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FEATURE ARTICLE

Spitsbergen's endangered bowhead whales sing through the polar night

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ABSTRACT: Bowhead whales *Balaena mysticetus* are long-lived cetaceans, uniquely adapted among the baleen whales to live year-round in the Arctic. All bowhead whale populations were greatly reduced by commercial whaling from the 1600s through the 1800s, with the largest, the Spitsbergen population in the North Atlantic, depleted to the point of extinction. Recent sightings of bowhead whales west of Svalbard precipitated an effort to listen for their vocalizations via 2 recorders deployed in 2008 on oceanographic moorings spaced 95 km apart at 78.8° N latitude in the Fram Strait. Year-round acoustic records were examined for the occurrence of bowhead whale sounds. Simple calls, call sequences, and complex songs were recorded. Repeated call sequences or bowhead whale songs were detected nearly every hour from early November 2008 through late April 2009 on the western Fram Strait recorder. More than 60 unique songs were recorded from October 2008 to April 2009. In contrast, simple calls and call sequences were the most common signals recorded on the central Fram Strait instrument. Peak levels of song production coincided with the period of lowest water temperature, dense ice concentration, and almost complete darkness. Given the diversity, loudness, and period over which songs were recorded, western Fram Strait appears to be a wintering ground — and potentially a mating area — for this Critically Endangered population of bowhead whales.

KEY WORDS: Bowhead whale · *Balaena mysticetus* · Fram Strait · Song · Acoustic sampling · Sea ice

Bowhead whale at the ice edge in the Fram Strait April 2010
Photo: Øystein Wiig

INTRODUCTION

Bowhead whales *Balaena mysticetus* are long-lived cetaceans, and the only baleen whales adapted to live year-round in the Arctic. Currently, 4 populations are recognized based on their geographic distribution (Heide-Jørgensen et al. 2010). Two of these, the Bering-Chukchi-Beaufort (BCB), and the Eastern Canada-West Greenland (EC-WG) populations appear to be increasing after being greatly reduced by commercial whaling in the 1600s to 1800s (George et al. 2004, Heide-Jørgensen et al. 2007). The Spitsbergen population, initially the largest, numbering somewhere in the range of 25 000 to 100 000 whales

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(Allen & Keay 2006), was depleted to the point of extinction by the early 1800s and has shown little evidence of recovery (Woodby & Botkin 1993), warranting its current IUCN status designation of Critically Endangered (Reilly et al. 2008; www.iucnredlist.org/apps/redlist/details/2472/0).

Bowhead whales have an extensive and varied acoustic repertoire that includes simple calls, call sequences, and complex songs (Ljungblad et al. 1982, Würsig & Clark 1993). Simple calls are frequency- (FM) or amplitude-modulated (AM), have most acoustic energy under 500 Hz, and show no pattern in their occurrence (Fig. 1a). Call sequences are composed of repeated simple FM calls that often occur in bouts of 3 to 25 similar calls (Ljungblad et al. 1982, Würsig & Clark 1993, Stafford et al. 2008, Delarue et al. 2009). These call sequences are sometimes repeated, and there are similarities in this calling pattern among different populations of bowhead whales (Fig. 1b). These call sequences have sometimes been called 'simple song' (Delarue et al. 2009, Stafford et al. 2008), but these patterns likely serve a different behavioral purpose than complex song and hereafter are referred to as call sequences following Würsig & Clark (1993).

Songs, in contrast, consist of a complex acoustic display of structured, stereotyped combinations of loud, raucous, complex FM and AM calls, referred to as notes, with little or no pause between them (Fig. 1c). Song notes are much broader-band than simple calls, with energy up to at least 5 kHz and are combined into phrases (Cummings & Holliday 1987). Further, bowhead whales appear to sing with 'two voices,' simultaneously producing high- and low-frequency and FM

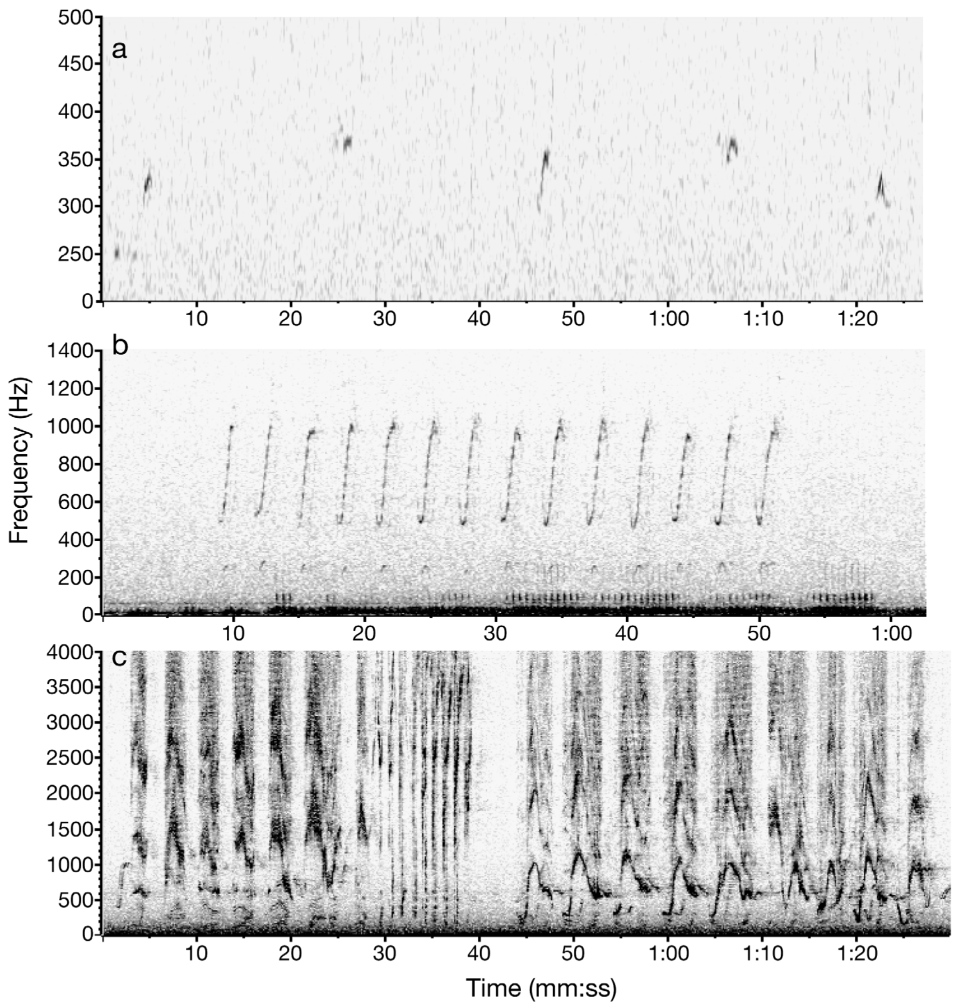


Fig. 1. *Balaena mysticetus*. Examples of bowhead whale sound categories: (a) simple calls; (b) call sequence; (c) song (2048 point Fast Fourier Transform [FFT], 50% overlap, Hann window). Song is loud and much more complex and consists of very closely spaced notes, while a call sequence displays a simple series of regularly spaced, repeated simple calls (FFT 1024, 50% overlap, Hann window for all)

and AM sounds at the same time (Würsig & Clark 1993, Tervo et al. 2011). Songs are often repeated for hours at a time and vary by and within populations and years (Cummings & Holliday 1987, Würsig & Clark 1993, Stafford et al. 2008, Delarue et al. 2009).

The Spitsbergen bowhead whale population was at one time found from northeast Greenland well into the western Russian Arctic. After initially killing all of the coastal whales, whaling operations became more pelagic and were centered in the central Fram Strait between 76° and 80° N during the 17th and 18th centuries (Woodby & Botkin 1993). It is in this area that most of the recent sightings of bowhead whales have been reported (Wiig et al. 2007, 2010), and the purpose of the present study was to use year-round passive acoustic sampling in an attempt to assess the distribution and seasonal occurrence of bowhead whales in this region.

MATERIALS AND METHODS

Two passive acoustic recorders (Multi-Électronique Aural M2; hydrophone sensitivity of –164 dB re 1 V/µPa and flat response from 5 to 30 kHz) were placed on oceanographic moorings deployed 95 km apart in Fram Strait (Fig. 2) to sample this remote area for marine mammal calls (Moore et al. 2012). The westernmost instrument was located near the east Greenland Shelf break (at 78° 49.9′ N, 4° 59.1′ W at 82 m depth in water 1021 m deep; deployed 9 September 2008), while the central-strait instrument (at 78° 50.2′ N, 0° 46.9′ W at 58 m depth in water 2611 m deep; deployed 21 July 2008) was located on a mooring on an east–west transect maintained by the Norwegian Polar Institute, directly south of a cluster of recent shipboard-based sightings of bowhead whales made from 17 to 28 April 2006 (Wiig et al. 2007). Both instruments recorded from 10 to 4096 Hz (sample rate 8192 Hz) on an hourly 30% duty cycle (9 min on, 21 min off) from September 2008 to September 2009 (western mooring) and July 2008 to July 2009 (central mooring). This duty cycle was chosen so that batteries powering the instruments would last throughout the year-long deployment. Combined, the deployment dates and duty cycling resulted in 2 records per hour being recorded simultaneously on both instruments beginning on the hour and half hour from 20 September 2008 to 14 July 2009. The total number of concurrent files for each instrument during this period of overlap was 14 298, or 2144.7 h of simultaneous recordings at each location.

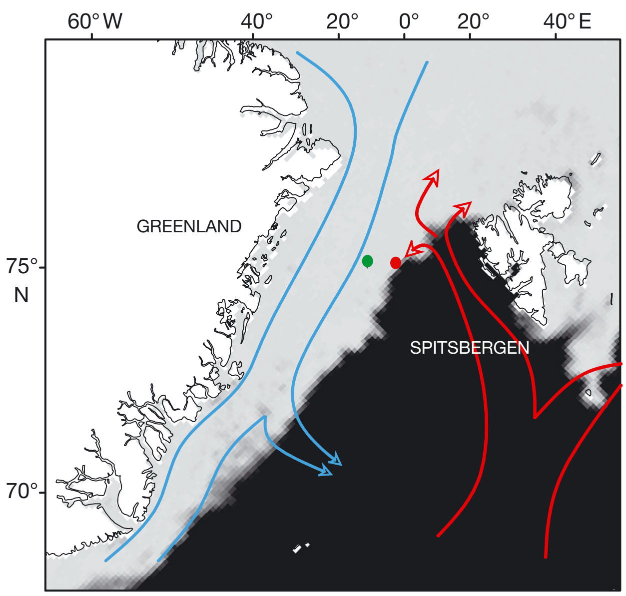
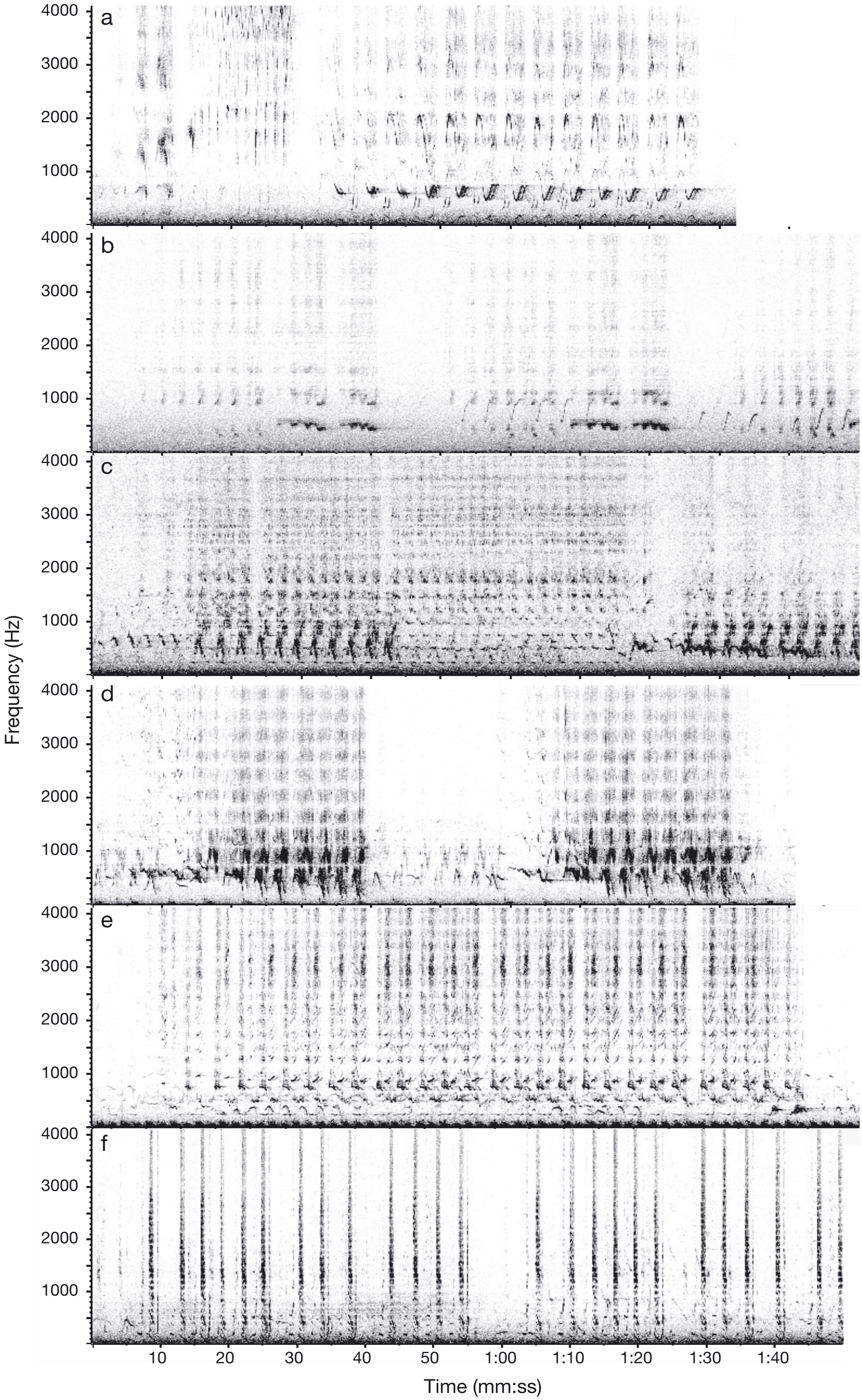


Fig. 2. Fram Strait mooring locations (green = western, red = central) with a sea ice image (black: no ice cover) from 18 January 2009 showing southward cold, East Greenland Current (blue) and northward, warm, recirculating West Spitsbergen Current (red) (adapted from Rudels et al. 2005)

Each 9 min data file was displayed as a spectrogram (2048 point Fast Fourier Transform, 75% overlap, Hann window) to determine whether bowhead whale sounds were recorded. It was during this process of noting the presence of any type of bowhead whale sounds in the data that a large variety of songs were detected. For the seasonality analyses, therefore, individual calls and call sequences were combined into 1 category, and all songs were combined into a second category. If songs were recorded in a given hour, individual calls and call sequences in that same hour were not noted separately.

Songs were assessed by visually examining spectrograms of each acoustic data file, augmented by listening to files. Songs were considered distinct from each other based on the arrangement of discrete notes and phrases and the duration of each song (Fig. 3). If the number of notes within a phrase differed between songs, but the arrangement of units and phrases remained the same, the songs were not classified as being distinct. Distinct songs were designated by numbers and the month in which they were recorded. To ascertain whether the same calls were recorded on both instruments within the same period, a random selection of 10% of all hours in which bowhead sounds were detected on both instruments were examined (102 of 1018 h) to compare call types recorded. Because the instruments were only 95 km apart, the maximum time delay between them was roughly 65 s, so most of the sig-


a
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Time (mm:ss)

Fig. 3. *Balaena mysticetus.* Examples of distinct songs recorded on the western mooring. (a) Song 9 from November 2008; (b) 2 iterations of song 15 from December 2008; (c) single song 34 from January 2009; (d) 2 iterations of song 38 from February 2009; (e) single song 60 from March 2009; (f) 2 iterations of song 64 from April 2009 (spectrogram parameters as for Fig. 1)

nals produced near one of the hydrophones would have been recorded during the same 9 min data file on the other hydrophone, making the inter-site comparison robust.

Daily sea ice concentration data with 12.5 km resolution were downloaded from ftp://n4ftl01u.ecs.nasa.gov/SAN/AMSA/AE_SI12.002 (Cavalieri et al. 2004). The ice coverage data were imported into ArcMap (© ESRI), where mean ice concentration for each pixel in a 30 km area around each hydrophone location was calculated by use of the zonal statistics toolbox.

RESULTS

Bowhead whales were heard from winter into spring on both hydrophones moored in Fram Strait, but there were clear differences between the types of sounds produced and the frequency with which they were recorded at each site. Bowhead whale songs were recorded daily, often hourly, throughout the winter in western Fram Strait (Fig. 4a). Conversely, songs were nearly absent in central Fram Strait, and call sequences occurred commonly during only a few days in a row and during far fewer hours of the day (Fig. 4b). None of the sub-sampled hours in which bowhead whale calls were recorded on both instruments showed evidence of the same call types being recorded on the 2 hydrophones. In addition, based on simple transmission loss calculations and previous source level measurements for songs recorded in the spring off Barrow, Alaska, USA (~177 dB re 1μPa; Cummings & Holliday 1987), the whales producing sounds were likely <20 km away from each recorder. Thus, the data sets represent discrete acoustic sampling at each location.

Western Fram Strait

Bowhead whale songs were initially detected on the western Fram Strait recorder in late October, with singing occurring almost constantly from the end of November until early March. Subsequently, singing occurred in bouts through March and early April before an abrupt decline in singing during the third week of April (Fig. 4a). A total of 3433 h of song from 58 d were recorded. No bowhead whale songs were detected from May through September. Peak levels of singing (in midwinter) coincided with the period of lowest water temperature (Fig. 4c) and almost complete darkness. During this time, the mean sea ice concentration within 30 km of this recorder ranged from 90 to 100%. Simple calls and call sequences, but no song, were recorded in some hours during days in late October (7 d) and November (18 d) and again in April (2 d).

Central Fram Strait

Only a few very faint songs were recorded in the central Fram Strait during 4 d in November (Fig. 4b). The songs were similar to those recorded to the west, but only loud units were visible in the spectrograms. Bowhead whale simple calls and call sequences were recorded on 76 d in 9 distinct time periods on the central mooring, each lasting roughly a week from mid-November until the end of February, with many fewer calls detected from mid-March to early May (Fig. 4b). No bowhead whale sounds were detected from mid-May to early November. Sea ice concentrations around this mooring were highly variable, ranging from less than 10 to over 95%. Water temperatures measured by the recorder were much higher (by 1 to 5°C) than at the western recorder and varied more over the season, reflecting the influence of warm Atlantic Water (Fig. 4c). In contrast to the western hydrophone, bowhead whale calls at the central-strait site were detected most often when ice concentrations were less than 70% (Fig. 4b).

Song diversity

As many as 66 different songs were recorded on the recorder in western Fram Strait (Table 1). The number of distinct songs per month and the percentage of hours with song were greatest in mid-winter (December, January, February). Not unexpectedly, songs that were recorded in one month were more likely to be recorded in the following month. Fewer new songs were recorded in March and April than in the early winter, but many songs recorded earlier in the season were detected again in these spring months (Table 1). For example, song 9 first identified in November 2008 was recorded again in April 2009, although it did not occur during the intervening

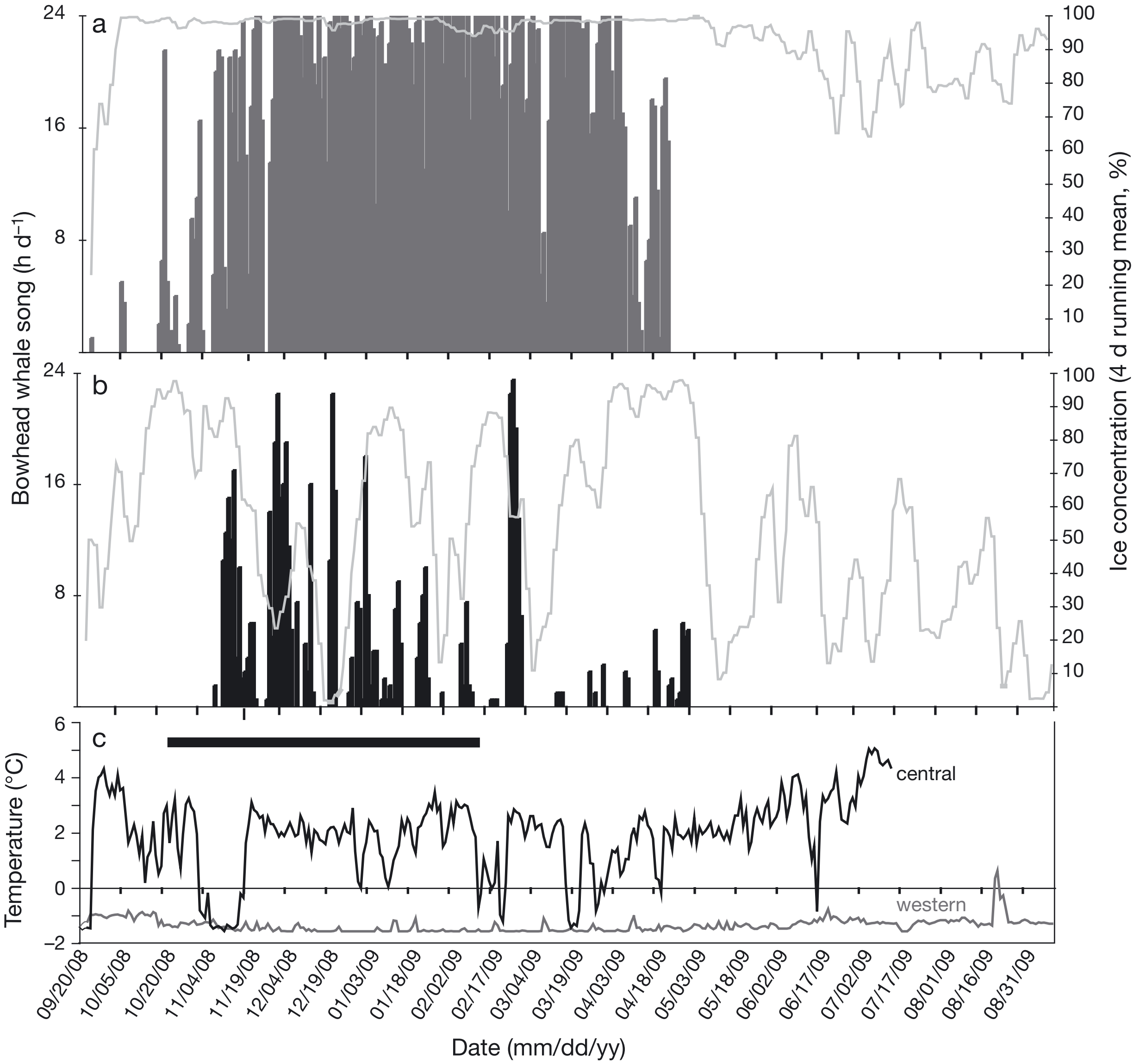

Fig. 4. *Balaena mysticetus.* Number of hours per day with bowhead whale sounds (left *y*-axes, histogram bars) and 4 d running mean of daily ice concentration averages (right *y*-axes, light gray lines) around the (a) western mooring (dark gray bars) and (b) central mooring (black bars). (c) *In situ* temperatures for each mooring (dark gray = western, black = central). The black horizontal bar represents the period of 24 h winter darkness

period, while song 18 was recorded in December and then again in March and April. Distinct songs recorded in multiple months were identified by the composition of notes and phrases, although these elemental features displayed some variability. The variability could be due to the song being produced by different individuals or at a different distance from the hydrophone, or it could simply be intra-song variation. It is not possible to determine which explanation is most accurate without additional information on the singing whales, which is unavailable given the acoustics-only nature of the data collection.

DISCUSSION

There were dramatic differences between bowhead whale acoustic detections as well as call types and song diversity recorded at the 2 deployment sites in Fram Strait. Despite their proximity, each instrument sampled very different oceanographic regimes. The westernmost mooring was on the slope near the east Greenland shelf break and within the East Greenland Current, which transports cold polar water southwards, while the central-strait mooring was located in warmer Atlantic Water, which recircu-

Table 1. *Balaena mysticetus.* Different songs recorded on the western Fram Strait hydrophone and months in which they were recorded. Distinct songs were numbered 1 to 66. **Bold** numbers are songs that were also recorded in a prior month

Month	Song	New in month (total for month)
October 2008	1,2	2 (2)
November 2008	3–11	9 (9)
December 2008	12–23, **7,8,10,11**	12 (16)
January 2009	24–42, **15,20,22**	19 (22)
February 2009	43–53, **28,30, 36–39**	11 (17)
March 2009	54–61,**15,18,20,38, 39,44, 51, 53**	8 (16)
April 2009	62–66, **9,18,20, 59–61**	5 (11)

lates locally (Holfort & Hansen 2005, Rudels et al. 2005). Historically, bowhead whales have been found near both recording sites (Moore & Reeves 1993), although most of the contemporary spring/summer sightings have been closer to the central-strait mooring (Wiig et al. 2007, 2010). It is noteworthy that sea ice is common at the western mooring site, even in summer, which makes the region less accessible to visual surveys. Whaling records provide some historic background regarding the seasonal migration of the Spitsbergen population of bowhead whales (Moore & Reeves 1993, Lydersen et al. 2012). Whales were hunted in waters northwest of Spitsbergen in April and May. By late spring, whalers surmised that adult males and females without calves migrated southwestward with the East Greenland Current, while others moved north from Spitsbergen into the receding pack ice. Before 1818, commercial catches were common between 76° and 80° N, with the 'best' area at 79° N, 150 to 200 km west of Spitsbergen (Scoresby 1823). After 1818, commercial hunting moved south, with catches common between 71° and 74° N, often within sight of the east coast of Greenland. Whales on this 'southern ground' were described as 'very large' with 'long heads and bodies,' different from bowheads with 'short broad heads' found at 78° to 79° N (Scoresby 1820). While it is speculative to interpret our acoustic findings within the context of this type of historical information, these descriptions suggest that the Spitsbergen bowhead whale stock might have comprised sub-populations; differences in singing behavior might have reinforced sub-group cohesion.

The nearly continuous loud singing and diversity of songs recorded in western Fram Strait suggests that this region was occupied by numerous bowhead whales for several months during winter. The extensive acoustic signaling by bowhead whales at this site during winter was an unexpected finding. While historic whaling records indicated that this was a summering area, virtually nothing was known about where the Spitsbergen population of bowhead whales overwintered. However, a previous report documented that bowhead whale sounds were recorded to the north of the central mooring (82.5° N, 0.5° W) during 2 wk in April 1989 (Moore & Reeves 1993), and recent satellite tracking of a single animal from this population showed a northward migration just prior to the onset of winter, in marked contrast to the movement patterns of other bowhead whale populations (Lydersen et al. 2012). Songs, which are produced primarily in winter and early spring (Würsig & Clark 1993, Stafford et al. 2008, Delarue et al. 2009), are thought to be male reproductive displays similar to the songs of humpback whales (Tyack & Whitehead 1983). This speculation is supported by our observations, since winter singing coincides with what is likely the peak breeding period for bowhead whales (Reese et al. 2001). A dense canopy of ice cover, such as that which was present over the western instrument, may provide a better acoustic habitat for the transmission and reception of song when compared to loose pack ice (Diachok & Winokur 1974) and therefore may be favored by the singing whales.

Bowhead whale sounds were much less common on the recorder in central Fram Strait. Most sounds at this site were simple call sequences recorded in 'bouts,' with only a few faint songs detected. Simple calls and call sequences may be used to aid in navigation (Ellison et al. 1987, George et al. 1989), to maintain cohesion during migration (Clark et al. 1986, George et al. 1989), or simply to maintain contact between whales (Würsig & Clark 1993). Calling bouts may be indicative of groups of whales migrating through an area (Noongwook et al. 2007, Wiig et al. 2010). Alternatively, because the instrument in central Fram Strait had less consistent ice cover, bowhead whales may have produced fewer sounds or spent less time in the area because of the potential risk of killer whale *Orcinus orca* predation, as has been suggested for the EC-WG population (Ferguson et al. 2010). Satellite-tagged whales from both the BCB and EC-WG populations spent most of their time in 90 to 100% ice cover and were usually far (>100 km) inside the ice edge (Ferguson et al. 2010, Citta et al. 2012). Thus, all 3 populations of bowhead whales appear to be using similar winter habitat.

In addition to the extensive singing recorded, many different songs were recorded on the western mooring. The production of multiple distinct songs in a single season seems to be a characteristic of bowhead whale singing behavior (Stafford et al. 2008, Delarue et al. 2009). Multiple (2 to 3 per year) distinct songs were recorded in the Chukchi Sea and Davis Strait, in areas with heavy ice cover, with these songs changing over time (Delarue et al. 2009). The Spitsbergen population appears to sing many more songs per year than either the BCB or EC-WG populations, despite the latter populations being much larger. However, acoustic data from these regions have so far been limited to fall and winter months in the Chukchi Sea (Delarue et al. 2009) and an area used predominantly by resting females in Davis Strait (Heide-Jørgensen et al. 2010). Collection and/or analysis of year-round acoustic recordings from wintering regions for the BCB and EC-WG populations (such as the northern Bering Sea and western Hudson Strait; Koski et al. 2006, Citta et al. 2012) may show more annual song diversity in these 2 populations than has been found to date.

Bowhead whale singing in the Fram Strait peaked when the region was dark, cold, and ice-covered, making it unlikely that these animals would be detected by traditional survey methods. Sound production greatly decreased between mid-April and the beginning of May, which may be why visual survey crews listening to towed arrays or sonobuoys during surveys in these months failed to detect bowhead whale sounds, even when whales were seen (Wiig et al. 2010). Given the diversity and loudness of songs and the period over which they were recorded in 2008 and 2009, western Fram Strait appears to be a wintering ground, and possibly a mating area, and is therefore important habitat for this Critically Endangered population. Further, there may be more animals in this population than previously believed, which is encouraging for the long-term survival of the population. Longer-term passive acoustic monitoring including a more detailed study of song diversity in this area will elucidate whether this region is used repeatedly over time or whether Spitsbergen bowhead whales are plastic in their choice of song and singing venue.

The song diversity noted here is unprecedented for baleen whales. Whether individual singers display 1, multiple, or even all call types, the size of the song repertoire for Spitsbergen bowheads in 2008 to 2009 is remarkable and more closely approaches that of songbirds than other baleen whales (cf. Krebs & Kroodsma 1980). Clearly, song diversity in bowhead whales and how it changes with year and location is a topic that is ripe for more detailed study, which, if undertaken, could lead to a much better understanding of the role of song in bowhead whale ecology.

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