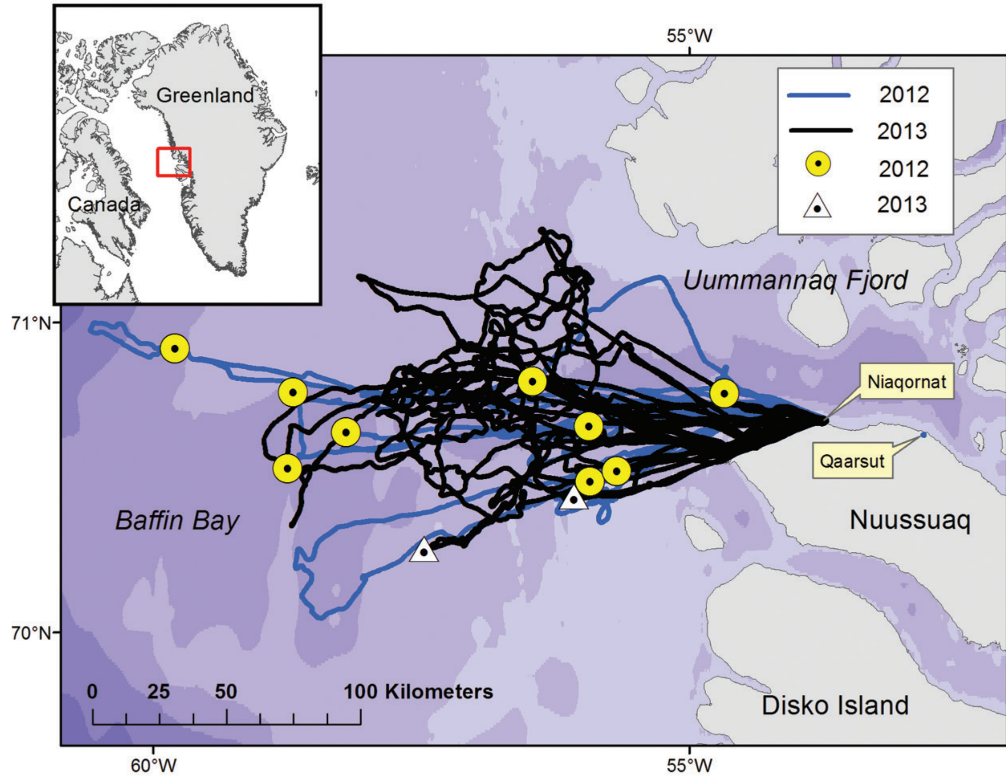

Figure 1. Map of the study area in Greenland, including the location of the recording site (see inset). The map shows search effort in 2012 (blue lines) and 2013 (black lines). The circles represent recording locations in 2012, and the triangles represent recording locations in 2013.

the minimum ICI is 4.2 ms. Animation recorded for this shows the same buzz sequence as shown in this figure recorded with the Reson hydrophone (see video clip posted on the *Aquatic Mammals* website: www.aquaticmammalsjournal.org/index.php?option=com_content&view=article&id=10&Itemid=147). The amplitude and frequency content changes as the animal presumably scans over the hydrophone. Another buzz example recorded with the Acousonde™ is shown in Figure 5. The minimum ICI during the buzz is 3.2 ms.

Discussion

This is the first description of high-frequency clicks from narwhals (Figure 3) and the first characterization of the entire bandwidth of echolocation clicks for this species. The clicks contain frequencies above 150 kHz and are similar to broadband clicks recorded from white-beaked dolphins (*Lagenorhynchus albirostris*) (Rasmussen & Miller, 2002) and as seen on the power spectra from bottlenose dolphins (*Tursiops aduncus*) in Wahlberg et al. (2011). For example, at 150 kHz, the amplitude is about 10 dB below the amplitude at the peak frequency. Frequencies this high have not been described previously for narwhals either due to the limitations of recording equipment or *a priori* sampling decisions. Marcoux et al. (2012) were able to describe spectral content with frequencies up to 30 kHz; and Stafford et al. (2011) described them up to 48 kHz, while Miller et al. (1995) were able to analyse frequencies up to 125 kHz. Other reasons may be the directionality of echolocation signals (Rasmussen et al., 2002, 2004; Au & Herzing, 2003). Concerning the 10-dB beamwidth, for bottlenose dolphins (*T. truncatus*), Au (1980) measured it as 22°, and for *T. aduncus* in Australian waters, Wahlberg et al. (2011) reported a 10° measurement, similar to what has been seen in white-beaked dolphins (Rasmussen et al., 2004). The -3-dB beamwidth in the horizontal plane has the lowest value of 6.2° for false killer whales (*Pseudorca crassidens*), and the highest value of 16.5° for harbour porpoises (*Phocoena phocoena*) (*sensu* Koblitz et al., 2012). White-beaked dolphins and *T. aduncus* have a -3-dB beamwidth of 8°. Since the properties of

Table 1A. Sound recordings collected in the pack ice of Baffin Bay in 2012

Recording date	Deployment time/ Local time	Recording duration (min)	Recording depth (m)	GPS position
22 March 2012	1951 – 2020 h	29	100	70 52.884, 54 38.826
22 March 2012	1852 – 1928 h	36	50	70 52.884, 54 38.826
23 March 2012	1425 – 1528 h	63	100	70 57.129, 60 07.957
23 March 2012	1611 – 1630 h	10	50	70 57.129, 60 07.957
24 March 2012	1450 – 1650 h	120	100	70 54.828, 54 39.496
24 March 2012	1558 – 1645 h	47	50	70 54.828, 54 39.496
28 March 2012	1750 – 1810 h	20	100	70 54.859, 56 33.272
29 March 2012	1200 – 1215 h	15	100	70 50.452, 58 55.600
29 March 2012	1354 – 1437 h	43	100	70.59258, 58.926727
29 March 2012	1710 – 1720 h	0	100	70 46.273, 55 59.203
30 March 2012	1215 – 1720 h	305	100	70 43.347, 58 22.633
30 March 2012	1236 – 1415 h	39	100	70 43.347, 58 22.633
31 March 2012	1420 – 1740 h	140	100	70 35.268, 56 16.522
31 March 2012	1435 – 1750 h	135	100	70 35.268, 56 16.522
1 April 2012	1300 – 1440 h	100	100	70.59258, 55.971042
1 April 2012	1315 – 1430 h	69	100	70.59258, 55.971042
1 April 2012	1640 – 1810 h	90	100	70 37.614, 55 42.411
1 April 2012	1702 – 1820 h	0	250	70 37.614, 55 42.411

Table 1B. Sound recordings collected in the pack ice of Baffin Bay in 2013

Recording date	Deployment time/ Local time	Recording duration (min)	Recording depth (m)	GPS position
23 March 2013	1420 – 1452 h	32	100	70.54553 56.12495
29 March 2013	1347 – 1348 h	1	100	70.35978 57.56456

the broadband narwhal clicks are similar to what is described for both white-beaked dolphins and for *T. aduncus*, we could expect a similar beam pattern for narwhals. Recordings using a hydrophone array could verify this. An animation of a click sequence is shown in the supplementary material and can be viewed online. In here, it is possible to see how the frequency contained in the clicks also varies above 150 kHz.

Out of 1,340 min of recordings from both recording systems, we recorded only clicks and no whistles. Sounds from bowhead whales (*Balaena mysticetus*)

Table 2. Information on high-frequency narwhal clicks and click characteristics, including peak frequency, center frequency, 3-dB bandwidth, 10-dB bandwidth, and 90% energy bandwidth

	Peak frequency ± SD (kHz)	Center frequency ± SD (kHz)	3-dB bandwidth ± SD (kHz)	10-dB bandwidth ± SD (kHz)	90% energy bandwidth ± SD (kHz)	90% energy duration ± SD (µs)
High-frequency clicks (N = 300)	69 ± 14	53 ± 13	30 ± 11	52 ± 11	74 ± 13	23 ± 9

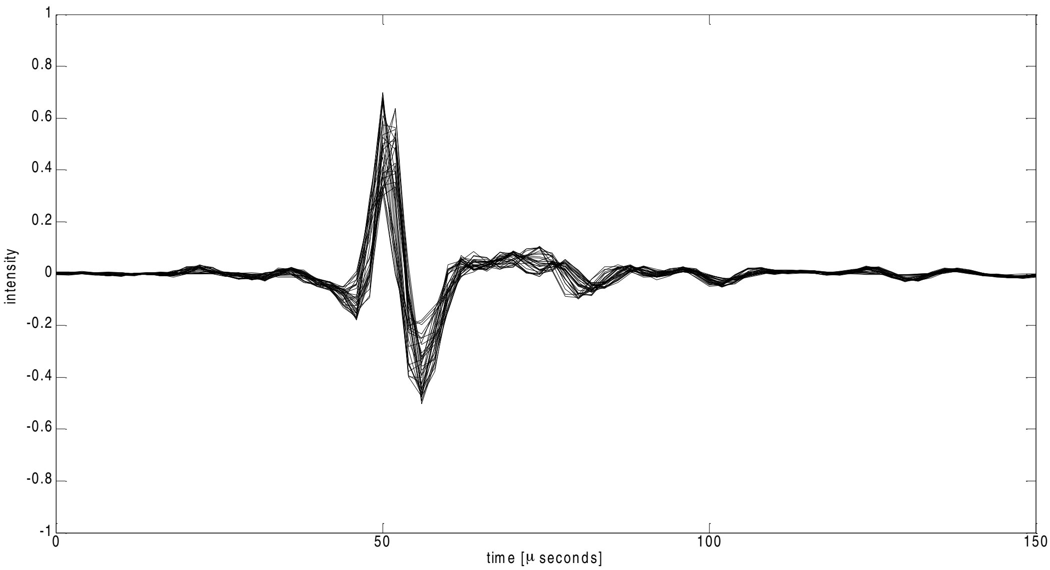

Figure 2. Waveforms of 34 clicks recorded and sampling rate of 500 kHz. These clicks are high amplitude clicks of a click train presumably scanning over the hydrophone.

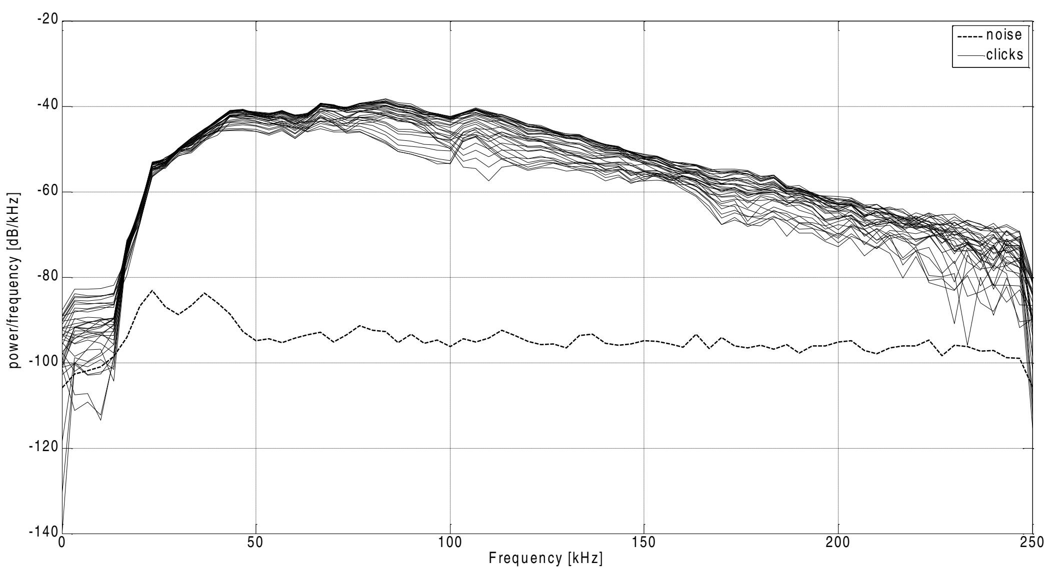

Figure 3. Spectra of 34 clicks recorded (solid lines) and spectra of noise level in the same recording (dashed line); peak frequency is at 66 kHz, but considerable energy extends up to 240 kHz.

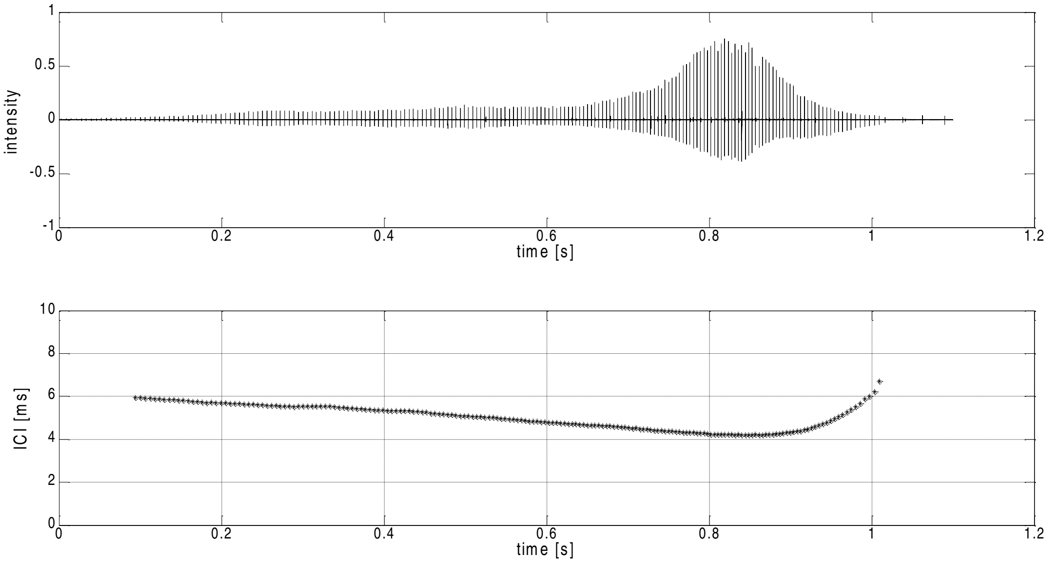

Figure 4. Buzz sequence recorded with the Reson system; the ICI decreases from 6 to a minimum of 4.2 ms.

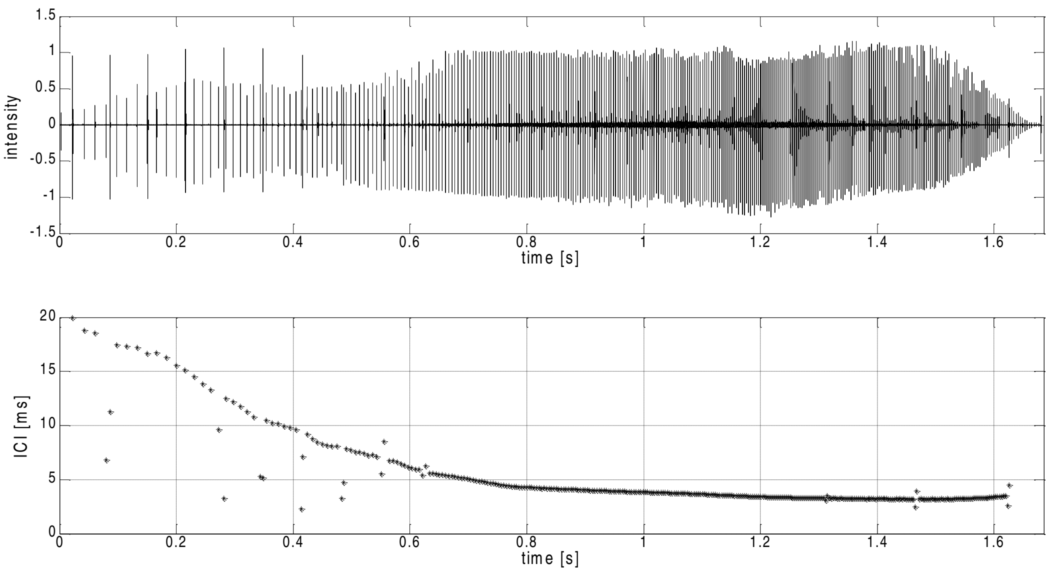

Figure 5. Buzz sequence recorded with the Acousonde™; the ICI decreases from 20 ms to a minimum of 3.2 ms. Clicks from a second animal are recorded at the beginning of this sequence. Notice that some of the clicks are clipped, but this does not change the ICI.

and bearded seals (*Erignathus barbatus*) were also obtained, which meant that low-frequency sounds could be detected. Rasmussen & Miller (2002) reported whistles from white-beaked dolphins when they were socializing (never when they were feeding), and this may be similar in narwhals, although a larger sample size would be needed to be conclusive. In contrast, pilot whales (*Globicephala melas*) have been reported to produce tonal sounds during deep foraging dives (Jensen et al., 2011).

We recorded only a few possible prey capture events (Figures 4 & 5), but this is likely due to the shallow recording depths (above 250 m) as narwhals are known to feed at deep depths (in some cases, > 1,000 m) (Laidre et al., 2003). Prey capture events have been described as decreasing