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The underwater soundscape in western Fram Strait: Breeding ground of Spitsbergen's endangered bowhead whales

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ABSTRACT

In the Arctic, warming and concomitant reductions in sea ice will affect the underwater soundscape, with the greatest changes likely being linked to anthropogenic activities. In this study, an acoustic recorder deployed on an oceanographic mooring in western Fram Strait documented the soundscape of this area, which is important habitat for the Critically Endangered Spitsbergen bowhead whale population. The soundscape was quasi-pristine much of the year, with low numbers of ships traversing the area. However, during summer/autumn, signals from airgun surveys were detected > 12 h/day. Mean received peak-to-peak SPLs for loud airgun pulses reached 160.46 ± 0.48 dB 1 μPa when seismic-survey ships were close (at ~57 km). Bowhead whales were present almost daily October–April in all years, with singing occurring in almost every hour November–March. Currently, loud anthropogenic sound sources do not temporally overlap the peak period of bowhead singing. This study provides important baseline data for future monitoring.

1. Introduction

The marine soundscape consists of both natural and anthropogenic sound sources. It can be divided into sounds resulting from natural physical processes (e.g. wind, rainfall, waves, ice ridging and breakup, and seismicity), biotic sources (e.g. marine mammals, fish and crustaceans) and sounds from anthropogenic sources (e.g. shipping, sonars, and oil and gas exploration) (Hildebrand, 2009). Acoustic characterisation and monitoring of marine environments is becoming a major focus for many science and management bodies, including the European Union, due to the importance of sound to marine life (i.e. The European Parliament and the Council of the European Union, 2008; Hildebrand, 2009; Boyd et al., 2011; Van der Schaar et al., 2014; Garrett et al., 2016). Sound can travel through water across vastly greater ranges than light and marine organisms have evolved to exploit this characteristic of their environment (Hildebrand, 2009; Williams et al., 2015). Marine mammals, fishes and other soniferous organisms use sound for orientation, navigation, feeding, communication and other social interactions. Human-generated noise is becoming more pervasive in many ocean acoustic environments, in direct-correlation with increasing industrialisation of the ocean (Andrew et al., 2011; Boyd et al., 2011). Anthropogenic ocean noise is now recognised as a significant pollutant that can affect behaviour, energetics and physiology of acoustically sensitive marine species, particularly marine mammals (Rolland et al., 2012; Williams et al., 2014, 2015; Blair et al., 2016). Although some of these effects are acute and rare, chronic sublethal effects may be equally or more important (Clark et al., 2009; Hatch et al., 2012). Characterisation of underwater sound levels (both natural and anthropogenic) and their distribution relative to the location and movements of marine mammals is essential for understanding the potential impacts of anthropogenic noise on these animals (Reeves et al., 2014; Rice et al., 2014). Currently, management of underwater noise pollution is constrained markedly by a lack of baseline data on ambient sound levels (Merchant et al., 2016).

In the Arctic, the sounds of ridging, break up and melting of sea ice are the abiotic sounds that often dominate the underwater soundscape (Milne and Ganton, 1964; Lewis and Denner, 1988; Farmer and Xie, 1989; Kinda et al., 2013). Ice sounds cover a broad range of frequencies from < 10 Hz to > 10 kHz (Mikhalevsky, 2001; Keogh and Blondel, 2009). Wind-created noise from breaking waves is the most prevalent source of sound in most of the world's oceans; it occurs at frequencies between 100 Hz and 20 kHz, typically peaking around 500 Hz (Knudsen et al., 1948; Wenz, 1962; Cato and Tavener, 1997). In the Arctic, this source of noise only influences sound levels in the marginal

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ice zone and in open water areas, since the presence of sea ice dampens wave formation. Biotic sounds that dominate the soundscape of the Arctic are primarily emitted by marine mammals.

Until recently, the Arctic has been relatively free of anthropogenic underwater noise because the seasonal presence of extensive areas of sea ice has restricted access by commercial operations within the Arctic. However, the Arctic is warming and sea ice cover is declining markedly, and thus the Arctic soundscape is expected to change (Kinda et al., 2013; Geyer et al., 2016). These changes will in part be due to increases in wind noise in the water column and sounds emitted by temperate species shifting their distributions northwards, but the greatest change will likely be due to increased noise arising from industrial development and commercial shipping. Increasing observations suggest that Arctic endemic cetaceans (white whales, *Delphinapterus leucas*, narwhals, *Monodon monoceros*, and bowhead whales, *Balaena mysticetus*) may be especially sensitive to anthropogenic underwater noise such as shipping and airgun seismic surveys (Finley et al., 1990; Cosens and Dueck, 1993; Richardson et al., 1995; Lesage et al., 1999; Blackwell et al., 2010, 2015; Heide-Jørgensen et al., 2013).

The bowhead whale is the only baleen whale that lives year round in Arctic waters (Niebauer and Schell, 1993; Ferguson et al., 2010; Seim et al., 2014). One of the four populations of bowhead whales, the Spitsbergen stock, is listed by the IUCN as Critically Endangered (Heide-Jørgensen et al., 2006; Reilly et al., 2012). Fram Strait, located between Greenland and Svalbard, was historically a core-use area for this population (Woodby and Botkin, 1993; Korte and Belikov, 1994), and most of the recent sightings in the region have been reported from the western parts of this area (Wiig et al., 2007, 2010). However, the presence of heavy Arctic sea ice in western Fram Strait, even during summer months, makes visual surveys and abundance estimates difficult. However, bowhead whales are vocally active throughout the year, which makes this species a good candidate for acoustic monitoring (Ljungblad et al., 1982; Würsig and Clark, 1993; but see Wiig et al., 2007). In recent years Passive Acoustic Monitoring (PAM) technology has proven to be a very efficient way to obtain year-round information on the distribution and seasonal occurrence of many difficult-to-study Arctic species (e.g. Moore et al., 2012; Stafford et al., 2012; MacIntyre et al., 2015; Marcoux et al., 2016). Acoustic recordings during 2008–2009 suggested that western Fram Strait was an important wintering ground (and thus a mating area) for the Spitsbergen stock of bowhead whales (Stafford et al., 2012).

Large vessels, as well as oil and gas exploration (including seismic airgun pulses and drilling machinery) are sources of high levels of low-frequency (< 1000 Hz) sounds in the ocean (Richardson et al., 1995; Wilcock et al., 2014). Such low-frequency anthropogenic sounds are believed to be problematic for bowhead whales because they overlap with the frequencies that are emitted and perceived by these whales. The impact of seismic airgun pulses on bowhead whale behaviour has been studied since the mid-1980s. These whales generally avoid areas with seismic operations and reduce their respiration rates and alter their time at the surface and their calling rates when in areas with seismic blasts (Richardson et al., 1986, 1995; Blackwell et al., 2013, 2015). The long-term population-level effects of these kinds of behavioural changes are unknown (Ellison et al., 2016).

Given the projected increase in anthropogenic activity in the High Artic and the importance of western Fram Strait for the Spitsbergen stock of bowhead whales, an understanding of spatial and temporal trends of both anthropogenic and natural sound sources is needed (Reeves et al., 2014). Baseline knowledge of historical and current sound levels along with long-term monitoring programs are required to track future changes in ocean noise and to mitigate against negative impacts on biota through area-based management (Hildebrand, 2009; Merchant et al., 2016). The purpose of the present study was to (i) characterise the current soundscape and document sound sources in the western Fram Strait (ii) examine the presence of airguns, ships, and bowhead whales by season and year to determine the extent of overlap of anthropogenic sound sources with bowhead whales and (iii) provide estimates of the recent annual ambient sound levels, which can be used as a basis for future long-term monitoring.

2. Materials and methods

2.1. Instrumentation and deployment location

An autonomous underwater acoustic recorder (AURAL M2, Multi-Électronique Inc.; system sensitivity of − 155 dB re 1 V/μPa and flat response from 5 to 30 kHz) was deployed on an oceanographic mooring located in western Fram Strait (Fig. 3) over a six year period, during which four years of data were retrieved: 2008–09, 2010–11, 2012–13 and 2013–14. The 2009–2010 deployment was lost when it was pulled off the bottom by ice-bergs and the 2011–2012 deployment experienced technical failure. The mooring (maintained by the Norwegian Polar Institute, see www.npolar.no/framstrait) is situated in the core of the southward flowing East Greenland Current (EGC) at roughly 78°50°′N, 5°W, in western Fram Strait, at a bottom depth of 1015 m on the continental shelf slope. The AURAL recorder was installed at a depth of 70–80 m. Thus, it was placed in the cold and somewhat fresh Polar Water which is exported from the Arctic via the EGC. At times warm eddies pass by the location, originating from the Polar Front between the cold Polar Water and the warm Atlantic Water that recirculates in Fram Strait. The EGC at this latitude is covered with heavy sea ice which is exported from the Arctic Ocean year-round, however, between June–October the sea ice concentration is usually < 100%.

Sampling rate, duty cycle and recording time varied somewhat between years; full deployment details of the recorder are presented in Table 1. Because battery life is a major limiting factor for these instruments, the longer duty cycle used during 2012–13 and 2013–2014 resulted in shorter data collection periods. Even though the 2008–2009 data were used in previous studies (Moore et al., 2012; Stafford et al., 2012), they were re-analysed and included in this study to provide a longer time-series for studying potential inter-annual changes in the soundscape.

2.2. Seasonal presence of bowhead whales and airguns

All sound files were examined for the presence of sounds produced by bowhead whales and airguns each year. Each file was displayed as a spectrogram and screened visually for these sounds. The following spectrogram settings were applied: for bowhead whales - a Fast Fourier Transform (FFT) with a window length of 2048/4096 data points, 75%

Table 1
Summary information for the deployment of an autonomous underwater recorder (AURAL) in western Fram Strait between 2008 and 2014. During 2012–13 and 2013–14, longer duty cycle resulted in shorter data collection period as the battery of the device was depleted over a shorter term.

Location	Year	Data collection period	Coordinates	Recorder depth (m)	Water depth (m)	Sampling rate (Hz)	Duty cycle
Fram Strait	2008–09	20.09.2008–11.09.2009	78°49.885N, 4°59.074W	82	1021	8192	9 min/30 min
	2010–11	25.09.2010–26.08.2011	78°50.191N, 5°00.692W	75	1017	16,384	14 min/h
	2012–13	02.09.2012–11.04.2013	78°47.972N, 4°59.2W	75	1014	32,768	17 min/h
	2013–14	08.09.2013–27.04.2014	78°50.038N, 4°59.591W	76	1015	32,768	17 min/h

overlap and Hanning window; and for airguns – a FFT with a window length of 8192/16384 data points, 50% overlap and Hanning window. If the visual inspection did not give unambiguous results, the corresponding sound files were listened to in order to classify the sounds. When possible, a distinction was made between recordings of bowhead whale song vs simple calls; the former can have energy up to 5 kHz while the latter tends to be under 500 Hz (Würsig and Clark, 1993; Stafford et al., 2012).

2.3. Ship location data

Data from the Automatic Identification System (AIS) for ships, consisting of ship identification number, geographic position and time of position, were sourced from The Norwegian Coastal Administration (Kystverket; www.kystverket.no) for 2013 and 2014 (data were not available for previous years) to examine the contribution of ships to the soundscape of the region. AIS data were obtained for AURAL sampling periods (first period: 1 January 2013–11 April 2013 and second period: September 2013–27 April 2014) and also for a full year period (1 September 2013–30 August 2014) to examine how ship traffic varies across seasons. The number of ships within 20, 60 and 150 km of the mooring site were documented.

2.4. Soundscape analysis

Power spectral densities (PSDs) were computed at 1-Hz resolution for 120 s spectral averages (using 50% overlap and Hanning window) to examine overall inter-annual variation in the sound spectrum. PSDs were calculated for the frequency band 10–8000 Hz (10–4000 Hz for 2008–09 data). Data analyses were carried out with the program AMBSTAT (Jasco Applied Sciences). Percentile levels (5, 50, 95) were plotted across the frequency spectrum to assess the annual sound levels according to frequency within western Fram Strait. Furthermore, PSDs were produced for each month individually to evaluate how sound levels varied by month.

Long-term spectrograms (LTS) were used to characterise how sound level varied with time at each frequency and to identify discrete acoustic events. Temporal trends in sound level were investigated by looking at particular frequency bands (mean 10–4000 Hz, mean 100–1000 Hz, 50 Hz) over each recording period. The mean 10–4000 Hz frequency band was selected to represent the overall broadband sound levels for each recording period. The mean 100–1000 Hz frequency band reflected bowhead whale vocalisations and the 50 Hz frequency band was the sound level reflecting airgun signals. All sound sources detected in the long-term spectrograms (both biological and anthropogenic) were further investigated and identified by visual inspection and/or by listening to the sound files.

Arithmetic means were calculated for the 1/3-Octave Level (TOL) bands centred at 63 Hz and 125 Hz to provide metrics as defined by the European Union Marine Strategy Framework Directive (2008/56/EC) for ambient noise monitoring, in particular for low-frequency continuous sound where the focus is shipping noise (Dekeling et al., 2013; Tasker et al., 2010). Two higher frequency bands were also explored: 250 Hz and 500 Hz (following Merchant et al., 2016) because these bands have been associated with broadband shipping noise (Merchant et al., 2014). Noise levels created by airguns were also of interest in this study, so the standard fifth TOL frequency band (50 Hz) was included in these analyses. All TOL band analyses were carried out in PAMGuide (Merchant et al., 2015). In addition to arithmetic means, three percentile levels (exceedance levels) were calculated for each frequency band, 5th, 50th and 95th (i.e. Van der Graaf et al., 2012). Sound levels were compared between seasons (Autumn: September–November; Winter: December–February; Spring: March–May; Summer: June–August) and recording periods.

2.5. Environmental data

Satellite-derived and in-situ environmental data were included in the analyses to characterise the soundscape and evaluate the possible contributions of natural physical processes to sound levels. Since the recorder was placed on an oceanographic mooring that is part of the Arctic Outflow Observatory, in-situ current speed measurements were available. Ocean currents on their own are not noisy, however moorings produce self-noise (strumming) in the presence of currents as a result of vibrating and moving metal parts such as chains and joints (Erbe et al., 2015). Even though the mooring was designed to minimise this noise, some strumming was detected in the recordings. Additionally, water flow past the hydrophone creates pressure fluctuations that are not of acoustic origin. This flow noise usually occurs at low frequencies (tens of Hz), but can extend to hundreds of Hz during periods with strong currents (Strasberg, 1979). Even though flow noise is not part of the soundscape, it appears in spectrograms and needs to be taken into consideration when investigating sound levels.

Daily sea ice concentration data (12.5 km^2 resolution through 10/2011, 25 km^2 thereafter) were downloaded from the U.S. National Snow & Ice Data Center for each year (Cavalieri et al., 2014). The zonal statistics toolbox in ArcMap 10.0 (ESRI 2011. ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute) was used to determine mean daily sea ice concentration within a 30-km radius around the mooring location. The 4-times daily surface wind data produced by NOAA's National Centers for Environmental Prediction (NCEP) were downloaded via NOAA's Climate Diagnostics Center (Kalnay et al., 1996; https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surface.html) and subsequently processed in MatLab for each recording period.

3. Results

3.1. Annual and seasonal presence of identifiable biotic and anthropogenic sounds

3.1.1. Sounds from bowhead whales and other marine mammals

Signals produced by bowhead whales were highly seasonal. They were detected almost daily from October through until April in all years, with significantly fewer detections in the period May–July (Fig. 1A). The number of hours/day with detections varied somewhat between years. For example, in 2010–11 there were fewer hours with bowhead signals in March and April when compared to the other three years, and 2013–14 had the greatest number of hours with bowhead sounds overall (Fig. 1A). However, for all recording periods singing increased from the beginning of November and continued almost constantly until mid/end of March. During April, singing declined and only simple calls were detected during the summer months of 2011 and no calling was detected in these months in 2009 (2013 and 2014 have no data for these months).

During the screening of sound files for bowhead whales, acoustic signals from other marine mammals were also identified but only the 20 Hz signals of fin whales (*Balaenoptera physalus*) were evident in the PSDs and LTSs (see more detailed results below). These signals dominated the lower frequencies of the soundscape between September and March. The acoustic detections of other marine mammals were opportunistic and therefore their presence is reported here only as a marine mammal species inventory of the area. For all recording periods, bearded seal (*Erignathus barbatus*) vocalisations were detected during the spring (March–June), narwhal (*Monodon monoceros*) vocalisations and echolocation clicks were recorded almost year-round and some blue whale (*Balaenoptera musculus*) calls were recorded during summer and autumn.

3.1.2. Anthropogenic sounds: airguns and ship traffic

Airgun signals from seismic operations were recorded in every

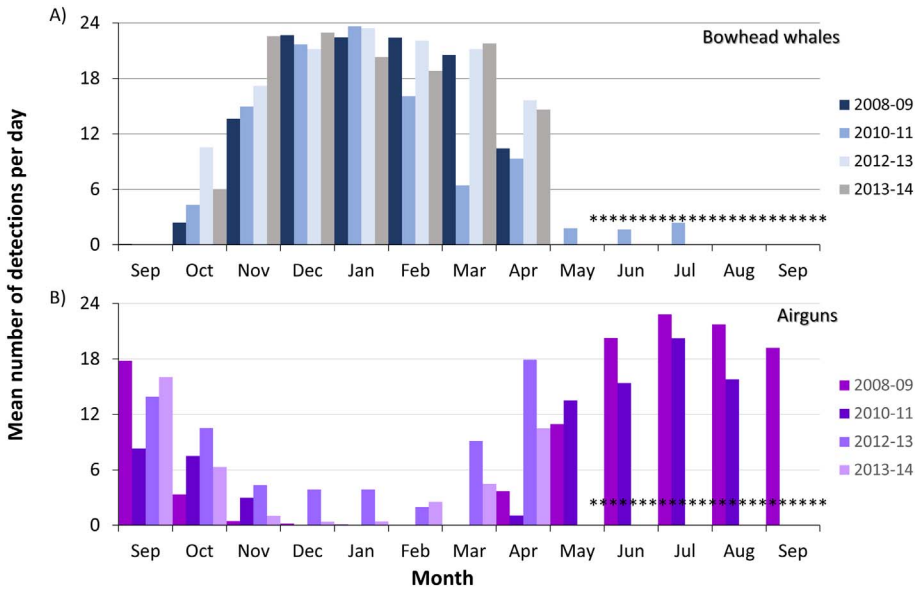

Fig. 1. Mean number of hours per day by month with A) bowhead whale sounds and B) airgun pulses for four years. Stars indicate missing data from May–August in both 2013 and 2014 and September 2011 and 2014 (See Table 1).

available month in some years. However, there were strong seasonal patterns within years (Fig. 1B). For 2008–09 and 2010–11 there were no airgun signals recorded during most winter months (February–March for 2008–09 and December–March for 2010–11). During all summer-months seismic signals were detected > 12 h per day, and in June, July, August and September of 2008 the number of hrs per day with detections exceeded 18 h per day on average. The detection prevalence and signal strength of the airgun pulses varied within recording periods. Airgun detections were more frequent (96–100% of days/month with detection) and the signals were stronger during the summer and autumn months for all years. The majority of the airgun signals detected were faint, low frequency (< 150 Hz) signals, most likely originating from distant seismic surveys (possibly > 1000 km away, Nieukirk et al., 2004).

AIS data records suggest that little ship traffic occurs in the vicinity of the mooring where the AURAL was deployed. The closest ship approach was 123 km away from the recorder in the first period from January to April 2013 (Norwegian Polar Institute (NPI) research vessel RV *Lance* during 19–20 March 2013). Furthermore, only two other vessels were registered within 150 km of the recorder during this period. During the second period from September 2013 to April 2014, one vessel was registered within 20 km of the recorder (Figs. 2, 3). This was again RV *Lance*, the ship that deployed the oceanographic mooring with the recorder (closest registered approach was 118 m on the day of the deployment). Three additional ships were registered within 60 km of the recorder. Even at a 150 km distance from the recorder only six ships in total were detected, indicating that boat traffic is not common in this region at present. All vessel registrations within 150 km from the recorder occurred between September and October.

Investigation of a year-round (1 September 2013 to 30 August 2014) AIS data-stream showed that the number of vessels was, unsurprisingly, higher in the summer period than during winter. Ships within 150 km of the recorder were registered during May, June, July and August, in addition to already reported September and October (Fig. 2). Nevertheless, regardless of the season, ship traffic in western Fram Strait is very limited. The AIS data clearly show that most vessel activities in the wider region take place far to the east of the mooring location, close to Svalbard (> 300 km away). However, the AIS data also revealed that one of the vessels operating near the recorder during September–October 2013 was a seismic survey vessel (green line and grid in Fig. 3). The closest point of approach to the mooring by this vessel was 57 km on 27 September 2013. This survey vessel was within 100 km of the recorder between 27 September and 1 October, within 150 km from 14 September to 3 October and within 200 km between 8 September and 8 October.

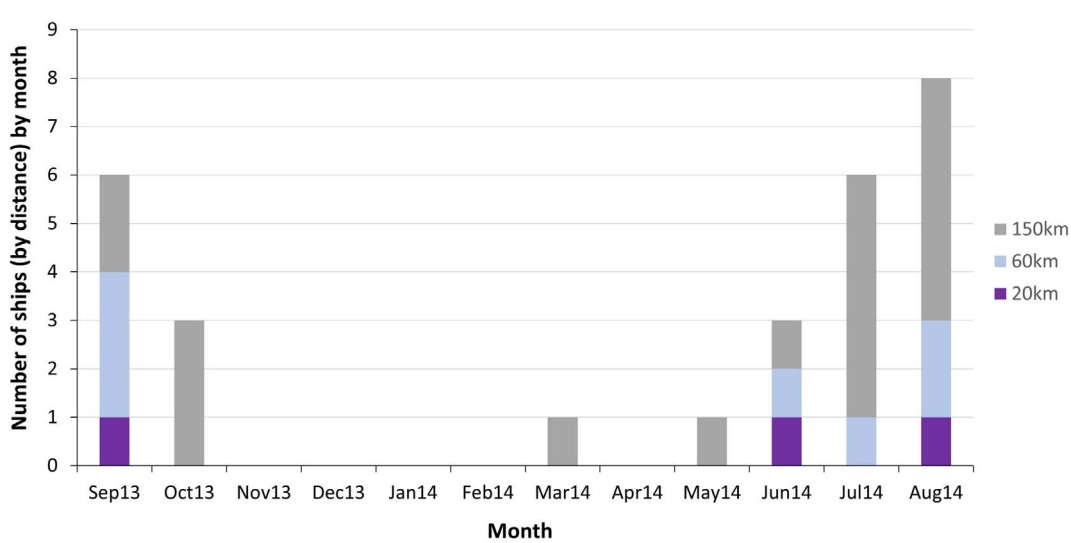

Fig. 2. Number of ships (by distance) by month within 150 km of the acoustic recorder in western Fram Strait from September 2013 to August 2014.

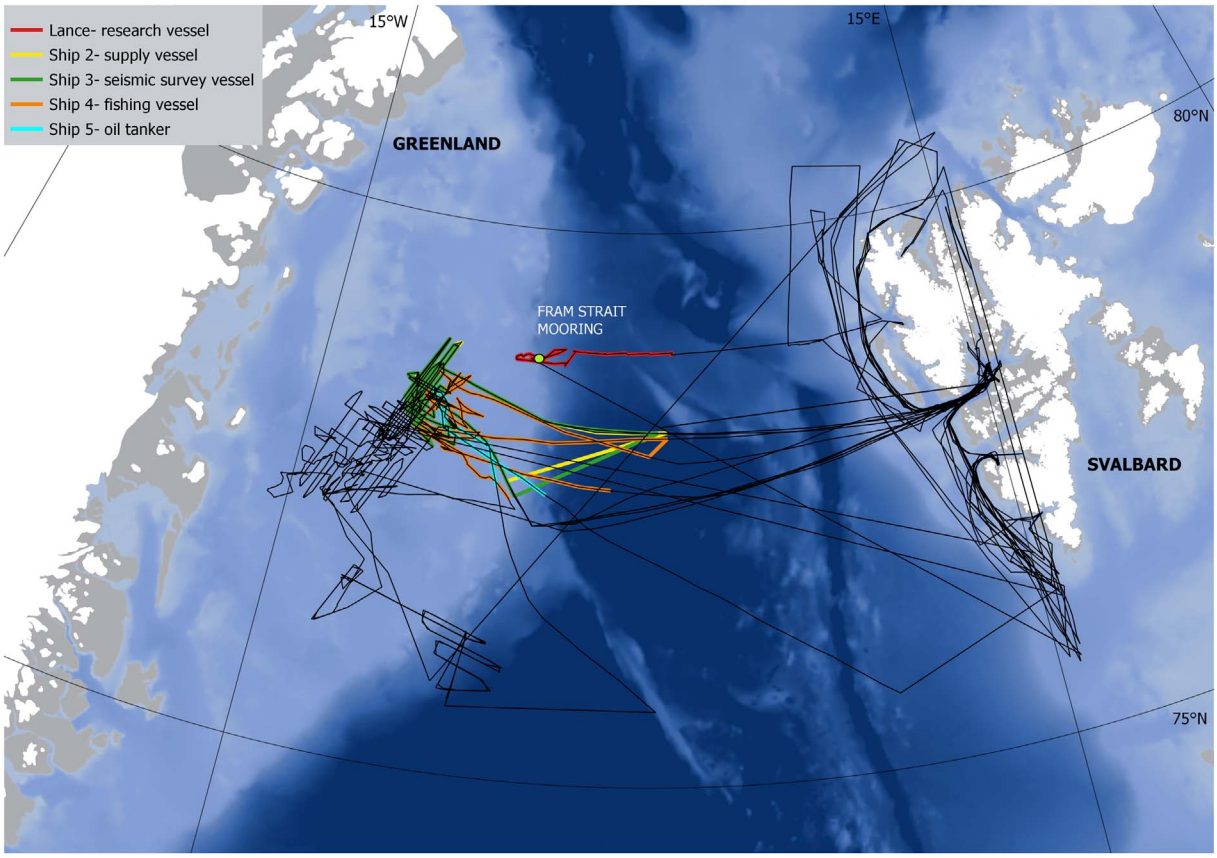

Fig. 3. Tracks of five vessels that passed the recorder within 150 km between September 2013 and April 2014. Each vessel track is colour-coded when the vessel was within 150 km from the recorder. Location of the oceanographic mooring instrumented with an autonomous recorder can be seen as green circle. Different shades of blue indicate different water depths. Only five out of six recorded vessels had enough location points to create track. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The only time period for which concurrent AIS data with ships in the region (within 100 km), and ambient noise data from the AURAL were available was September and October 2013. However, potential effects of passing vessel noise on the soundscape was difficult to assess, since all close vessel approaches occurred when the seismic survey described above was on-going. The strong airgun signals masked any sounds from other vessels, preventing analysis of ship noise in isolation. During manual screening of all sound files over the four-year period, occasional signals from possible ship engine noise could be seen, but the source or distance for these noises cannot be confirmed due to a lack of AIS data.

3.2. Characteristics of the western Fram Strait soundscape

3.2.1. Overall features

The LTSs contained acoustic signatures from seismic airguns, marine mammal vocalisations, self-noise from cable strumming/flow noise and ice noise (Fig. 4A–D). Annual LTSs were plotted with current and wind speeds and sea ice concentrations, presence of bowhead whale signals and airguns over each of the recording periods as well as signal strengths of sounds within three selected frequency bands (mean 10–4000 Hz, mean 100–1000 Hz, 50 Hz) to have a comparative overview of the soundscape in each study year.

Decreased ice cover and increased wind and current speed increase the sound levels at the mooring site. Increases in wind speed were often correlated with higher levels of ice noise in acoustic recordings (grey ellipses in the spectrograms Fig. 4A–D). For example, in November 2012 (Fig. 4C, around 28 November) there is a clear decrease in ice cover concomitant with increases in both current and wind speeds, which increased the sound levels in all frequency bands. A good example of how increased current speed causes strumming/flow noise can be observed in September 2012 (Fig. 4C) both visually on the spectrogram (purple ellipses in spectrogram), but also increased sound levels at 50 Hz (blue line bottom panel Fig. 4C).

Hourly bowhead whale presence (within daily periods) was plotted against the LTSs. Bowhead whale singing could be seen at frequencies above ~300 Hz (red ellipses in spectrograms, Fig. 4A–D) in the winter in each recording period. In addition, signals from fin whale 20 Hz calls could be seen clearly in LTSs from September/October to February/March of each recording period (black arrows). Only strong and close airgun signals were visible in the spectrograms (black ellipses in spectrograms, Fig. 4A, B, C). The best examples of this sound source occur in September–October 2013 when a seismic survey was conducted close to the mooring (Fig. 4D). At times, these stronger signals were masked by ice noise and noise from cable strumming (orange boxes in spectrograms, Fig. 4A and B).

3.2.2. Sound metrics for western Fram Strait 2008–2014

The overall annual distribution of sound by frequency was fairly similar among the four years of the study (Fig. 5). Overall, 2008–09 had somewhat higher median levels than the other study years. The most obvious signals in all four years were distant fin whale signals, evident as a hump at roughly 20 Hz seen in the 5th and 50th percentiles annually. In both 2008–09 and 2010–11, there is evidence of the contribution of bowhead whales in the 95th percentile values, seen as slight elevations in the sound pressure level from 150 Hz to 1 kHz. Also in 2008–09 and 2010–11, the 95th percentile values from 30 Hz to 50 Hz were slightly higher than for 2012–13 and 2013–14. This could be due to airgun signals that were detected during the summer months in 2008–09 and 2010–11. For all years sound levels were highest at low

frequencies (< 100 Hz) and decreased with increasing frequency, being much quieter above 1000 Hz.

3.2.3. Month by month assessment

Monthly PSDs were used to investigate the intra-annual variability in the soundscape (Fig. 6). Median (50th percentile) monthly PSDs revealed that the 20 Hz peak from distant fin whales was present from October to February in each recording period. This peak was also present in September 2010–11 and March 2013–14. Furthermore, the low frequency (< 100 Hz) sound levels varied over months and across recording periods (Fig. 6). Sound levels at 50 Hz were extracted and examined separately in order to assess the differences between months and recording periods in levels of low-frequency sounds that likely reflect anthropogenic noise (Table 2). The highest annual mean levels were recorded during 2010–11, followed by 2008–2009, 2013–14 and 2012–13, respectively. The monthly variation within recording periods was relatively large (between 12 and 16.7 dB). In general, the highest sound levels at 50 Hz were associated with the presence of strong

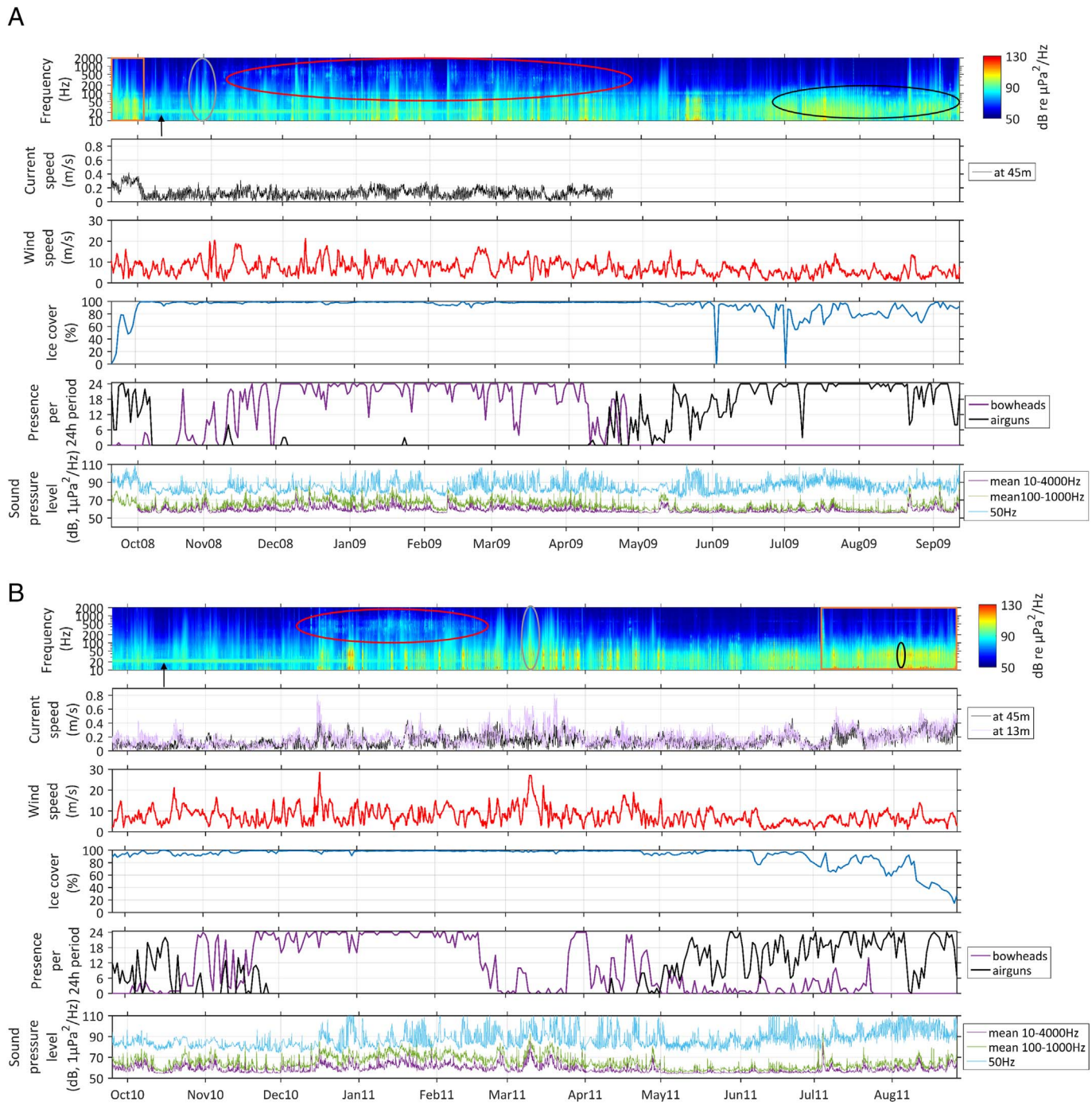

Fig. 4. Long-term spectrograms for A) 2008–09, B) 2010–11, C) 2012–13 and D) 2013–14 recording periods. Each spectrogram is plotted with current and wind speed, ice concentration, presence of bowhead whales and airguns over each of the recording periods as well as mean 10–4000 Hz, mean 100–1000 Hz, 50 Hz frequency bands. Red ellipses indicate signals from bowhead whale singing, black ellipses strong airguns signals, purple ellipses noise from cable strumming/flow noise, grey ellipses ice noise and black arrows fin whale 20 Hz pulse calls. Orange boxes in LTSs for 2008–09 and 2010–11 demonstrate times when stronger airgun signals are masked by ice noise and cable strumming. Current speed data were only available for 7 months at 45 m in 2008–09; no current data was available for 2013–14 due to equipment failure. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

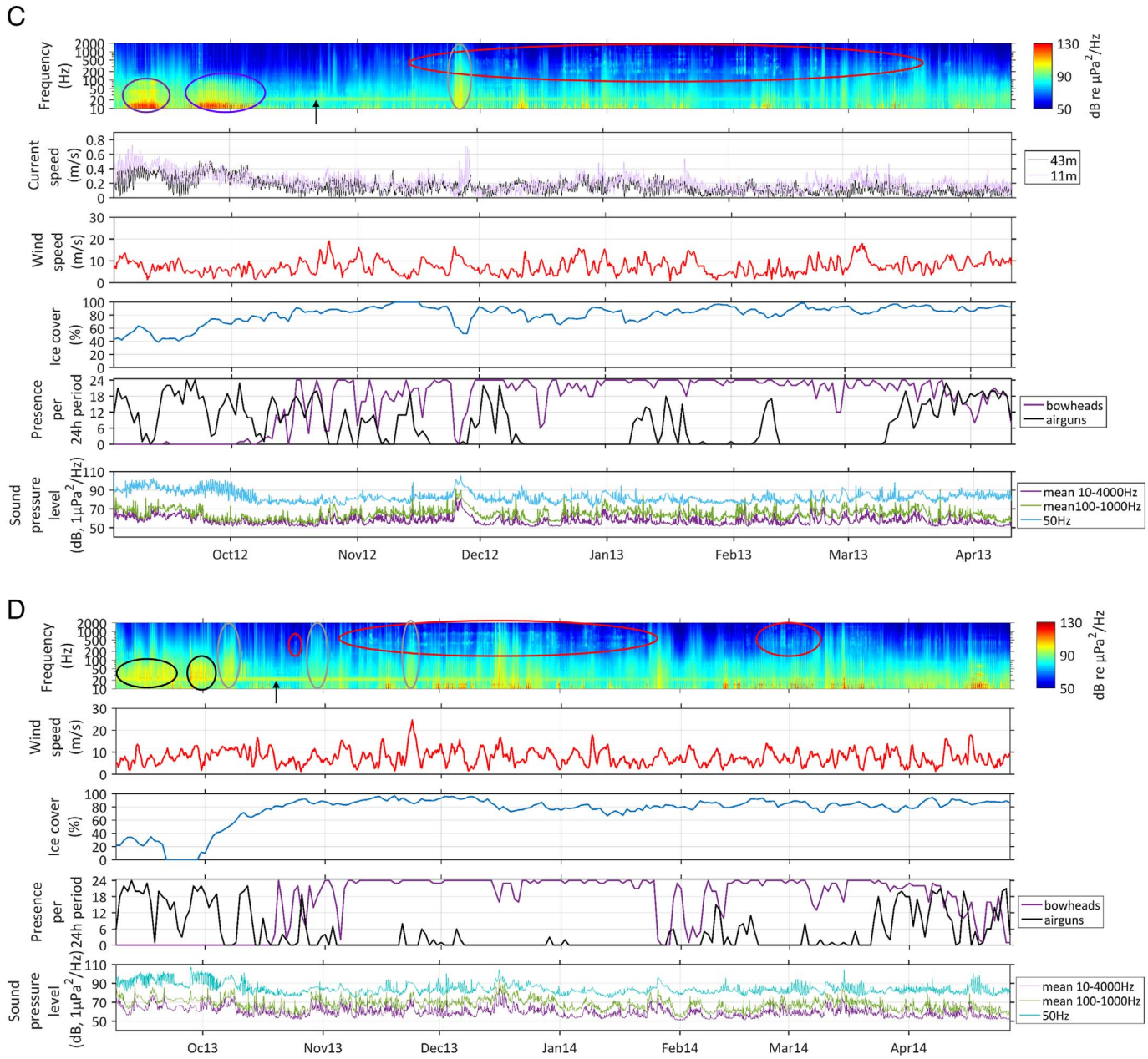

Fig. 4. (*continued*)

airgun signals in August and September. The greatest differences were detected between September months when all four recording periods were available (up to 10.7 dB) and also between August months for 2008–09 and 2010–11 recording periods (12.1 dB). Inspection of sound files and LTSs revealed that in September 2008 and 2013 airguns signals were stronger than during 2010 and 2012, the sound levels at 50 Hz for 2012 were similar to 2008 and 2013. This was due to mooring line strumming noise that resulted from high current speeds during this time (Fig. 4C). Airgun signals were detected in both August 2009 and 2011, however in 2011 the signals were clearly stronger for many days, explaining higher sound levels at 50 Hz. Furthermore, signals from ice noise and mooring line strumming are also detected during this month, influencing the overall pattern of this low frequency band. Fig. 7 shows an example of how strong airguns signals elevate sound levels at 50 Hz. During the closest point of approach by the seismic vessel on 27 September 2013 (57 km away from the recorder), the sound level at 50 Hz rose to 107.4 dB (re 1 uPa), an elevation of 30 dB when compared to periods without airgun signals. To analyse this event in more detail, the maximum received peak-to-peak SPL was calculated by selecting 20 loud airgun signals. The mean received peak to peak SPL for these pulses was 160.46 ± 0.48 dB re 1 µPa.

Variation in the sound spectrum between months within and among recording periods was detected for frequencies between 100 and 1000 Hz (Fig. 6). Given that signals from bowhead whale singing were seen very clearly above 150 Hz on the LTSs (Fig. 4), variations in median (50th percentile) monthly PSDs over these frequencies might be explainable by the vocal presence or absence of these animals. For monthly comparisons within and among recording periods, 500 Hz was used to represent a sound level that might be indicative of bowhead whale singing (it is the middle of the 300 Hz–700 Hz band in which sound levels were elevated when bowhead whales were singing; see Fig. 8). The highest annual mean levels of sound were recorded during 2013–14, followed by 2012–13, 2010–11 and 2008–09, respectively (Table 2). The highest maximum monthly sound value at 500 Hz was recorded for January 2011 and the lowest monthly sound value was for May 2011. The monthly variation within recording periods was

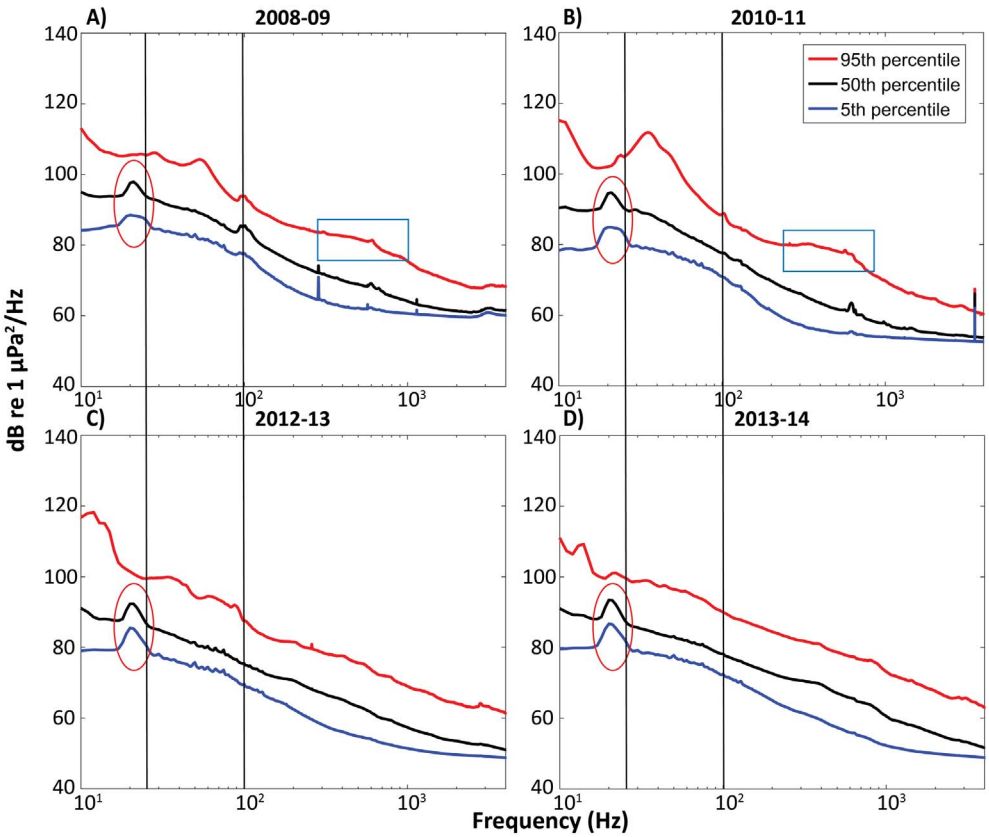

Fig. 5. Annual PSDs for 10 Hz to 4000 Hz showing 5th (blue lines), 50th (black lines), and 95th (red lines) percentiles for the entire duration of each of the four deployments: A) 2008–09; B) 2010–2011; C) 2012–2013; D) 2013–2014. Red ellipses indicate signals from fin whale 20 Hz pulse calls, blue rectangles signals from bowhead singing and areas between black vertical lines show airgun energy. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

relatively large (between 9.3 and 18.7 dB). For 2010–11 the months with the highest sound levels at 500 Hz were clearly associated with bowhead singing (December–March, Fig. 6). A similar pattern was detected for the other recording periods, although not as strongly. The smallest differences in sound levels at 500 Hz among recording periods were found for months March, June and July (all 3 dB or less). The greatest difference was detected between January sound levels among recording periods (up to 10.8 dB, between January 2010–11 and 2012–13 for example), suggesting that bowhead singing might have been more intense in the vicinity of the mooring during 2010–11.

The PSDs for a month with constant bowhead singing (74.3 dB re 1 μPa2/Hz at 500 Hz, January 2011) and for a month with none (57.9 dB re 1 μPa2/Hz at 500 Hz, August 2009) were plotted to demonstrate how bowhead singing can increase the sound levels. The presence of bowhead whale singing increased the sound level between 300 and 700 Hz by 16.4 dB (Fig. 8). The mean 100–1000 Hz frequency band was also plotted with LTS and presence of bowhead whales for each recording period (Fig. 4A–D). For 2010–11 a clear increase in sound levels at this frequency band was detected in the period from December to February (Fig. 9 presents a close-up of months with bowhead singing). Similar, although not as high, increases in sound levels were detected for other years over the time period when bowhead vocalisations were detected.

3.2.4. Annual and seasonal 1/3-Octave Levels

Data for five TOL bands were calculated for each recording period (centred at 50 Hz, 63 Hz, 125 Hz, 250 Hz and 500 Hz). Sound levels varied by season with the summers of 2009 and 2011 showing the loudest mean TOLs for both the 50 Hz and 63 Hz bands (Fig. 10). For 2013 and 2014 (when there were no summer data), the highest mean TOL at 50 Hz and 63 Hz were detected in autumn. The seasonal pattern differed between bands (except for seasons during 2013–14 recording period) with winter 2008–09 and 2010–11 showing the loudest mean TOLs for both 250 Hz and 500 Hz. For 2012–13 all seasonal means were relatively similar at 250 Hz and 500 Hz, whereas 2013–14 autumn period had also highest mean TOL for both 250 Hz and 500 Hz. Overall the TOL were lower for 250 Hz and 500 Hz than for the other bands (50 Hz, 63 Hz and 125 Hz - Fig. 10).

Mean annual sound levels for all five TOL bands are reported in Table 3 with 5th, 50th and 95th percentiles. Mean sound level at 50 Hz and 63 Hz were highest for 2010–11 recording period and lowest for 2012–13 recording period. For 125 Hz, 250 Hz and 500 Hz the highest mean sound levels were for 2013–14 recording period. Overall, the results for percentiles were similar to each mean (with some slight changes in ranking order for 5th and 95th percentiles). The 50 Hz and 250 Hz bands (with difference 0.6–4.8 and 0.4–4.1 dB, respectively) showed the highest variability. For other TOL bands, the difference varied between 0.3 and 2.7 dB (63 Hz), 0.9–3.0 dB (125 Hz) and 0.2–3.5 dB (500 Hz). No significant differences at a 5% significance level were found between annual means for any of the five TOL bands (Kolmogorov-Smirnov test; after correction for multiple tests).

4. Discussion

This study documents the underwater sound levels in the sea-ice-covered western Fram Strait over a period spanning six years to characterise the soundscape and determine seasonal and annual variability in sound levels for an area that is important habitat for one of the world's most endangered cetacean stocks – the Critically Endangered Spitsbergen bowhead whale. This multi-year data set confirms that bowhead whales routinely occupy this area for much of the year. Furthermore, nearly constant singing during winter months and the diversity of songs recorded support the suggestion that western Fram Strait is a mating area for the Spitsbergen bowhead whale population (Stafford et al., 2012). Long-term monitoring programs for areas that have high animal density and currently low anthropogenic pressure are considered important for management purposes (Williams et al., 2015).

The results of this study reveal that the western Fram Strait soundscape can be considered “quasi-pristine” for much of the year due

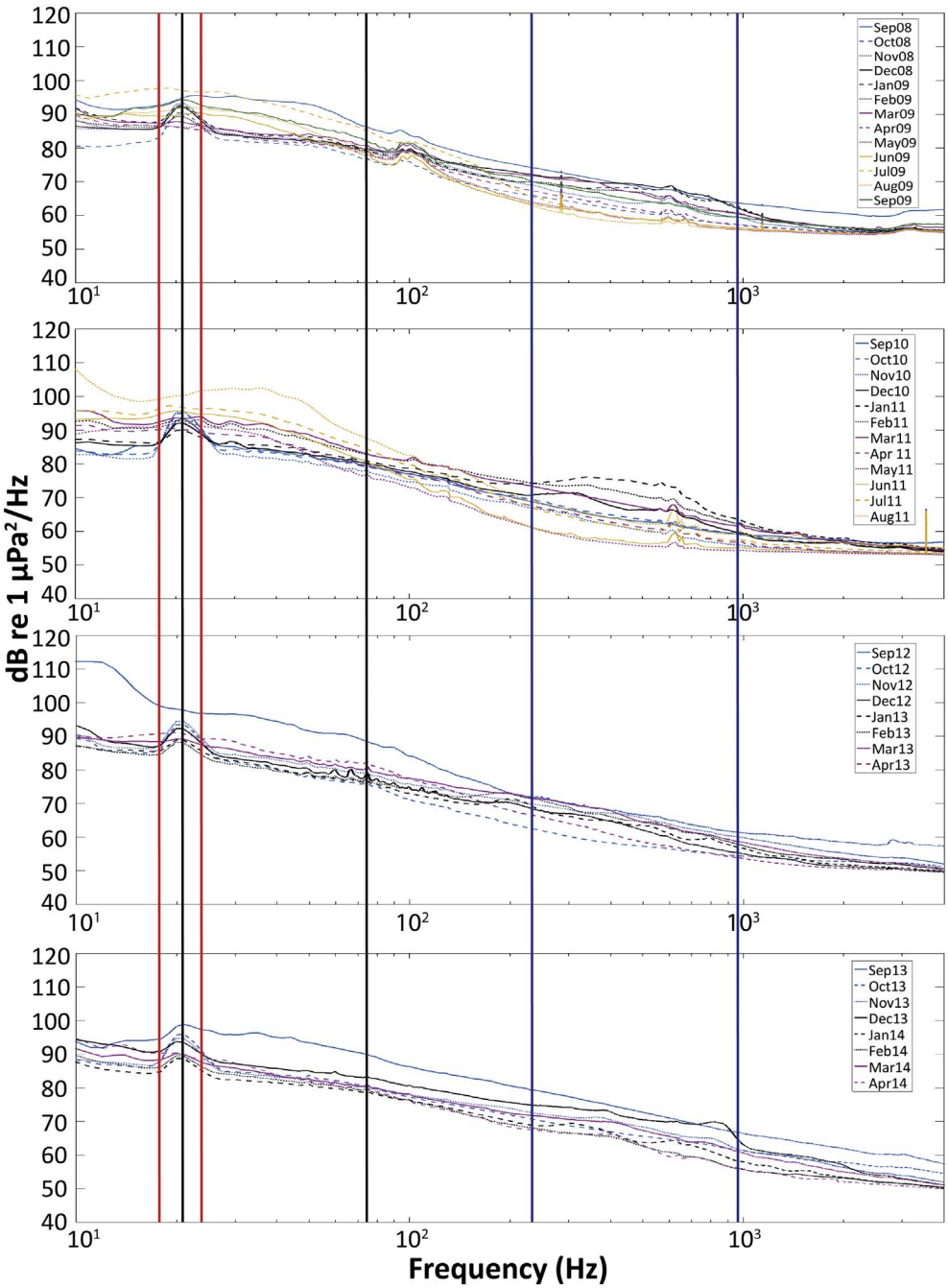

Fig. 6. Median (50% percentile) PSDs by month and year for the Fram Strait: A) 2008–09; B) 2010–2011; C) 2012–2013; D) 2013–2014. The area between the vertical red lines shows fin whale energy, between black lines: airgun energy, blue lines: bowhead whales. Colour and line types used for each month are consistent across year. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to the low number of ships in the area. However, the area is subjected to seismic airgun surveys that take place off Northeast Greenland (and elsewhere) in summer and autumn. Significant reductions in sea ice over recent decades and the ongoing downward trends in sea ice extent and thickness, could result in increased industrial activities in this area (Reeves et al., 2014). The underwater sound levels and presence of biotic and anthropogenic sound sources presented herein form a baseline from which changes and trends can be monitored in the future.

Table 2
Annual medians (50% percentile) and minimum and maximum monthly sound values (in dB re 1 μPa2/Hz) at 50 Hz and 500 Hz for all four recording periods. Difference in dB between minimum and maximum sound values for each year is given in last two columns for both 50 Hz and 500 Hz.

	Annual median		Min (month)		Max (month)		Δ dB	
Year	50 Hz	500 Hz	50 Hz	500 Hz	50 Hz	500 Hz	50 Hz	500 Hz
2008–09	83.8	63.3	81.0 (Oct)	57.9 (Aug)	93.0 (Sep09)	69.0 (Dec)	12.0	11.1
2010–11	85.5	62.9	80.7 (Nov)	55.6 (May)	97.4 (Aug)	74.3 (Jan)	16.7	18.7
2012–13	81.4	64.3	78.5 (Oct)	57.3 (Oct)	91.6 (Sep)	66.6 (Sep)	13.1	9.3
2013–14	83.2	67.7	81.2 (Jan)	62.7 (Feb)	93.4 (Sep)	72.8 (Sep)	12.2	10.1

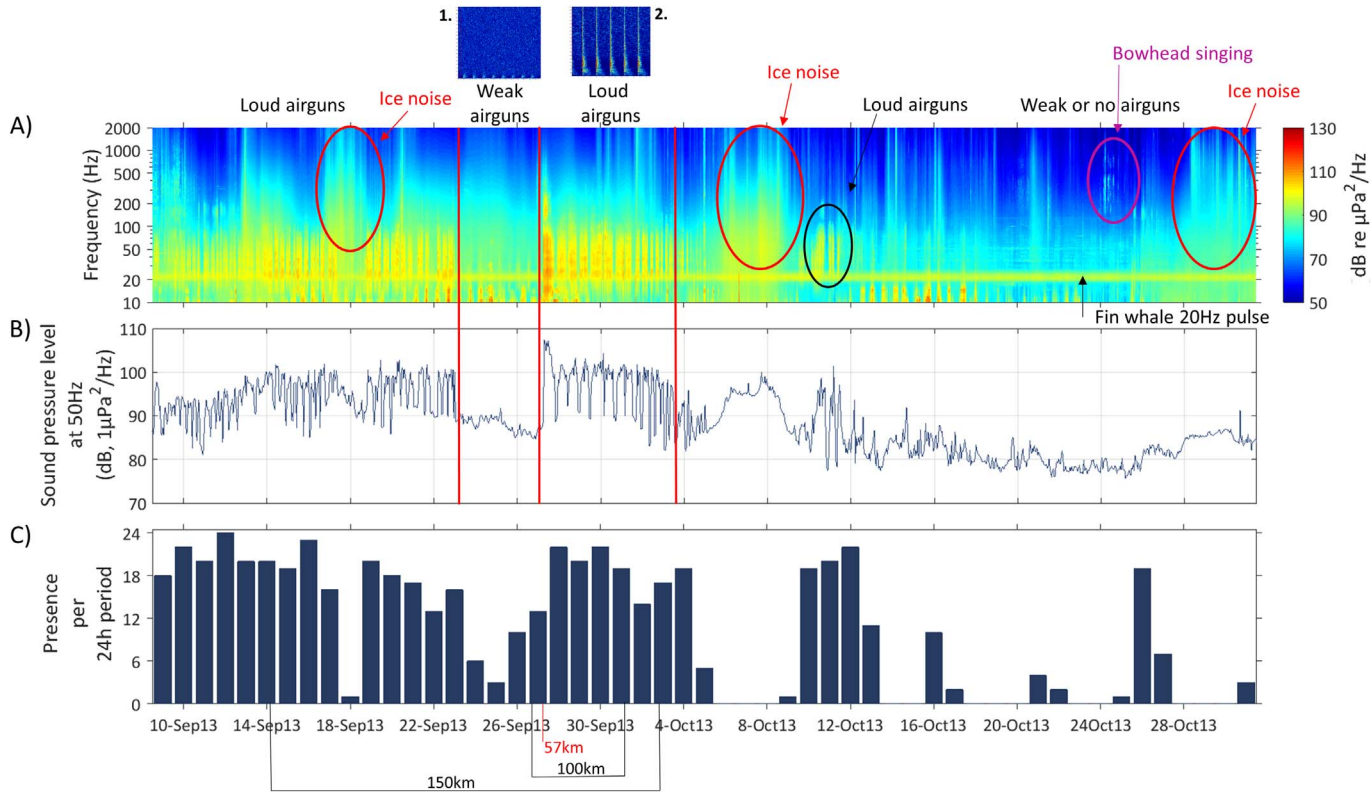

Fig. 7. Example data from a period when a seismic survey vessel was operating within 150 km of the western Fram Strait recorder (from 9th of September to 30th of October 2013). Loud airgun signals can be seen both visually in the spectrogram (A) and in the 50 Hz frequency band (B) that reflects the noise generated by airguns. C) Presence of airguns during this time period. The bottom panel shows the distances between the survey vessel and the recorder. Signals from ice noise and bowhead and fin whale vocalisations can also be seen in spectrogram (A). Vertical red lines divide periods with loud and weak airguns present. Example spectrograms for both weak and loud airgun signals are presented above panel A (1. weak airguns and 2. loud airguns). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

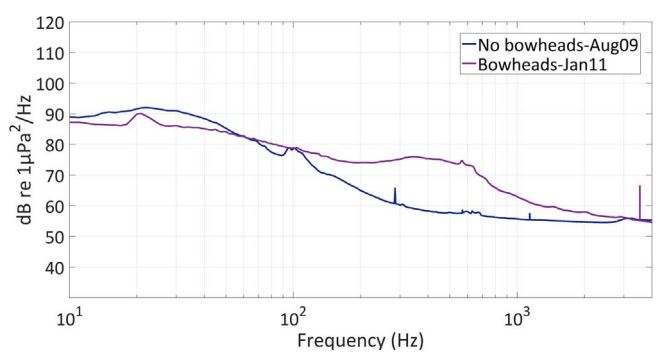

Fig. 8. Median (50% percentile) PSDs for a month with constant bowhead singing (January 2011) and for a month with no bowhead vocalisation (August 2009).

4.1. Acoustic habitat and sound sources of western Fram Strait

4.1.1. Overall features and geophysical processes

The present soundscape of western Fram Strait consists of seasonally varying marine mammal sounds, seismic airgun signals and occasional shipping noise in addition to sounds generated by natural physical processes such as ice and wind. Currently, sea ice is present in this region throughout the year (70–100% ice cover for most months), with the lowest levels of ice cover generally observed in August and September (between 2008 and 2014 the lowest mean monthly ice cover was 23%, which was observed for August 2010). Signals from ice noise were detectable throughout the year. When there was a reduction in the ice cover the influence of strong winds on the soundscape could be detected as increased sound levels throughout the frequency spectrum. The mean sound level is currently low to moderate (< 60 dB) for this area, but during the period of low ice cover, the overall sound levels increase by up to 20 dB due to physical processes such as wind. During periods with strong current, the sound levels were "artificially" elevated due to noise from mooring line strumming or flow noise. Increasing flow noise with increasing current speed is a commonly detected phenomenon (e.g. Willis and Dietz, 1961; Erbe et al., 2015). However, it is important to acknowledge that even though this noise is detected by the AURAL, it is of course not considered to be a part of the natural soundscape of western Fram Strait. The only prolonged period with this kind of noise in this study was in September 2012. During this month the strumming/flow noise increased the sound levels markedly; this is something that needs to be taken into account when comparing monthly sound levels. Furthermore, this kind of noise can mask other, especially low frequency, signals in LTSs. Frequent and strong flow noise can hinder the detectability of whale species that produce low frequency vocalisations (e.g. fin and blue whales). For example in September 2012, when strong flow noise was prevalent, the 20 Hz peak in PSD was not detectable. Here signals from fin whale chorusing could be masked by flow noise and a lack of detection explained by hindered detectability rather than an absence of vocalisation in this month. However, in this study strumming or flow noise was not large enough to influence estimates of ambient sound levels in western Fram Strait.

4.1.2. Biotic sound sources

Clear seasonal variations were seen in the presence of various marine mammal vocalisation in western Fram Strait. Screening of sound files identified signals from bearded seals, narwhals and blue whales. However, vocalisations of fin and bowhead whales were the dominant contributors to the soundscape of this area. Low frequency signals from fin whale chorusing were documented between September and March. These results are similar to those reported by Klinck et al. (2012) for a site east of the western Fram Strait mooring (at 78°50′N

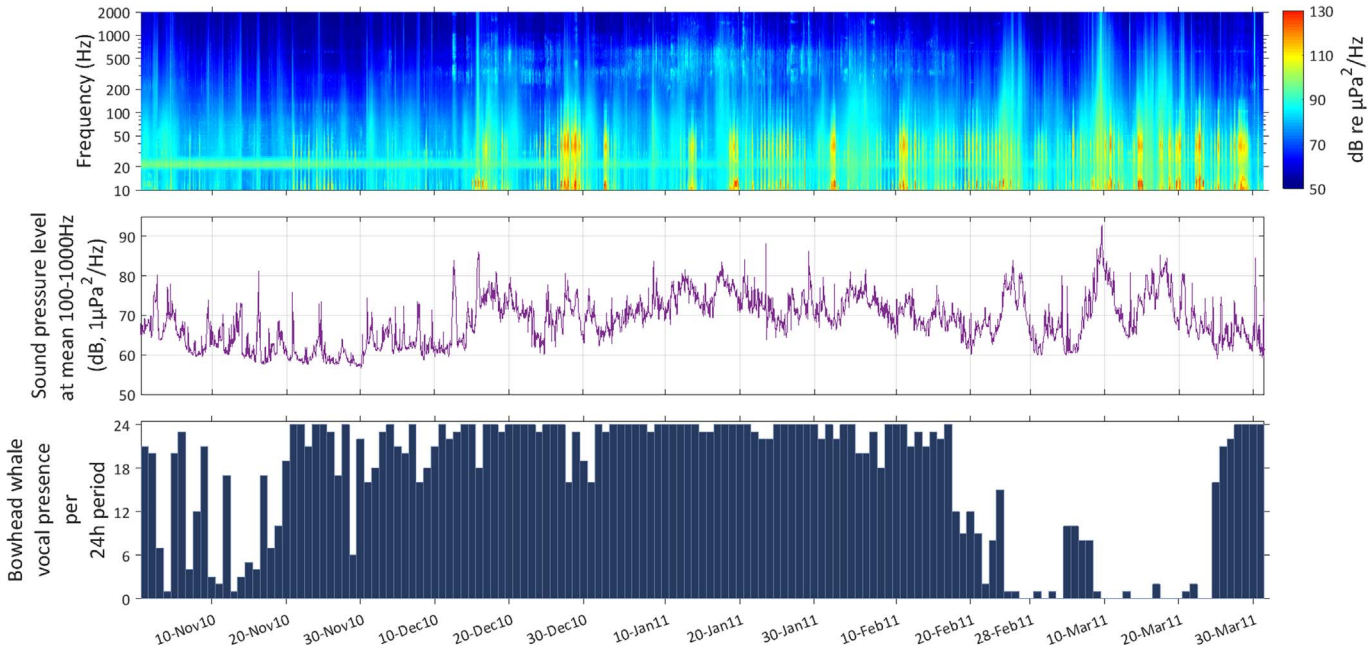

Fig. 9. Long-term spectrogram over period of bowhead whale singing (from 1st of November 2010 to 30th of March 2011). Mean 100–1000 Hz frequency band (middle panel) that reflects bowhead vocalisation and presence of bowhead whales (lower panel) are plotted against the spectrogram.

and 05°29′E in eastern Fram Strait). Even though fin whales were the major biological contributor to sound levels around 20 Hz, it is most likely that these animals were far away from the AURAL because individual 20-Hz pulses were seldom detected during examinations of the spectrograms; such signals would have been detected if these animals were vocalising close by. However, the band of energy at 20 Hz indicated their distant presence and revealed their contribution to the soundscape (e.g. Curtis et al., 1999). The Fram Strait is the northernmost area where records of fin whale vocalisation have been obtained. Considering the propagation range of fin whale calls (which can vary with location and season from some 50 to a few hundred kilometres; Cummings and Thompson, 1971; Širović et al., 2007; Stafford et al., 2007; Simon et al., 2010), the results in this study support the suggestion that some fin whales stay at high latitudes during winter (Aguilar, 2009; Simon et al., 2010).

Vocalisations of bowhead whales were detected almost daily from October through until April in all years. Based on detection range estimates from the Beaufort Sea, these animals were likely < 40 km from the recorder (Abadi et al., 2014; Bonnel et al., 2014). The Spitsbergen population, which is thought to extend from east Greenland across the northern Barents Sea to Franz Josef Land (Reeves, 1980), is the smallest of the four currently recognised geographical stocks. This stock was depleted to near extinction by harvesting that stopped toward the end of 19th century (Jonsgard, 1981). The Fram Strait has historically been an important area for this species and results from the first passive acoustic deployment in this area (2008–09 data; Moore et al., 2012; Stafford et al., 2012) combined with the additional years presented herein clearly show that bowhead whales are present in western Fram Strait for large parts of the year. No bowhead whale sounds were detected between May and September during the 2008–09 recording period but simple calls were detected during the summer of 2011 suggesting that it is possible that these whales spend most of the year in this area. Vocal behaviour of these animals differs between summer (lower-frequency, narrower band calls) and winter (broadband songs) in other geographic areas where distribution patterns and abundances are better known that in the Fram Strait (Stafford et al., 2012), so the lower levels of detections in summer may simply represent a change in vocal behaviour and not necessarily the presence of fewer animals in the study region. However, a lone Spitsbergen bowhead whale that was instrumented with a satellite-linked tag moved southwards along the Greenland shelf break during summer months from northern Fram Strait (78–79°N) down to 70°N (Lydersen et al., 2012). Additionally, two recent aerial surveys found bowheads in significant numbers in the marginal ice zone (MIZ) north of the Svalbard Archipelago, far east of the PAM site (Vacquié-Garcia et al., 2017), and in the Northeast Water Polynya in northeast Greenland (Boertmann et al., 2015). These studies suggest that Spitsbergen's bowhead whales might have multiple possible summering areas. However, our current knowledge of distribution patterns of this stock are very limited (Lydersen et al., 2012). The single Fram Strait PAM device covers only a small part of the possible range of this stock; a wider array of recorders in Fram Strait is needed for better coverage of this area. Klinck et al. (2012) did not mention any bowhead vocalisations at their recording site, however their instrument was limited to a maximum frequency of 840 Hz, so it is not ideal for bowhead detections. Another AURAL recorder situated east of the western Fram Strait recorder (Stafford et al., 2012, referred as the central Fram Strait recorder) had considerably fewer bowhead whale detections compared to the western Fram Strait in 2008–09 (over the same frequency band), indicating that bowhead whales seem to preferentially occupy the western parts of Fram Strait, where sea ice concentrations are higher.

Singing by bowhead whales was basically constant from November until mid/end of March in all years and contributed to the winter soundscape of western Fram Strait at frequencies between 100 and 1000 Hz, increasing sound levels up to ~17 dB. Stafford et al. (2012) suggested that constant loud singing and diversity of songs might indicate that western Fram Strait is a mating area for the Spitsbergen bowhead whales. The results of the current study confirm that this region is used consistently over time by bowhead whales and that constant singing is the norm in this area during the winter. Thus, it is clear that this site is important winter habitat for the Spitsbergen bowhead whale population. Average ice cover over in the period from November to March was 98% for 2008–09 and 2010–11 and 86% and 84% for 2012–13 and 2013–14, respectively. Citta et al. (2012) also found that bowhead whales in the Bering Sea were found in areas with high (90–100%) ice concentration during the winter. However, bowhead whales from the Eastern Canada-West Greenland stock are found in much lower ice concentrations (35%–65%) during winter (Ferguson

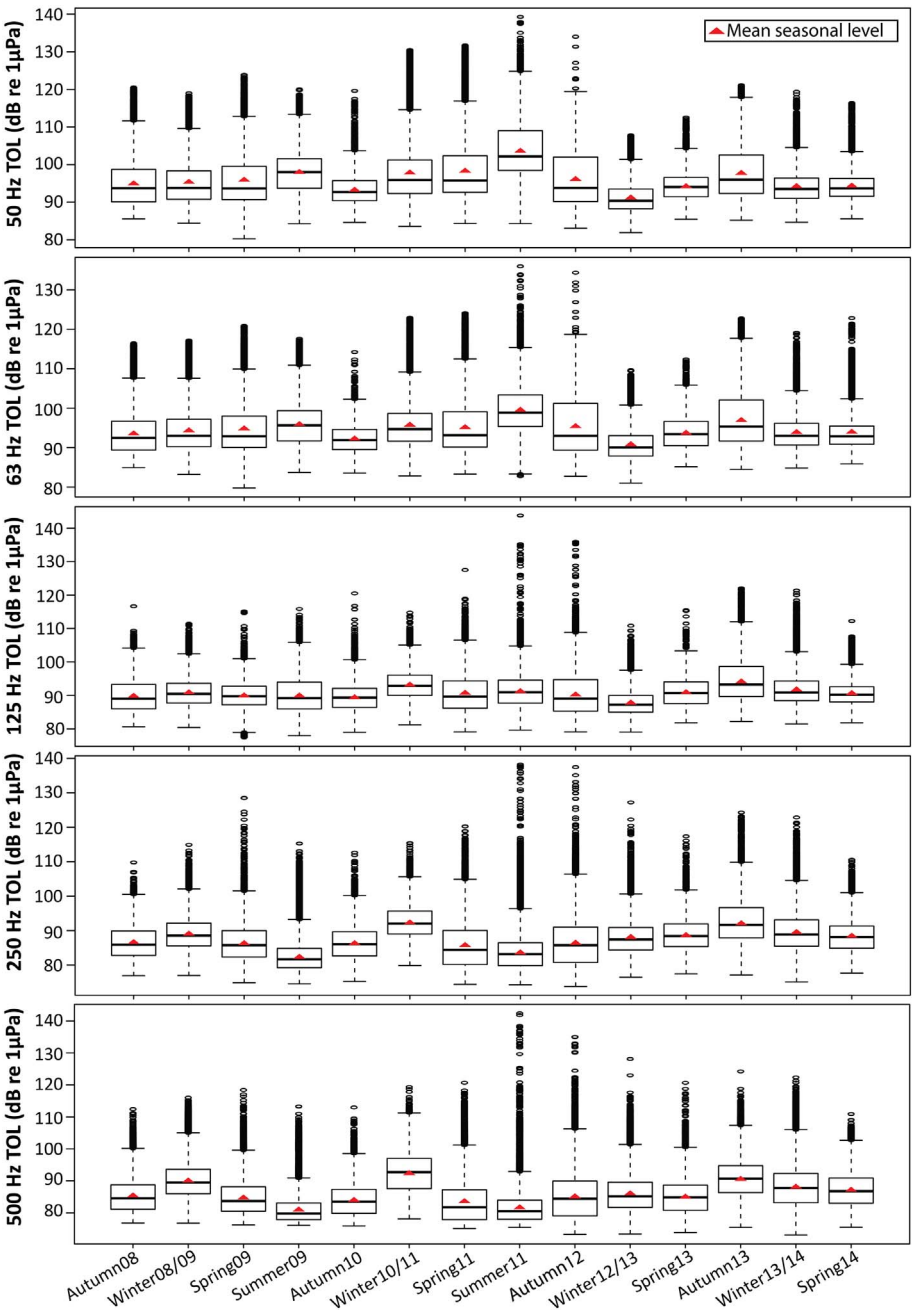

Fig. 10. Mean and median levels by season (Autumn: September–November; Winter: December–February; Spring: March–May; Summer: June–August). The median level is given by the centre of the box. The 25th and 75th percentiles are given by the upper and lower bounds of the box, respectively.

et al., 2010). Preference for areas with lower ice concentration during winter was considered to be a way to reduce risk of ice entrapment, while still being close to the shelter provided by the ice (Ferguson et al., 2010). Stafford et al. (2012) suggested that a dense canopy of ice cover may provide better transmission and reception conditions for the bowhead whale song. Higher ice cover (> 65%) during summer was also preferred by the Eastern Canada-West Greenland bowhead whales, presumably to reduce the risk of killer whale (*Orcinus orca*) predation. Citta et al. (2012) proposed that the sea ice quality (e.g. thinness, age) might explain the differences observed in bowhead whale movements relative to sea ice concentration between different areas. The quality and dynamics of the ice could also explain why bowhead whales are present throughout the winter in high ice concentration in western Fram Strait. The ice in the Fram Strait is not fast-ice, it is mobile and fast moving and presents little risk of ice entrapment. More detailed investigation of the presence and movement patterns of bowhead whales in western Fram Strait in relation to different environmental variables is needed to unravel factors that determine the summer and winter distribution of Spitsbergen bowhead whales and to identify the possible impact of declining sea ice trends on the stock.

4.1.3. Anthropogenic noise sources –ships and airguns

Compared to many other regions, the Arctic has been relatively free of anthropogenic underwater noise thus far, due to the perennial presence of sea ice and large seasonal variation of the MIZ, which has limited commercial access to the Arctic. However, dramatic decreases in sea ice over the past three decades have occurred in the Barents/Greenland Sea region (Laidre et al., 2015). This region is experiencing the most rapid declines in the seasonal extent of sea ice in the Arctic, concomitantly with higher atmospheric and ocean temperatures (Kelly et al., 2010; Pavlov et al., 2013; Nordli et al., 2014; Onarheim et al., 2014; Laidre et al., 2015). Downscaled projections from climate models indicate that this warming trend will continue unabated through to the end of this century (Førland et al., 2011). Not only will these changes

Table 3
Long-term mean and percentile 1/3-Octave Levels (TOLs) for each recording period (in dB re 1 μPa).

	Year	50 Hz	63 Hz	125 Hz	250 Hz	500 Hz
Mean (± SD)	2008–09	96.2 (± 6.5)	94.8 (± 6.0)	90.3 (± 4.8)	86.1 (± 5.8)	85.3 (± 6.3)
	2010–11	98.6 (± 8.1)	95.9 (± 6.4)	91.3 (± 5.3)	87.1 (± 6.7)	85.6 (± 7.5)
	2012–13	93.8 (± 6.1)	93.2 (± 6.2)	89.4 (± 5.3)	87.5 (± 6.2)	85.5 (± 6.6)
	2013–14	95.6 (± 5.7)	95.1 (± 5.8)	92.4 (± 5.3)	90.2 (± 6.1)	88.8 (± 6.5)
Min	2008–09	80.3	79.8	77.4	74.5	76.1
	2010–11	83.6	82.8	79.0	74.2	75.1
	2012–13	81.9	81.0	79.0	73.8	73.3
	2013–14	84.7	84.5	81.5	75.1	73.1
Max	2008–09	137.3	137.9	137.9	138.0	138.1
	2010–11	139.3	136.0	143.8	138.2	142.4
	2012–13	134.0	134.9	135.9	137.5	135.0
	2013–14	121.1	122.8	122.0	124.3	124.2
5th percentile	2008–09	87.9	87.2	83.1	77.7	77.3
	2010–11	88.9	87.8	83.5	77.2	76.4
	2012–13	86.3	85.9	82.5	78.4	76.1
	2013–14	88.7	88.0	85.4	81.2	78.8
50th percentile	2008–09	94.9	93.5	89.8	85.5	84.3
	2010–11	96.6	94.6	90.9	86.5	83.9
	2012–13	92.3	91.7	88.4	87.1	84.9
	2013–14	94.2	93.6	91.4	89.6	88.6
95th percentile	2008–09	109.1	106.9	98.6	96.3	97.0
	2010–11	115.4	108.8	100.6	99.0	99.8
	2012–13	106.4	106.2	99.1	98.0	97.2
	2013–14	108.1	107.4	103.1	101.1	99.9

result in reduced habitat for ice-dependent marine mammals, but they will undoubtedly also promote increased interest for development of shipping and exploration in this region. The petroleum industry has already expanded into the Norwegian Arctic, with gas and oil exploration and production already taking place in the Norwegian and southern Barents Seas. Greenland has issued a large number of exploratory licenses in East Greenland that will almost certainly affect various populations of marine mammals, including the Spitsbergen stock of bowhead whales (Boertmann and Mosbech, 2012). Furthermore, commercial shipping and fishing as well as marine cruise tourism, research and recreational traffic are all expected to increase further as sea ice becomes less prevalent in this area (Reeves et al., 2014).

This study found that the level of anthropogenic activity around the study site in western Fram Strait is currently low and mainly present only during summer and early autumn. This is the period when ice cover is at a minimum, allowing ships to access this region. Increased shipping activity throughout the year would mean elevated sound levels at frequencies associated with anthropogenic activity. Unfortunately, this study was not able to measure the effect of passing shipping noise to current sound levels in western Fram Strait, since all known (registered with AIS) close vessel approaches occurred at a time when nearby seismic surveys were on-going, making it impossible to assign distinct noise levels to each of the two sources of concurrent noise. Shipping noise was detected in the eastern part of the Fram Strait by Klinck et al. (2012) during summer months at a location near Spitsbergen where shipping is more extensive. However, that study did not report how shipping noise increased sound levels. A recent short-term (four day) study in the marginal ice zone in the Fram Strait identified that ship cavitation caused by heavy ice breaking increased the sound levels by > 10 dB below 1000 Hz and 28 dB at 15 Hz (Geyer et al., 2016). These increases in sound levels were detected at distances as great as 100 km. Given that the current level of shipping activity in western Fram Strait is low, the annual and seasonal sound levels reported here can be used as a baseline for monitoring future effects of shipping to the soundscape of this area.

Airguns signals were prevalent throughout most of the year (except during a few winter months in 2008–09 and 2010–11 but the majority of the signals detected were faint, and most likely originated from distant seismic surveys. In shallow water areas in the Pacific Arctic, airgun pulses were detectable from a 3-airgun source up to 1300 km away under ice-free conditions (Thode et al., 2010). In the mid-Atlantic, airgun surveys were detected over 3000 km away from the source (Nieukirk et al., 2004). Although airgun signals were clearly visible in our spectrograms, the distant low frequency signals did not noticeably elevate the overall sound levels. However, both PSD and TOL results indicated that sound levels at frequencies that are usually connected with anthropogenic activity (50 Hz and 63 Hz) were higher for summer and autumn months, which coincides with strong airgun signals being detected in this study only during summer and autumn. The results for 50 Hz frequency band (PSDs) in this study show similar seasonal variation and levels to those reported by Klinck et al. (2012) for a site east of the western Fram Strait mooring. As noted above, ship traffic is very limited in this area, so increases in these levels are most likely from seismic surveys. Furthermore, in September–October 2013 when a seismic survey vessel was operating within 150 km of the mooring an elevation up to 30 dB in low frequency sound levels was detected.

4.2. Extent of overlap between anthropogenic activity and bowhead whales

At present, shipping traffic and strong airgun signals do not spatially or temporary overlap with key periods of bowhead whale singing in western Fram Strait. However the possibility that these animals are present, but silent, in this region when noise levels increase during the summer/early autumn cannot be ruled out. In fact, several visual surveys have recorded the presence of bowhead whales during the summer months near this area (Wiig et al., 2008, 2010; Norwegian Polar Institute's Svalbard Marine Mammal Sighting Data Base). It cannot be discounted that the presence of airgun surveys may change the vocal behaviour of bowhead whales and thus the ability to detect them using PAM. Blackwell et al. (2015) found that bowhead whales from the Bering-Chukchi-Beaufort (BCB) Sea population increased their calling rate in the presence of low levels of airgun noise but ceased producing sounds when airgun pulses were loud. Those authors were able to localize both whales and airgun survey ships to compare the sound exposure levels of whales, which was not possible with a single omnidirectional instrument used in the current study.

Currently, there is little overlap between anthropogenic sound sources and whales during the winter in western Fram Strait, a time that is believed to be the mating period for bowhead whales. Some

airgun signals were recorded during winter months in 2012–13 and 2013–14 recording periods, however these signals were faint and most likely originated from distant seismic surveys reducing the risk of such signals impacting the bowhead whales in the area. Presence of heavy ice cover restricts ship traffic during the winter period in this area and increases the distance to potential seismic surveys and passing ships. Nevertheless, ice cover does not need to retreat much before the shelf slope will be exposed, facilitating seismic operations (year round) in areas where bowhead whales might be impacted. Based on finding by Blackwell et al. (2015), this could mean increased calling rates (at low received levels of airgun sounds) or cessation of singing (after certain threshold for received levels is reached) even during the breeding season when acoustic communication is especially critical. The population-scale impacts of this kind of behavioural response are not known. The BCB population of bowhead whales has been exposed to airgun pulses on and off since about 1968 but has shown a consistent population increase, which suggests that noise is not having a readily observable effect at the population level (Givens et al., 2013; Blackwell et al., 2015). However, it is important to be cautious when making comparison between different areas that have different historical exposure levels to anthropogenic activities.

Finally, even though a summer ice-free Arctic is rapidly approaching (Wang and Overland, 2012), the scenario where nearby seismic surveys (< 50 km) overlap with the winter presence of bowhead whales does not seem immediate. The East Greenland Current in Fram Strait exports ice collected from nearly the whole Arctic Ocean (Hansen et al., 2013), and will continue to do so at least in the winter and spring periods in the coming decades.

4.3. Annual sound levels and long-term monitoring

Although western Fram Strait can be described as having a dynamic soundscape with intra-annual variability, inter-annual variability is not as profound. Biotic sound sources (e.g. bowhead and fin whales) were present in the same seasons each year and no obvious differences or trend in sounds resulting from natural physical processes (e.g. wind and ice noise) were detected among recording periods. Only small variations were found in annual means of all five TOL bands examined and none of these were significantly different. The long-term means reported here for the 63 Hz band (93.2–95.9 dB) are similar to levels reported for four deep ocean sites around the world (ranged from 90.0 dB to 96.3 dB; Van der Schaar et al., 2014) and interestingly also for levels measured in Falmouth Bay, UK, an area that supports a commercial port (92.6 dB over 12 months deployment; Garrett et al., 2016). Based on the AIS data, ship traffic is very limited in this area, so other sources like ice noise, airgun signals and marine mammal calls are the most likely contributors to these levels. Every ocean environment has its own characteristics, and without baseline knowledge of these it is not possible to provide region-specific appropriate management advice. This highlights the importance of long-term monitoring to provide baseline data on sound levels to properly understand the current ambient sound levels and their sources in order to detect changes in future soundscapes. There is currently no target level or trend data for underwater noise levels in the European Union Marine Strategy Framework Directive. The results presented herein provide data that will allow the exploration of trends in the western Fram Strait sound levels in the future if monitoring is maintained.

In conclusion, the findings in this study provide the first baseline knowledge of the soundscape of western Fram Strait and will allow for evaluation of future changes in this sensitive region. The focus in this paper has been bowhead whales and how current and future noise from anthropogenic activity might impact the Critically Endangered Spitsbergen bowhead whale stock. However, other marine mammals are also observed and recorded in this region. Species like narwhals and fin whales (during their latitudinal migration) are currently present in the peak periods of ship traffic and seismic operations and it might be that these species will be the first to be affected by future expansion of anthropogenic activity. Hence, a multi-species approach and future monitoring is needed to be able to appropriately manage human activities and mitigate threats for the various species of marine mammals occupying this area.

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