Seasonal Trends in Acoustic Detection of Marine Mammals in Baffin Bay and Melville Bay, Northwest Greenland

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ABSTRACT. The expansion of hydrocarbon exploration in northwest Greenland has made it increasingly important to understand the occurrence of marine mammals in the region. We describe the seasonal occurrence of marine mammals and the spatial distribution of their calls in Baffin Bay and Melville Bay. Four Autonomous Multichannel Acoustic Recorders (AMARs) were deployed during summer 2012 (late July to early October), five recorders during September 2013, and two recorders from late September 2013 to early September 2014. The call presence of several species was analyzed using automatic call detection and manual verification analysis methods. A novel approach to discern narwhal (*Monodon monoceros*) clicks from beluga (*Delphinapterus leucas*) clicks was implemented during the verification process. Narwhal calls were detected in spring and fall, showing a south-to-north migration pattern in spring and a north-to-south migration pattern in fall. Few beluga whales were detected during fall 2013 and spring 2014. Bearded seal (*Erignathus barbatus*) calls were detected mainly during spring (mating period). A small number of bowhead whale calls (*Balaena mysticetus*) were detected during fall 2013 and spring and summer 2014. For the first time at this latitude in Baffin Bay, long-finned pilot whales (*Globicephala melas*) and sperm whales (*Physeter macrocephalus*) were detected during summer and fall. Our results suggest that the presence of marine mammals in Baffin Bay and Melville Bay is governed mainly by the annual cycle of sea ice formation and decay.

Key words: northwest Greenland; Baffin Bay; Melville Bay; passive acoustic monitoring; sperm whales; narwhals; long-finned pilot whales; bearded seals; bowhead whales; beluga whales; narwhal clicks; beluga clicks

RÉSUMÉ. Le développement de l'exploration des hydrocarbures dans le nord-ouest du Groenland rend indispensable une meilleure compréhension de la présence des mammifères marins dans la région. La distribution saisonnière et spatiale des vocalisations de mammifères marins dans la baie de Baffin et la baie Melville sont décrites. Quatre AMAR (enregistreurs acoustiques autonomes multicanaux) ont été déployés durant l'été 2012 (de la fin de juillet au début d'octobre), cinq enregistreurs en septembre 2013 et deux enregistreurs de la fin de septembre 2013 au début de septembre 2014. La présence des vocalisations de plusieurs espèces animales a été déterminée au moyen de leur détection automatique et d'une vérification manuelle. Une approche novatrice pour distinguer les clics de narvals (*Monodon monoceros*) des clics de bélugas (*Delphinapterus leucas*) a été utilisée lors du processus de vérification. Les vocalisations de narvals ont été détectées au printemps et à l'automne, reflétant des directions de migration du sud au nord au printemps et du nord au sud à l'automne. Peu de bélugas ont été détectés à l'automne 2013 et au printemps 2014. Les vocalisations de phoques barbus (*Erignathus barbatus*) ont été principalement détectées durant le printemps (période de reproduction). Un petit nombre de vocalisations de baleines boréales (*Balaena mysticetus*) a été détecté à l'automne 2013 ainsi qu'au printemps et à l'été 2014. Pour la première fois à cette latitude dans la baie de Baffin, des globicéphales (*Globicephala melas*) et des cachalots (*Physeter macrocephalus*) ont été détectés en été et en automne. Nos résultats suggèrent que la présence des mammifères marins dans la baie de Baffin et la baie Melville peut être principalement expliquée par le cycle annuel de la formation et du retrait de la glace.

Mots clés : nord-ouest du Groenland; baie de Baffin; baie Melville; suivi acoustique passif; cachalots; narvals; globicéphales; phoques barbus; baleines boréales; bélugas; clics de narvals; clics de bélugas

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INTRODUCTION

The waters of Baffin Bay and Melville Bay off northwest Greenland are some of the most productive and tightly connected physical-biological systems in the marine environment (Laidre et al., 2010). The region is ice covered in the winter and thus far has had limited vessel traffic, so that the local soundscape is dominated by icebergs,

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sea ice, wind, waves, and wildlife sounds. However, human activities are increasing in these waters. In 2010, five petroleum exploration license blocks were awarded in Baffin Bay (Fig. 1), and the potential opening of the Northwest Passage could lead to regular vessel transits in this area. Vessels associated with transportation and oil and gas exploration and production have the potential to change the soundscape and affect local species, particularly marine mammals (Heide-Jørgensen et al., 2013b). Marine mammals depend on sounds for many critical life processes such as navigating, communicating, monitoring young, mating-related and social displays, and foraging (Tyack and Clark, 2000). The masking effects of anthropogenic noise can disrupt such crucial activities, leading to reduced fitness, loss of usable habitat, or both (Bejder et al., 2006).

A number of marine mammals, including narwhals (*Monodon monoceros*), beluga whales (*Delphinapterus leucas*), bowhead whales (*Balaena mysticetus*), and bearded seals (*Erignathus barbatus*), are known to occur in Baffin Bay and Melville Bay off northwest Greenland (Finley and Renaud, 1980; Doidge and Finley, 1993; Dietz and Heide-Jørgensen, 1995; Stafford et al., 2008, 2012b). The spring bloom of primary productivity triggered by retreating sea ice attracts high densities of prey species in the lower trophic level, including forage fish and zooplankton that many marine mammal species follow into the region (Laidre et al., 2010; Heide-Jørgensen et al., 2013a). Little is known about the year-round occurrence of marine mammals, particularly in winter when environmental conditions make traditional monitoring methods challenging. Thus far, research in the region has been limited to visual surveys, which can take place only from spring to late fall (Finley and Renaud, 1980; Heide-Jørgensen et al., 2013a), and studies using satellite transmitters on a few individuals from a population (Dietz and Heide-Jørgensen, 1995; Teilmann et al., 1999; Heide-Jørgensen et al., 2003a, 2006). More detailed information on marine mammal occurrence in and around Baffin Bay, south of the North Water polynya, is required to adequately manage the risks to marine mammals from offshore oil and gas exploration.

Passive acoustic monitoring using multiple recorders is a reliable method for measuring temporal and spatial distributions of sound-producing marine mammals over large areas for long periods, as well as in remote locations and during weather conditions or seasons that would otherwise prohibit direct observation (e.g., Hannay et al., 2013). Acoustic detection and classification of marine mammal calls require that animals produce sounds that 1) have sufficient amplitude to be detected in the presence of other sounds and 2) are species-unique to allow confident species identification. Thus, the results obtained from acoustic studies apply only to acoustically active animals producing relatively unique calls within a given distance from the recorders. Species with high vocalization rates and long calling bouts (e.g., bearded seals) are more likely to be recorded incidentally compared to species with lower vocalization rates, short calling bouts, or whose calls do not propagate as far (e.g., beluga whales). Sounds below 1 kHz (typical of mysticete calls) have significantly less seawater absorption loss than sounds above 10 kHz (typical of odontocete calls) and thus can be detected at greater distances (Mellinger et al., 2007). Mysticete calls are commonly detected at ranges of several tens of kilometres on a single hydrophone (Stafford et al., 2007), while odontocete clicks and whistles can be detected at ranges of 1–6 km (Quintana-Rizzo et al., 2006; Wang et al., 2006; Jensen et al., 2012; Ainslie, 2013).

Stafford et al. (2012a) and Marcoux et al. (2012) discuss the large overlap in vocal repertoires of the two Monodontid species (beluga whales and narwhals) that share migration routes in Baffin Bay (Heide-Jørgensen et al., 2003a, c). To our knowledge, no studies have systematically discriminated between calls of these species. Their repertoires have been explored independently, often focusing on tonal calls (Ford and Fisher, 1978; Belikov and Bel'kovich, 2006). While such information is useful, narwhals and especially beluga whales have large vocal repertoires that are only partially described, resulting in potential interspecies overlap of calls and low reliability of identification (Sjare and Smith, 1986). Both species are ranked as near threatened by the International Union for Conservation of Nature and of special concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2004a, b). Therefore, the ability to discriminate reliably between the Monodontid whales by acoustic means is particularly important to allow for accurate monitoring of species-specific distribution and habitat use.

Most of the West Greenland marine mammal acoustic data published to date are recordings from Disko Bay or central Baffin Bay in spring (Stafford et al., 2008; Tervo et al., 2009) and winter (Tervo et al., 2009, 2011; Stafford et al., 2012a; Rasmussen et al., 2015) and from Inglefield Bay in summer (Miller et al., 1995). Here we present results of recordings of marine mammal calls at 11 locations in the Greenlandic waters of northern Baffin Bay: four locations from late July to September 2012 (including one recorder in Melville Bay), five locations in September 2013, and two locations from September 2013 to September 2014. We examine the acoustic presence of several marine mammal species and describe a method to differentiate narwhal clicks from beluga whale clicks when repertoires overlap. We investigate whether there is an association between marine mammal detections and ice presence.

MATERIAL AND METHODS

Deployments

Between 29 July and 2 October 2012, we deployed Autonomous Multichannel Acoustic Recorders (AMARs, JASCO Applied Sciences) at stations BB1–BB4 (Fig. 1
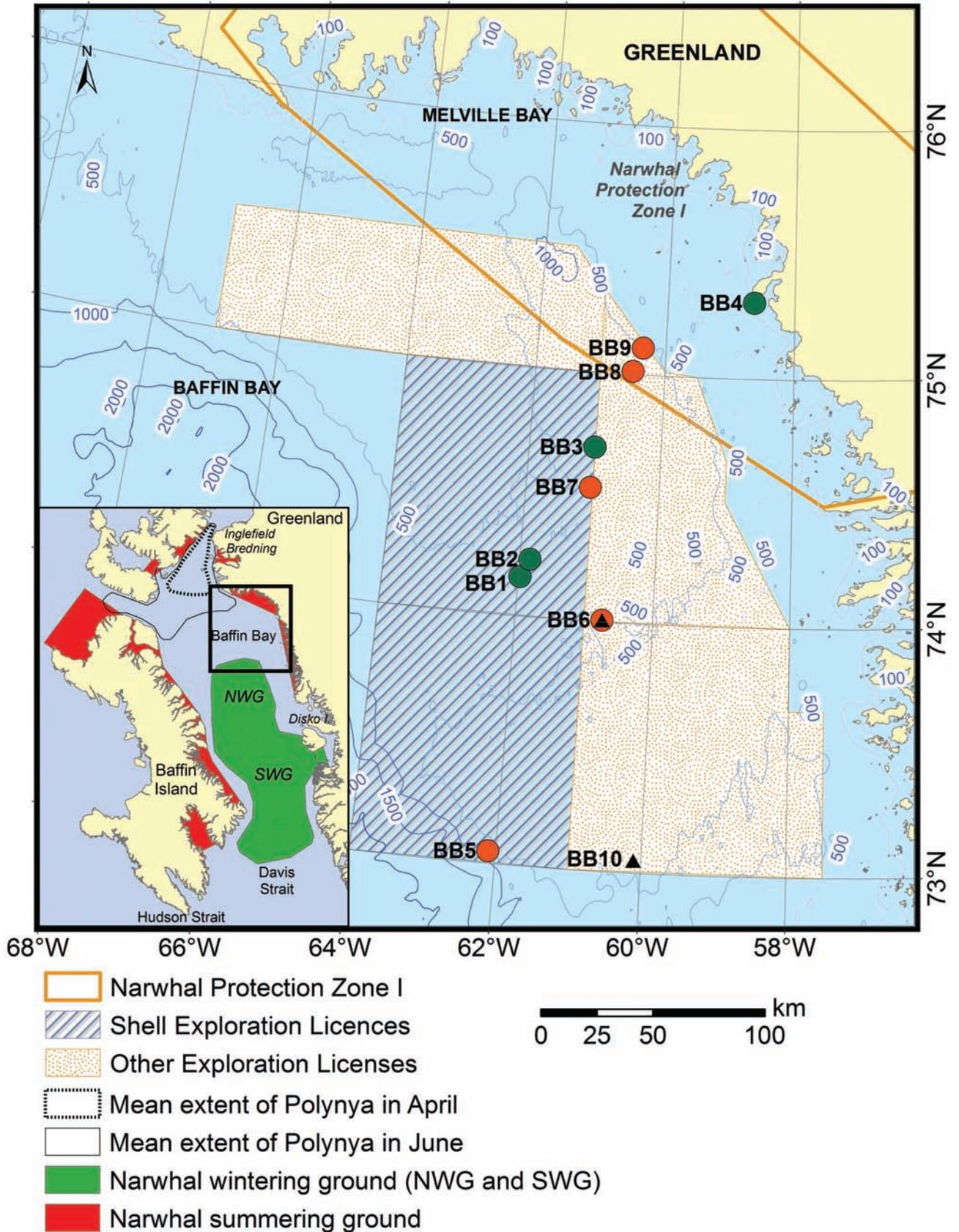
FIG. 1. Map of recording station locations for deployments in Baffin Bay for summer 2012 (green circles: BB1–BB4), summer 2013 (orange circles: BB5–BB9), and overwinter 2013–14 (black triangles: BB6 and BB10). Inset shows approximate summer (red) and winter (green) distributions of the narwhal subpopulation summering in West Greenland and overwintering in Baffin Bay, Davis Strait, or Disko Bay (data from Laidre and Heide-Jørgensen, 2005a, b). NWG = northern overwintering ground and SWG = southern overwintering ground. Mean extents of the polynya in April and June are derived from Dunbar (1969).

TABLE 1. Recorder deployment details for acoustic monitoring programs in Baffin Bay in summer 2012, summer 2013, and overwinter 2013 – 14.

Recording period and station	Location	Recording period	Hydrophone depth (m)
Summer 2012:			
BB1	74.16° N, 61.98° W	29 July to 29 September	100, 200, 400
BB2	74.23° N, 61.85° W	29 July to 1 October	100, 200, 400
BB3	74.70° N, 61.01° W	30 July to 2 October	100, 200, 400
BB4	75.31° N, 58.64° W	14 August to 15 September	370
Summer 2013:			
BB5	73.05° N, 62.10° W	1 September to 30 September	450
BB6	74.01° N, 60.74° W	1 September to 30 September	272
BB7	74.54° N, 61.04° W	1 September to 29 September	365
BB8	75.01° N, 60.50° W	31 August to 29 September	350
BB9	75.11° N, 60.36° W	31 August to 29 September	400
Overwinter 2013 – 14:			
BB6	74.01° N, 60.74° W	29 September 2013 to 6 September 2014	302
BB10	73.05° N, 60.10° W	30 September 2013 to 19 August 2014	550

and Table 1). Each AMAR was fitted with a GTI-M8H current-loop hydrophone (GeoSpectrum Technologies Inc.; −199 dB re 1 V/µPa nominal sensitivity) with no gain applied. Stations BB1 – BB3 were vertical arrays, with hydrophones at depths of 100, 200, and 400 m from the surface. The top hydrophone (100 m depth) sampled continuously at 64 kilo-samples per second (ksps) to record both seismic air gun pulses and marine mammal calls. The two lower hydrophones (200 and 400 m depth) sampled continuously at 8 ksps, primarily to record seismic air gun pulses. The usable bandwidth was 10 Hz to 30 kHz for the top hydrophone and 10 – 3750 Hz for the lower hydrophones (the maximum frequency was limited by the anti-aliasing filter in the analog-to-digital converter to 0.47 of the sampling rate). At station BB4, located within Melville Bay, we deployed an AMAR at the seabed (370 m) with a single omnidirectional GTI-M8E hydrophone (−165 dB re 1 V/µPa nominal sensitivity) sampling at 64 ksps, which resulted in a usable bandwidth of 10 Hz to 30 kHz.

Between 31 August and 30 September 2013, we deployed AMARs at stations BB5 – BB9 (Fig. 1 and Table 1). The systems recorded continuously for 513 s at 64 ksps followed by 43 s at 375 ksps. Each AMAR was fitted with a single omnidirectional GTI-M8E hydrophone (GeoSpectrum Technologies Inc.; −165 dB re 1 V/µPa nominal sensitivity) with no gain applied, positioned at mid-water column depth. The spectral noise floor was 23 dB re 1 µPa2/Hz for the 64 ksps recording channel and 30 dB re 1 µPa2/Hz for the 375 ksps recording channel. Both recording channels could measure a maximum sound pressure level (SPL) of 171 dB re 1 µPa.

Between 29 September 2013 and 6 September 2014, we deployed AMARs at stations BB10 (south; 1000 m water depth, 550 m recorder depth) and BB6 (north; 575 m water depth, 302 m recorder depth) (Fig. 1 and Table 1). Each AMAR was fitted with an M8E-V35 dB omnidirectional hydrophone (GeoSpectrum Technologies Inc.; −164 dB re 1 V/µPa sensitivity). The AMARs sampled on a 30-min duty cycle: 340 s at 64 ksps, then 43 s at 375 ksps, and then 1418 s of sleep. The 64 ksps recording channel had a spectral noise floor of 23 dB re 1 µPa2/Hz and could measure a maximum

SPL of 171 dB re 1 µPa. The 375 ksps data were recorded with a spectral noise floor of 30 dB re 1 µPa2/Hz and a maximum SPL of 171 dB re 1 µPa.

Marine Mammal Visual Observations

We supplemented the passive acoustic detections of marine mammals with visual observations by marine mammal observers during the geophysical surveys in the summers of 2012 and 2013. Commencing on 16 July 2012 and 1 August 2013, marine mammal observers on the survey and support vessels surveyed animals during the transit from Nuuk, Greenland, to the prospect area. During the survey period, animal observations were recorded as the support vessel made various transits to Upernavik and Nuuk. In 2012, the last observations were carried out on 16 October during transit to port. In 2013, while actual site survey activities ended on 17 October 2013, as per Mineral Licence and Safety Authority guidelines, the vessel was used as much as possible for marine life surveying by marine mammal observers. The last observations were carried out on 20 October 2013 during transit to port.

Marine Mammal Acoustic Detection

Automated Detection and Classification: Clicks from narwhals (Fig. 2), beluga whales (Fig. 3), and sperm whales (*Physeter microcephalus*; Fig. 4A) were automatically detected and classified using JASCO's custom acoustic analysis software that identifies the oscillation of a click across the signal's normal level, a process known as a zero-crossing. The detector/classifier removed energy below 8 kHz, created a 0.5 ms root-mean-square (rms) time series, and identified potential clicks with a Teager-Kaiser energy detector. The time window of each click was then defined and used to compute three classification features: the number of zero crossings, the median time between zero crossings, and the slope of the change in time between zero crossings. The extracted features were then compared to a template for each species using the Mahalanobis distance. Each click was classified as the species with the
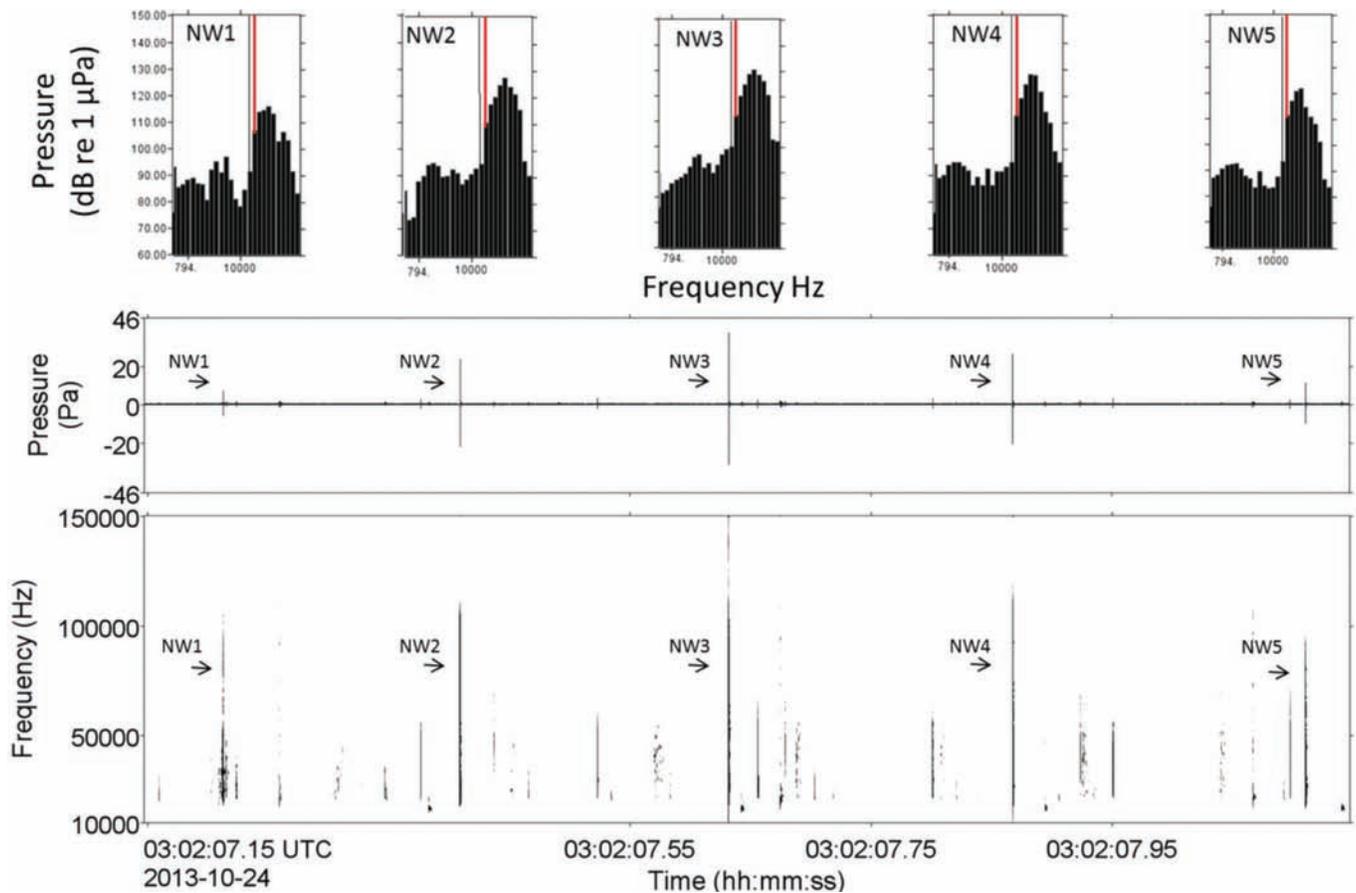
FIG. 2. The frequency spectra, time series graphs, and histograms for a narwhal (NW) click train recorded in West Greenland on 24 October 2014 (Table 2). Species identification was confirmed. Corresponding clicks across graphs are labelled appropriately and the vertical lines in all pressure/frequency graphs indicate frequencies of (black) 15 849 Hz and (red) 19 953 Hz (512 Hz frequency resolution, 0.266 ms time window, 0.02 ms time step, Hamming window).

lowest Mahalanobis distance within specified thresholds. The templates were determined by selecting ~100 high signal-to-noise examples of each species' click, measuring the feature values for those clicks, and computing their covariance matrix.

Calls from bearded seals (Fig. 4B) and bowhead whales (Fig. 4C) were detected using JASCO's custom acoustic analysis software. The software identified call energy in the time-frequency domain. Contours were created by joining adjacent time-frequency bins that met specific threshold criteria before implementing a contour-following algorithm comparable to that of Nosal (2008). The contours were then assigned to a species if they were within specified parameters.

Automated detections were not carried out for long-finned pilot whale (*Globicephala melas*) calls (Fig. 4D). There was no species-unique click template for lack of truth data (high resolution recordings with confident confirmation of species identification). It is important to note that acoustic analysis based on automatic detectors alone (without manual verification) is not reliable for some species, including long-finned pilot whales, in noisy environment conditions (faint calls). Long-finned pilot whales produce typical delphinid sounds, such as clicks, buzzes, and a variety of pulsed calls including whistles

similar to those of narwhals and beluga whales (Weilgart and Whitehead, 1990; Nemiroff and Whitehead, 2009). In this study, long-finned pilot whale–like calls were refuted or accepted on the basis of expert opinions on the whistles and time of year, as this species does not occur in ice-covered areas (Nemiroff and Whitehead, 2009).

Manual Validation of Automated Detections: Our marine mammal results are displayed as the presence of each species over time. Since most automated marine mammal detectors generate a small number of false alarms, we determined a threshold number of calls per species per unit of time that maximized the true positive detections while minimizing the false detections. Files for analysis were selected from the 64 ksps 2012 summer data (30 min/file), the 375 ksps 2013 summer data (43-second file), and the 375 ksps 2013–14 overwinter data (43-second file). By analyzing the highest broadband files available for each recording (64 and 375 ksps), we were able to observe a greater range of calls types (e.g., clicks and whistles) allowing for greater accuracy when classifying calls to different species. For each recorder, 20 files per species detected were manually reviewed. Files were selected to represent a spectrum of automated detector results relative to the six species detected: 10 files with high numbers of detections, five with moderate detections, and five with
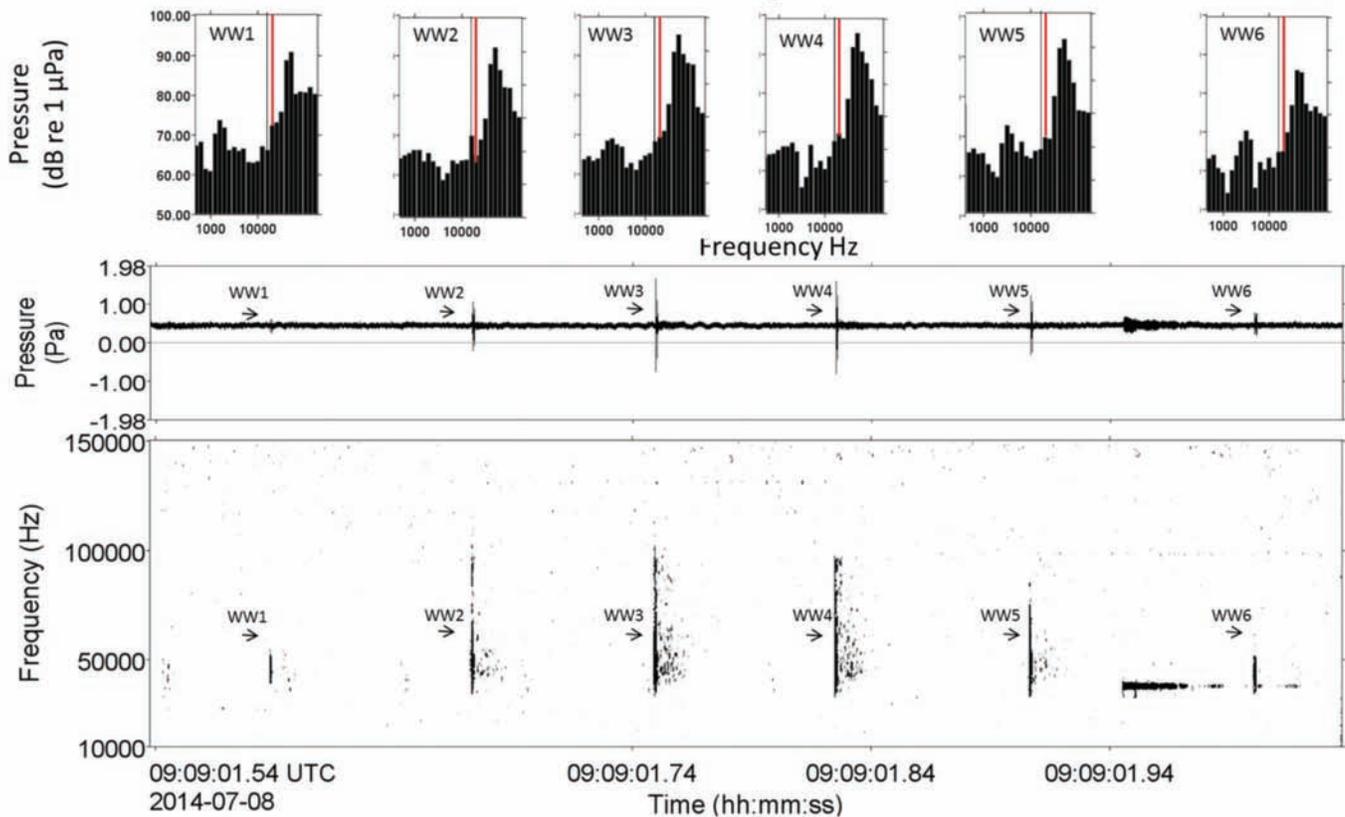
FIG. 3. The frequency spectra, time series graphs, and histograms for a beluga whale (WW) click train recorded in the Gulf of St. Lawrence on 8 July 2014 (Table 2). Species identification was confirmed. Details as in Figure 2.

low detections. Files were selected throughout recording periods, and files within 3 h of each other were avoided. To identify when the detector missed calls (false negatives), the presence or absence of all species was logged in every reviewed file. Vessel and ice presence were also logged for all files.

Some Arctic species create sufficiently unique calls to allow for relatively easy and confident identification during manual analysis. Bowhead whales were identified by their moans, which typically range between 100 – 400 Hz and last about 1 s (Clark and Johnson, 1984). Bearded seals were identified by their characteristic trills (Risch et al., 2007). Sperm whales were identified by their clicks, which occur at a slower pace and lower frequency than other odontocete clicks (Goold and Jones, 1995).

Delphinoidea, especially closely related species, are challenging to distinguish from one another acoustically, and few studies have directly explored interspecific variation (Steiner, 1981; Miller et al., 1995; Rendell et al., 1999; Baron et al., 2008; Gannier et al., 2010). Such is the case for the phonetically similar long-finned pilot whales, narwhals, and beluga whales that inhabit Arctic waters. To discriminate between such species during manual analysis, we focused on calls known to be species-unique. Long-finned pilot whales were identified by their repeated pulsed calls (Nemiroff and Whitehead, 2009) and the time of year of the calls, as they are not known to occur in ice-covered

areas. Distinguishing narwhal calls from beluga calls was more challenging, as both species occur in ice-covered areas.

Narwhal and Beluga Calls – A Novel Approach to Click Differentiation: Occasionally, species-unique calls allowed us to differentiate easily between the two Monodontid species. Narwhals could be identified when whistles and buzzes were paired with low frequency clicks near 19 kHz (Miller et al., 1995), 2 – 10 kHz, or 7 – 14 kHz (Stafford et al., 2012a). Beluga whales could be identified when bird-like whistles were paired with high-frequency clicks, peaking at up to 100 – 120 kHz (Au et al., 1985). However, in many instances during the ice-covered winter months, recordings contained only clicks centered at 30 – 60 kHz, a click type consistently observed in both narwhals and beluga whales (Au et al., 1985; Miller et al., 1995; Roy et al., 2010; Stafford et al., 2012a; Rasmussen et al., 2015).

To address this area of uncertainty, we analyzed click trains from known recordings of narwhals and beluga whales in detail (Table 2), including recordings containing narwhal clicks obtained from several studies in West and East Greenland. West Greenland data include 1) JASCO's recordings with sufficient narwhal whistles for positive identification and 2) recordings collected with a 96 ksps dipping hydrophone by Kate Stafford and Kristin Laidre (University of Washington) that contained positively identified narwhal calls. Susanna Blackwell (Greeneridge
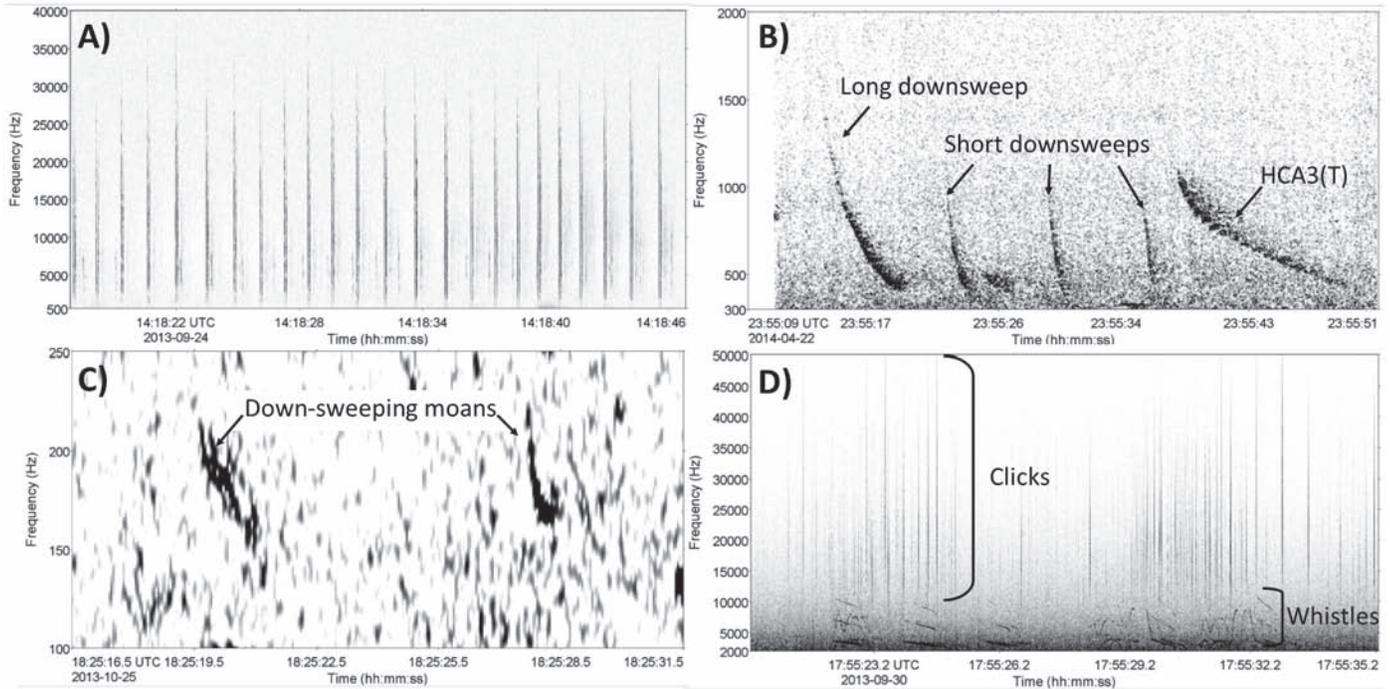
FIG. 4. A) Spectrogram of sperm whale clicks recorded at station BB4 on 24 September 2013 (UTC) (183 Hz frequency resolution, 5.46 ms time window, 2.73 ms time step, Hamming window). B) Spectrogram of bearded seal downsweeps recorded at station BB10 on 22 April 2014 (UTC) (0.715 Hz frequency resolution, 200 ms time window, 50 ms time step, Hamming window). C) Spectrogram of bowhead downsweeping calls recorded at station BB10 on 25 October 2013 (UTC) (0.715 Hz frequency resolution, 200 ms time window, 50 ms time step, Hamming window). D) Spectrogram of long-finned pilot whale clicks (and whistles) recorded at station BB10 on 30 September 2013 (UTC) (1.43 Hz frequency resolution, 12.8 ms time window, 3.2 ms time step, Hamming window).

TABLE 2. Number of narwhal and beluga whale click trains and individual clicks analyzed from different regions.

Recording supplier	Recorder type	Region	Click trains	Clicks
Narwhal:				
JASCO	AMAR	Northwest Greenland	13	125
K. Laidre and K. Stafford	Dipping hydrophone	West Greenland	3	25
S. Blackwell	Acousonde tag	East Greenland	1	36
Beluga:				
JASCO	AMAR	Gulf of St. Lawrence	9	59
JASCO	AMAR	Chukchi Sea	11	103

Sciences, Inc.) and the Greenland Institute of Natural Resources provided a recording of a narwhal click train from East Greenland recorded with a 155 ksps Acousonde tag attached to an animal not responsible for the clicks. Beluga whale clicks from the Gulf of St. Lawrence and the Chukchi Sea were also analyzed. Recordings from these studies were collected by JASCO at 128 and 375 ksps, respectively. A total of 17 narwhal and 20 beluga whale click trains were analyzed, resulting in 186 and 162 clicks per species, respectively (Table 2).

Narwhal clicks substantially increased in one-third octave band sound pressure level (SPL) between the 15 849 Hz and 19 953 Hz bands (Fig. 2), a feature consistently lacking in beluga clicks (Fig. 3). A single exception was found in a narwhal click train from East Greenland in the Acousonde tag data, where all clicks peaked, rather than increased, in SPL in the 19 953 Hz one-third octave band. Regardless, the mean SPL change between the 15 849 Hz and 19 953 Hz one-third octave

bands (dB re 1µPa) was found to be significantly greater for narwhal (10.4 dB re 1µPa) than for beluga (0.9 dB re 1µPa) whale clicks (Fig. 5; non-parametric Kruskal-Wallis test; $\chi^2 = 211$, df = 1, p-value < 0.001). Therefore, to distinguish narwhals from beluga whales when analyzing clicks within the 30–60 kHz range during manual analysis, the per-click one-third octave band SPL were analyzed. If the SPL of all clicks within a click train increased greatly (at least by 5 dB re 1µPa) or peaked in the same band, calls were identified as narwhal calls. If the pressure was low at the 19 953 Hz band relative to the rest of the click, calls were identified as beluga whale calls.

Automated Detector Accuracy: In total, more than 280 h of recordings were manually validated to determine how accurately autodetectors identified the occurrence of marine mammals in Baffin Bay in the period from 2012 to 2014. To define the minimum number of automated calls per unit time that accurately represented species presence, we used a maximum likelihood estimator to compare the
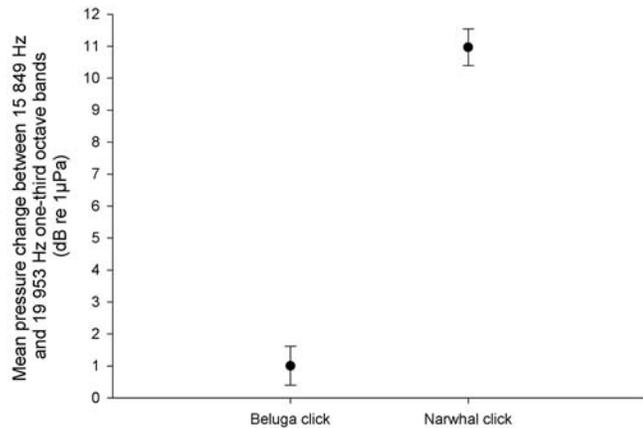
FIG. 5. Mean pressure change between 15 849 Hz and 19 953 Hz one-third octave bands (dB re 1μPa) of narwhal clicks (n = 186) and beluga clicks (n = 162) with 95% confidence intervals.

validated manual analysis and the automated results. The algorithm maximized the detection probability, while minimizing the number of false detections using the "F-score" (Powers, 2011):

$$F = \frac{(1+\beta^2)P*R}{(\beta^2)P+R}; P = \frac{TP}{TP+FP}; R = \frac{TP}{TP+FN}$$

where true positive (TP) is the number of correct detections, false positive (FP) is the number of inaccurate detections, and false negative (FN) is the number of missed detections. Precision (P) is the proportion of automated detections that are accurate, and Recall (R) is the proportion of calls that are autodetected (Davis and Goadrich, 2006; Roch et al., 2011). To put a greater emphasis on precision than on recall, $\beta = 0.5$ was used.

For the 2012 summer recordings, we analyzed manually more than 100 h (203 30-min files) from the 64 ksps data set: 42 h from station BB1, 28 h from BB2, 14 h from BB3, and 16 h from BB4. The automated classifier was found to be ineffective for the 2012 summer acoustic data. Most recorders were inundated with vessel and seismic activity sounds, and ice sounds dominated on station BB4, creating false automated detections. Despite the presence of seismic and vessel sounds, sperm whales and narwhals were detected during manual analysis.

Of the 2013 summer 375 ksps recordings, 2.8 h (231 43-second files) were manually analyzed: 30 min from station BB5, 34 min from BB6, 36 min from BB7, 40 min from BB8, and 26 min from BB9. Sounds from vessels and a small seismic array (140 in³) were detected occasionally, particularly at stations BB7–BB9. Long-finned pilot whales, sperm whales, and narwhals were also detected during manual analysis. The comparison of present or absent results from manual analysis to results from the automated detector count revealed that a minimum of 50 narwhal and 211 sperm whale detections per file were required for the detector results to be accepted as true for each species and considered present within the file. These

parameters were applied to the 2013 summer detector results, giving narwhal and sperm whale detections a precision of 0.91 and 0.78, respectively (online Appendix 1: Table S1).

In the 2013–14 overwinter 375 ksps data, 3.6 h (299 43-second files) were manually reviewed: 1.8 h from station BB10 and 1.8 h from BB6. Bowhead whales, sperm whales, long-finned pilot whales, narwhals, beluga whales, and bearded seals were detected. Vessel sound was rare at these stations, but ice sound occurred consistently from late November to late March at station BB10 and from late November to late April at station BB6. The comparison of manual analysis results to automated detector results revealed that a minimum of three narwhal, seven sperm whale, 97 beluga whale, and four bearded seal detections were required per file for the species to be considered present at that time. These parameters were applied to the 2013–14 overwinter detector results giving narwhal, sperm whale, beluga whale, and bearded seal detections a precision of 0.94, 0.88, 0.5, and 1, respectively (online Appendix 1: Table S2). Automated detections of bowhead whales were unreliable, as they were often triggered by ice, other cetaceans, or both; therefore, we present here only those results that were manually verified.

Sea Ice Data

Sea ice concentration data were obtained at a 10 km resolution from the Ocean and Sea Ice Satellite Application Facility (http://www.osi-saf.org). Daily sea ice concentrations were calculated from the closest measurement pixel to each recorder. The locations of sea ice edges were obtained from satellite imagery (NOAA National Ice Center, Washington, D.C., http://www.natice. noaa.gov/products/).

We evaluated the effect of ice presence on the occurrence of marine mammal calls at stations BB6 and BB10 over the winter of 2013–14 using a binary generalized linear model in the R software package (version 3.2.2; R Development Core Team, 2010) and assessed significance using Wald's tests.

RESULTS

Results of visual observations are presented here to support the acoustic findings. In summer 2012, marine mammal observers made a total of 857 observations of marine mammals in the license areas, representing 1428 individuals. In summer 2013, a total of 58 visual observations of marine mammal species representing 342 individuals were documented in the license areas (Fig. 1). The number of sightings in 2013 was lower because the project scope was significantly reduced, with fewer vessels and thus fewer observers. Several marine mammal species, including sperm whales and long-finned pilot whales, were visually observed from mid-July to mid-October 2012
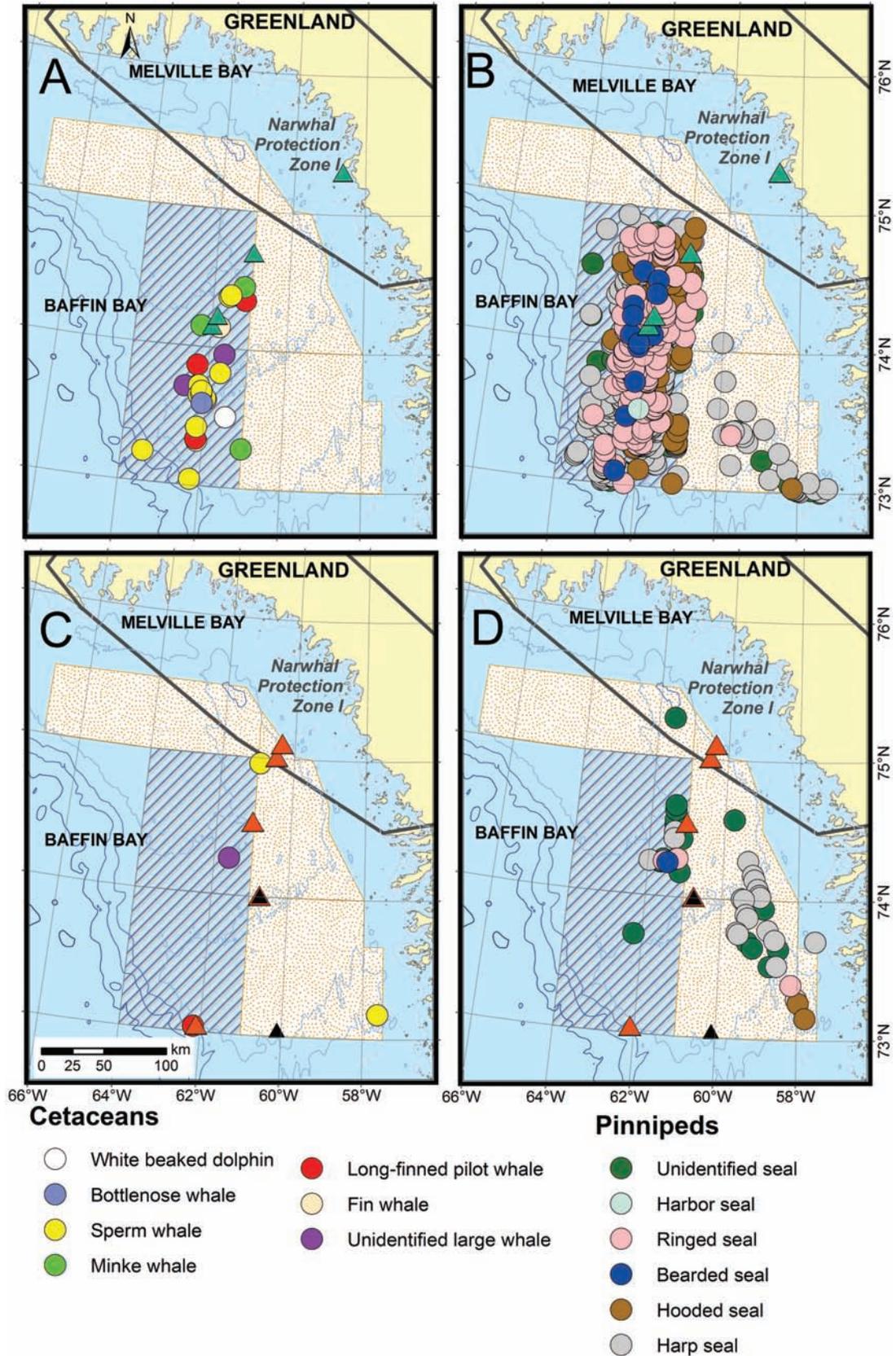
FIG. 6. Maps of sightings in license areas by on-effort marine mammal observers from survey ships deployed during Shell's marine mammal visual monitoring and mitigation program from (A and B) 19 July to 16 October 2012 and (C and D), 1 August to 20 October 2013. Panels A and C show cetacean sightings, and panels B and D, pinniped sightings. In panels A and B, the green triangles represent 2012 summer stations, and in panels C and D, the orange triangles represent 2013 summer stations, and the black triangles, the 2013–14 overwinter stations.

(Fig. 6A) and from early August to mid-October 2013 (Fig. 6C). Bearded seals, ringed seals (*Pusa hispida*), harp seals (*Pagophilus groenlandicus*), hooded seals (*Cystophora cristata*), and harbor seals (*Phoca vitulina*) were observed in the vicinity of the stations (Fig. 6B and 6D).

Narwhal clicks were detected during summer 2012 and September 2013 (Fig. 7). The percentage of days per month with detected narwhal clicks was higher at the northern (inshore) stations (BB4 in August and September 2012; BB8 and BB9 in September 2013) than at other stations with detected narwhal clicks (BB3 in August 2012; BB5 and BB6 in September 2013). In 2013, the ice concentration in Baffin Bay (Fig. 8) increased in late October (station BB6) and early November (station BB10). The study area was fully ice-covered from early December 2013 until early June 2014. During fall (late September to late December) 2013, narwhal clicks were detected at the southern station (BB10) on 25 days and at the southeastern station (BB6) on 15 days (Fig. 8). Narwhals were detected at the southern station (BB10) on 55 days and at the southeastern station (BB6) on 72 days during spring (March to late June) 2014 (Fig. 8). The probability of occurrence of calls (Fig. 9) increased significantly with ice concentration for narwhals (Wald's test: $\chi^2 = 25.5$, $p < 0.001$).

Beluga whale clicks (Fig. 8) were detected at both southeastern (BB6) and southern (BB10) stations before the ice formation (October to early November 2013), during the ice formation (mid-November 2013), and in spring 2014 when the area was still ice covered (more than 90% of ice concentration).

Bearded seal calls were manually identified at the southeastern station (BB6) on one day during winter 2013 – 14 (Fig. 8). Bearded seal calls were also detected on several days during spring 2014 and peaked from early May to mid-June at both southeastern (BB6) and southern (BB10) stations (Fig. 8). The probability of occurrence of calls (Fig. 9) increased significantly with ice concentration for bearded seals (Wald's test: $\chi^2 = 73.6$, p < 0.001).

Bowhead whales were identified during manual validation analysis at the southern station (BB10) on four days in fall 2013 and spring 2014 and at the southeastern station (BB6) on two days in spring/summer 2014 (Fig. 8).

Long-finned pilot whales were manually identified on several occasions in September 2013 at the offshore stations (BB5 and BB6) (Fig. 7). They were manually detected at the southern station (BB10) during winter 2013 and at the southeastern station (BB6) during summer 2014 (Fig. 8).

In summer 2012, sperm whale clicks were detected at all stations except the nearshore one (BB4) (Fig. 7). Sperm whale clicks were detected at all stations in summer 2013 (Fig. 7). During overwinter 2013 – 14 (Fig. 8), sperm whale clicks were detected at both southeastern (BB6) and southern (BB10) stations on a few days during fall 2013 and spring/summer 2014. Sperm whales were detected before and after ice formation. The probability of occurrence of calls (Fig. 9) decreased significantly with ice concentration for sperm whales (Wald's test: $\chi^2 = 10.6$, $p = 0.001$).

DISCUSSION

Narwhals, beluga whales, bearded seals, bowhead whales, long-finned pilot whales, and sperm whales were acoustically detected off northwest Greenland. Although continuous recordings would have been ideal, the duty cycle of the majority of deployments allowed us to analyze only a portion of the acoustic data. Nevertheless, our method of analyzing many short time frames produced more accurate estimates than other methods (Thomisch et al., 2013). This technique has been found to be particularly effective for species that call regularly, such as the species of interest here.

Narwhals were detected in spring and fall, showing a south-north migration pattern in spring and a north-south migration pattern in fall. During the open-water period (July to September), narwhals were detected mainly at the more inshore stations. Similarly, Dietz and Heide-Jørgensen (1995) reported that during the open-water period, narwhals equipped with satellite transmitters were frequently found close to shore and glaciers within the Melville Bay Wildlife Sanctuary. In fall, narwhals move to the southern overwintering ground, a localized area of 23 125 km² in central Baffin Bay, where they reside from November through April (Dietz et al., 2001; Heide-Jørgensen et al., 2003a). Heide-Jørgensen et al. (1993) sighted narwhals along the western Greenland coast in March and April, primarily in the deep water at the southern entrance to Disko Bay. Our findings suggest that they pass through this area before returning to the summering grounds in June or July, when the sea ice opens (Heide-Jørgensen et al., 2003c).

The detection period of beluga whale clicks during fall 2013 was very short and suggests a southward migration through Baffin Bay. Beluga whales from the Canadian High Arctic are known to migrate southward along the northwestern Greenland coast through Baffin Bay in September – November (Doidge and Finley, 1993; Heide-Jørgensen, 1994). Previous studies have revealed that a large number of tagged beluga whales actually overwinter in the North Water polynya (northwest Baffin Bay and Smith Sound) (Richard et al., 2001; Heide-Jørgensen et al., 2003c). Beluga whales have been found in a range of ice types (Moore et al., 2000; Suydam et al., 2001), but they avoid dense pack ice (Barber et al., 2001) by overwintering in open-water polynyas or loose ice (Richard et al., 2001; Heide-Jørgensen et al., 2003c). Our beluga whale detections from April to late May in 90% ice cover were therefore unexpected. It is generally assumed that most beluga whales overwintering in the North Water polynya move toward the southwest to the mouth of Lancaster Sound in April and early May (Koski et al., 2002) in order to summer in the Canadian Arctic Archipelago (Richard et al., 2001). Even though beluga whales are seen occasionally in spring and summer on the Greenland side of the North Water polynya (Heide-Jørgensen et al., 2013a), it is most probable that the beluga whales detected in the present study during spring
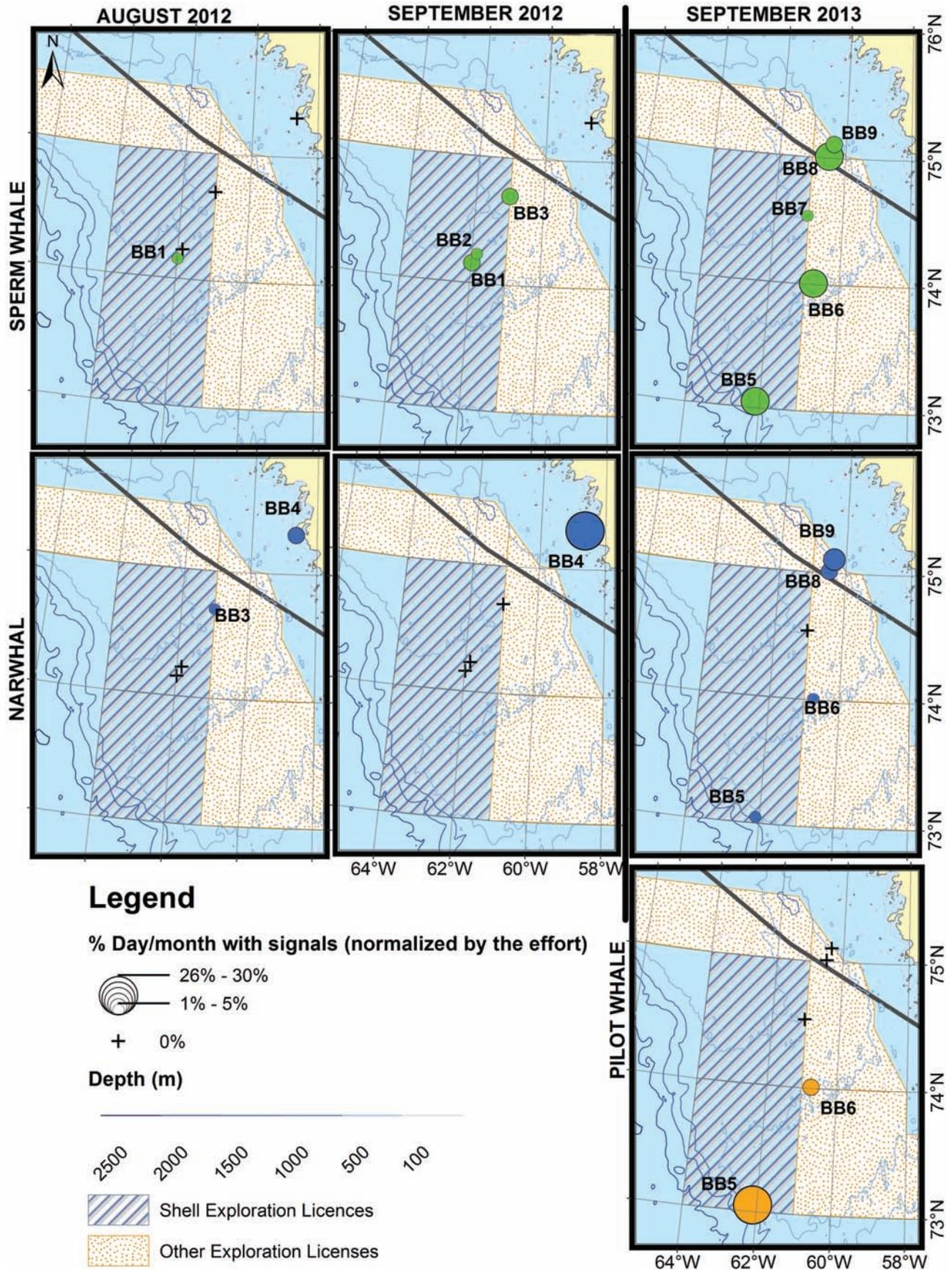
FIG. 7. Percentage of recording days per month (normalized by effort) during which marine mammal calls were detected (from sperm whales, narwhals, and pilot whales) in August 2012, September 2012, and September 2013. The plus sign (+) indicates 0%.
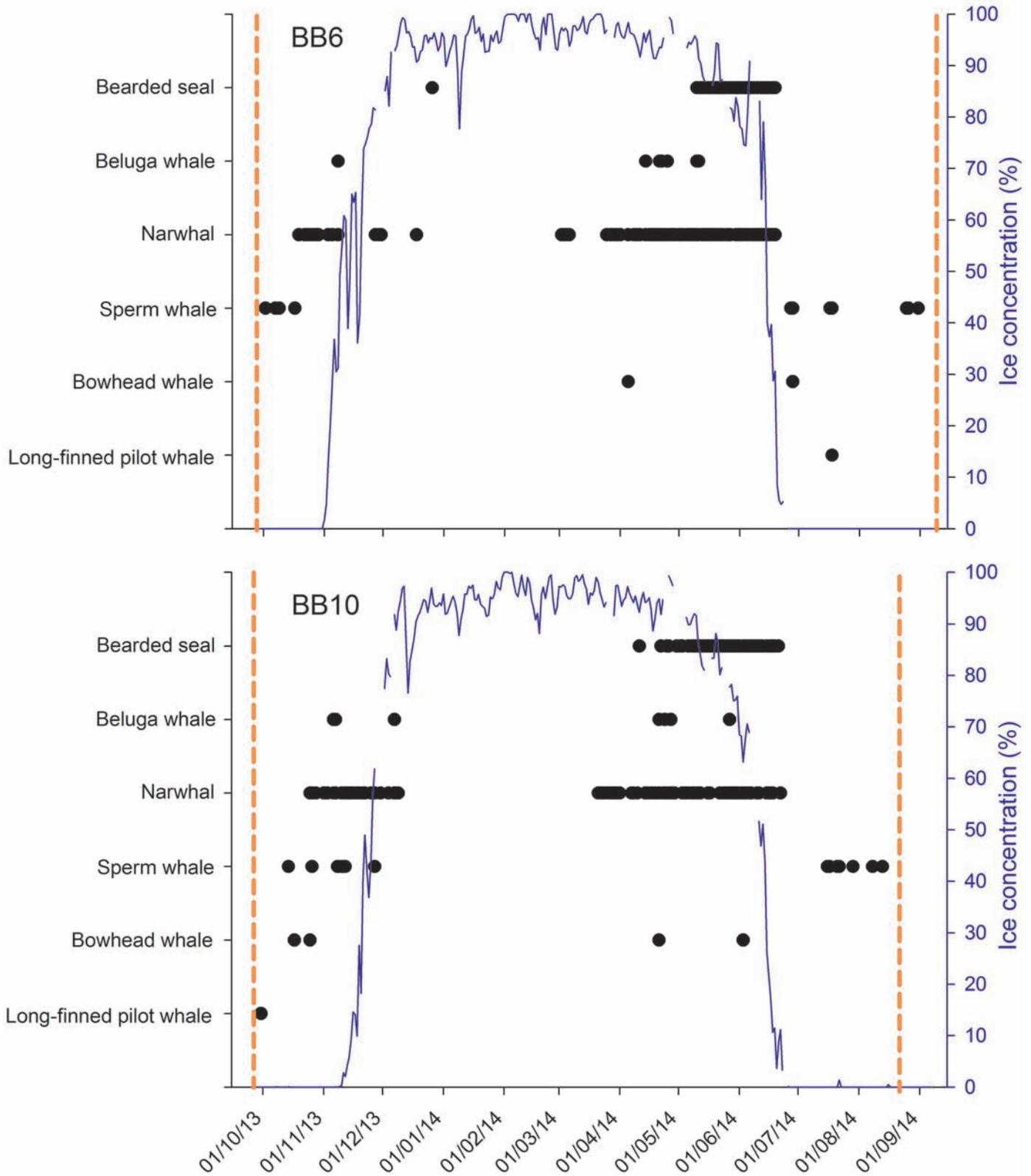
FIG. 8. Acoustical detections of marine mammals at stations BB6 and BB10, September 2013 to September 2014. Species detected are shown on left vertical axis. Black dots indicate detections; orange dashed lines, start and end times of recordings; and blue line, the temporal variation of sea ice concentration over the recording site. Ice scale is on the right axis.
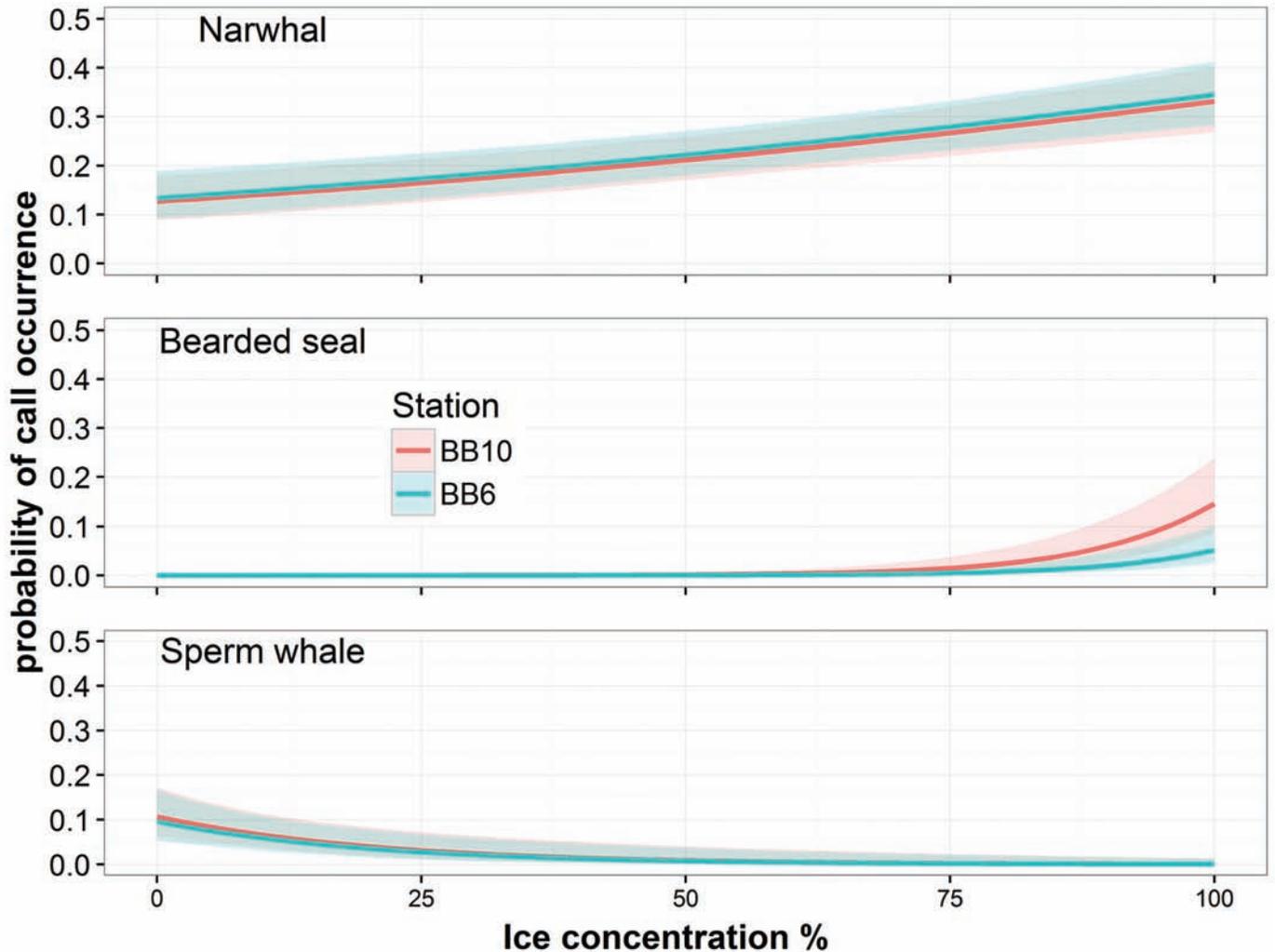
FIG. 9. Estimated relationship between the probability of call occurrence and the ice concentration for narwhals, bearded seals, and sperm whales (from observations at stations BB6 and BB10 over the winter of 2013–14).

2014 were en route to the Canadian summering grounds in the High Arctic.

Bearded seals were detected mainly during spring, which coincides with their mating season (Cleator et al., 1989). The absence of call detections in our data while bearded seals were visually observed in the vicinity of our recorders in August to October 2013 confirms that this species is vocally active during the mating period, but less loquacious at other times of year (Frouin-Mouy et al., 2016). We observed a trill (Fig. 4B) similar to the Canadian High Arctic trill labeled HCA3(T) by Risch et al. (2007). Interestingly, a patterned sequence was recorded in our overwinter database. This sequence is composed of one long downsweep followed by three short downsweeps (cf. Fig. 4B). During a spring survey, Heide-Jørgensen et al. (2013a) detected bearded seals on ice floes and along the ice edge, primarily over shallow water in the eastern part of the North Water polynya. Also of interest, stations BB10 and BB6 were located in deep waters (1000 m and 575 m, respectively), suggesting that the bearded seal distribution in Baffin Bay is not limited to shallow areas,

as previously reported (Kovacs et al., 2011). Finley and Renaud (1980) reported that during a survey along the east coast of Ellesmere Island, Canadian Arctic Archipelago, more than 50% of bearded seals observed were in areas where the water depth exceeded 500 m. Other seal species were visually observed as well, but our detectors were not configured to detect their calls.

Few bowhead whales were detected during fall 2013 and spring and summer 2014. Their distribution is likely driven largely by migration patterns. Previous studies on movements of the Eastern Canada–West Greenland bowhead whale population show that these animals are widely distributed throughout the eastern Canadian Arctic and West Greenland, where they perform long seasonal migrations (Heide-Jørgensen et al., 2003b). They overwinter in Hudson Strait, Cumberland Sound, West Greenland, and the North Water polynya (Ferguson et al., 2010). In spring, they inhabit the west coast of Greenland (particularly Disko Bay, Tervo et al., 2009), Cumberland Sound, Foxe Basin, and Lancaster Sound in Canada (Ferguson et al., 2010). Their summer range includes the fjords and bays

of the Canadian High Arctic, Hudson Bay, and Foxe Basin (Cosens et al., 1997). Bowhead whales use a wide range of habitats, suggesting flexible use of foraging areas (Nielsen et al., 2015), and this species may be expanding its distribution, as suggested by its recent presence in the Northwest Passage (Heide-Jørgensen et al., 2011). Recent satellite-tracking studies (tagging in 2008–10) showed that bowhead whales moved out of the Disko Bay area between late May and early June (Laidre and Heide-Jørgensen, 2012) and then followed the continental shelf off West Greenland northward towards the northern part of Baffin Bay (Nielsen et al., 2015). Those observations are in agreement with bowhead detections in 2014 at stations BB10 and BB6 in early and late June, but they do not explain the detections in April.

The presence of long-finned pilot whales along Baffin Bay has not been reported in the literature to date; however, in an aerial line transect survey conducted off northwest Greenland during August to September 2007, these whales were observed southwest of Greenland between 65° N and 68° N (Heide-Jørgensen et al., 2013b). In the present acoustic data, long-finned pilot whales were detected on several occasions at two offshore stations (BB5 and BB6; September 2013) and at the southern station (BB10) during fall 2013 (30 September, which matches visual observations of 100 individuals that day). Heide-Jørgensen et al. (2013b) mentioned that long-finned pilot whale sightings and catches were reported along the coast of Greenland from Qaqortoq to Upernavik between May and October, which suggests a summer-winter movement resulting from the spring bloom of primary production and subsequent prey abundance. Heide-Jørgensen et al. (2013b) observed that long-finned pilot whales were present in deep offshore waters, with a preference for depths between 300 and 2000 m and at least 30 km from land. His observation suggests that pilot whales, whether traveling or foraging, are usually not found on the Greenlandic shelf, but primarily in the deeper waters beyond the shelf. Interestingly, long-finned pilot whales were most acoustically active in September 2013 at station BB5. This station is at the shelf edge, where upwelling may augment primary productivity. In long-finned pilot whales, vocal activity increases during foraging periods, with greater numbers of most whistle types produced when whales are spread over a larger area (Weilgart and Whitehead, 1990). Our results demonstrate that long-finned pilot whales are present in the northern part of Baffin Bay at certain times of the year and are more acoustically active at the Greenlandic shelf edge, which suggests that their preferred prey may be there as well.

Our results also indicate that sperm whales were present in Baffin Bay farther north than has been previously reported in the literature. On leaving their female relatives, which almost always inhabit waters deeper than 1000 m at latitudes of less than 40°, the males gradually move to higher latitudes: the larger and older the male, the higher the average latitude (Whitehead, 2002). Sperm whales have been reported to inhabit northern waters such as the Gulf of Alaska (Mellinger et al., 2004) and the Norwegian Sea (Christensen et al., 1992; Madsen et al., 2002) during summer. In the present acoustic dataset, sperm whales were detected in August and September 2012 and from September to November 2013, before sea ice had covered stations BB6 and BB10. They were also detected sporadically in summer 2014 from late June to late August, after the sea ice had disappeared.

The detection of sperm whales in our data may be explained, at least partially, by the distribution of their prey. Kawakami (1980) reviews studies of sperm whale diets and found that in most areas cephalopods (squid and octopods) form the bulk of their food source. The boreoatlantic armhook squid (*Gonatus fabricii*) is the most abundant squid in Arctic and sub-Arctic waters of the North Atlantic (Gardiner and Dick, 2010). Because of its importance as food for sperm whales, Bjørke (2001) suggests that the distribution of the boreoatlantic armhook squid can, to a great extent, explain the presence of sperm whales in the Norwegian Sea. Boreoatlantic armhook squid adults are common in oceanic mid-water, while juveniles occur in surface waters closer to the continents (Piatkowski and Wieland, 1993). During summer, many juveniles occur in Davis Strait. Hatching begins off Kap Farvel at the end of April, and juveniles are transported up the West Greenland coast by prevailing currents (Kristensen, 1984). They have been reported in our study area (Gardiner and Dick, 2010). In Disko Bay, boreoatlantic armhook squid are believed to hatch in autumn and early winter (Kristensen, 1984).

Given the relative paucity of marine mammal sighting data in Baffin Bay during the non-summer months, passive acoustic monitoring is a good tool to learn about the seasonal and interannual movements of marine mammals in this remote area. The present study, which documents the spatial and temporal distribution of several marine mammal species in Baffin Bay, helps identify the use of the oil and gas license areas by marine mammal populations. Year-round data collection provided baseline patterns of species occurrence to help gauge the management (mitigation) efforts needed in this area. Spring and fall detections of narwhals in the license area suggest that narwhals use the area for migrations. Few detections of beluga whales in spring suggest that they migrate through the project area without pausing to forage. Unsurprisingly, bearded seal vocalizations dominated the soundscape during the mid-May to mid-June breeding season. Bowhead whales were detected sporadically in spring, which agrees with our understanding of a highly variable spring migration of these whales. Long-finned pilot whale calls were present along the southern continental shelf edge of the study area in August and September; this location is significantly north of previous reports of long-finned pilot whale distribution. Detections of sperm whales were unexpected and extend the range of sperm whales significantly north of previous reports; however, the presence of known sperm whale prey species suggests that these detections are reasonable.

ACKNOWLEDGEMENTS

APPENDIX 1

The following tables are available in a supplementary file to the online version of this article at:

http://arctic.journalhosting.ucalgary.ca/arctic/index/php/arctic/rt/suppFiles/4632/0

TABLE S1. Summer 2013 thresholds for detections with the precision (P), recall (R), and F-score (F) before the threshold is applied (original) and afterwards (threshold).

TABLE S2. Overwinter 2013 – 14 thresholds for detections with the precision (P), recall (R), and F-score (F) before the threshold is applied (original) and afterwards (threshold).

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