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Short Note

Fin whale (*Balaenoptera physalus*) song pattern in the southern Chukchi Sea

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Received: 2 November 2020 / Accepted: 25 March 2021

Abstract

The number of migrating fin whales (*Balaenoptera physalus*) appears to be increasing in the Pacific Arctic after changes in the marine ecosystem and recovering from depletion by commercial whaling. Fin whale songs are sequences of sounds produced repeatedly, and they may be used for population structure assessments. However, little is known about song types and population structures in the Pacific Arctic. We recorded fin whale songs using a fixed passive acoustic monitoring system from July 2012 to June 2015 in the southern Chukchi Sea. We randomly selected one hour of data from each week of the study period and measured the inter-pulse intervals (IPIs) of the songs. Songs were detected from August to November 2012–2014. All songs had a sequence of doublets with two IPIs (10.5 and 19.6 s), and they were similar to previously reported songs of whales from the eastern North Pacific in 2001–2013 but differed from those of whales from the Bering Sea and northeastern Chukchi Sea in 2007–2010. These results suggest that one group of fin whales migrated to the southern Chukchi Sea from the eastern North Pacific in 2012–2014, or the song changed. Comparing songs from different areas of the Pacific Arctic during the same years will reveal whether this group dispersed in this area.

Keywords

Fin whale
Chukchi Sea
Song pattern
Passive acoustic monitoring
Pacific Arctic

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1007/s00300-021-02855-y.

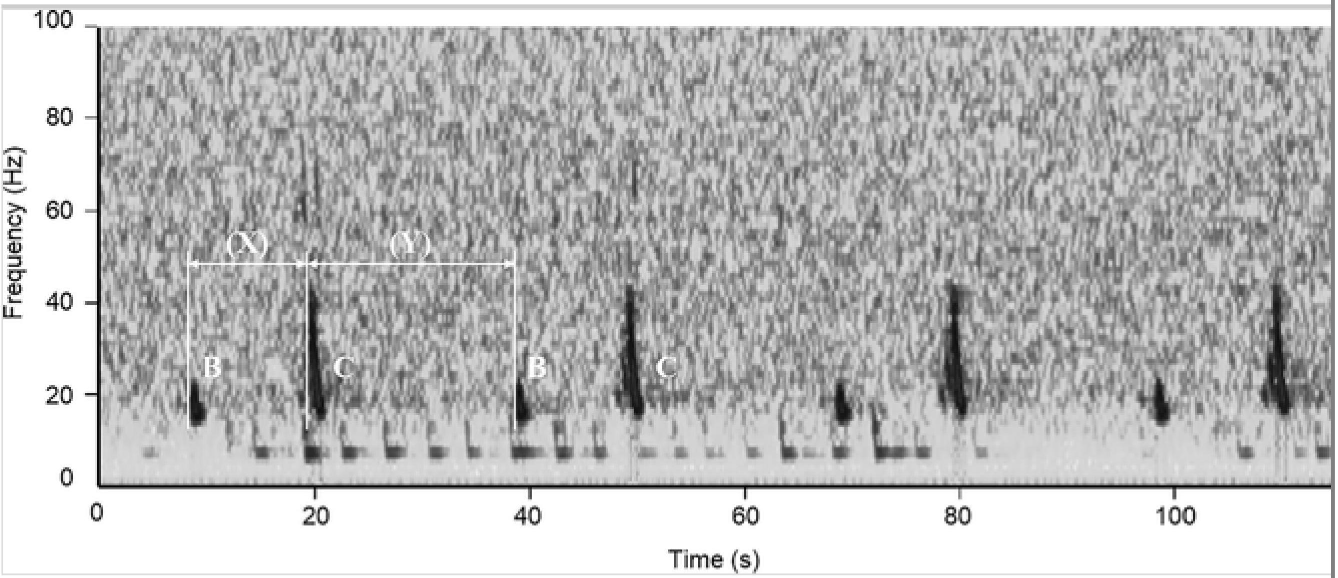
Introduction

Fin whales (*Balaenoptera physalus*) are cosmopolitan cetaceans distributed in most oceans and open seas from the Arctic to Antarctic (Mizroch et al. 1984). Acoustic and visual (aerial and vessel) surveys in the last 10 years have indicated that the number of migrating fin whales in the Pacific Arctic is increasing (Clarke et al. 2013; Crance et al. 2015), and there are several hypotheses to explain this increase. First, longer ice-free periods in the Arctic Ocean resulting from global climate changes may be expanding the distribution range of fin whales and extending their stay in some regions (Moore and Huntington 2008; Tsujii et al. 2016a, b). Second, the recovery of fin whale populations (Zerbini et al. 2006; Cookie 2018) may be leading them to expand their range or return to areas from which they once emigrated (Brower et al. 2018). Thirdly, this increase may result from an increased survey effort (Brower et al. 2018). And lastly, it may result from a combination of all three hypotheses (Brower et al. 2018). For an adequate fin whale management, it is important to understand the population structure of whales and its changes, and to consider the effects of the dramatic transformation of the Arctic marine ecosystem as well as the recovery from depletion by commercial whaling. However, little is known about the population structure of fin whales in the Pacific Arctic Ocean.

Some baleen whale species produce “songs” composed of a series of repeated sounds (Payne and McVay 1971; McDonald et al. 2006). As whale songs have geographical variations, they may be used for population structure assessments. The acoustic recording of songs is a relatively cost-effective method of obtaining samples of sufficient size for population structure analyses (McDonald et al. 2006). Males of each population produce songs with a same pattern over many hours, and the number of song occurrence increases from the autumn to spring breeding season (Watkins et al. 1987, 2000; Croll et al. 2002; Stafford et al. 2007). Fin whale songs consist of regular sequences of repeated short (< 1 s), down-sweep pulses (Watkins 1981; Watkins et al. 1987). These pulses occur around 20 Hz and have been named the 20-Hz pulses or 20-Hz notes. There are two types of 20-Hz pulses, the “classic” (C) and the “backbeat” (B) pulse, which differ in center frequency, bandwidth, and source level (Fig. 1; Clark et al. 2002). The variations appear in the interval between successive 20-Hz pulses (inter-pulse interval, IPI; Fig. 1) and pulse types (C and B) (Watkins et al. 1987; Hatch and Clark 2004; Širović et al. 2017). Based on the IPI patterns, songs can be classified into three categories: singlet, doublet, and triplet (Thompson et al. 1992; Hatch and Clark 2004; Oleson et al. 2014; Širović et al. 2017; Archer et al. 2020). Singlet songs have only one distinct IPI, whereas doublet songs have two different IPIs and sometimes different pulse types, and triplet songs have at least two different IPIs (Širović et al. 2017; Archer et al. 2020). In a same song category (singlet, doublet, and triplet), there are several song types with different IPIs (Koot 2015; Širović et al. 2017). For example, Širović et al. (2017) reported that two types of doublets with different IPIs, “long doublet” and “short doublet,” and two types of triplets with different IPIs, “long triplet” and “short triplet.” Furthermore, a song type can be defined as a song with the same IPI in the same category.

Fig. 1

Spectrogram of fin whale (*Balaenoptera physalus*) songs recorded on 24 October 2013. Y-axis is frequency in hertz and x-axis is time in seconds. Two types of fin whale 20-Hz pulses are shown, C indicates a “classic” pulse, and B indicates a “backbeat” pulse. Inter-pulse intervals (IPIs) for (X) IPI_BC, in which B is followed by C, and (Y) IPI_CB, in which C is followed by B. Spectrogram was produced with 16,384-point FFT algorithm (0.37 s temporal resolution, 2.69 Hz spectral resolution) with the Hamming window



There is a hypothesis that song pattern differences indicate differences in the population of singing individuals, and that song patterns are population specific (Thompson et al. 1992; Clark et al. 2002; Hatch and Clark 2004; Delarue et al. 2009; Širović et al. 2017). There has been no direct study of genetic differences among individuals with different song patterns. Delarue et al. (2009) showed, however that fin whales in the Gulf of Maine and Gulf of St. Lawrence in the North Atlantic Ocean, which were separate stocks revealed by previous individual identification and genetic studies, each had a different song pattern. Another hypothesis is that the cultural transmission has been suggested, with song patterns being exchanged between different groups of fin whales (Weirathmueller et al. 2017; Helble et al. 2020). Helble et al. (2020) reported that individual fin whales in Hawaiian waters sang with multiple IPI patterns, suggesting that fin whales can change their songs over time.

Previous studies in the Pacific Arctic have suggested that only one population migrated to the northeastern Chukchi Sea from the Bering Sea (Delarue et al. 2013; Archer et al. 2020). Since then, the only triplet song type with IPIs of 7.8–8.9 s/14.9–15.4 s/18.5–19.2 s consisting of one backbeat and two classic pulses in the northeastern Chukchi Sea was detected in 2007 and 2009–2010, and this song type was similar to that detected in the Bering Sea (Delarue et al. 2013; Archer et al. 2020). Contrarily, in the Bering Sea, at least two types of songs have been documented. A doublet with IPIs of 19.1–23.5 s/28.4–34.4 s consisting of one backbeat and one classic pulse was detected in 2001–2002 and 2005–2006 (Oleson et al. 2014; Koot 2015). Additionally, a triplet with IPIs of 8.3 s/14.8 s/18.9 s consisting of one backbeat and two classic pulses was detected in 2007–2009 (Delarue et al. 2013). This suggests that at least two different fin whale populations migrate to the Bering Sea (Delarue et al. 2013), which is consistent with Discovery tag recoveries in the commercial whaling era

(Mizroch et al. 2009). Nevertheless, it remains unclear whether only one whale population migrates to the Arctic Ocean or whether only one of several populations that entered the Arctic region reaches the northeastern Chukchi Sea while the others remained south of the northeastern Chukchi Sea, if different song patterns indicate differences in populations. Moreover, in order to test the cultural transmission hypothesis, it is necessary to report song patterns in many years and areas, and reveal song patterns in the Arctic Ocean, where few studies have been conducted.

In this study, we recorded fin whale calls in the southern Chukchi Sea using a fixed passive acoustic monitoring system to identify the song types and compare them to those recorded in other regions, and discussed about the population structure of fin whales in the southern Chukchi Sea. In addition, we examined the difference of inter- and intra-annual differences in fin whale song patterns in the southern Chukchi Sea to clarify the changes in the song patterns.

Materials and methods

Call recording

This study used the same dataset as that of Tsujii et al. (2016a, b). Observations were conducted in Southern Chukchi Hotspot (SCH) located at the entrance of the Arctic Ocean from 16 July 2012 to 1 October 2015 (Fig. 2). We used an Automatic Underwater Sound Monitoring System ver. 3.5 (AUSOMS ver. 3.5; Aqua Sound Inc., Japan) to record the fin whale calls. The AUSOMS had a model SH20K hydrophone, the frequency response was between 20 Hz and 20 kHz (+ 1/-3 dB), and sensitivity was -190 dB (re 1 VμPa^{-1}). We recorded the calls using a 44.1-kHz sampling rate, 16-bit data resolution, 20-kHz cut-off frequency of the low-pass filter, and 60-dB gain. The AUSOMS was used in a pressure-tight cylinder case made of stainless steel (SUS314), and its total memory capacity was of 762 GB using six 128-GB SDXC memory cards. We recorded the calls at different duty cycles according to the recording periods (Table 1).

Fig. 2

Map of the study area and location of acoustic moorings (black star). AS, Anadyr Strait; BS, Bering Strait. From Tsujii et al. (2016a)

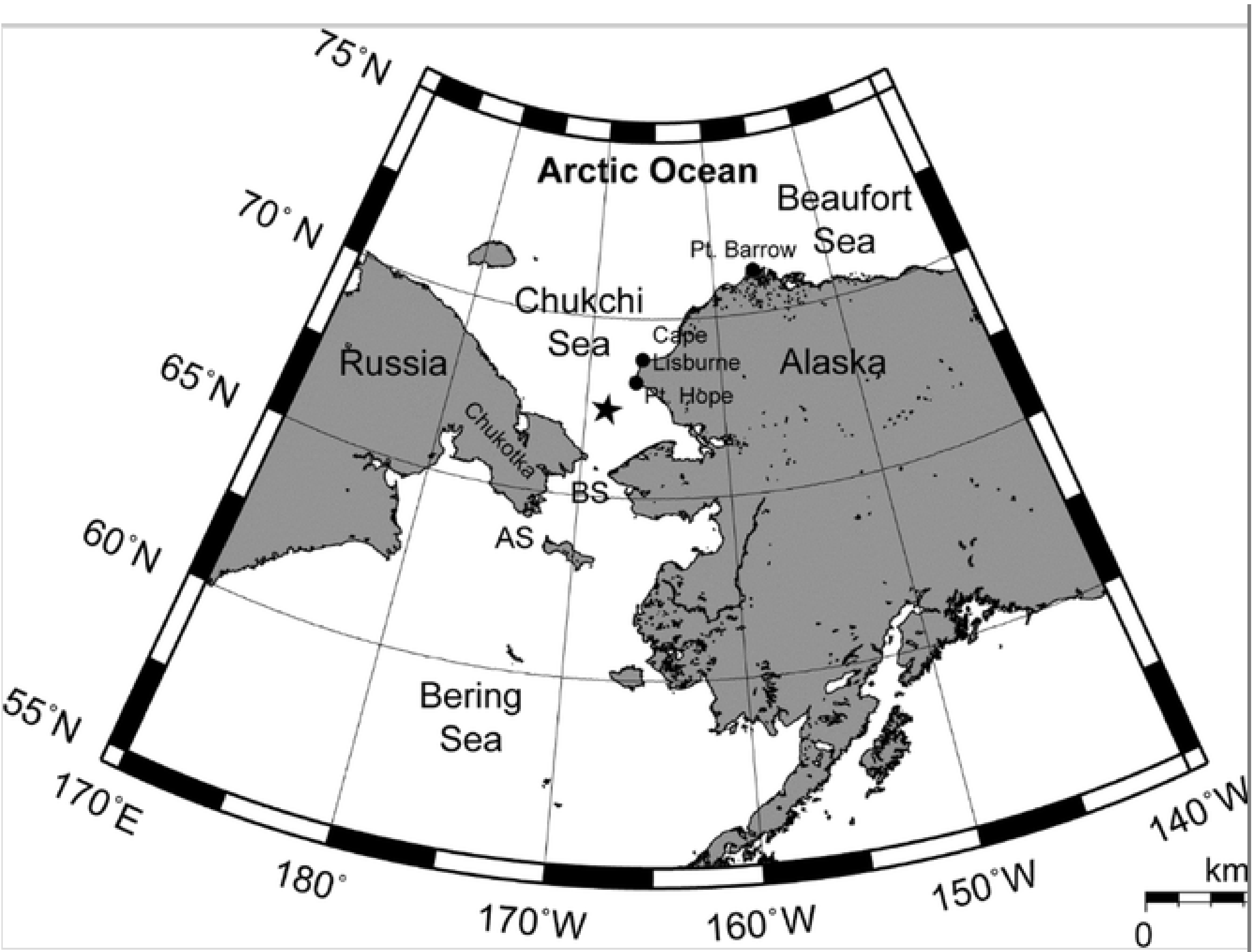


Table 1

Deployment details for AUSOMS. Location, dates, times, and recording parameters

Latitude (N)	Longitude (W)	Deployment period	Recording period	Bottom Depth (m)	Duty cycle (h) (ON/OFF)
67°43.09′	168°50.01′	16 July 2012–2 October 2012	16 July 2012–2 October 2012	52	24/0
67°03.01′	168°50.00′	2 October 2012–20 July 2013	2 October 2012–15 May 2013	60	6/16
68°03.01′	168°50.00′	20 July 2013–19 July 2014	20 July 2013–4 March 2014	60	6/16
68°02.98′	168°50.01′	19 July 2014–1 October 2015	19 July 2014–12 June 2015	60	5/14

Call analysis

We detected fin whale calls automatically from the recording data using the “Passive Program,” which is a custom-made vocalization analysis software written in Matlab (Mathworks Inc., Natick, MA, USA) (Tsujii et al. 2016a). A detection condition with a correct detection rate of 35.3% and a false positive rate of 0% was used (Tsujii et al. 2016a). Fin whale calls were detected from 4 August to 20 October 2012, from 25 July to 1 November 2013, from 26 July to 14 November 2014, and on 7 June 2015, for a total of 1,410 h (Tsujii et al. 2016b). For each year, we delimited the detection period by one week with day 1 being the first day that fin whale calls were detected by the automatic detector and randomly selected one hour of data per week. If for a given week some whale calls overlapped in intensity, spectral features, or pulse sequences, another hour of data from the same week was selected. We aurally and visually analyzed the each selected one-hour data using Adobe Audition CS6 (Adobe System, Inc., San Jose, CA). Sound spectrograms were made with a 16,384-point FFT algorithm (0.37 s temporal resolution, 2.69 Hz spectral resolution), and the Hamming window. Since the automatic detector could not detect all the pulses, we checked manually all the selected one-hour files. We marked all the pulses, including missing pulses by the detector in the one-hour files, and measured IPIs, which was defined as the beginning of a pulse to the beginning of the next pulse in the spectrogram (Thompson et al. 1992; Morano et al. 2012; Delarue et al. 2013) (Fig. 1). Measurable sequences consisted of at least five pulses (Watkins et al. 1987; Morano et al. 2012). We defined intervals greater than 60 s as gaps or rests in the calls (rather than as IPIs) and excluded them from the IPI analysis (Watkins et al. 1987). We divided sequences into irregular sequences and stereotyped sequences. The latter sequences were defined as songs. Hereafter, we analyzed only songs.

Each 20-Hz pulse in each song was identified as C or B based on the relative frequency content and bandwidth of the pulses, with B being lower in frequency and narrower in bandwidth than C. We classified IPIs into four types: B followed by B (IPI_BB), B followed by C (IPI_BC), C followed by B (IPI_CB), and C followed by C (IPI_CC). Based on the IPIs, the song types were classified and compared to those from the previous study (Delarue et al. 2013; Oleson et al. 2014; Koot 2015; Sugioka et al. 2016; Širović et al. 2017). The between-year differences in the IPIs were examined using the Steel–Dwass test. The statistical significance level of $\alpha = 0.05$ was used. All statistical analyses were performed using R version 3.5.2 (R core team 2018).

Results and discussion

We analyzed a total of 44 h of data of which 23 h had songs, 15 h had irregulars, four hours had no pulses detected by the automatic detector, and two hours had pulses detected by the automatic detector during the week, but no sequences (less than five consecutive pulses existed in an interval of 60 s or less) or no pulses when manually checked the selected time (Online Resource 1). Songs were recorded from August to November, but they were most frequent from September to November 2012–2014 (Online Resource 1). Only one type of song was identified (Fig. 1): a doublet consisting of repeatedly alternating C and B with a shorter IPI_CB (X ± SD = 10.5 ± 1.4 s, $n = 1824$) and a longer IPI_BC (19.6 ± 3.9 s, $n = 1751$). IPI_BB and IPI_CC were less frequent and had larger variation than the other IPIs. IPI_BB and IPI_CC had 32.7 ± 14.9 s ($n = 14$) and 18.2 ± 10.4 s ($n = 199$), respectively (Fig. 3). The IPIs in each year were: IPI_BC in 2012 (10.3 ± 1.6 s, $n = 367$), in 2013 (10.4 ± 1.8 s, $n = 621$), in 2014 (10.7 ± 0.8 s, $n = 836$); IPI_CB in 2012 (19.0 ± 4.1 s, $n = 359$), in 2013 (19.7 ± 3.7 s, $n = 591$), in 2014 (20.0 ± 4.0 s, $n = 801$). IPI_BC and IPI_CB significantly varied in 2012–2014 (Steel–Dwass test, all $p = < 0.0001$ for 2012 vs. 2013, 2012 vs. 2014, and 2013 vs. 2014 in IPI_BC and IPI_CB, Table 2). Also, IPI_BC and IPI_CB significantly varied within a year in 2012–2014 (one-way ANOVA, all $p < 0.05$ in IPI_BC and IPI_CB). The between-year difference and intra-annual difference for each IPI was approximately 1 s (Fig. 4, Online Resource 4). The doublet song was the only song pattern detected in the southern Chukchi Sea. Our results indicate a significant increase in IPIs between and within years of approximately 1 s. However, large changes did not occur, such as the change in doubles and singlet switching within the year or changes in IPI pulse type (backbeat and classic) pairings between years, as reported by Helble et al. (2020). The increases in IPIs between and within years within 10 s of doublet pattern have been reported in other areas and are considered as variations in IPIs of the same song type (Morano et al. 2012; Oleson et al. 2014; Širović et al. 2017; Weirathmueller et al. 2017). Therefore, we herein consider that only one doublet type was detected in the southern Chukchi Sea in 2012–2014, which in turn suggests that only one fin whale population is seasonally present in this area or the song patterns of the group migrated to the Arctic region changed.

Fig. 3

Detected number of inter-pulse intervals of fin whale (*Balaenoptera physalus*) songs recorded in the southern Chukchi Sea from 2012 to 2014. Y-axis is detected number of inter-pulse interval in 1 s class in seconds and x-axis is inter-pulse intervals. In legend, BB indicates backbeat (B) followed by B, BC indicates B followed by classic (C), CB indicates C followed by B, and CC indicates C followed by C

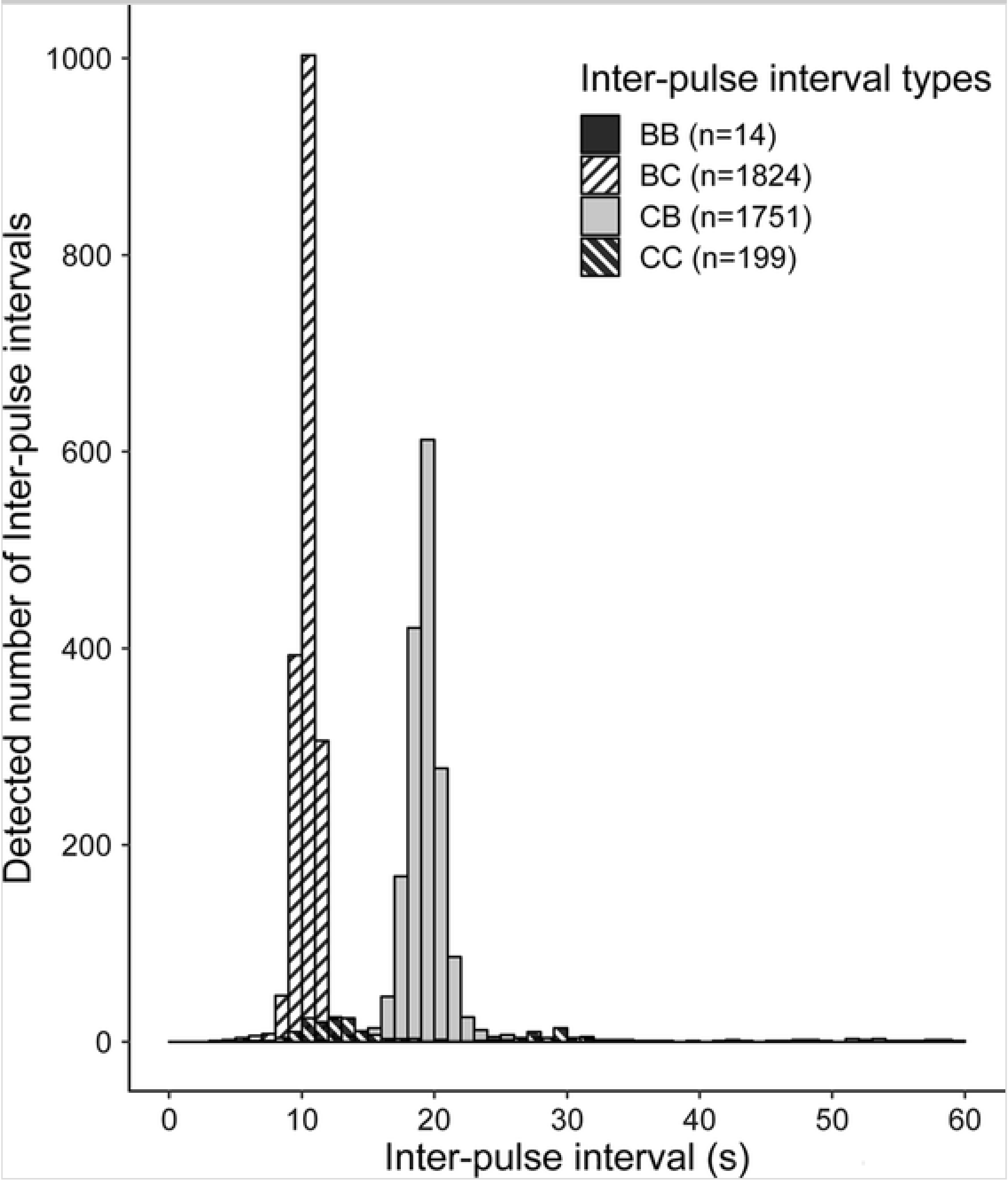


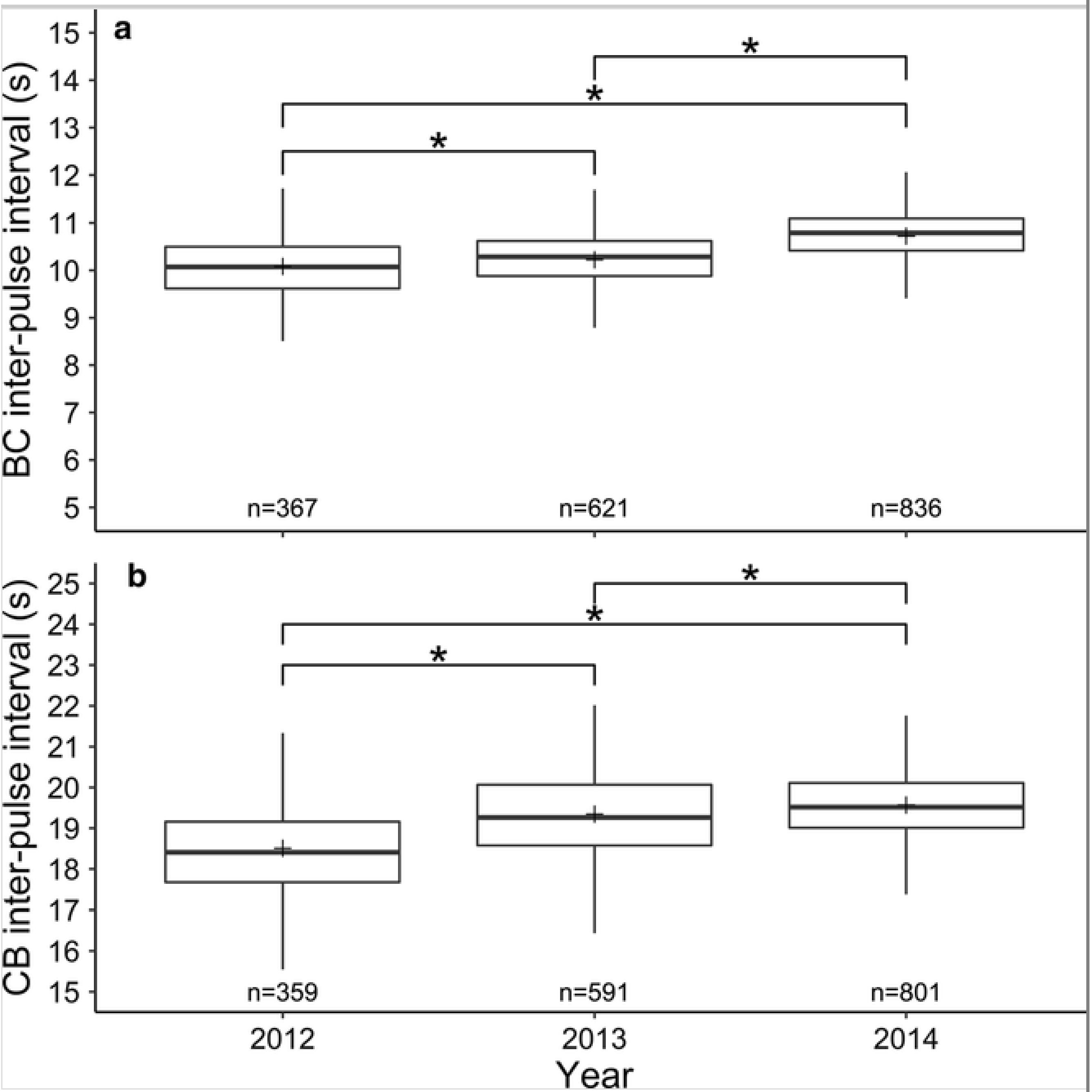
Table 2

The between-year differences in inter-pulse intervals. Results of Steel–Dwass test

Year	IPI_BC		IPI_CB	
	W Statistic	*p*-value	W Statistic	*p*-value
2012 vs. 2013	6.0206	0.0001*	12.7218	< 0.0001*
2012 vs. 2014	19.3887	< 0.0001*	18.6893	< 0.0001*
2013 vs. 2014	19.8432	< 0.0001*	5.846	0.0001*
IPI_BC indicates an inter-pulse interval (IPI) with backbeat (B) followed by classic (C), and IPI_CB indicates an IPI with C followed by B				
*α < 0.05				

Fig. 4

The between-year differences in **a** IPI_BC, in which backbeat (B) is followed by classic (C) and **b** IPI_CB, in which C is followed by B of fin whale doublet songs recorded in the southern Chukchi Sea from 2012 to 2014. Y-axis is inter-pulse interval in seconds and x-axis is recording year. Boxes indicate the interquartile range (25–75th %), whiskers represent 1.5 × interquartile range, horizontal bars in the boxes indicate the median, and cross marks indicate the mean. The numbers above each year are sample sizes. *$\alpha < 0.05$ (Steel–Dwass test)



Although the doublet was widely detected in the northern Pacific Ocean and the Bering Sea, IPI varies by region (Online Resource 2). The doublet with 10.5 s/19.6 s IPIs is similar to Type 2 songs and bout cluster 1 from the coasts of

British Columbia (Canada), Washington, and Oregon (the US) recorded in 2001–2013 (Koot 2015; Archer et al. 2020), whereas the doublets in the other regions had longer IPIs (Online Resource 2). This suggests that the fin whale population herein studied may migrate for from the eastern North Pacific Ocean.

In our study, only one type of song pattern was detected in the southern Chukchi Sea. This is similar to the results of previous studies conducted in the northeastern Chukchi Sea (Delarue et al. 2013) apart from the fact that the song type recorded in the previous study changed from 2007–2010 to 2012–2014 (Delarue et al. 2013). In 2007–2010, a triplet song with IPIs of 7.8–8.9 s/14.9–15.4 s/18.5–19.2 s consisting of one backbeat and two classic pulses was detected (Delarue et al. 2013). In 2012–2014, the same doublet songs as those detected in the southern Chukchi Sea were recorded from Cape Lisburne (St. CL1; 69.3°N, 167.6°W) (Berchok, unpubl. data). The reason for the song having changed may be due to a change in the fin whale groups that migrate to Arctic region, or it may be due to culture transmission within the groups (Helble et al. 2020). If we adopt the hypothesis that different singing patterns are produced by different resources or populations, our results suggest that only one stock of fin whales with a doublet song type migrated to the southern and northeastern Chukchi Sea from the eastern North Pacific in 2012–2014, and that group migrating to Arctic region changed between 2010 and 2012. Besides, if we adapted the culture transmission hypothesis, our findings suggest that the group migrating to the Arctic has significantly changed their song pattern in the short period between 2010 and 2012, supporting Helble et al. (2020) that fin whales can change their song patterns. However, we could not determine from this study. Further investigations using genetic analysis and photo identifications are necessary to understand whether the fin whale population observed in the Arctic Ocean in 2012–2014 was different from that observed in 2007–2010. Multiple studies of song measuring exist and it would also need genetics research to answer population questions. Long-term acoustic recordings combined with genetic research may allow us to understand why the song changed from triplet to doublet.

In conclusion, the fin whale song identified in the southern Chukchi Sea in 2012–2014 was a doublet similar to Type 2 reported by Koot (2015) and bout cluster 1 from eastern Gulf of Alaska reported by Archer et al. (2020). This finding suggests that one population migrated to the southern Chukchi Sea from the eastern North Pacific or the song patterns of the group migrated to the Arctic region changed. Future studies should continuously monitor fin whale songs and their changes in this region to assess population recovery and expansion. Furthermore, expanding the monitoring area to the western North Pacific could clarify the migration route of these fin whales.

Acknowledgements

We would like to acknowledge to Dr. Takashi Kikuchi, Dr. Shigeto Nishino, Dr. Yuka Iwahara, and the captains and crews of the R/V *Mirai*, JAMSTEC, the *W. Laurier*, Canadian Coast Guard for deployment and retrieval of monitoring systems. Dr. Daisuke Mizuguchi helped us with the setup of the device. Dr. Catherine L. Berchok provided recording data in the northeastern Chukchi Sea and the Bering Sea and helpful comments. We are grateful to Dr. Manuel Castellote who provided method and results from fin whale song study in the North Pacific and comments. We thank Dr. Mayuko Otsuki and Ms. Mina Jimbo for help with acoustic analysis. Thanks to Dr. Kazushi Miyashita, Dr. Jun Yamamoto, Dr. Hokuto Shirakawa, Dr. Makoto Tomiyasu, and Dr. Ippei Suzuki (Hokkaido University), the members and the staff of the laboratory of marine ecosystem change analysis and the members of MMS for their comments and supports. This study was funded by the Green Network of Excellence Arctic Climate Change Research Project and partially carried out in the Arctic Challenge for Sustainability Project. We would like to thank Editage (www.editage.com) for English language editing. We thanks are grateful to Dr. Ana Širović and the other reviewers and editors for their help in reviewing this manuscript.

Authors' contributions

YM conceived and designed research and conducted experiments. SF and KT analyzed data. SF wrote the manuscript. All authors read and approved the manuscript.

Funding

This study was funded by the Green Network of Excellence Arctic Climate Change Research Project and partially carried out in the Arctic Challenge for Sustainability Project.

Data availability

Not applicable.

Code availability

Not applicable.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Supplementary Information

Below is the link to the electronic supplementary material.

Supplementary file1 (docx 20 kb) Supplementary file2 (docx 17 kb)

Supplementary file3 (docx 16 kb) Supplementary file4 (docx 192 kb)

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