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The migration of fin whales into the southern Chukchi Sea as monitored with passive acoustics

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Fin whales (*Balaenoptera physalus*) undergo seasonal migration in the Arctic Sea. Because their migration and distribution is likely affected by changes in global climate, we aimed to examine the migration timing of fin whales, and the relationship with prey availability within the oceanographic environment of the Arctic Sea, using passive and active acoustic monitoring methods. Automatic Underwater Sound Monitoring Systems were deployed in the southern Chukchi Sea from July 2012 to 2014 to determine the acoustic presence of fin whales. Furthermore, water temperature and salinity were recorded by a fixed data logger. An Acoustic Zooplankton Fish Profiler was additionally deployed to estimate prey abundance through backscattering strength. Sea ice concentrations were obtained by remote sensing data. Fin whale calls were automatically detected using a custom-made software, and the per cent of half-hours containing calls were counted. Fin whale calls were detected from 4 August to 20 October 2012 (78 d) and 25 July to 1 November 2013 (100 d). The extended period of acoustic presence of fin whales during 2013 when compared with 2012 is likely related to a longer ice-free period during 2013. Furthermore, generalized linear model analyses showed that half-hour periods containing calls increased with a rise in water temperature and zooplankton abundance during the initial call presence period, while they decreased with a decrease in water temperature and salinity during the end of the call presence period. Our results suggest that the rise in water temperature and zooplankton abundance affect the timing of migration of fin whales in a way that is consistent with the expansion of their suitable habitats and the extension of their presence in the Arctic Sea.

Keywords: Chukchi Sea, fin whale, migration, passive acoustic monitoring.

Introduction

Changes in distributions of species due to climate change have been increasingly reported during recent years (Walther *et al.*, 2002). Especially in the Arctic, the environment has drastically changed, and rapid loss of sea ice has occurred over the past decade, with the sea ice cover being its lowest in recorded history in 2012 (e.g. Comiso *et al.*, 2008; Parkinson and Comiso, 2013). In the Chukchi Sea which is one of the most biologically productive areas in the world (Grebmeier, 2012), the increasing inflow of warm freshwater through the Bering

Strait, south vicinity of the Chukchi Sea (Woodgate *et al.*, 2012), is thought to have caused lengthened the sea ice-free season (e.g. Overland and Wang, 2013). These environmental changes are considered to affect ecosystem structure and prey availability of cetaceans, which are the apex predators of the Arctic Sea (Moore and Huntington, 2008).

In the Arctic Sea, two types of cetaceans are observed; (i) the seasonally migrant species, such as fin whales (*Balaenoptera physalus*), minke whales (*Balaenoptera acutorostrata*), and humpback whales (*Megaptera novaeangliae*), which migrate to the Arctic Sea for feeding during summer (Moore and Huntington, 2008), and (ii) the ice-associated species, such as bowhead whales (*Balaena mysticetus*), which distribute around the Arctic Sea all year round and migrate between the Arctic Sea and sub-Arctic Sea (Moore and Huntington, 2008; Quakenbush *et al.*, 2012). Seasonally migrant species can enter the Chukchi Sea during summer, only after sea ice reduction, and move southward during autumn, usually before sea ice formation begins (Fay, 1974). Therefore, Arctic sea ice reduction may affect the distribution of seasonally migrant species by expanding their range and their length of stay in the Arctic Sea. As a result, competition for prey and habitat with ice-associated species appears to occur (Moore, 2010). Because of this, an investigation of the timing of migration of seasonally migrant species to the Arctic Sea, which can be related to the biological and physical environment, is important in understanding the impacts of environmental changes on the ecosystem of the Arctic Sea.

During recent years, passive acoustic monitoring (PAM) has been widely applied to study the behaviour and distributions of cetaceans (e.g. Stafford *et al.*, 2010; Clarke *et al.*, 2013; Delarue *et al.*, 2013). Recording acoustic calls by deploying hydrophones over an extended time has advantage over vessel or aerial-based visual surveys of continuous monitoring of the presence of calling animals over the long term, even within the ice-covered areas such as the Arctic Sea.

Fin whales, the most common whales in the Bering Sea (Moore *et al.*, 2002), mainly produce a "20 Hz pulse": a downsweep call that decreases in frequency from ~25 to 18 Hz over its duration of ~1 s (Watkins *et al.*, 1987; Hatch and Clark, 2004; Oleson *et al.*, 2014). In addition, pulses can be produced in irregular series and extend up to 35 Hz or higher during socialization, feeding, or travelling during summer (Watkins, 1981; McDonald and Fox, 1999; Charif *et al.*, 2002). These characteristics can be used to distinguish the calls of fin whales from those of other baleen whales. In recent PAM revealed that the period of fin whale calls detection changes latitudinally; all year round in the south-eastern Bering Sea (Stafford *et al.*, 2010), from July to September in the southern Chukchi Sea (Clarke *et al.*, 2013), and from August to October in the northern Chukchi Sea (Delarue *et al.*, 2013; Crance *et al.*, 2015), although fin whales have scarcely been observed in the Chukchi Sea north of the Bering Strait using visual methods. These surveys provided visual sightings (vessel and aerial surveys) and acoustic detections (sonobuoys) data for only a few months during summer; therefore, long-term monitoring is required to understand the timing of fin whale migration to the Arctic Sea. For PAM, typical detection ranges for fin whale calls in the Chukchi Sea are likely to be ~50 km based on analogy with right whale calls in the Bering Sea (Munger *et al.*, 2011), and Delarue *et al.* (2013) described that the maximum detection ranges for fin whale calls were 14–74 km in the northeastern Chukchi Sea.

The distribution and migration of the baleen whales are closely related to the distribution and movements of their prey; fin

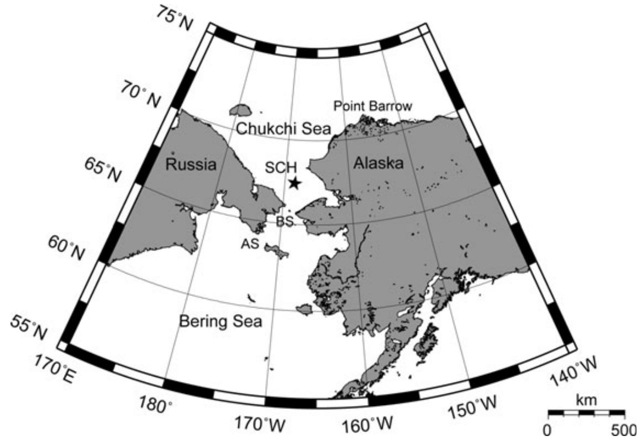

Figure 1. Map of the study area in the Chukchi Sea, and the Bering Sea located south of the Chukchi Sea. The black star indicates the SCH station where we deployed the moorings. AS, Anadyr Strait; BS, Bering Strait.

whales and fish schools, zooplankton along the southeastern Bering Sea shelf (Moore *et al.*, 2000, 2002), and bowhead whales and euphausiids at Barrow (Berline *et al.*, 2008). Therefore, the trigger for migration may include prey abundance and physical properties of the marine environment (water temperature and salinity as proxies for the prey abundance, and sea ice as a physical barrier). When fin whales migrate to the northern Bering Sea during summer, they mainly feed on zooplankton such as euphausiids (krill) and small nektonic fish such as capelin (*Mallotus villosus*), Alaskan pollock (*Theragra chalcogramma*) and Pacific herring (*Clupea pallasi*; Nemoto, 1959; Nemoto and Kawamura, 1977). Active acoustic moorings can monitor the presence and abundance of zooplankton and fish within the water column over long periods by recording the properties of the acoustic backscatter. Simultaneous monitoring of the acoustics and the physical environments, such as water temperature and salinity, allow us to compare the timing of migration of fin whales to the Arctic Sea as well as the length of their stay, with the biological and physical environment. Furthermore, this information facilitates an understanding of the impacts of environmental changes in the Arctic Sea on fin whales.

In the current study, we aimed to determine the triggers for the fin whales' arrival in and departure from the southern Chukchi Sea. First, we conducted PAM from July 2012 to 2014 in the southern Chukchi Sea, and determined the timing of their migration. We then examined the relationships among the timing of migration, prey abundance, and physical environment (sea ice concentration, water temperature, and salinity) of fin whales. Finally, we discussed the impacts of environmental changes in the Arctic Sea on fin whales.

Material and methods

Call recording

Observations were conducted at the Southern Chukchi Hotspot (SCH), located at the entrance of the Arctic Sea from 16 July 2012 to 19 July 2014 (Figure 1). We used an Automatic Underwater Sound Monitoring System ver. 3.5 (AUSOMS ver. 3.5; Aqua Sound Co., Japan) to record fin whale calls. The AUSOMS had a model SH20K hydrophone, with the frequency response between 20 Hz and 20 kHz, and a sensitivity of -190 dB re 1 V μPa^{-1}. We

Table 1. Deployment details for the Automatic Underwater Sound Monitoring System.

Station	Latitude (N)	Longitude (W)	Deployment period	Recording period	Depth (m)	Duty cycle
SCH	67°43.09′	168°50.01′	16 July 2012 – 2 October 2012	16 July 2012 – 2 October 2012	52	Continuous
	68°03.01′	168°50.00′	2 October 2012 – 20 July 2013	2 October 2012 – 15 May 2013	60	6 h on/16 h off
	68°03.01′	168°50.00′	20 July 2013 – 19 July 2014	20 July 2013 – 4 March 2014	60	6 h on/16 h off

recorded at a 44.1 kHz sampling rate, 16 bits data resolution, a 20 kHz cut-off frequency of the low-pass filter (LPF), and a 60 dB gain. The AUSOMS used in the current study was encased in a pressure-resistant cylinder case composed of stainless-steel (SUS314). The memory capacity of the AUSOMS was 762 GB in total, which comprised six 128 GB SDXC memory cards. The AUSOMS was placed on a mooring and deployed at 67°43.09′N, 168°50.01′W at 52 m depth from 16 July 2012 to 2 October 2012, at 68°03.01′N, 168°50.00′W at 60 m depth from 2 October 2012 to 20 July 2013, and at 68°03.01′N, 168°50.00′W at 60 m depth from 20 July 2013 to 19 July 2014 (Table 1). We continuously recorded underwater sound from 16 July 2012 to 2 October 2012, and periodically with a duty cycle of 6 h on, 16 h off from 2 October 2012 to 20 July 2013 and from 20 July 2013 to 19 July 2014.

Zooplankton acoustic and marine environment data collection

To monitor zooplankton abundance, we deployed an Acoustic Zooplankton Fish Profiler (AZFP; ASL Environmental Sciences Inc., Canada) over the same period as the AUSOMS. Bottom depths at the mooring sites were 52, 59, or 60 m, and the AZFP was deployed at 7 m above the seabed. We measured the volume backscattering strength (Sv) at four frequencies: 125, 200, 455, and 769 kHz. Pulse length was 0.5 or 0.3 ms, ping rate was 1 or 2 ping s^{-1}, recording interval was 30 s per 1 or 2 min, and echo integration (thickness and cycle) was 0.5 or 0.2 m, and 30 s. Sensitivity was confirmed using a 12.7 mm diameter sphere made of tungsten carbide. To examine zooplankton species composition, we did not carry out the verification of acoustic target organisms, but biological sampling using a ringnet was also conducted in the same waters in autumn 2012 and summer in 2013.

Water temperature and salinity were additionally recorded every hour using a SBE 37-SM MicroCAT C-T (P) Recorder (Sea-Bird Electronics Inc., USA) attached to frame of the AZFP. Daily sea ice concentrations at a spatial resolution of 25 km were obtained from the NSIDC (National Snow and Ice Data Center, University of Colorado Boulder). Sea ice concentrations were recorded by the Defense Meteorological Satellite Program (DMSP) special sensor microwave imager (SSM/I), and was calculated using the National Aeronautics and Space Administration Team algorithm 2 (Markus and Cavalieri, 2000).

Detection of fin whale calls

We automatically detected the calls of fin whales from the recording data using "Passive Program", which is a custom-made vocalization analysing software (by Professor IM, Tohoku Gakuin University, 2014) written in Matlab (Math Works Inc., Natick, MA, USA). The program detected calls consisting of a frequency downsweep from 40 Hz down to 20 Hz with 1–2 s duration (Figure 2).

First, we marked all fin whale calls in one of the recording files with Adobe Audition CC (Adobe System, Inc., San Jose, CA, USA) using an 4096 Fast Fourier Transform (FFT) algorithm with a Hamming window. The playback speed of the marked calls file

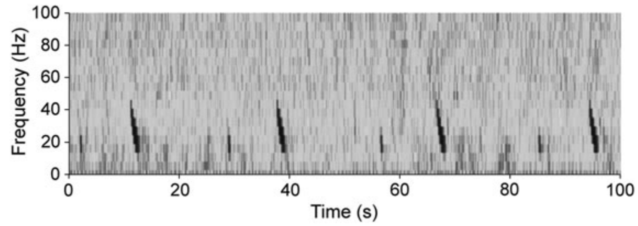

Figure 2. Spectrograms of fin whale calls (4096-point FFT, Hamming window) recorded at the SCH station on 4 October 2012. *Y*-axis is frequency in Hertz and *x*-axis is time in seconds. Fin whales mainly produce a "20 Hz pulse", which is a downsweep that decreases from ~25 to 18 Hz over its duration of ~1 s. In this spectrogram, we can isolate a downsweep that decreases from ~40 to 20 Hz and a lower-frequency note, called a "backbeat" between pulses.

was increased by 16 times. We isolated ~5 min in total of recorded calling data from the marked calls file, and analysed fin whale call characteristics in this file using Passive Program. According to the manual extraction and analysis of fin whale calls, a range of extraction parameters of call characteristics was determined. When comparing the manual and automatic extractions, the receiver operating characteristics (ROC) curve was examined. The ROC curve shows the performance of all detection conditions by plotting the call detection rate on *y*-axis and the false alarm rate on *x*-axis. Finally, we selected the optimal condition, and calls were automatically detected from all of the recording files, which resulted in the playback speed being 16 times that of the original speed to shorten the time for analysis.

AZFP analysis

We calculated volume backscattering strength (Sv) from 125 kHz echo data at depths shallower than 40 m. The data between the surface and 10 m depth were excluded from the analyses because of sea surface noise such as air bubbles due to waves or seasonal sea ice. During the daytime, zooplankton may maintain a deeper depth than that of the AZFP; therefore, the Sv data between 1 h before and 1 h after midnight were used for analyses. To understand the seasonal variation of the biomass in the water column, we finally calculated the area backscattering strength (SA) as the index of zooplankton abundance.

Data comparison

We focused on the presence or absence of acoustic detection rather than the absolute numbers of call counts. The detection results were presented as the daily number of half-hour periods containing at least one fin whale call detection. The per cent of half-hours containing fin whale calls were represented as fractions of the 48 half-hours in a day (e.g. 6 h = 12 half-hours).

We defined 1 month before and after the first fin whale call detection day as the fin whale arrival period because their calls were detected continuously within 2 weeks of the first call detection. We also defined 1 month before and after the last call detection day as the departure period. We derived a generalized linear

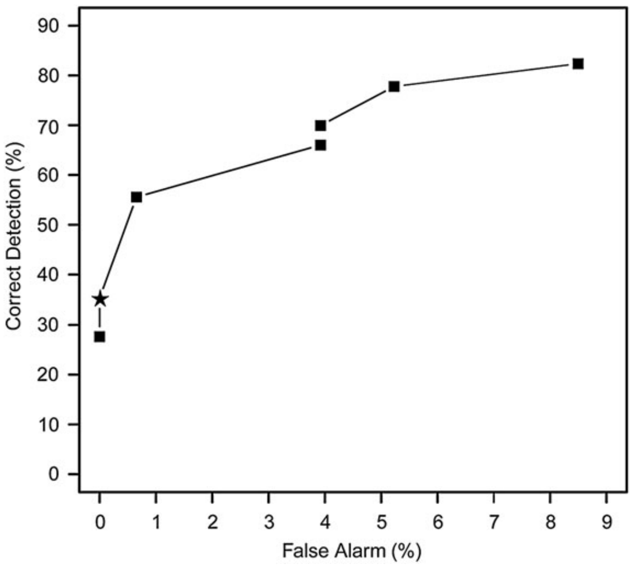

Figure 3. The receiver operating characteristic curve of detection conditions of fin whale calls. Y-axis is call detection rate and x-axis is false alarm rate. The star shows the condition (correct detection rate is 35.3%, false alarm rate is 0%) that we used to detect fin whale calls.

model (GLM) with a negative binomial distribution to describe the fin whale arrival period and departure period to understand the triggers for their arrival in and departure from the southern Chukchi Sea. The response variable was the number of half-hours containing fin whale calls per day, and the explanatory variables were zooplankton abundance (SA), water temperature, salinity, and year. Additionally, the recording time was used as the offset variable to take account of the difference of the recording time per day. The variance inflation factor (VIF) was additionally estimated to test multicollinearity within the explanatory variables. To select the best mode, we used Akaike's information criterion (AIC). Moreover, Welch's *t*-test was used to compare the water temperature between 2012 and 2013. We also used the Wilcoxon rank-sum test to compare the water temperature and salinity between the call detected period and the period of call absence. Statistical analyses were conducted in R ver. 3.1.2 (R Core Team, 2014).

Results

Automatic detection condition of fin whale calls

We obtained recording data from 16 July 2012 to 15 May 2013, and from 20 July 2013 to 4 March 2014 (Table 1). The periods from 16 May 2013 to 19 July 2013, and from 5 March 2014 to 19 July 2014 were not recorded because of a lack of data capacity.

The ROC curve was used to assess the automatic detection condition of fin whale calls (Figure 3). We chose a detection condition of 35.3% correct detection and 0% of false alarm. Ranges of extraction parameters were: a duration of 0.05–0.4 s, a maximum amplitude frequency of 290–500 Hz, a periodicity of 0.52–0.85, a maximum amplitude spectrum of >18, the 10 dB bandwidth was 160–400 Hz, and the threshold value was 1.3.

Fin whale calls were detected from 4 August 2012 to 20 October 2012 and from 25 July 2013 to 1 November 2013 (Figure 4a). The number of call detection days was 39 d during 2012 and 42 d during 2013. The period from the first call detection to the last call detection was 78 d during 2012 and 100 d during 2013. Therefore, the period of call presence during 2013 was longer than that during 2012.

Comparison with biological and physical environmental data

Sea ice concentrations were 0% during the fin whale call detection period during 2012 and 2013 (Figure 4b). The ice-free period during 2013 (from 9 June to 14 December: 189 d) was 28 d longer than that during 2012 (from 9 June to 16 November: 161 d). The first call in the season was detected 1–2 months after sea ice had retreated from this area, and the last call was detected 1–2 months before sea ice, for both 2012 and 2013.

The backscattering layers were observed in the recording data of the AZFP. Additionally, zooplankton such as copepods and krill were collected by net sampling. Estimated zooplankton abundance (SA) started to increase from late May to July, and a high SA level was maintained from August to November (Figure 4c). Fin whale calls were detected during the high SA period during both years.

During the call detected period, water temperature was 0.66 ± 0.66°C (average ± standard deviation), and salinity was 32.73 ± 0.40 parts per thousand (ppt) during 2012, whereas during 2013, the water temperature was 1.70 ± 0.46°C and salinity was 32.43 ± 0.16 ppt. Water temperature during 2013 was higher than that during 2012 (Welch's *t*-test, $p < 0.05$). In addition, water temperature and salinity during the call detected period was higher than that during the period of call absence (Wilcoxon rank-sum test, $p < 0.05$; Figure 4a, d, and e).

When we compared fin whale calls with environmental factors, we excluded 1 month before and after the initial detection of calls during 2013, as the recording data duration 1 month before the detection of the first call was 6 d due to a lack of data capacity. In the result of model selection, SA and water temperature were selected as predictor variables in the best model for predicting the arrival period (both $p < 0.05$; Table 2, The best model selected for the arrival period of fin whales). This demonstrated a positive correlation between SA and water temperature with the number of half-hour periods containing calls (Figure 5a and b). However, water temperature, salinity, and year were selected as the best predictor variables in the model to determine the departure period (except for year $p < 0.05$; Table 2, The best model selected for the departure period of fin whales). This demonstrated that, as water temperature and salinity decreased, the number of half-hour periods containing calls decreased (Figure 5c and d). Multicollinearity did not present a problem among all variables.

Discussion

The migration timing of fin whales

Many fin whales mate at low latitudes in winter, though there appear to be exceptions which are not fully understood (Mizroch *et al.*, 2009), and some move into the Chukchi Sea from the Bering Sea during summer in search of food (Fay, 1974). In previous studies, fin whale calls were detected in the southeastern Bering Sea all year during 2007 (Stafford *et al.*, 2010), and their calls were detected in the northeastern Chukchi Sea from August to October in the acoustic survey conducted from middle July to middle October during 2007, 2009, 2010 and during the short-term survey in 2012 (Delarue *et al.*, 2013; Crance *et al.*, 2015). The whales were detected in the southern Chukchi Sea over the period of July to September during the years 2009–2012 (Clarke *et al.*, 2013). However, in this study, fin whale calls were detected in the southern Chukchi Sea during late July to early November. Therefore, it is suggested that a certain proportion of the fin whales south of the Bering Sea move into the Chukchi Sea during late July, and return southward

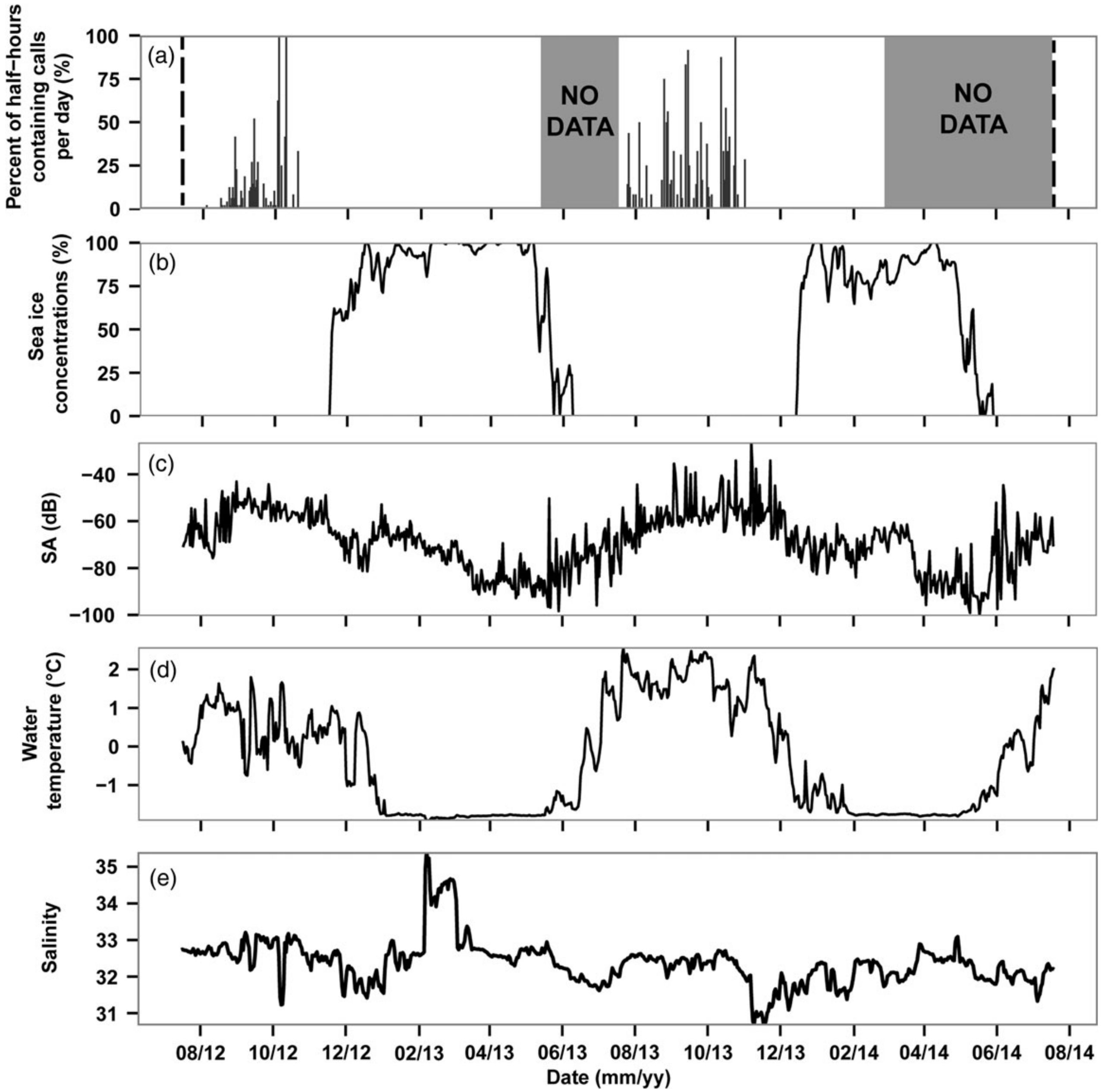

Figure 4. Time-series variation in: (a) the percent of half-hours containing fin whale calls per day; (b) daily sea ice concentrations; (c) estimated zooplankton abundance; (d) water temperature; and (e) salinity in the southern Chukchi Sea from 16 July 2012 to 19 July 2014. In (a), grey parts indicate no data periods because of the lack of recording capacity, and dashed lines indicate the first recorder deployment and the last recorder recovery.

during early November. The result of the current study showed that fin whales remain longer in the southern Chukchi Sea than has been previously reported. We considered that their period of presence in the northern Chukchi Sea may be underestimated.

The relationships among the migration timing, biological and physical environments

Fin whale calls were detected during the ice-free period, both during 2012 and 2013. In addition, both the call detection and the ice-free period during 2013 were longer than those during 2012. In the western Antarctic Peninsula, the number of detected calls of fin whales showed a negative correlation with sea ice concentrations, and it was suggested that fin whales were absent in ice-covered areas (Širović *et al.*, 2004). This suggests that fin whales arrive in the southern Chukchi Sea after the sea ice has melted, and leave the southern Chukchi Sea before sea ice extends. Our observation showed that the timing of their migration was consistent with the ice-free period.

Zooplankton abundance, water temperature, and salinity during the period of fin whale call detection were higher than that during the period of call absence. In the Arctic Sea, variations in SA, water temperature, and salinity may be caused by an increase in primary production and water temperature due to solar radiation, sea ice melting by the inflow of warm water, and advection of zooplankton and nutrients from the Bering Sea. In the Arctic Sea, several water masses such as Alaska Coastal Water, Bering Shelf

Table 2. The parameters of the best model based on Akaike's information criterion.

Variable	Estimate	Std error	*Z*-value	*p*-value
The best model selected for the arrival period of fin whales				
Zooplankton abundance (SA)	0.1353	0.0362	3.741	0.000183*
Water temperature	2.3570	0.8893	2.650	0.008038*
The best model selected for the departure period of fin whales				
Year	−0.8867	0.4657	−1.904	0.0569
Water temperature	1.7569	0.3243	5.417	6.06e−08*
Salinity	1.7795	0.3253	5.470	4.50e−08*

The response variable is the number of half-hours containing calls. There are significant positive correlations between the response variable and the explanatory variables except for year. Asterisk shows $p < 0.05$.

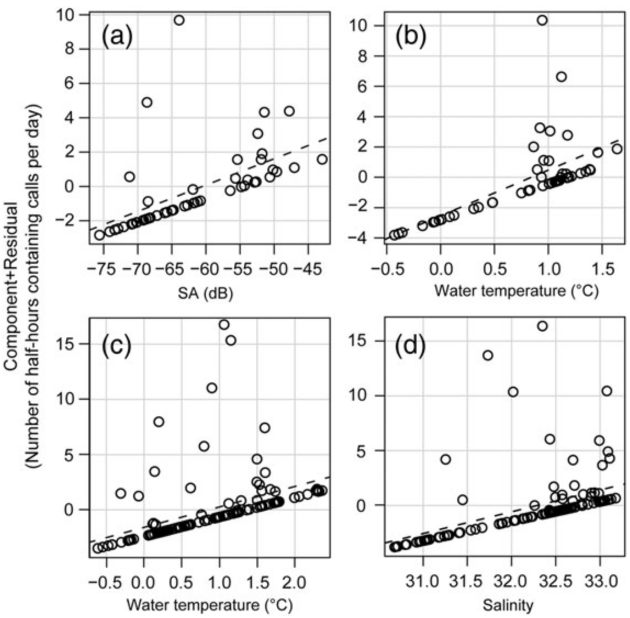

Figure 5. Component-plus-residual plots showing the relationship between the number of half-hours containing fin whale calls per day and (a) estimated zooplankton abundance and (b) water temperature during the arrival period, and the relationship between the number of half-hours containing fin whale calls per day and (c) water temperature and (d) salinity during the departure periods. The black dashed line indicates the least-squares lines.

Water, and Anadyr Water flow through the Bering Strait into the Chukchi Sea (Coachman *et al*., 1975). The inflow of water masses reaches a maximum during summer and a minimum during winter. This seasonal cycle strongly influences the pattern and timing of sea ice melt (Spall, 2007). The existence of the Bering-Shelf Anadyr Water, which is a combination of Bering Shelf Water and Anadyr Water, is known. The water temperature of Bering-Shelf Anadyr Water is ~0–4°C, and salinity is ~32.5–33 ppt (Eisner *et al*., 2013). During the call detection period, the mooring region was dominated by Bering-Shelf Anadyr Water, as inferred from water temperature and salinity. This water mass contains a large abundance of zooplankton, including euphausiids and large copepods (Eisner *et al*., 2013), and it is indicated that Bering-Shelf Anadyr Water continuously transports nutrients northward from the Anadyr Strait after the ice melt during June brings on the onset of winter storm mixing during September (Sambrotto *et al*., 1984). In addition, Eisner *et al*. (2013) suggested that sub-Arctic Pacific zooplankton taxa common to the Bering Sea ecosystem are transported northward with Bering-Shelf Anadyr Water, and Berline *et al*. (2008) indicated the Chukchi Sea is an advective pathway for euphausiids. Thus, the inflow of water masses from the Bering Sea as well as solar heat may cause increases in zooplankton abundance, water temperature, and salinity at St SCH during the residence period of the fin whales.

From the result of the selection of the best model to predict the arrival period, we found that the timing of arrival of fin whales in the southern Chukchi Sea corresponds to an increase in water temperature and zooplankton abundance. The abundance of zooplankton started to increase from late May to July, and showed high abundance from August to November. It is considered that this high abundance of zooplankton in the Chukchi Sea is largely due to transport from the Bering Sea (Springer *et al*., 1989; Weingartner, 1997). Fin whale calls were detected during the period of high abundance of zooplankton. Therefore, it is suggested that the trigger for the arrival of fin whales in the southern Chukchi Sea is an increase in water temperature and zooplankton abundance due to transport from the Bering Sea. However, an increase in water temperature may not be the direct trigger for the arrival of whales. It is considered that an increase in water temperature is associated with the inflow of water masses and solar heat that triggers an increase in zooplankton abundance that attracts whales.

From the results of the best model selection for departure period, it is evident that fin whales departed the southern Chukchi Sea with the decrease in water temperature and salinity, whereas there was no correlation with zooplankton abundance, as zooplankton maintained a high abundance 1 month after fin whales had departed. Therefore, the physical environments may trigger the departure of fin whales for their wintering area. The variation in water temperature and salinity might showed the variation in water masses containing preferred prey species of fin whales since distributions of large zooplankton species are related to water masses (Eisner *et al*., 2013). In addition, fin whales could possibly need to start migrating to reach the breeding in wintering area at this time, although it is not true always. Future study such as satellite tracking will contribute to clarify these problems.

Impact on fin whales by environmental changes in the Arctic Sea

In the Arctic Sea, a rapid loss of sea ice has occurred over the past decade, with the sea ice cover being the lowest in recorded history during 2012 (e.g. Comiso *et al*., 2008; Parkinson and Comiso 2013). In addition, in the Chukchi Sea, the inflow of warm freshwater in the Bering Strait, located to the south of the Chukchi Sea, has increased (Woodgate *et al*., 2012), and as a result, the period of the ice-free season has been lengthening (e.g. Overland and Wang, 2013). Our study suggests that fin whales arrive at the southern Chukchi Sea after sea ice has melted and water temperature has elevated. Fin whales remain within the southern Chukchi Sea until a decrease in water temperature occurs and sea ice is formed. In the previous study, a greater number of calls were detected during 2007 than during 2009 and 2010 in the northern part of the southern Chukchi Sea (Delarue *et al*., 2013). During 2007, the Arctic experienced exceptional environmental conditions characterized by an early sea ice retreat, a record-low ice extent, and higher than average sea surface temperatures (Stroeve *et al*., 2008). In addition, the transport and heat flux within the Bering Strait during 2007 were the highest recorded during the period from 1991 to 2007

(Woodgate *et al*., 2010). Therefore, the combination of environmental and physical conditions may have triggered increased local productivity or prey advection from the Bering Sea, the formation of a major fin whale feeding ground, or both (Moore *et al*., 2000, 2002), and thus attracted a greater number of fin whales during 2007 (Delarue *et al*., 2013). In addition, our results support earlier findings that the period of detected fin whale calls was longer during 2013 than during 2012. Based on these results, the timing of fin whales' arrival in and departure from the southern Chukchi Sea possibly changes according to the timing of melting and freezing of sea ice in the Arctic sea. If loss of sea ice extends, and the increases in water temperature and inflow of the water mass from the Bering Sea continue, the distribution range of fin whales in the Arctic Sea will extend.

Conclusion and recommendations for future studies

In the current study, we conducted long-term passive and active acoustic monitoring in the southern Chukchi Sea for the first time, and determined the timing of migration of fin whales. In contrast to a previous study that used only PAM, by comparing migration timing with biological and physical environments, we additionally determined that the timing of migration is related to sea ice concentrations, zooplankton abundance, water temperature, and salinity. To assess the impacts of environmental changes in the Arctic Sea on the distribution of fin whales and other apex predators, a multidimensional approach, such as that taken in the current study, will be of value.

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