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Acoustic Occurrence and Affiliation of Fin Whales Detected in the Northeastern Chukchi Sea, July to October 2007–10

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ABSTRACT. Fin whales are common throughout the North Pacific region, particularly in the Gulf of Alaska and the Bering Sea, even though these areas were heavily depleted by decades of whaling. Whalers also took fin whales in the southwestern Chukchi Sea, but only five sightings have been reported for the entire Chukchi Sea in the past 30 years. Large-scale arrays consisting of 26–44 bottom-mounted acoustic recorders were deployed in the northeastern Chukchi Sea from July to October in 2007 to 2010. Fin whales were detected off Cape Lisburne and Point Lay in 2007, 2009, and 2010. Large interannual variations in the number of acoustic detections may be related to environmental conditions. Calls detected during summer months consisted primarily of irregular sequences. Stereotyped sequences, called songs, were also detected at the end of the recording period in 2007 and 2010. Their structure matched that of one of the songs recorded in the Bering Sea, suggesting that only one of the stocks occurring in the Bering Sea extends its range into the northeastern Chukchi Sea. These detections currently represent the northernmost fin whale records in the North Pacific region.

Key words: fin whale, *Balaenoptera physalus*, Chukchi Sea, distribution, detection, passive acoustic monitoring, song, stock assessment

RÉSUMÉ. Les rorquals communs sont relativement abondants dans le Pacifique Nord et en particulier dans le golfe d'Alaska et la mer de Béring, bien qu'ils y aient été décimés par plusieurs décennies de campagnes baleinières. Les baleiniers ont également pris des rorquals communs dans le sud-ouest de la mer des Tchouktches, mais seulement cinq observations ont été rapportées pour l'ensemble de la mer des Tchouktches au cours des 30 dernières années. De juillet à octobre 2007 à 2010, de grands réseaux consistant en 26 à 44 enregistreurs acoustiques ont été déployés dans le nord-est de la mer des Tchouktches. Des rorquals communs ont été détectés au large de la pointe Lay et du cap Lisburne en 2007, 2009 et 2010. Les importantes variations interannuelles du nombre de détections acoustiques pourraient être liées aux conditions environnementales. Les sons détectés consistaient principalement en des séquences irrégulières qui caractérisent le répertoire estival de l'espèce. Des séquences stéréotypées, appelées chants, ont aussi été enregistrées à la fin de l'étude en 2007 et 2010. Leur structure correspondait à celle d'un des chants enregistrés dans la mer de Béring, ce qui suggère que seul un des stocks présents dans la mer de Béring inclut le nord-est de la mer des Tchouktches dans son aire de distribution estivale. Ces détections représentent les mentions de rorquals communs les plus nordiques de la région du Pacifique Nord.

Mots clés : rorqual commun, *Balaenoptera physalus*, mer des Tchouktches, distribution, détection, surveillance acoustique passive, chant, évaluation de stock

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INTRODUCTION

The fin whale (*Balaenoptera physalus*) is a cosmopolitan cetacean distributed in most oceans and open seas from the tropics to the ice edge (Mizroch et al., 1984). In the North Pacific region, fin whales have been sighted or recorded in the Sea of Cortez (Thompson et al., 1992; Croll et al., 2002); off Hawaii (Mobley et al., 1996; McDonald and Fox, 1999); along the west coast of the United States, including California (Barlow and Forney, 2007) and Oregon (McDonald et al., 1995); in the central (Moore et al., 1998, 2000; Watkins et al., 2000) and western north Pacific (Moore et al., 1998); and in the Bering Sea and the Gulf of Alaska (Watkins et al., 2000; Moore et al., 2002, 2006; Stafford et al., 2007). In the eastern Bering Sea, fin whales are the most common large whale, numbering more than 4000 individuals (Moore et al., 2002). They are also the most commonly sighted cetacean on the central Bering Sea shelf (Moore et al., 2000) and the most frequently recorded species in the Gulf of Alaska (Stafford et al., 2007). The spatial distribution of fin

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whale catches in the North Pacific during the 20th century is in good agreement with these recent sightings and acoustic detections (Mizroch et al., 2009).

Fin whales were heavily exploited after World War II, particularly in the Gulf of Alaska and the Bering Sea (Zerbini et al., 2006; Springer et al., 2007; Mizroch et al., 2009). More than 20 000 fin whales were taken in the Bering Sea, including waters along the Aleutian Chain (Mizroch et al., 2009). Fin whales were regularly observed by Japanese and Russian whalers in the southwestern Chukchi Sea. Their range extended west until Long Strait and north to Wrangel and Herald Islands (Sleptsov, 1961). During whaling campaigns by the Russian vessel *Aleut* in 1933 – 35 and the Japanese vessel *Tonan Maru* in 1940, many fin whales were caught in an area extending west up to Cape Schmidt and north to 69˚ N, 171˚ W (Fig. 1) (Mizroch et al., 2009). However, the exact number of fin whales caught there during those years is unclear. The *Aleut* continued to hunt between the Kuril Islands and the Chukchi Sea until 1972, but the frequency at which the ship operated in the Chukchi Sea is unknown (Sleptsov, 1961; Berzin and Rovnin, 1966). Japanese scientists reported seeing many fin whales at about 66˚40′ N, 170˚ W in mid-August 1927 and about 70 individuals near the Bering Strait in October 1927 (Nasu, 1960). Japanese whalers took 74 fin whales along the Chukotka coast in the summer of 1941 (Nemoto, 1959). During an oceanographic cruise in the southwestern Chukchi Sea in August 1958, only one fin whale was sighted 90 km west of Point Hope (Nasu, 1960). A decade later, while hunting gray whales between 1969 and 1978, the Russian catcher-boat *Zvedny* reported seeing fin whales occasionally within a 50 km radius of 67˚20′ N, 171˚45′ W (Votrogov and Ivashin, 1980). However, the most recent Russian sighting cruises in the Chukchi Sea, between 1979 and 1992, did not see any fin whales (Vladimirov, 1994).

During the modern whaling period, fin whales were present in the southwestern Chukchi Sea, at times in sizeable numbers: 320 individuals were counted during a six-day survey between the Bering Strait and Cape Serdtse-Kamen in September 1939 (Sleptsov, 1961), even though these numbers are not reflected in the catch data (Springer et al., 2007; Mizroch et al., 2009). Large interannual fluctuations in abundance were noted and correlated to food and ice conditions (Nikulin, 1946; Sleptsov, 1961), but a decline in abundance over time is evident from the available sighting and catch data. Fin whales were apparently largely absent off Alaska except near the Bering Strait. The amount of searching effort in the northeastern Chukchi Sea is unknown, but presumably low. Fin whales were present in the Chukchi Sea at least from July to September, with a few isolated individuals staying until October (Berzin and Rovnin, 1966).

Whaling for fin whales in the North Pacific was banned in 1975 by the International Whaling Commission (Allen, 1980). There are signs of recovery in some areas (Zerbini et al., 2006), but fin whales remain rare in the Chukchi Sea, where only five post-whaling sightings have been reported.

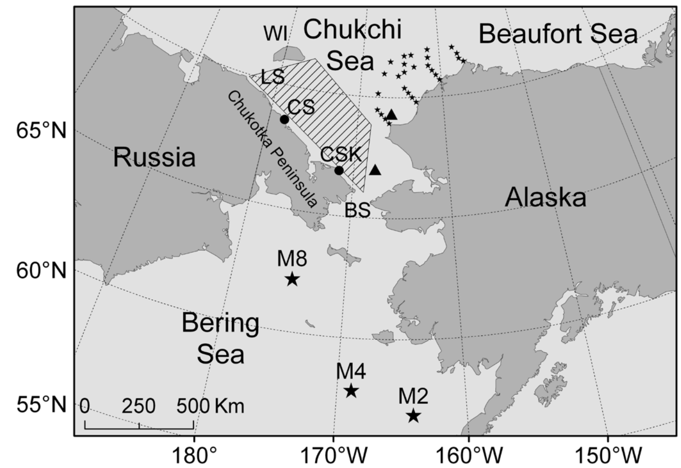

FIG. 1. Map of the study area. Stars indicate the locations of the recorders used in this study. The dashed area indicates the maximum extent of fin whale catches and sightings during the modern whaling period. The two triangles show the approximate location of recent fin whale sightings (bottom: 1981 and 2006; top: 2008). Abbreviations: BS: Bering Strait; CS: Cape Schmidt; CSK: Cape Serdtse-Kamen; LS: Long Strait; WI: Wrangel Island.

Three fin whales were sighted just north of the Bering Strait in 1981 (Ljungblad et al., 1982); three fin whales were sighted in the southeastern Chukchi Sea in 2006 (Patterson et al., 2007); and three sightings involving five individuals were recorded north of Cape Lisburne in July 2008 (Ireland et al., 2009; Clarke and Ferguson, 2010) (Fig. 1).

Fin whales produce various signals, the most common of which is a descending note that decreases from about 25 to 18 Hz over its duration of about one second (Watkins et al., 1987; Edds, 1988; Thompson et al., 1992; Hatch and Clark, 2004). During the breeding season, males (Watkins et al., 2000; Croll et al., 2002) produce stereotyped sequences of pulses characterized by stable inter-pulse intervals (Watkins et al., 1987; Hatch and Clark, 2004; Delarue et al., 2009). Several sequences of pulses make up a song, which can last several hours (Watkins et al., 1987). In some areas, doublets of pulses marked by two different, alternating pulse intervals happen to be the repeated unit, as observed in the Sea of Cortez (Thompson et al., 1992). A lower-frequency note, called backbeat, is sometimes inserted at the beginning or end of a sequence, or displayed between pulses, or both (Clark and Gagnon, 2002; Hatch and Clark, 2004). Songs are considered breeding displays and have been recorded mainly from fall until spring (Watkins et al., 2000; Stafford et al., 2007). Pulses can also be produced in short, irregular series when whales are socializing, feeding, or traveling (Watkins, 1981; McDonald et al., 1995). Pulses in these irregular series typically cover a larger bandwidth than song notes, extend up to 35 Hz or higher, and are most common in summer (Watkins, 1981; McDonald and Fox, 1999; Charif et al., 2002), when songs are largely absent.

This paper reports on acoustic detections of fin whales in the northeastern Chukchi Sea from July to October 2007 – 10, discussing them in relation to past occurrence of fin whales and increasing human activities in the Chukchi

Sea. In addition, we present information on the affiliation of the detected fin whales. Mizroch et al. (2009) compiled evidence suggesting that several fin whale stocks mingle in the Bering Sea – Aleutian Islands area. The structure of fin whale songs is defined by the duration of pulse intervals, which are known to vary geographically (Watkins et al., 1987; Thompson et al., 1992; Hatch and Clark, 2004; Delarue et al., 2009; Castellote et al., 2011). There is evidence that geographic variations, even on a relatively small scale, are related to stock structure (Delarue et al., 2009). Fin whale song detections in the Chukchi Sea prompted us to analyze Bering Sea acoustic data in order to investigate whether these songs could also be found in the Bering Sea and could serve as an index of stock affiliation.

METHODS

Recorder Deployment

The northeastern Chukchi Sea is the object of a long-term passive acoustic monitoring program aimed at measuring ambient noise and monitoring marine mammals and human activities in areas of interest for oil and gas development. This program is focused primarily on the open-water season, which lasts from July to October. During the summers of 2007 to 2010, large-scale networks of hydrophones were deployed in the Chukchi Sea between Cape Lisburne and Barrow, Alaska (Figs. 1 and 2). These networks were composed of up to 26 autonomous underwater recorders for acoustic listening (AURAL, Multi-Électronique, Inc.) in 2007 and 44 autonomous multi-channel acoustic recorders (AMAR, JASCO Applied Sciences) in 2008 – 10. Recordings typically started in the last week of July or the first week of August except in 2007, when ice conditions allowed early deployment (in mid-July). Retrievals occurred between mid-September and mid-October (Table 1). The 2008 recorders experienced hardware failure that interfered with data collection, and consequently, those data were not included in this study. In 2007, the recorders were divided into four parallel arrays, each composed of 6 – 8 recorders and extending up to 210 km from shore. In 2009 and 2010, these arrays were supplemented by two (2009) or three (2010) clusters of recorders at selected locations (Fig. 2).

All AURALs were fitted with HTI-96 (High Tech Inc.) hydrophones with -164 dB re 1V/μPa nominal sensitivity. Data were sampled at a rate of 16 384 Hz with 16-bit resolution using a recorder gain setting of +22 dB, which provided a spectral noise floor of 57 dB re 1 μPa^2/Hz. The usable bandwidth was 10 – 7700 Hz. AMARs were equipped with GTI-M15B (GeoSpectrum) hydrophones with -160 dB re 1V/μPa sensitivity. Acoustic data were recorded continuously at a rate of 16 000 Hz with 24-bit resolution and a gain setting of 0 dB in 2009 and +18 dB in 2010. The usable bandwidth was 10 – 7600 Hz, and the spectral noise floor was 45 dB re 1 μPa^2/Hz in 2009 and 42 dB re 1 μPa^2/Hz in 2010. All recorders were deployed on the seafloor at depths ranging from 15 to 100 m.

Acoustic recorders were deployed at three stations in the Bering Sea (Table 1). Haruphones (Haru Matsumoto, CIMRS/NOAA, Newport, Oregon) were deployed in 2007 at stations M2 and M4 (Fig. 1; Table 1). These recorders sampled continuously at 2 kHz. AURAL recorders fitted with HTI-96 (High Tech Inc.) hydrophones with -164 dB re 1V/μPa nominal sensitivity were deployed at stations M8 in 2008 and M2 in 2009. Data were sampled at a rate of 8192 Hz with 16-bit resolution, using a recorder gain setting of +16 dB. The 2009 M2 AURAL sampled continuously, while the 2008 M8 AURAL sampled on a duty cycle of 9 min on/21 min off.

Call Detection

For the 2007 Chukchi Sea data set, the spectrogram correlation detection tool implemented in the software Ishmael (Mellinger, 2002) was used to automatically detect all fin whale calls, whether in irregular sequences or songs. Sound files were visualized using a Hamming window, a 4096-point Fast Fourier Transform, and a hop size of 0.5. From a preliminary analysis of call characteristics, the contour targeted for detection was defined as follows. The start and end frequencies were 40 and 15 Hz, respectively, the duration was 2 s, and the contour width (instantaneous bandwidth) was 10 Hz. The spectrogram correlation detector was applied to all data files of all recorders.

A random sample of detections (7 – 15% of sound files with detections, depending on the station) was manually verified to ensure the accuracy of results. The performance of the detector varied between recorders and was primarily affected by the presence or absence of impulsive background noise (possibly caused by the mooring or by benthic organisms interacting with the hydrophone) in the frequency band of interest. Because of concerns that differences in ambient noise between recording stations might affect the comparability of call counts, the detection results were presented as the daily number of half-hours containing at least one fin whale detection.

Starting in 2009, a standardized manual analysis protocol (consisting of manual review of 5% of the acoustic data) was established to determine the occurrence of marine mammal calls in the data. The Chukchi Sea passive acoustic monitoring program is indeed intended to monitor all species occurring in the northeastern Chukchi Sea, some of which produce calls that automated methods cannot easily detect. Daily summary files were generated by appending the first 90 s sample from of each of the 48 30 min files recorded at each station each day. One summary file thus contained 5% of the data from one station for one day. Fin whale calls (from both irregular sequences and songs), if present, were annotated in each sample, thus providing a record of the species' acoustic occurrence in the area. All of

TABLE 1. First possible fin whale detection date, or deployment date (Chukchi Sea: all call types; Bering Sea: triplet songs or units only), date of first and last detections, last possible detection date (recovery date), and number of detection days for all stations where fin whale calls were detected in the northeastern Chukchi Sea in summer 2007, 2009, and 2010 and in the Bering Sea between October 2007 and September 2009.

Year	Station	Deployment date	First detection day	Last detection day	Recovery date	Number of detection days
Chukchi Sea:						
2007	CL35	16 July	9 August	13 September	13 September	26
	CL50	16 July	5 August	13 September	13 September	26
	CLN40	17 July	8 September	11 September	14 September	3
	CLN80	18 July	11 August	14 September	14 September	34
	PL50	18 July	14 September	15 September	15 September	2
2009	CL50	5 August	20 August	5 September	6 October	7
	CLN90	27 August	29 August	30 August	10 October	2
	PL50	6 August	21 August	28 August	3 October	2
2010	CL50	26 July	7 August	1 October	15 October	5
	CLN90	26 July	1 September	2 September	11 October	2
	PL50	27 July	14 August	3 October	11 October	2
Bering Sea:						
2007–08	M4	1 October	2 October	10 February	8 May	133
	M2	28 December	28 December	3 May	6 May	131
2008–09	M8	30 September	19 October	11 December	27 April	71
2009	M2	5 May	18 May	25 September	25 September	144

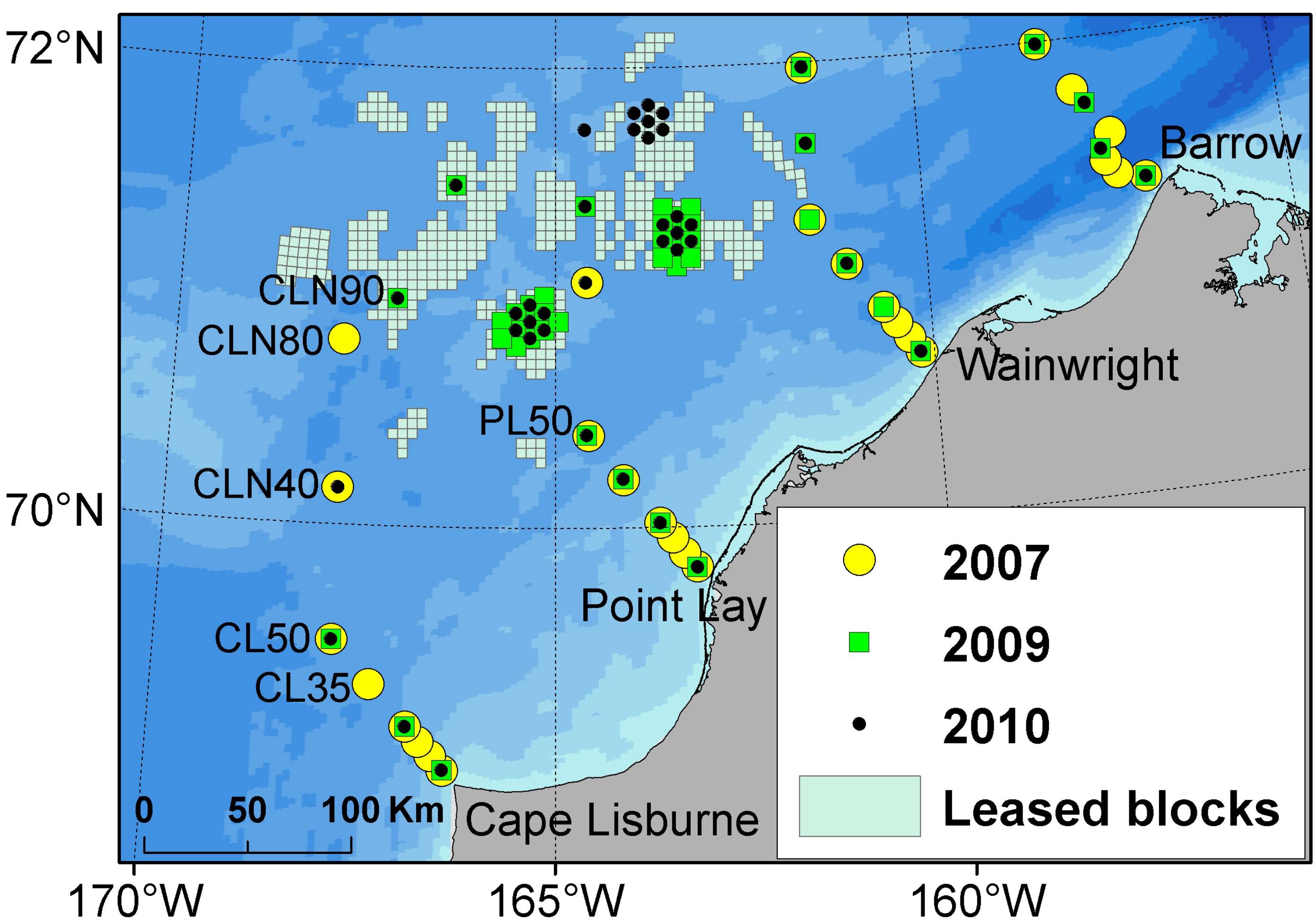

FIG. 2. Map of the study area in the northeastern Chukchi Sea, showing the position of the acoustic recorders in 2007 (○), 2009 (■), and 2010 (•). Groups of smaller squares indicate locations of leased blocks.

the 2009 and 2010 acoustic recordings were analyzed using this protocol, and no fin whale automatic detectors were applied subsequently.

In order to assess the effectiveness of the 5% manual analysis protocol in providing a representative picture of the acoustic occurrence of fin whale calls in the entire data set, we calculated the probability that a randomly selected 90 s sample would contain calls if calls were present within its 30 min source file. This is referred to as the detection probability (DP). Nine randomly selected sound files recorded in 2009 and 2010 were fully annotated by the manual analysts so that all calls were identified. A random start time within the file was then chosen, and the next 5% of the file was searched for manual detections. This random sample selection was repeated 2000 times. A detection probability was obtained for each file by dividing the number of samples containing at least one annotation by the number of iterations (2000).

The detection results for the 2007 data were presented as the daily number of half-hours containing at least one fin whale detection.

The Bering Sea data analysis was restricted to detecting the presence of songs matching the Chukchi Sea type (a single song type was detected in the Chukchi Sea). Ten-minute spectrograms were generated (0–50 Hz bandwidth) and reviewed by an experienced analyst (C.L. Berchok). A custom-made program in Matlab was used to review the spectrograms and mark them for the presence or absence of Chukchi-type songs. If this song type was present, the program skipped ahead to the first image file of the next half-hour segment; otherwise, the program moved to the next 10 min spectrogram. The detection results were presented as the daily number of half-hours containing at least one Chukchi-type song detection.

Call Analysis

Maximum (start) and minimum (end) frequency, as well as duration, were measured for a sample of high signal-to-noise ratio Chukchi calls (both summer calls and song notes) and Bering Sea calls (song notes only), using custom-built acoustic analysis software. In order to account for the different sampling frequencies of the Bering and Chukchi Sea recordings, call parameters were extracted from spectrograms generated using standardized parameters (Reisz window with 1 Hz frequency resolution, 0.128 s frame size and 0.064 s time step). Files selected for analysis were recorded on different days and at different stations. The time interval between consecutive notes of songs recorded in the Chukchi and Bering Seas was measured from the beginning of a pulse to the beginning of the next pulse in the spectrogram. Differences in the duration of corresponding pulse intervals of songs recorded during the same year (Chukchi Sea) or within the same area (Bering Sea) were tested using one-way ANOVA followed by Tukey's Honestly Significant Difference post-hoc tests, or Kruskal-Wallis tests followed by Conover-Inman post-hoc tests when the normality and equal variance assumptions were not met. The normality and equal variance assumptions were tested using the Lilliefors and Levene's tests, respectively. Call parameters (frequency range and duration of individual notes) and pulse intervals were compared between years and areas using one-way ANOVA or Mann-Whitney *U* tests. All tests were carried out with Systat 13.

RESULTS

The following results rely on the automated analysis (followed by partial manual verification) of 35 131 hours of acoustic data, corresponding to an average of 56.3 recording days at 26 stations in summer 2007, as well as the manual analysis of 1835 hours of data in 2009 and 2130 hours of data in 2010, representing 5% of the data recorded in each year (average of 63.7 recording days at 24 stations in 2009; average of 70 recording days at 25 stations in 2010). Fin whale call detections were restricted to the stations labeled in Figure 2.

Chukchi Sea Call Descriptions

The large majority of calls recorded in the Chukchi Sea were irregular sequences of pulses (Fig. 3). Pulses analyzed at three stations on five different days randomly selected throughout the 2007 detection period were all descending notes, decreasing from 34.7 ± 5.0 Hz (n = 106; range: 21.5–43.7 Hz) to 19.8 ± 3.9 Hz (n = 106; range: 12–29.5 Hz). Pulses lasted 0.9 ± 0.2 s (n = 104; range: 0.5–1.3 s). Additionally, songs were detected at CLN80 and PL50 from 13 to 15 September 2007 and at CL50 and PL50 from 1 to 3 October 2010 (Fig. 4). Almost all sequences were composed of repetitions of a three-note unit. The first note was a short, down-sweeping pulse ranging between 22 and 13 Hz (a backbeat) followed by two more broadband, slightly longer pulses, decreasing from about 34 to 16 Hz (Table 2; the 2010 songs were too faint for reliable note measurements). The intervals between consecutive notes in a unit were not equal in duration, but both the intervals between the same notes (i.e., between note 1 and note 2) in different units and the time between consecutive units were stable (Tables 2 and 3). This song will hereafter be referred to as the triplet song in reference to the three notes making up its units.

Songs recorded in 2007 and the majority of those recorded at PL50 in 2010 were composed of similar triplet units (Tables 2 and 3). The units of all songs recorded at CL50 in 2010 consisted only of two broadband notes but the intervals between these notes strongly suggest that this song can be categorized as a triplet song. The interval between the two broadband notes (I-2′) indeed matched the second interval (I-2) for other triplet songs (Fig. 4; Tables 2 and 3) and the interval between the second note of a unit and the first note of the next unit (I-3′, Table 3) approximated the sum of I-2 and I-3 in triplet songs (Tables 2 and 3), which suggests that the backbeat note was omitted or

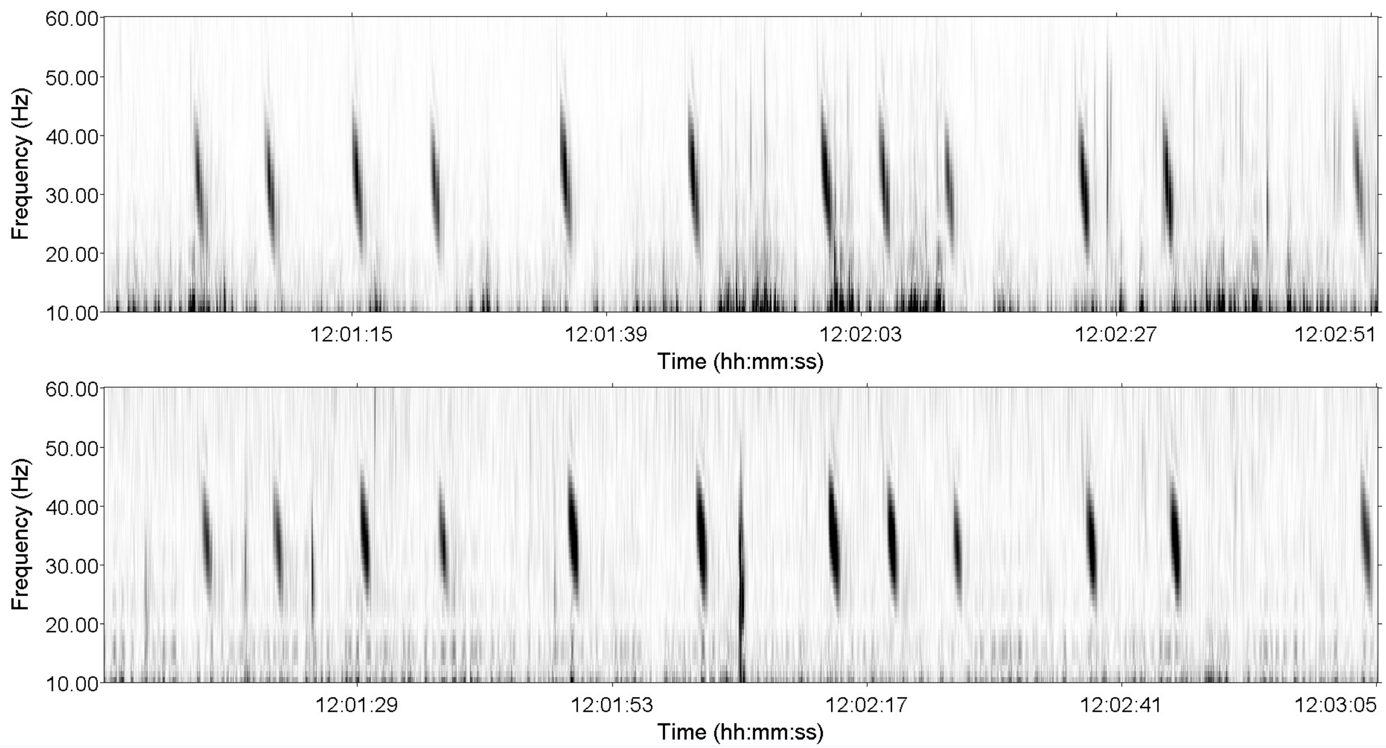

FIG. 3. A fin whale irregular pulse sequence recorded at CL35 (top) and CL50 (bottom) on 11 September 2007. These recorders were 28 km apart. The spectrogram was generated using a Reisz window with 1 Hz frequency resolution, a frame size of 0.128 s, and a time step of 0.064 s. Time on the x-axis is in hours, minutes, and seconds (hh:mm:ss).

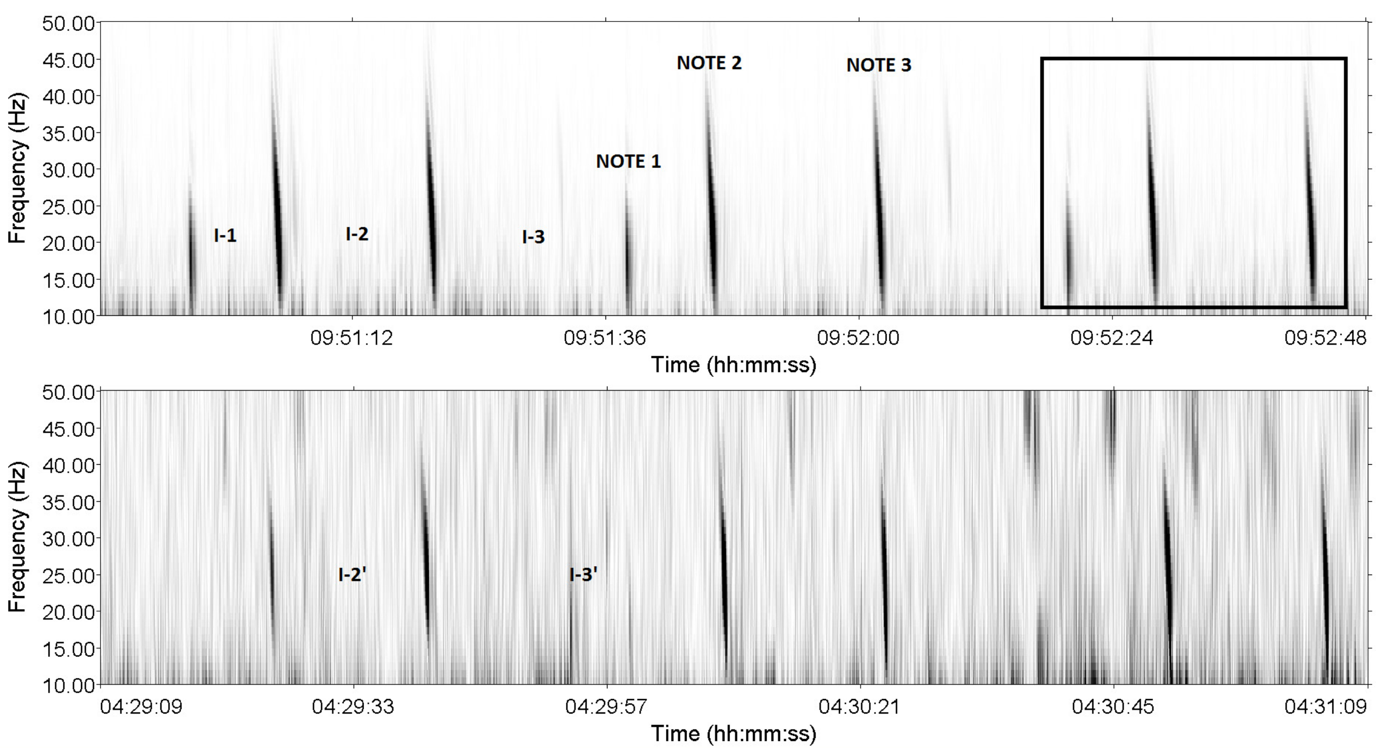

FIG. 4. Segments of fin whale songs recorded at station PL50 in the northeastern Chukchi Sea (top) on 15 September 2007 and (bottom) on 3 October 2010. The box shows a song unit, called a triplet. Notes 1, 2, and 3 represent the three components of a triplet. I-1, I-2, and I-2′ refer to the intervals between consecutive notes; I-3 and I-3′ refer to the interval between two consecutive triplet units. Note 1 is not present in the 2010 song. The spectrogram was generated using a Reisz window with 1 Hz frequency resolution, a frame size of 0.128 s, and a time step of 0.064 s. Time on the x-axis is in hours, minutes, and seconds (hh:mm:ss).

TABLE 2. Mean (standard error) of note frequencies and durations of notes and the intervals between them for fin whale triplet songs recorded at CLN80 and PL50 in the Chukchi Sea on 13–15 September 2007. Measurements of time (s) and frequency (Hz) were obtained from spectrograms generated using a Reisz window, 1 Hz frequency resolution (16384-pt FFT), a frame size of 0.128 s, and a time step of 0.064 s.

Interval	Duration	n		
1	7.8 (0.2)	89		
2	14.9 (0.7)	85		
3	18.5 (0.7)	71		
Note	MinF	MaxF	Duration	n
1	13.0 (1.3)	22.4 (1.4)	0.5 (0.1)	90
2	15.9 (0.7)	34.4 (1.0)	0.9 (0.1)	89
3	15.6 (0.8)	33.9 (1.4)	0.9 (0.1)	85

TABLE 3. Mean (standard error) of duration of intervals between notes for fin whale triplet songs recorded at CL50 and PL50 in the Chukchi Sea in October 2010. The interval durations were measured from spectrograms generated using a Reisz window, 0.976 Hz frequency resolution (16384-pt FFT), a frame size of 0.128 s, and a time step of 9.964 s.

	CL50		PL50	
Interval	Duration	n	Duration	n
1			8.9 (0.3)	28
2			15.4 (0.6)	28
3			19.2 (0.6)	22
2′	15.5 (0.5)	61	15.5 (0.4)	8
3′	28.1 (1.2)	59	27.7 (0.5)	9

not detected. We also observed a few units in triplet songs recorded at PL50 in 2010 in which the backbeat note was lacking or barely detectable. The pulse intervals of these units matched those of the CL50 songs. Knowing that backbeat notes usually have a lower amplitude than regular downsweeps (Clark and Gagnon, 2002) and that the songs detected at CL50 in 2010 had a lower signal-to-noise ratio than other songs that contained all three notes, the lack of backbeat detections is most likely the result of transmission losses occurring as song notes traveled from a distant source to the recorder. Thus, one can conclude that a single fin whale song type was recorded in the northeastern Chukchi Sea.

When we compared the second intervals of the five songs measured in 2007, no significant differences were detected. The same was true for the third intervals (the spaces between the last note of a series and the first note of the following one). However, half of the pairwise comparisons for the first pulse interval were statistically significant (all $p < 0.026$). There were no significant differences between the three pulse intervals of the four songs measured in 2010. When all 2007 songs were pooled, the mean duration for each interval was significantly different from the corresponding mean from the 2010 songs (I-1: $U = 0$; $p < 0.001$; I-2: $U = 798$; $p < 0.001$; I-3: $U = 313$; $p < 0.001$).

TABLE 4. Mean (standard error) of notes and note interval characteristics for fin whale triplet songs recorded at station M4 in the Bering Sea from 5 October to 21 November 2007. Time (s) and frequency (Hz) measurements were obtained from spectrograms generated using a Reisz window, 0.976 Hz frequency resolution (2048-pt FFT), 0.128 s frame size, and 0.064 s time step.

Interval	Duration	n		
1	8.3 (0.5)	57		
2	14.8 (0.7)	49		
3	18.9 (1.2)	50		
Note	MinF	MaxF	Duration	n
1	14.1 (1.1)	21.9 (0.8)	0.5 (0.1)	61
2	15.3 (0.7)	27.9 (2.6)	0.8 (0.1)	57
3	14.9 (0.9)	26.2 (2.5)	0.7 (0.1)	58

The between-year difference for each of the three pulse intervals ranged from 0.5 to 1.1 s (Tables 2 and 3).

Chukchi versus Bering Sea Song Comparison

The pulse intervals measured for the triplet songs recorded in the Bering Sea (Table 4) were comparable to those measured for the Chukchi Sea triplet songs. When we combined the 2007 and 2010 Chukchi Sea songs, we found that the mean durations of all three intervals differed by up to 0.25 s from those of the corresponding intervals in the Bering Sea songs. These differences were statistically significant for I-1 ($U = 5{,}816$; $p < 0.001$) and I-3 ($U = 3.342$; $p = 0.039$), but not for I-2 ($F = 3.728$; $p = 0.55$). The same results were obtained when comparing the Bering Sea songs to the 2007 Chukchi Sea songs alone (I-1: $U = 2{,}613$; $p < 0.001$; I-2: $F = 0.69$; $p = 0.407$; I-3: $U = 2.903$; $p = 0.003$). The comparison of the Bering and 2010 Chukchi Sea songs showed that I-1 ($U = 213$; $p < 0.001$) and I-2 ($F = 18.999$; $p < 0.001$) were significantly different, while I-3 ($U = 439$; $p = 0.175$) was not. When we compared the pulse intervals of Bering Sea songs alone, all three showed significant differences (I-1: $H = 29.805$; $p < 0.001$; I-2: $F = 3.317$; $p = 0.009$; I-3: $H = 22.301$; $p = 0.001$) although the number of significantly different pairwise comparisons varied from 2 for I-2 to 11 and 12 for I-3 and I-1 (out of 21), respectively. All frequency and duration measurements for the Chukchi (2007 only) and Bering Sea song notes were significantly different ($p < 0.001$) except for the maximum frequency of note 1 ($U = 2{,}414.5$; $p = 0.21$) and its duration, which showed only a marginally significant difference ($U = 3{,}274$; $p = 0.045$).

Spatiotemporal Detection Patterns

Chukchi Sea: In 2007, detections started on 5 August at CL50, 9 August at CL35, and 11 August at CLN80, and they continued at these three stations until the end of the recording period (13–15 September). Detections at CLN40 and PL50 were restricted to the end of the deployment, occurring specifically from 8 to 11 September at CLN40 and on

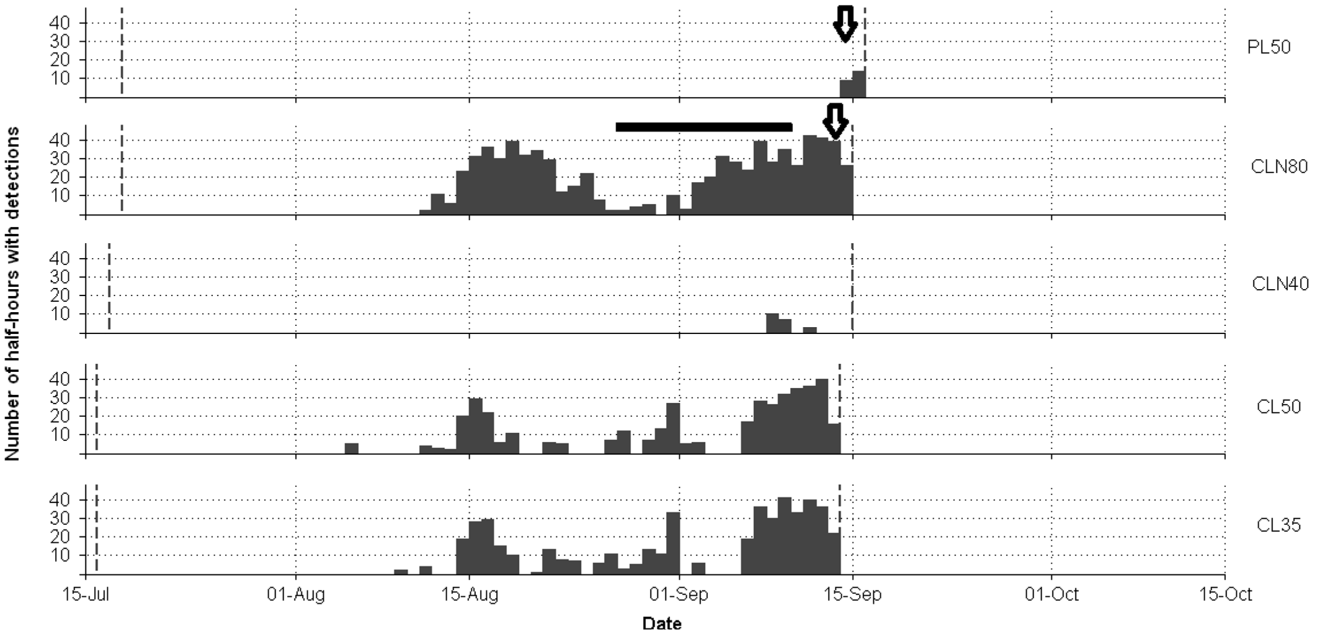

FIG. 5. Daily number of half-hours with automatic fin whale detections in the Chukchi Sea from mid-July to mid-September 2007 at all stations where fin whale calls were recorded. Vertical dashed lines indicate recorder deployment and retrieval. The black bar represents the duration of the seismic survey detected at CLN80. The arrows mark the first song detection.

14 and 15 September at PL50 (Table 1; Figs. 2 and 5). Triplet songs were detected on 13 to 14 September at CLN80 and on 14 and 15 September at PL50.

Fin whale detections were most abundant at CLN80, and next at CL35 and CL50 (Table 1; Fig. 5). Detections at CLN80 had a bi-modal distribution, with a first detection period from 14 to 24 August, a quasi-absence of detections until the beginning of September, and a second detection peak that lasted until just before the recorder's retrieval in mid-September (Fig. 5). Detections at CL35 and CL50 had a multi-modal distribution. A first detection peak that occurred around mid-August was followed by several small peaks separated by days with few or no detections. A final, strong peak, similar to that seen at CLN80, occurred from 6 to 13 September (Fig. 5). During both peaks at CLN80 and the second peak at CL35 and CL50, fin whales were detected 62% to 87% of the time. Detections at CLN40 were few and coincided with the second detection peak at CL35, CL50, and CLN80. Detections at PL50 were also limited and occurred on the last two days of recording at that station (Fig. 5).

On several occasions, the same call sequences were received simultaneously at CL35 and CL50 (28 km apart; Fig. 3), but the majority of detected calls were unique to one station. The calls recorded at CLN40 were not detected at CLN80 or CL50, each 74 km away from CLN40.

In 2009, acoustic detections were restricted to stations CL50, CLN90, and PL50. Calls were detected from 20 August to 5 September, over 2–7 days at each station. Typically several events were detected each day, but no event lasted more than three consecutive hours (Table 1; Fig. 6). No songs were detected in that year. Detection probability averaged 81.8% in 2009.

In 2010, acoustic detections were restricted to stations CL50, CLN90, and PL50. Detections occurred from 7 August to 3 October (Table 1; Fig. 6), over 2–5 days at each station. In all but one case, fin whales were detected several times per day, but no detection lasted more than two consecutive hours. Triplet songs were detected only on 1 October at CL50 and 3 October at PL50. Detection probability averaged 60.9% in 2010.

Bering Sea: In 2007–08, triplet song detections at M4 occurred almost daily from 2 October to 2 December 2007, with a few more isolated detections around 11 and 22 December and later on 28 January and 9 February 2008 (Fig. 7). Triplet song detections at M2 started upon deployment (28 December 2007), decreased steadily until the end of January 2008, and rebounded for 2–3 weeks until 22 February. A few isolated triplet songs were detected in March. The last two detections occurred on 3 April and 3 May 2008 (Fig. 7).

In 2008–09, triplet song detections at M8 lasted from 19 October until 11 December 2008, although the main detection period ended the third week of November (Fig. 8). In 2009, the M2 recorder was the only one deployed early enough to capture the onset of singing. Three isolated triplet song detections occurred from 18 May to 13 June. From 10 July until the end of August, detections occurred daily and in increasing numbers, but all were single triplet units rather than songs composed of multiple triplets in sequence. From 30 August on, however, most detections were triplet songs. Recordings ended on 25 September 2009 (Fig. 8).

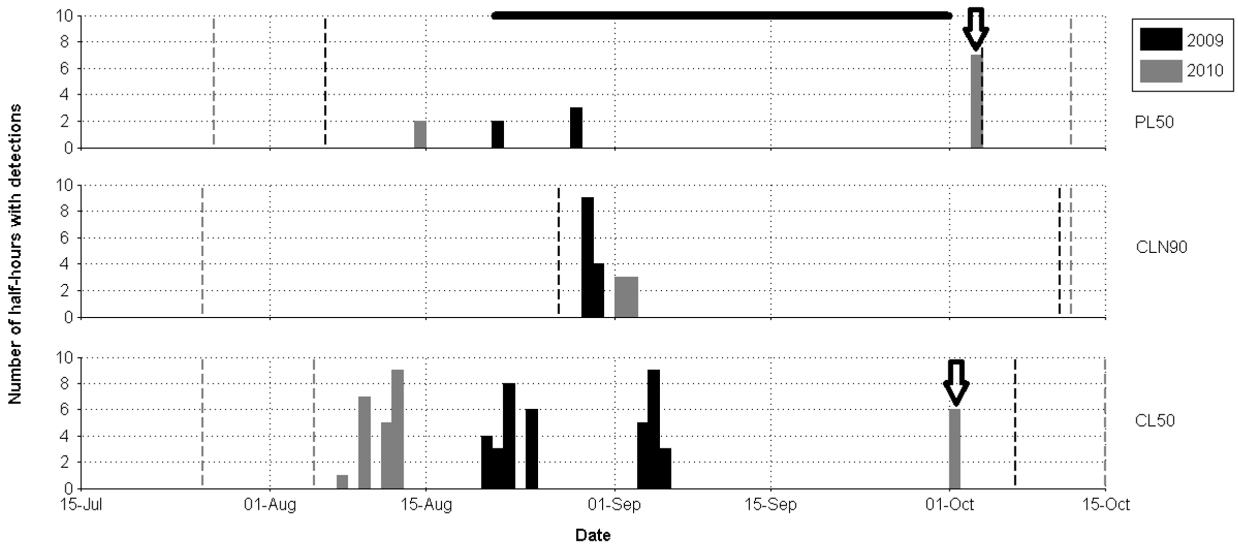

FIG. 6. Daily number of half-hours with manual fin whale detections based on the analysis of 5% of acoustic data recorded in the Chukchi Sea from late July to mid-October in 2009 (black) and 2010 (grey). Only the stations where fin whale calls were recorded are shown. Vertical dashed lines indicate recorder deployment and retrieval. The black bar represents the duration of the seismic survey detected at CLN90 and PL50 in 2010. The arrows mark the first song detection.

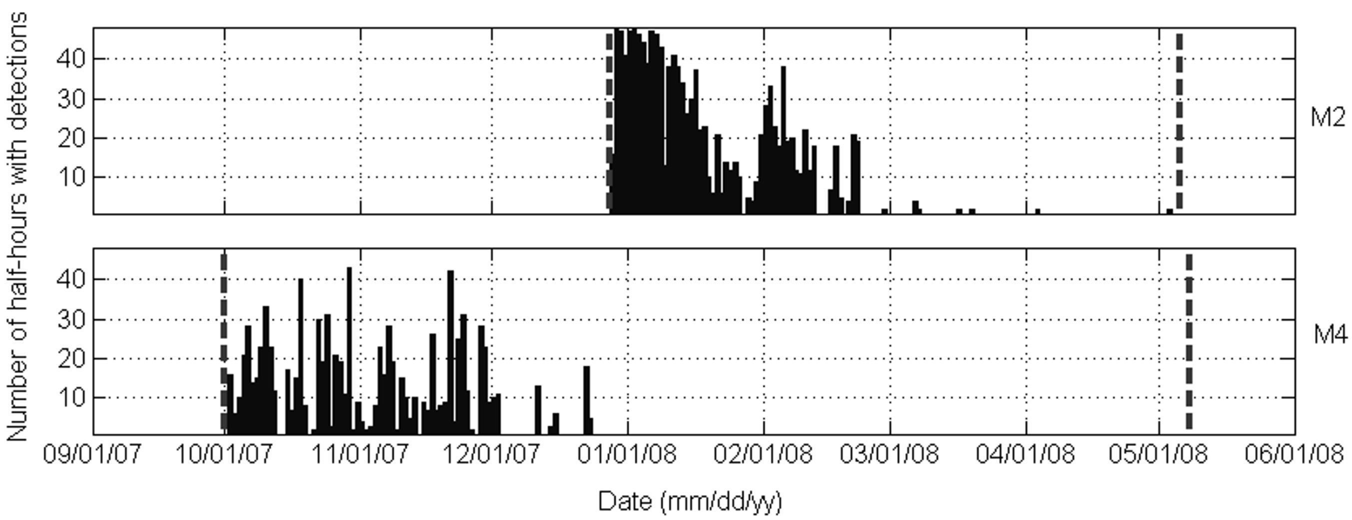

FIG. 7. Daily number of half-hours with detections of fin whale triplets based on the manual analysis of acoustic data recorded in the Bering Sea from October 2007 until May 2008. Dashed lines indicate recorder deployment and retrieval.

DISCUSSION

Chukchi Sea Acoustic Detections and Implications

The detections at station CLN90 currently represent the northernmost records of fin whales in the Pacific region, near 71˚ N, confirming that this species is not constrained to subarctic waters. In the North Atlantic, fin whales are regularly sighted north of the Arctic Circle, for example, near Disko Island off west Greenland (70˚ N; Heide-Jorgensen et al., 2003) or off northern Norway (69˚ N) and Svalbard (78˚ N) (Mizroch et al., 1984). The consistency in detection locations in 2007, 2009, and 2010 suggests that at least three areas in the northeastern Chukchi Sea, near stations CL50, CLN80-CLN90 and PL50, have a higher probability of fin whale occurrence. The lack of detections at CLN40, in particular in 2007, remains unexplained; masking of calls by higher ambient noise cannot explain it, as noise levels at CLN40 were intermediate between those at CL50 and CLN80 (Martin et al., 2009). In 2010, the lack of detections at CLN40 could simply be due to the low overall occurrence of fin whales combined with the limited analysis protocol. No fin whales were detected northeast of a line perpendicular to the shore extending from Point Lay, nor were they detected at any stations less than 65 km from shore. Simultaneous detections of different call sequences at several stations along the Cape Lisburne array indicate that several groups of fin whales were present and broadly distributed in the study area during the summer of 2007.

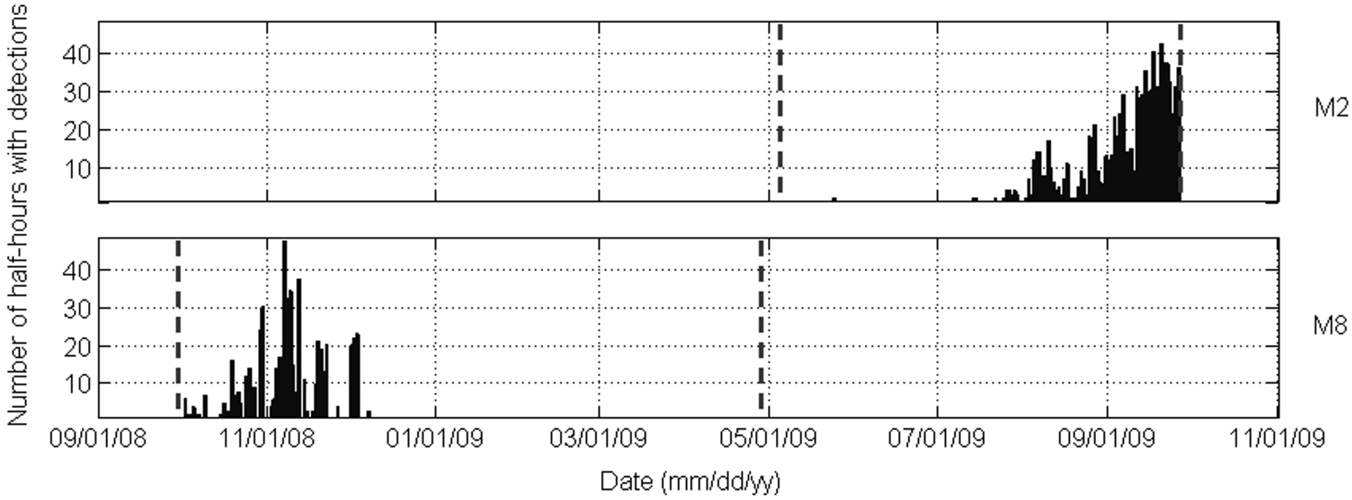

FIG. 8. Daily number of half-hours with detections of fin whale triplets based on the manual analysis of acoustic data recorded in the Bering Sea from October 2008 until September 2009. Dashed lines indicate recorder deployment and retrieval.

The timing of these detections substantiates evidence derived from sightings during the modern whaling period regarding the temporal pattern of fin whale presence in the Chukchi Sea (in summer and early fall). The fact that the detection period coincided with the peak feeding season, as well as the nearly continuous fin whale detections at three stations for several consecutive days in 2007, indicate that fin whales were likely feeding in the Chukchi Sea. The short duration of each detection in 2009 and 2010 indicates shorter residency times, which may be related to poorer feeding opportunities in those years.

The clear decrease in detections at station CLN80 from 25 August to 1 September 2007, which occurred between two large detection peaks, suggests either a cessation of calling or a temporary movement of fin whales out of the recorder's detection range. A 3D seismic survey (airgun volume: 3147 in^3) was conducted from 27 August to 9 September 2007 about 165 km to the northeast of station CLN80 (Fig. 5). The received sound pressure levels (SPL) of airgun sounds detected at station CLN80 ranged from 77.3 to 116.7 dB (rms) re 1μPa. But the decrease in the number of daily detections began before the onset of the seismic survey, and fin whale detections in large numbers resumed halfway through the survey and continued after it ended. Thus, airgun sounds are not believed to have caused the drop in detections observed at CLN80 even though fin whales in the Mediterranean Sea have previously been shown to react strongly to airgun sounds at SPL below 120 dB (rms) re 1μPa (Castellote et al., 2012). A shallow hazard survey (airgun array volume: 40 in^3) was also conducted in the northeastern Chukchi Sea in the summer of 2009 but was not detected at the stations where fin whale detections occurred, except on 1 October 2009 at CLN90. This survey is not believed to be the cause of the limited number of detections observed that year. A 3D survey (airgun volume 3000 in^3) was conducted between 21 August and 1 October 2010 in the northern part of the study area (Fig. 6). Airgun sounds were detected at stations CLN90 (SPL: 93.1 – 121.5 dB (rms) re 1μPa) and PL50 (SPL: 87.4 – 123.8 dB (rms) re 1μPa), but not at CL50. It is unclear whether the long duration of the seismic survey was a factor in the small number of detections observed that year. The similarity with the 2009 detections (when no airgun sounds were detected) and the similar pattern of detections between PL50 and CL50 (no airgun sounds were detected at CL50) suggest that other factors may have contributed to the difference in the number of acoustic detections between 2007 and 2009 – 10.

The number of detections was strikingly lower in 2009 and 2010 than in 2007. Although 2009 and 2010 were also relatively warm years, during the summer of 2007 the Arctic experienced exceptional environmental conditions characterized by an early ice retreat, record-low ice extent, and higher-than-average sea surface temperatures (Stroeve et al., 2008). In addition, the Bering Strait transport and heat flux in 2007 were the highest recorded during the period 1991 – 2007 (Woodgate et al., 2010). In a study of planktonic communities in the northeastern Chukchi Sea between 2008 and 2010, Hopcroft et al. (2011) described a large interannual variability in species composition and abundance and suggested that it is related to a combination of local physical parameters and the intensity of physical transport from the Bering Strait. Most planktonic species in the Chukchi Sea are indeed Pacific in origin. The combination of environmental and physical conditions observed in 2007 may therefore have triggered increased local productivity or prey advection from the Bering Sea, a major fin whale feeding ground, or both (Moore et al., 2000, 2002), and thus attracted more fin whales. These conditions may also explain what appear to be the first sightings of humpback whales in the northeastern Chukchi Sea (Ireland et al., 2009). These observations are valuable in the context of changing environmental conditions in the Arctic, which may ultimately offer favorable conditions for species more commonly found in subarctic areas (Moore and Huntington, 2008).

Fin Whale Sightings Versus Acoustic Detections

The last three decades have been characterized by an almost complete lack of fin whale sightings in the Chukchi Sea, despite a number of surveys. Aerial surveys conducted mostly in nearshore waters of the Chukchi and Beaufort Seas in July and August of 1982–86 and September and October of 1982–91, with track lines in the vicinity of the locations of our detections (Moore and DeMaster, 1998), never yielded any fin whale sightings, except for one close to the Bering Strait in 1981 (Ljungblad et al., 1982). The latest Russian whale sighting cruises in the Chukchi Sea, conducted between 1979 and 1992, did not see any fin whales (Vladimirov, 1994). A ship survey throughout the Chukchi and Beaufort Seas in July and August 2003 (Bengtson and Cameron, 2003) also saw no fin whales. Although the passive acoustic monitoring program did not target their historical range in the Chukchi Sea (i.e., along the Chukotka coast), several surveys have searched this area for bowhead (*Balaena mysticetus*) and other endangered large whales at various times between late July and late October (though primarily in September and October) in 1979, 1980, 1982, 1992, and 1993 (Miller et al., 1986; Moore et al., 1995). Fin whales were never sighted in this area.

Since 2006, the increasing human activity off Alaska linked to oil and gas exploration has led to an increase in marine mammal monitoring programs, which increased the probability of detecting species visually in the survey area. However, recent boat-based visual surveys reported only one fin whale observation in the southeastern Chukchi Sea (outside of the current study area) in September 2006 (Patterson et al., 2007), and two sightings off Cape Lisburne in July 2008 (Ireland et al., 2009). In parallel, the resumption of the Chukchi Offshore Monitoring in Drilling Area (COMIDA) aerial surveys in the northeastern Chukchi Sea since June 2008 resulted in one fin whale sighting in July 2008 off Cape Lisburne (Clarke and Ferguson, 2010). Overall, the visual records over the last 30 years all indicate that fin whales are rare in the Chukchi Sea.

In contrast, the present acoustic monitoring program yielded fin whale detections in all years when recorders were operational, although with large interannual variations. Marine mammal observers did not observe fin whales in any of those years, but it is worth noting that visual observation effort was relatively limited near the stations where fin whales were detected acoustically (Funk et al., 2010; Aerts et al., 2011). As discussed above, the 2007 acoustic detections were probably an exception triggered by unusual environmental conditions. The similarities in the number of detection days and the location of the detections in 2009 and 2010 suggest that the patterns observed in these two years may represent baseline fin whale occurrence in the northeastern Chukchi Sea. Fin whales thus appear to occur occasionally but annually between August and October off Cape Lisburne and Point Lay. Although the absence of sightings in the northeastern Chukchi Sea during the 20th century whaling campaigns could be largely due to a lack of survey effort, as whalers focused on the more productive southwestern Chukchi Sea, it is consistent with the idea that fin whales have never been abundant in the northeastern Chukchi Sea.

The larger number of acoustic detections demonstrates that acoustic monitoring offers a greater detection probability than visual surveys, which are limited to a few kilometers and restricted to daylight hours and good weather conditions. The range of acoustic detections of fin whales was found to be 56 km off the Antarctic Peninsula (Širović et al., 2007) and 10–100 km in the Gulf of Alaska, depending on ambient noise conditions (Stafford et al., 2007). The maximum detection range in this study, 14–74 km in the northeastern Chukchi Sea in 2007, was based on the simultaneous detection of the same calls at two stations 28 km apart, which never occurred at stations 74 km apart.

Calling Behavior and Stock Structure Implications

The calls recorded in this study are in agreement with current knowledge of fin whale vocal behavior. Irregular sequences were largely predominant, and the calls covered a broader bandwidth than typical 20 Hz pulses, as has been previously shown for fin whales in summer (Watkins, 1981; McDonald et al., 1995). Although more variable than the stereotyped song units detected in the fall, winter, and spring, these summer broad bandwidth pulses were reliably detected using spectrogram correlation techniques.

The stock structure of North Pacific fin whales is still unclear. All fin whales in this area are managed as a single stock (Mizroch et al., 1984), although there is increasing evidence in support of two migratory stocks wintering along the Asian and American coasts and probably intermingling in the Bering Sea and the Aleutian Islands during the summer feeding season (Kellog, 1929; Berzin and Rovnin, 1966; Mizroch et al., 2009). Several song types, including the triplet song, were detected in the Bering Sea (C.L. Berchok, unpubl. data), suggesting that several fin whale stocks occupy this area. The triplet song was the only song detected in the northeastern Chukchi Sea although 2009 and 2010 deployments there lasted until the first half of October and should have provided an opportunity to record other song types if any were present. Thus, it appears that only one of the stocks summering in the Bering Sea currently extends its range into the northeastern Chukchi Sea. Acoustic recorders should be deployed along the northern Chukotka coast to determine whether several stocks are present in the southwestern Chukchi Sea, where fin whales were historically abundant.

Slight differences in pulse intervals between the 2007 and 2010 Chukchi Sea songs may reflect the songs' natural variability, small sample sizes, and the fact that in both years songs were detected at the onset of the singing season, when song structure may not yet be fully stabilized. Differences between the Chukchi and Bering Sea songs in the frequency and duration of song notes may be the result of differences in propagation conditions and the distance between singers and recorders. Although statistical tests revealed significant differences between the Chukchi (either combined or individually) and Bering songs for two of the three intervals, significant differences were also found among Bering Sea songs for all three intervals. The latter could not be explained by a seasonal variation in pulse interval, as observed in other areas (e.g., Morano et al., 2012). Further, the differences in mean pulse intervals observed between all Chukchi and Bering Sea songs (about 0.25 s) are well within the range of variations observed for songs recorded within a month of each other in other areas (J. Delarue, unpubl. data). These differences, although statistically significant, may therefore not have biological significance for fin whales. A better understanding of the natural variability of triplet songs throughout fall and winter is needed to address this question.

The temporal distribution of the detections at M2 indicates that some individuals belonging to the stock characterized by the triplet song may be present in the southeastern Bering Sea most of the year. However, the abrupt end of song detections in late February 2008 at M2, combined with the absence of detections at M4 and M8 past December, suggests that the majority of fin whales displaying the triplet song are absent from the Bering Sea in late winter and spring. Indeed, fin whale songs are a prominent acoustic feature in the North Pacific between August and April (Watkins et al., 2000; Stafford et al., 2007), and a lack of songs in this period can reasonably be interpreted as an absence of fin whales.

CONCLUSION

This study has shown that fin whales are yearly visitors to the northeastern Chukchi Sea. Their occurrence is typically low but can increase in some years, presumably as a result of enhanced local prey availability. The 2007 observations hint at a possible future increase in fin whale occurrence in this area under a continuing Arctic warming scenario. Acoustic monitoring is needed to evaluate the occurrence of fin whales in the southwestern Chukchi Sea. This monitoring, combined with a detailed description of all Bering Sea song types, would allow us to determine whether only one of the Bering Sea acoustic stocks indeed enters the Chukchi Sea.

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