay of the signal’s tail.

A monochromatic 9 kHz ping (0.25 s long) emitted by a transponder to establish an acoustic link with an ocean bottom seismometer (OBS) is shown in Figure 11b. The resonance and response from the OBS are also seen at 18 and 8 kHz, respectively.

The “messenger” was deployed at the surface and produced a specific whistle-like sound as it dove due to the Doppler effect, starting at ∼5 kHz, with a down-sweeping harmonic series to a flat 2.1 kHz signal until a broadband impulsive impact 8 s later at a certain depth, which triggered the closure of the water sampler (Figure 11c).

Finally, there were some strong low-frequency artificial-like sounds that we could not interpret but were observed a couple of times (e.g., Figure 11d). These signals had monochromatic waveforms with a dominant frequency at 0.5 kHz and echoes for ∼2 s after the first arrival of the signal.

### 4. Discussion

#### 4.1. Narwhals Encounters

We collected ∼17.3 hr of hydroacoustic records and were in acoustic contact with narwhals for at least 13% of this period, which was slightly better than the 8% experience of Miller et al. (1995) in August 1990.
However, we could not identify any acoustic vocalizations from a young narwhal near the calving front, despite our close proximity, which could be attributed to either a poor signal-to-noise ratio or the silence of the apparently stressed animal. Local hunters noted that the young narwhal was alone and that its mother had probably been killed. Recent studies have suggested that stressed narwhals display reduced vocalizations (Blackwell et al., 2018).

Aerial surveys of narwhals in August 2001, 2002, and 2007 have identified that the northern side of Inglefield Bredning Fjord and Bowdoin Fjord have the lowest densities of narwhals (Heide-Jørgensen, 2004; Heide-Jørgensen et al., 2010). Specifically, no groups were identified in the study area in 2001, two groups
Figure 8. (a) Band-pass-filtered time series (20–5,000 Hz) of an iceberg rumbling recorded at IBF on 19 July 2019 (time is relative to 13:19:53 UTC). The corresponding spectrogram was generated using a 1,024-point FFT with a 0.0104 s Hamming window and 50% overlap. Note that the energy leaking from the high-frequency clicks is also visible. (b) Band-pass-filtered time series (1–47 kHz) of an iceberg melt noise recorded (right next to a piece of ice) at Kangerluarsuk, Bowdoin Fjord, on 20 July 2019 (time is relative to 01:44:47 UTC). The corresponding spectrogram was generated using a 1,024-point FFT with a 0.0104 s Hamming window and 50% overlap. Note that the same frequency band shown in Figure 3 is an order of magnitude less noisy.
(6 ± 2 narwhals in total) were identified in 2002, and one group (2 ± 1 narwhals) was identified in 2007, whereas tens of groups of a larger size were sighted on the opposite side of IB Fjord each time. No groups were closer than 10 km from Bowdoin Glacier. However, we encountered narwhals at the entrance of Bowdoin Fjord and within a kilometer of the calving front in this study (end of July) (Figure 1). Furthermore, at least two narwhals were caught and butchered near the Bowdoin Glacier (within 3 km of the calving front) and in front of Kangerlussuk on the days of our survey (on 19 and 20 July 2019) (Figure 1), which has been an important hunting site for at least 60 years (Hastrup, 2019) or even 135 years (Peary, 1898). Nevertheless, our own narwhal sighting (12–15 narwhals), combined with catch numbers (two narwhals), suggests that there is no evidence of high densities of narwhals in this area. At this stage, it remains unclear whether narwhals are more abundant than previously thought on the northern side of Inglefield Bredning and Bowdoin fjords. Moreover, even if narwhal sightings are rare in areas very close to an unstable calving front, our observations fall short of informing us about their habitat selection. A comprehensive study in Melville Bay, West Greenland, by Laidre et al. (2016), analyzed the movements of 15 narwhals relative to 41 ocean-terminating glaciers. They suggested that it was “unknown at what distances glacier fjords attract narwhals,” although they observed at least three narwhal locations almost 1 km from the glaciers and concluded that regions within ∼7 km of calving fronts were attractive to narwhals. Blackwell et al. (2018) recently documented the passage of one narwhal within 1 km of a calving front of the Sydbræ Glacier (based on continuous bio-logging of six narwhals for 4–7 days in the Scoresby Sound fjord system, East Greenland). To clarify this issue, further significant surveys on larger spatial and temporal scales are required.

4.2. Biogenic Sources

4.2.1. Species

Inuit people from the Qaanaaq and Qeqertat settlements hunt narwhals, belugas (their nearest relatives, also known as white whales; *Delphinapterus leucas*), and pinnipeds (harp, ringed, and bearded seals; *Pagophilus groenlandicus*, *Pusa hispida*, and *Ergignathus barbatus*, respectively) in the IBF area. All of these species produce characteristic acoustic vocalizations (e.g., Frouin-Mouy et al., 2017). For example, bearded seal calls (∼300–1500 Hz and up to 8 kHz) are common, particularly during their reproductive period in spring and early summer, and can be classified by their frequency (e.g., De Vreese et al., 2018; Frouin-Mouy et al., 2017).
Beluga and narwhal vocalizations (largely clicks and click bursts) share very similar frequency bands (between 2 and 150 kHz). It was recently shown that these two monodontid species can be distinguished by a difference in power centered around 20 kHz (Frouin-Mouy et al., 2017). However, this frequency overlap is of minor concern here because no belugas were sighted or caught during our observation period, and the locals indicated that these whales usually appeared later in autumn, around September–October. We therefore suggest that all of the biological sounds reported in this paper were produced by narwhals.

**4.2.2. Clicks**

The high-amplitude clicks recorded at the closest distance to a narwhal (Figure 2) provide an important constraint on the source level and are very similar in magnitude to the clicking recorded by narwhal-borne sensors (Blackwell et al., 2018). However, it remains unclear if these recordings are off-axis or not (relative to the on-axis direction corresponding to the maximal intensity of the beam). Koblitz et al. (2016) recently showed that narwhals have a highly directional sonar beam, probably the most directional among odontocetes. A previous study in IBF by Möhl et al. (1990) reported a source level of 209–227 dB peak-to-peak relative to 1 μPa (pp re 1 μPa) at a distance of 1 m, which is close to the more recent observations of 215 ± 6 dB pp re 1 μPa made by Koblitz et al. (2016) and approaches the level of a seismic air-gun blast (Kyhönen et al., 2019; Jones, 2019). Such high source levels prompt the question of whether narwhals are able to stun their prey (Möhl et al., 1990; Miller et al., 1995), but this remains unknown. We obtained 161.6 dB for the received level [RL] (Figure 12), using 

$$RL = 20 \log_{10}(Pp/1 \mu Pa),$$

where Pp is the peak-to-peak amplitude of the clicks (μPa) (Koblitz et al., 2016; Möhl et al., 1990). This suggests that our records are probably off-axis, especially
Figure 11. (a) Band-pass-filtered time series (20–10,000 Hz) of engine ignition in a boat parked near the observer’s boat in IBF on 20 July 2019 (time is relative to 14:30:26 UTC). The corresponding spectrogram was generated using a 1,024-point FFT with a 0.0052 s Hamming window and 50% overlap. (b) Transponder 9 kHz ping and OBS transceiver response (5–22,000 Hz; 0.1 s window with 90% overlap was used for the corresponding spectrogram), recorded on 21 July 2019 (time is relative to 22:19:53 UTC). (c) “Messenger” descent, starting at 1,218 s and ending with an impulsive impact at 1,226 s (1–8 kHz; 0.0227 s window with 90% overlap was used for the corresponding spectrogram), recorded on 28 July 2019 (time is relative to 00:02:41 UTC). (d) Unknown artificial-like sound with a monochromatic frequency (∼0.5 kHz) and echoes lasting up to 2 s, recorded on 19 July 2019 (time is relative to 16:19:41 UTC) (band-pass filtered at 0.2–5 kHz; 0.0052 s window with 90% overlap was used to produce a spectrogram using a 4,096-point FFT).

since we know that one narwhal was very close to the boat. For example, if we reduce the source pressure level by 23 dB relative to an on-axis click (Koblitz et al., 2016), and assume a spherical transmission loss with a distance of $20 \times \log_{10}(R)$ and a seawater absorption coefficient of 0.03 dB/m (Kyhn et al., 2019; Koblitz et al., 2016), the sonar equation has the following form:

$$ L = 215 \pm 6 - 23 - 20 \times \log_{10}(R) - 0.03 \times R, $$

where $L$ is the observed SPL, which corresponds to the reasonable distance, $R$, ranging between 16 and 60 m (Figure 12).

Miller et al. (1995) recognized two types of echolocation clicks from narwhals in IBF: high-frequency clicks (25–100 kHz, with maxima at 48 kHz) with low repetition rates (4–10 clicks per second) and short click durations (∼32.5 μs), corresponding to bat searching pulses, and medium-frequency click bursts (20–60 kHz, with maxima at 36 kHz) with high repetition rates (110–400 clicks per second) and longer click durations (∼45 μs), corresponding to the bat’s buzz just before it captures its prey. Miller et al. (1995) pointed out that the buzzes appeared to be stronger at the deeper sensors (100 vs. 10–30 m). Recent narwhal tagging in East Greenland confirmed that terminal buzzes are common at the end of prolonged click trains at 350–650 m depths (Blackwell et al., 2018).

However, the behavioral context of click bursts remains unclear. There is also contradictory evidence on the summer foraging of narwhals. Some studies have suggested that narwhals do not feed in the fjords during the summer (see references in Marcoux et al., 2012), whereas Miller et al. (1995) reported that the stomachs of killed narwhals contained cod and crustaceans remains during their August campaign at IBF. Furthermore,
there is a lack of clarity in signal classification. As we mentioned above, some studies apparently reported click bursts as “pulsed calls” and interpreted them as one of the two main types of communicative sounds (Ahonen et al., 2019; Marcoux et al., 2012).

If the click bursts were emitted to detect prey, as observed in belugas and killer whales, the click intervals could be used to estimate the distance to the target as (Miller et al., 1995):

\[ R \leq \frac{\Delta t v}{4}, \]

where \( R \) is the distance, \( \Delta t \) is the click interval, and \( v \) is the speed of sound in seawater (1,500 m/s). The observed 3 ms interval (330 clicks per second; Figures 3a and 5b) yields a distance of <1.1 m. The ICIs in the burst sequences observed in this study agree well with those previously reported (Miller et al., 1995; Rasmussen et al., 2015). This strongly suggests that the waveforms previously labeled as communicative “pulsed calls” (e.g., see Figure 2 in Marcoux et al., 2012, which is nearly identical to our Figure 3a) are in fact terminal buzzes used for echolocation. We also observed that the ICI decreased for both the terminal buzz and echolocation clicks, with intervals that were approximately an order of magnitude longer (Figure 5a). If we apply the same equation (1), with \( \Delta t = 95 \) ms, it yields a distance of \(~36\) m, which is roughly consistent with the distance to the narwhal during our closest encounter with the animal in that time segment. This is consistent with the hypothesis that these clicks function in echolocation.

It is also important to examine the double clicks in more detail to clarify whether this feature is attributed to the source or path (Figure 2). We manually extracted the time delays, \( \Delta t \), between the same six primary and secondary clicks recorded by each sensor during the sequences with the highest amplitudes (1,285–1,290 s relative to 19 July 2019, 13:19:53 UTC), using the same 10–22 kHz frequency band for consistency. This yielded \( \Delta t_s = 2.36 \pm 0.02 \) ms and \( \Delta t_d = 3.5 \pm 0.02 \) ms for the shallow and deep sensors, respectively (Figure 13a). Interestingly, the ratio between the two values, 1.48, is relatively close to the ratio between the cable lengths of the two sensors (1.64), suggesting that the secondary clicks may represent reflections. For example, an echo reflecting off the submerged parts of the boat, the water surface, or a second animal (least likely because we did not notice any) may arrive later than the first signal, which is traveling in a direct path. This implies that the time delay may represent the difference between the direct propagation path and the reflection path. \( \Delta t \times 1,500 \) m/s yields 5.3 and 3.5 m for the deep and shallow sensors, respectively, and agrees with the setup dimensions to within a factor of approximately two (Figure 13b), suggesting that the double-click feature is unlikely to represent the source. On the other hand, if secondary clicks are caused by reflection from the sea surface, one should expect to find phase-reversed signals. However, we find no
Figure 13. (a, b) Box-and-whisker plots of time delays between double clicks at each sensor with the associated length scale ($dL = v \times \Delta t$, where $v$ is the speed of sound in seawater and $\Delta t$ is in seconds). (c, d) Synchronized primary and secondary clicks (by removing a lag identified through an autocorrelation of the SoundTrap signal shown in Figure 2b).

Evidence for that and observe that the positive correlation ($\sim +0.44$) between the primary and secondary arrivals is larger in amplitude than the negative correlation ($\sim -0.26$) (Figures 13c and 13d).

Here, we note that high frequency of clicks may be missing from our data due to undersampling (the highest Nyquist frequency of our instrumentation was 48 kHz). According to Miller et al. (1995), the click trains spectra have upper corner frequencies at $\sim 100$ kHz, whereas those of bursts extend up to 60 kHz. Rasmussen et al. (2015) recently presented the entire bandwidth of narwhal echolocation clicks, which can extend up to 200 kHz. Undersampling could lead to an underestimation of the absolute amplitudes of the clicks (Koblitz et al., 2016). This could also imply that we may not be able to resolve the possible phase reversal correctly. Against this background, let us stress that in any case care should be taken when interpreting data from equipment deployed at very shallow depths and close to the sources.

4.2.3. Whistles

Whistles were generally rare events, in agreement with the observations by Ford and Fisher (1978), Miller et al. (1995), and Blackwell et al. (2018). For example, Miller et al. (1995) observed fewer that two whistles per hour of acoustic contact with narwhals, which is very similar to the 2.5 whistles per hour we identified. Interestingly, Rasmussen et al. (2015) recorded no whistles from sea ice in narwhal wintering grounds offshore of the Uummannaq region in West Greenland.
Short whistles that were similar to the one shown in Figure 6 were previously recorded (e.g., Ford & Fisher, 1978; Marcoux et al., 2012) and interpreted as communicative vocalizations. Blackwell et al. (2018) recently confirmed that tagged narwhals produced the majority of “calls” (a category including whistles), in the upper 50 m, where they spent most of their time, and therefore had more opportunities to socialize.

Miller et al. (1995) noted that two frequency-modulated whistles with durations exceeding 0.3 s followed the launch of the hunter’s kayak in IBF. Although multiple kayak launch events occurred during our survey, we could not confirm this anecdotal evidence. It therefore remains unclear whether narwhals can communicate danger or are able to recognize such events in the first place.

4.2.4. Train of Reverberating Clicks

The 7 s whistle-like click train appears to be an unusual type (Figure 7). Ford and Fisher (1978) described the so-called pulsed tones, in addition to whistles (e.g., pure tones), click series, and other pulsed emissions with irregular ICIs. Pulsed tones mainly differ from the latter due to their highly regular changes in repetition rates (Table 2). However, these pulsed tones differ from the reverberating click train presented in Figure 7 in its (i) long duration, (ii) low repetition rate, and (iii) lack of any change in the repetition rate.

Finally, we note here that the only signal that somewhat fits the “pulsed tone” class described by Ford and Fisher (1978) was the previously shown narrowband (10–20 kHz) whistle with tightly spaced overtones and a descending pitch (Figure 6c). However, it is difficult to say if it was continuous or composed of discrete pulses due to its poor signal-to-noise ratio.

4.3. Environmental Sources

Many transient and continuous phenomena are known to fill the polar oceans with a cacophony of sounds (Risch & Parks, 2017). For example, iceberg-related sounds constitute a significant, ocean-scale source of noise (Matsumoto et al., 2014). Locally, icebergs and glacier ice are also known to create the oceans’ noisiest soundscapes due to the continuous burst of air bubbles (pressurized up to 3 MPa) from the melting ice (Pettit et al., 2015). Glacier calving is also a strong source of hydroacoustic emissions, which have recently been used as a proxy for calving flux (Glowacki & Deane, 2019; Köhler et al., 2019). Sea ice is another major contributor to the high noise levels in the ocean, arising from thermal fracture, mechanical deformation, and the relative motion of ice floes (e.g., Milne et al., 1967).

Iceberg-related sounds and ice melt were the dominant types of noise in this study. Higher noise levels were usually observed closer to the ice volumes, particularly the calving front of Bowdoin Glacier (Figure 9). The spectral peak between 1 and 4 kHz close to the calving front (Figure 10) is similar to those previously reported in glacierized fjords (Pettit et al., 2015). However, simultaneous measurements of the absolute noise levels at different distances from Bowdoin Glacier should be made to clarify this dependence since our observations were asynchronous. Furthermore, the significance of the lateral variation in noise levels along the calving front remains unclear.

Ice melt noise is similar to the well-known shrimp-generated noise in tropical waters to a degree because it also masks other signals (e.g., Watanabe et al., 2002). Other whale and dolphin species are known to change their calls and whistles when exposed to elevated noise (Jones, 2019; Leroy et al., 2018), and it is suggested that narwhals respond to stressors, such as icebreaker noise, killer whales, or tagging, by ceasing their acoustic emissions (e.g., Blackwell et al., 2018). How narwhals adapt to the noisier soundscapes near a glacier calving front requires further study. However, we note here that narwhals approached the calving front of Bowdoin Glacier during our survey (e.g., several hundred meters on 27 July 2019).

5. Conclusions

Here, we present close-up hydroacoustic recordings of the narwhal vocal repertoire and environmental sounds in a glacier fjord. Together with a general description of a glacier fjord soundscape, which was noisier closer to the calving front, this study provides the following new findings:

1. Narwhals approach to the Bowdoin Glacier calving front, despite the fact that such fronts are known as some of the noisiest places in the ocean (Pettit et al., 2015).
2. Narwhal echolocation click trains, reaching pressures of 60 Pa, are composed of clicks with a previously unreported high-frequency onset (≥30 kHz).
3. The ICI decrease occurs in both the click bursts and click trains without any terminal buzz (ICI ≥ 50 ms).
4. Narwhals produce previously unreported reverberating click trains within a narrow frequency band (12–21 kHz).
5. So-called pulsed calls and click bursts can be easily confused as the same type of vocalization, leading to different interpretations in the literature. Therefore, either a better understanding of their behavioral context or more robust classification criteria are required to interpret these signals.
6. The previously unreported double-click feature of the high-amplitude click trains observed during the closest encounters with narwhals is unlikely to represent the source and is most likely related to a reflection. This should be verified in future studies.

This study provides valuable baseline information for acoustic monitoring in remote areas around Greenland. Collecting such information in the absence of anthropogenic sounds has been the objective of several recent studies (Blackwell et al., 2018; Koblitiz et al., 2016). Possible increases in shipping, exploration, and industrial activities, such as titanium-rich sand mining in the region (by Dundas Titanium A/S), highlight the growing need for additional comprehensive long-term monitoring studies.

The present study, the rapid development of hydroacoustic methods (e.g., real-time acoustic location with open-source software, such as PAMGUARD) and the future extension of such work in the region raise some fundamental ethical questions. Inuit hunters usually detect the presence of narwhals either visually or by listening for their respiration when resurfacing. The hunters asked the hydrophone observers if they could hear narwhals underwater after arriving at each new spot. Such a simple piece of information can accelerate the hunting effort and the decision to wait or continue to another spot. Therefore, the extent to which hydroacoustic technology should be allowed to enhance hunting practices must be carefully considered.

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