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Volume 125, Issue 5 e2020JCO16116 Narwhal acoustic phonation is embedded in the icy cacophony of one of the noisiest soundscapes in the ocean. The high susceptibility of the narwhal to climate change highlights the need for further efforts to document baseline descriptions of the sounds it produces, especially given the potential anthropogenic impacts on their habitats. However, observations are rare, and narwhal acoustic behavior and habitats are poorly understood (attributed to both the skittish nature of hard-to-approach narwhals and the difficult access to remote and often dangerous glacier fjords). Here, we provide acoustic measurements in a narwhal summering ground in glacial fjords in Northwest Greenland that were mainly collected during Inuit hunting expeditions. This unique observational strategy near a key narwhal hot spot allowed the acquisition of supervised near-source recordings of narwhal vocalizations, which confirms the animal's presence within several hundred meters of an actively calving Bowdoin Glacier. We accurately describe the acoustic signals and noise related to the cetacean, environmental, and anthropogenic sources, show previously unreported signals and their properties, report elevated background noise levels near the calving front, and discuss the general soundscape features of a glacier fjord. The baseline information presented here should encourage long-term follow-up acoustic monitoring in the area and provides an important reference for comparisons with future conditions and other regions. We also anticipate that our work will be a starting point both for the development of criteria to distinguish pulsed calls from terminal buzzes and for a thorough discussion of the dual use of passive acoustic monitoring in traditional hunting practices. The narwhal (Monodon monoceros) is a relatively small whale, measuring 4–5 m long and weighing 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 Ingfield Breeding 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 of 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; Mikhalevsky 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; Møhl 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 1” observatory at N79.05° W12.53°). 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 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. The study site is located near Qaanaaq settlement in Northwest Greenland (Figure 1). IBF spans ~100 km, is ~15–20 km wide, extends to >900 m depth (Willis et al., 2018), and contains ~20 ocean- or land-terminating glaciers. One of the tidewater glaciers, known as Kangerluarsup 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). (a) Map of Ingfield Breeding 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 (Kangerluarsup Sermia), and (e) calving front of Bowdoin Glacier visited by narwhals. 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. 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. Table 1. Descriptions of the Instrumentation Used in This Study Setup 1 (monitor) Setup 2 Hydrophone AQH-020 by AquaSound Inc. SoundTrap SD3000 by Ocean Instruments NZ Bandwidth 20 Hz to 20 kHz 20 Hz to 60 kHz Amplifier Aquafeeler III (SQE-1001B) by AquaSound Inc. — Recorder PCM-M10 by Sony — Sampling rate 44.1 kHz, 16 bit 96 kHz, 16 bit Gain 50 dB 176.2 dB Deployment depth 6.6 m 10.8 m 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. 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). 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). Table 2. Main Classes of Narwhal Vocalizations and Their Behavioral Context (Rr is the Click Repetition Rate) No. Class Subclass Behavioral context 1a Click series Train Echolocation 1b — Burst Feeding 2 Whistles — Communication 3a Pulsed tones Irregular Communication 3b — Regular Communication The click class has two subclasses: (1a) click trains, with repetition rates of less than

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