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Variability in fin whale (*Balaenoptera physalus*) occurrence in the Bering Strait and southern Chukchi Sea in relation to environmental factors

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ABSTRACT

Fin whales (*Balaenoptera physalus*) are common summer visitors to the Pacific Arctic, migrating through the Bering Strait and into the southern Chukchi Sea to feed on seasonally-abundant prey. The abundance and distribution of fin whales in the Chukchi Sea varies from year-to-year, possibly reflecting fluctuating environmental conditions. We hypothesized that fin whale calls were most likely to be detected in years and at sites where productive water masses were present, indicated by low temperatures and high salinities, and where strong northward water and wind velocities, resulting in increased prey advection, were prevalent. Using acoustic recordings from three moored hydrophones in the Bering Strait region from 2009–2015, we identified fin whale calls during the open-water season (July–November) and investigated potential environmental drivers of interannual variability in fin whale presence. We examined near-surface and near-bottom temperatures (T) and salinities (S), wind and water velocities through the strait, water mass presence as estimated using published T/S boundaries, and satellite-derived sea surface temperatures and sea-ice concentrations. Our results show significant interannual variability in the acoustic presence of fin whales with the greatest detections of calls in years with contrasting environmental conditions (2012 and 2015). Colder temperatures, lower salinities, slower water velocities, and weak southward winds prevailed in 2012 while warmer temperatures, higher salinities, faster water velocities, and moderate southward winds prevailed in 2015. Most detections (96%) were recorded at the mooring site nearest the confluence of the nutrient-rich Anadyr and Bering Shelf water masses, ~35 km north of Bering Strait, indicating that productive water masses may influence the occurrence of fin whales. The disparity in environmental conditions between 2012 and 2015 suggests there may be multiple combinations of environmental factors or other unexamined variables that draw fin whales into the Pacific Arctic.

1. Introduction

The Arctic has undergone unprecedented environmental shifts as a result of climate warming (Post et al., 2019). Prominent among these shifts is the loss of sea-ice cover during the summer (Comiso et al., 2008; Cavalieri and Parkinson, 2012; Vaughan et al., 2013; Wood et al., 2015a, b; Walsh et al., 2017) along with earlier melting in the spring and delayed onset of freezing in the fall (Markus et al., 2009; Stroeve et al., 2014; Frey et al., 2015; Stabeno et al., 2019; Baker et al., this issue). Environmental shifts as a result of climate change are especially evident in the Chukchi Sea where annual sea-ice cover has declined by ~13 days each decade from 1979 to 2013 (Laidre et al., 2015), extending the open-water season (Grebmeier et al., 2010; Stroeve et al., 2014; Wood et al., 2015b; Woodgate, 2018). Declining sea ice is expected to result in range expansions of temperate and subarctic species into the Arctic (Root et al., 2003; Wassmann et al., 2011; Laidre and Heide-Jørgensen, 2012; Woodgate et al., 2015). Subarctic cetaceans, such as fin whales (*Balaenoptera physalus*), are thought to be expanding their range and residence time in the Chukchi Sea (Woodgate et al., 2015), which could lead to increased competition with Arctic cetaceans (Clarke et al., 2013).

Fin whales are a cosmopolitan mysticete whose range extends through most of the world's oceans (Mizroch et al., 1984). Though their exact migration patterns are unclear, fin whales are thought to breed in lower latitudes during winter and migrate to high-latitude areas, such as the Bering and Chukchi seas, in summer to feed on seasonally abundant prey (Mizroch et al., 1984, 2009). Fin whale diets vary seasonally and spatially across the North Pacific, but typically include euphausiids and forage fish species (Pike, 1950; Nemoto, 1959; Nemoto and Kasuya,

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1965; Mizroch et al., 1984; Flinn et al., 2002; Witteveen and Wynne, 2016). Fin whales are generally thought to avoid sea ice, though they have been observed swimming along the ice edge in the Arctic (Sleptsov, 1961; Mizroch et al., 1984).

Fin whales produce low frequency signals (<100 Hz), with high intensities (source levels up to 189 dB re 1 μPa at 1m) and short durations (≤1 s; Watkins, 1981; Watkins et al., 1987; Širović et al., 2007). The most commonly documented call is a short (~1 s) down-sweep generally starting around 25 Hz and ending at 15 Hz with peak energy centered near 20 Hz (Watkins, 1981; Watkins et al., 1987). The fin whale "20-Hz pulse" can occur in regular sequences, forming a stereotyped song that lasts from <1 h to ~33 h (Watkins et al., 1987). Such sequences are believed to be produced by males as a mating display starting in the fall and lasting through spring (Watkins et al., 2000; Croll et al., 2002; Stafford et al., 2007). Fin whales also produce 20-Hz and higher frequency pulses in short, irregular sequences that may serve as contact calls (Watkins, 1981; McDonald et al., 1995; Edds-Walton, 1997), especially during the summer months (Širović et al., 2013).

Historical records dating back to the early 20th century suggest fin whales commonly occurred in the southwest Chukchi Sea during the summer (Mizroch et al., 2009). Soviet and Japanese whaling expeditions in the 1930–1940s captured fin whales as far west as Cape Schmidt (68°55′18.3″N 179°27′42.7″W), and as far north as the central Chukchi Sea (69°04′N, 171°06′W) and Wrangel Island (Tomilin, 1957; Nemoto, 1959; Sleptsov, 1961; Mizroch et al., 2009, Fig. 1). Fin whales were observed in the Chukchi Sea as early as June (Nikulin, 1946) and stayed in the area until October (Nikulin, 1946; Nasu, 1960; Votrogov and Ivashin, 1980). Sleptsov (1961) describes fin whales as 'one of the numerous baleen whales that inhabit the Chukchi Sea' and reported seeing hundreds of fin whales in the span of six days between the Bering Strait and Cape Serdtse-Kamen in September 1939. By the mid-20th century, intense whaling in the North Pacific had taken a toll on fin whale populations and fin whales were rarely seen in the Chukchi Sea. Only a few sightings of fin whales were recorded between 1958 and 1981 (Nasu, 1960; Votrogov and Ivashin, 1980). More recent visual and acoustic observations of fin whales chart their presence in portions of the northeastern Chukchi Sea (Delarue et al., 2013), southcentral Chukchi Sea (Clarke et al., 2015; Brower et al., 2018), and the southern Chukchi Sea north of the Bering Strait (Tsujii et al., 2016).

We hypothesize that observed spatial variability in fin whale presence may be connected to environmental variability in the study region. In addition to the seasonal cycle of sea ice, the Chukchi Sea is characterized by the presence of distinct water masses defined by differences in temperature and salinity which vary from year to year (Coachman et al., 1975). The water masses in the Chukchi Sea have varying levels of nutrients and chlorophyll-*a* (chl-*a*), leading to distinct phytoplankton and zooplankton communities (Hopcroft et al., 2010; Eisner et al., 2013; Pisareva et al., 2015; Danielson et al., 2017; Sigler et al., 2017). Large, chain-forming diatoms are found in areas with high chl-*a* concentrations, such as the productive Anadyr Water (AW) in the western Chukchi Sea, whereas smaller phytoflagellates occur in low-nutrient areas, such as the less productive Alaskan Coastal Water (ACW) in the eastern Chukchi Sea (Springer and McRoy, 1993; Eisner et al., 2013; Danielson et al., 2017). Consequently, large copepods and other zooplankton groups are found in the AW while smaller copepods are ubiquitous in the ACW zooplankton community (Eisner et al., 2013; Sigler et al., 2017). It might be therefore expected that fin whales would occupy areas where the AW, or similarly productive water masses, dominate.

The Chukchi Sea is a highly advective ecosystem that is heavily influenced by the inflow of Pacific Water which enters through the Bering Strait (Woodgate et al., 2005a, Fig. 1). Advection from the northern Bering Sea provides the main source of zooplankton for the Chukchi Sea and is an important factor in determining zooplankton biomass and secondary production (Weingartner, 1997; Kitamura et al., 2017). High northward water velocities through the strait likely translate to increased advection of Pacific-origin prey into the Chukchi Sea. Therefore, we hypothesize that years with high detections of fin whale calls will have high northward (along-channel) water velocities.

The Bering Strait is divided into two channels by the Diomede Islands roughly mid-strait (Fig. 1). The western channel of Bering Strait is comparatively cold and salty due to the prevalence of the AW, while the eastern channel tends to be warmer and fresher due to the presence of the ACW (Coachman et al., 1975; Woodgate et al., 2005b, 2015). The cold and salty Bering Shelf Water (BSW) passes through the central strait (Coachman et al., 1975; Woodgate et al., 2005b). Variability in wind strength and direction can influence the position of these water masses

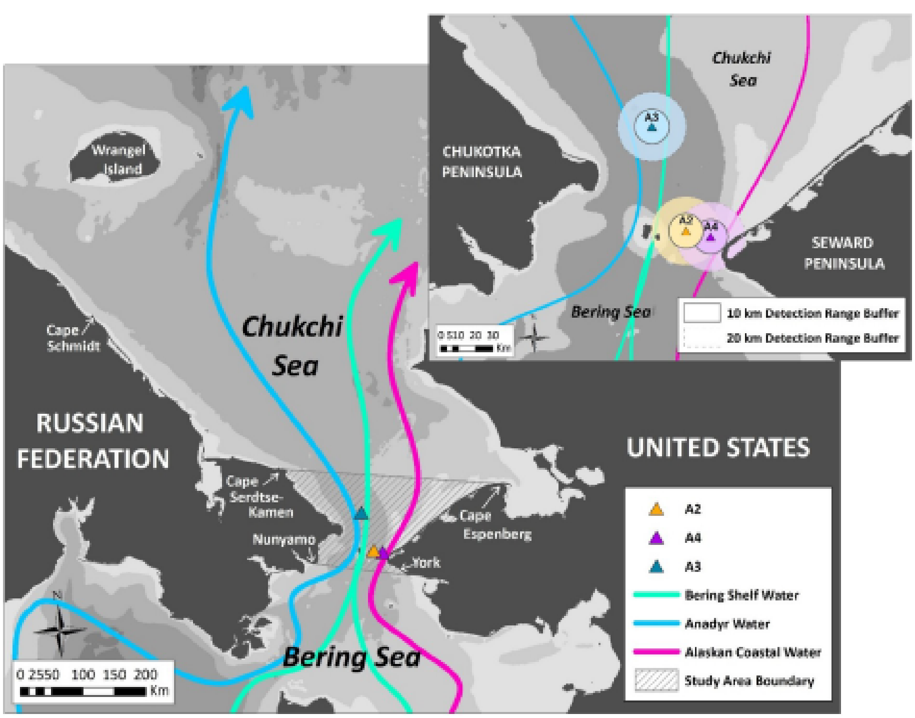

Fig. 1. Map of the study region with typical annual mean flow patterns of the three dominant water masses in the Bering Strait region and 20-m bathymetric contours (International Bathymetry Chart of the Arctic Ocean [IBCAO], v. 3; Jakobsson et al., 2012). Positions of the three moorings along with the boundaries of the study area polygon used in the sea ice concentration analysis are also displayed. Inset map shows estimated call detection range buffers around each mooring (10 and 20 km). Note that the Alaskan Coastal Water is only present seasonally.

and overall transport in the strait. Strong along-channel (northward) winds through Bering Strait may push the less productive surface ACW against the Alaskan coast via Ekman transport, allowing the more productive AW to shift east and replace it in the surface waters (Woodgate, 2018). Similarly, southward winds spread the ACW westwards across the surface of the strait and draw AW to the east at depth (Woodgate et al., 2015). Thus, wind changes could affect feeding opportunities for fin whales at different depths across the strait. Northward winds are linked to northward flow through the strait (Woodgate et al., 2005a), which leads to higher advection of prey into the Chukchi Sea, in general. Therefore, we hypothesize that fin whale occurrence may be related to northward wind velocity through the strait.

Given that the Bering Strait is the only gateway from the Pacific Ocean into the Chukchi Sea (Fig. 1), the region is an ideal study area for recording the occurrence of migrating fin whales. In this paper, we investigate whether fin whales exhibited any interannual variation in their acoustic presence during the open-water season (July November) from 2009 2015 and explore correlations between the acoustic presence of fin whales and environmental variation in the Bering Strait region. We hypothesize that high levels of fin whale calls occur in the years when and at the mooring sites where the highly productive AW and BSW are prevalent, when/where there are higher northward water velocities (and thus primarily northward winds) through the strait, and in years when sea ice forms later in the fall, allowing fin whales to remain in the Chukchi Sea longer into the season.

2. Methods

2.1. Acoustic data

Acoustic data were collected from three AURAL-M2 hydrophones (Autonomous Underwater Recorder for Acoustic Listening-Model 2, Multi-Electronique, Inc.; sensitivity of 154 dB re 1 V/ Pa and 16-bit resolution) attached to oceanographic moorings positioned within the eastern channel of the Bering Strait (A2 in the center of the eastern channel, and A4 in the Alaskan Coastal Current (ACC) on the east side of the channel), and a central strait location ~35 km north of the strait in the southern Chukchi Sea (A3; Fig. 1). Hydrophones were first installed on the moorings in September 2009 and recorded through 2015. Each hydrophone was positioned 4 8 m above the seafloor and sampled at 8192 Hz or 16384 Hz with various hourly duty cycles and recording start dates (Table 1). We assume that calls recorded during the hydrophones duty cycle are representative of fin whale acoustic activity for the entire hour in which the calls were recorded.

We quantified fin whale calling activity as the number of hours per day with fin whale calls present, hereafter referred to as 'fin whale hours (FWH). Note that since we were only able to detect calling whales, we could not assume the absence of fin whales during any hour, nor could we estimate the abundance of fin whales using call abundance alone. The term 'recording years refers to years that each hydrophone actively recorded data. Analysis of the recordings was restricted to the recording start date (typically July) until the end of November, called here as the 'recording period. Given the shallow depth of the study area, it is likely that all calls from individuals within 10 20 km of the hydrophones were recorded (Woodgate et al., 2015). If we use the conservative call detection range of 10 km, the hydrophones cover a total of 892 km^2, or ~3% of the study area (Fig. 1). Hydrophones at A2 and A4 cover ~64% of the eastern channel area (~900 km^2), while the width of the A3 10-km call detection buffer covers ~10% of the across-strait distance at its latitude north of the strait.

We identified hours with fin whale 20-Hz pulses using the spectrogram correlation tool implemented in Ishmael (2014 version; Mellinger and Clark, 2000; Mellinger, 2002). Detector parameters included a threshold of 10 to reduce the number of false detections and a smoothing time constant of 0.3 s. Each hour identified by the detector was then manually verified to contain fin whale calls by inspecting the spectrogram in Ishmael (FFT 4096, Hanning window, spectrogram equalization enabled with a time constant of 30 s) and eliminating any false positives from the dataset. The hours before and after a true positive FWH were examined to capture any hours with calls that were not picked up by the detector, adding a total of 269 FWH to our detections (~11% of the total number of FWH for all three sites).

To investigate spatial and temporal patterns in the presence of fin whales, we compared FWH between years and sites using a nonparametric two-sample Wilcoxon rank-sum test under the null hypothesis of equal distributions. Since all hydrophones recorded in October, we restricted our interannual comparisons of FWH within each mooring site and between the three sites to October only to avoid issues with unequal recording period lengths. We also compared the date of departure of calling fin whales from the study region by calculating the 95% quantile of the cumulative distribution of days with fin whale calls starting on 1 October of each year, following the procedure of Hauser et al. (2017). We used a significance threshold of 0.05 for all statistical tests and assumed independence between daily values.

2.2. Environmental data collection

Six environmental variables were recorded *in-situ* by other sensors on the same moorings, including: near-bottom temperature and salinity (40 55 m depth) measured by Sea-Bird (SBE) SBE16 and SBE37 sensors;

Table 1
Recording settings and positions of the three hydrophones. Dates are in the format 'mm/dd/yyyy.

Mooring	Year	Latitude N	Latitude W	Record Start Date	Record End Date	Sampling Rate (Hz)	Hourly Duty Cycle
A2	2009	65.80	168.80	9/1/2009	1/16/2010	16384	12 min
	2010	65.80	168.80	8/11/2010	12/8/2010	16384	15 min
	2012	65.80	168.80	9/1/2012	5/15/2013	16384	10 min
	2013	65.78	168.57	7/15/2013	7/1/2014	8192	20 min
	2014	65.78	168.57	7/10/2014	7/4/2015	8192	20 min
	2015	65.78	168.57	7/5/2015	7/8/2016	8192	20 min
A3	2009	66.33	168.97	9/1/2009	3/3/2010	16384	12 min
	2010	66.33	168.97	8/11/2010	2/19/2011	16384	15 min
	2011	66.33	168.97	10/1/2011	5/25/2012	8192	10 min
	2012	66.33	168.97	9/1/2012	5/17/2013	16384	10 min
	2013	66.33	168.97	7/15/2013	7/2/202014	8192	20 min
	2014	66.33	168.97	7/10/2014	7/2/2015	8192	20 min
	2015	66.33	168.97	7/5/2015	7/8/2016	8192	20 min
A4	2012	65.75	168.37	9/1/2012	6/24/2013	16384	10 min
	2013	65.75	168.26	7/15/2013	7/2/2014	8192	20 min
	2014	65.75	168.25	7/10/2014	7/2/2015	8192	20 min
	2015	65.75	168.25	7/5/2015	7/8/2016	8192	20 min

near-surface temperature and salinity (14 19 m depth) measured by the ISCAT system developed at the University of Washington (e.g. Woodgate et al., 2015), which includes a SBE37 temperature-salinity-pressure sensor in an ice-resistant housing; and water velocity (cm s ^{1}) and direction ( ) measured by Teledyne s Workhorse Acoustic Doppler Current Profilers (ADCPs). The ADCPs measured water velocity in 2-m bins from ~15 m to ~45 m depth (see Supplemental Tables S1 S3 for instrument depths). For simplicity, we used only data from the ADCP bin closest to ~30 m depth. Note that henceforth the term 'near-surface refers to measurements taken by the ISCATs and 'near-bottom refers to those taken by the SBEs. Some ISCAT recorders were lost/stopped recording before the 30 November cut-off date (see Woodgate et al., 2015 and Supplemental Tables S1 S3 for data gaps along with other mooring sensor information). Note that the ISCAT for A3 stopped recording in August 2014, 45 days after deployment, thus near-surface temperature and salinity data are not available for fall 2014.

In addition to the *in-situ* data, we examined northward wind velocity, and satellite-derived sea surface temperatures (SST) and sea-ice concentrations. Wind velocity data were obtained from the National Center for Environmental Prediction (NCEP) R1 dataset, with a spatial resolution at the Bering Strait of 2.5 . We used the National Oceanic and Atmospheric Administration s (NOAA) Optimum Interpolation satellite sea surface temperature (OISST) gridded product with a 0.25 resolution (https://www.esrl.noaa.gov/psd/; Reynolds et al., 2007). Daily mean SSTs were extracted from the cell containing each mooring s position.

For sea-ice concentrations, we sought datasets with the highest resolution available. We required data from different passive microwave sea-ice satellites to cover the entire duration of the study. For years 2009 and 2010, we used Advanced Microwave Scanning Radiometer Earth Observing System (AMSR-E) sea-ice concentration data with a resolution of 6.25 km from the Integrated Climate Date Center (ICDC, icdc.cen.uni-hamburg.de; Kaleschke et al., 2001; Spreen et al., 2008). The AMSR-E satellite failed in early October 2011, consequently for 2011 and 2012 we used data from the Special Scanning Microwave/Imager (SSM/I) with a spatial resolution of 25 km (Cavalieri, 1996). High resolution Advanced Microwave Scanning Radiometer 2 (AMSR-2) data with a grid resolution of 6.25 km were used for 2013 2015 (Beitsch et al., 2014; Kaleschke and Tian-Kunze, 2016).

We derived daily mean sea-ice concentration for the area of the Chukchi Sea as defined by the International Hydrographic Organization (IHO; http://www.marineregions.org/gazetteer.php?p details &id 4257), and for a custom study area polygon (Fig. 1). The study area polygon was defined by the bounds set by Cape Serdtse-Kamen, Russian Federation, in the northwest; Nunyamo, Russian Federation, to the southwest; York, Alaska, USA, on the Seward Peninsula to the southeast; and Cape Espenberg, Alaska, USA, to the northwest (Fig. 1). We determined the study area polygon by estimating where sea ice, if present, could potentially create a migration barrier for fin whales. All satellite-derived data were visualized in ArcMap (v. 10.1) using the WGS 1984 datum and projected in a custom polar stereographic projection with a central meridian of 171 W.

2.2.1. *Environmental data analysis*

To ensure consistency when comparing the environmental data over time, we calculated summary statistics for October data since there were no data gaps in the *in-situ* temperature and salinity data in this month (except for a gap in the near-surface data for 2014 at A3). For the ADCP data, we elected to compare the monthly mean northward water velocities for June to November to capture the summertime peak in transport through the Bering Strait (Woodgate et al., 2005b). We investigated correlations between days with fin whale calls present (i.e. FWH 0) and select individual environmental variables using non-parametric Kendall s rank correlation tests. The Kendall s rank coefficient, tau ( ), indicates the direction of association (1 1) and the resulting *p*-value indicates presence of a statistically significant correlation under the null hypothesis of non-correlation between the samples.

We tested for interactions between fin whale presence and along-channel (northward) wind patterns within the Bering Strait by comparing the daily mean northward wind velocity on days when the number of FWH reached above a certain threshold (1 h, 6 h, 12 h, and 18 h) and days without any FWH. We calculated summary statistics for northward wind velocities in October only, including an overall mean along-channel wind velocity as well as mean wind velocity for days with no FWHs and days with FWHs above a threshold (see categories above). We then compared the overall October mean along-channel wind velocity to the mean wind velocities for days with and without FWHs using a Wilcoxon rank sum test.

For the sea ice analysis, we calculated the melt-out and freeze-up dates as the day of the year when the sea ice concentration within the study area decreased/increased below/above 80%, respectively, following Markus et al. (2009) and Stroeve et al. (2014). We defined an area as 'ice-free if the mean sea ice concentration was 15%, a threshold commonly used to indicate the presence of sea ice (Serreze et al., 2009, 2016; Stroeve et al., 2012). We calculated the melt period length using the number of days between the initiation of melting (80% concentration) and when the study area was ice-free (15% concentration). For the freeze-up period length, we calculated the number of days between the first day sea ice concentration reached 15% and the first day the sea ice reached 80% concentration in the fall. We compared the calculated fin whale departure date and sea ice freeze-up date for each year using a two-sided Pearson correlation test after testing for normality.

2.3. *Water masses*

Water mass presence for each day was estimated for the near-surface and near-bottom using temperature and salinity (T/S) bounds suggested by Danielson et al. (2017). These authors distinguish five water mass categories: the Alaskan Coastal Water (ACW), Bering Chukchi Summer Water (BCSW), Bering Chukchi Winter Water (BCWW), Melt Water (MW), and water from the Atlantic layer in the Arctic (AtlW). Danielson et al. (2017) combine the Anadyr Water (AW) and the Bering Shelf Water (BSW) into one water mass, the BCSW, since the T/S properties of these three water masses are often indistinguishable from each other. Note that since the T/S bounds of these waters vary interannually (Coachman et al., 1975), there are limitations to the representativeness of the above water mass identifications.

Chi-squared tests of independence were performed for each mooring site using pooled presence/absence of fin whale calls for each day across all recording years along with the daily water mass designations to determine whether there was a significant association between the presence of fin whale calls and water mass. If a chi-squared test was inappropriate (e.g. in the case of small sample sizes), a Fisher s exact test was applied instead. Fisher s exact test evaluates the significance of association, or contingency between two categorical variables, and is insensitive to sample sizes. All analyses were performed using in the statistical software R (v. 3.5.3; R Core Team, 2019).

3. Results

3.1. *Fin whale detections*

We processed a total of 52,272 audio files collected from ~July to November 2009 2015 (Table 1). Fin whales were detected at all three sites, with the highest frequency and abundance of fin whale hours (FWH) at site A3 by a large margin (Fig. 2; Supplemental Figs. S1 S3). About one third (34.4%) of the total recording days at A3 had at least 1 h with fin whale calls, compared to only 4.6% at A2 and 1.5% at A4. Calling fin whales were detected in all recording years at A2 and A3, but were only detected in 2014 and 2015 at A4. October had the highest

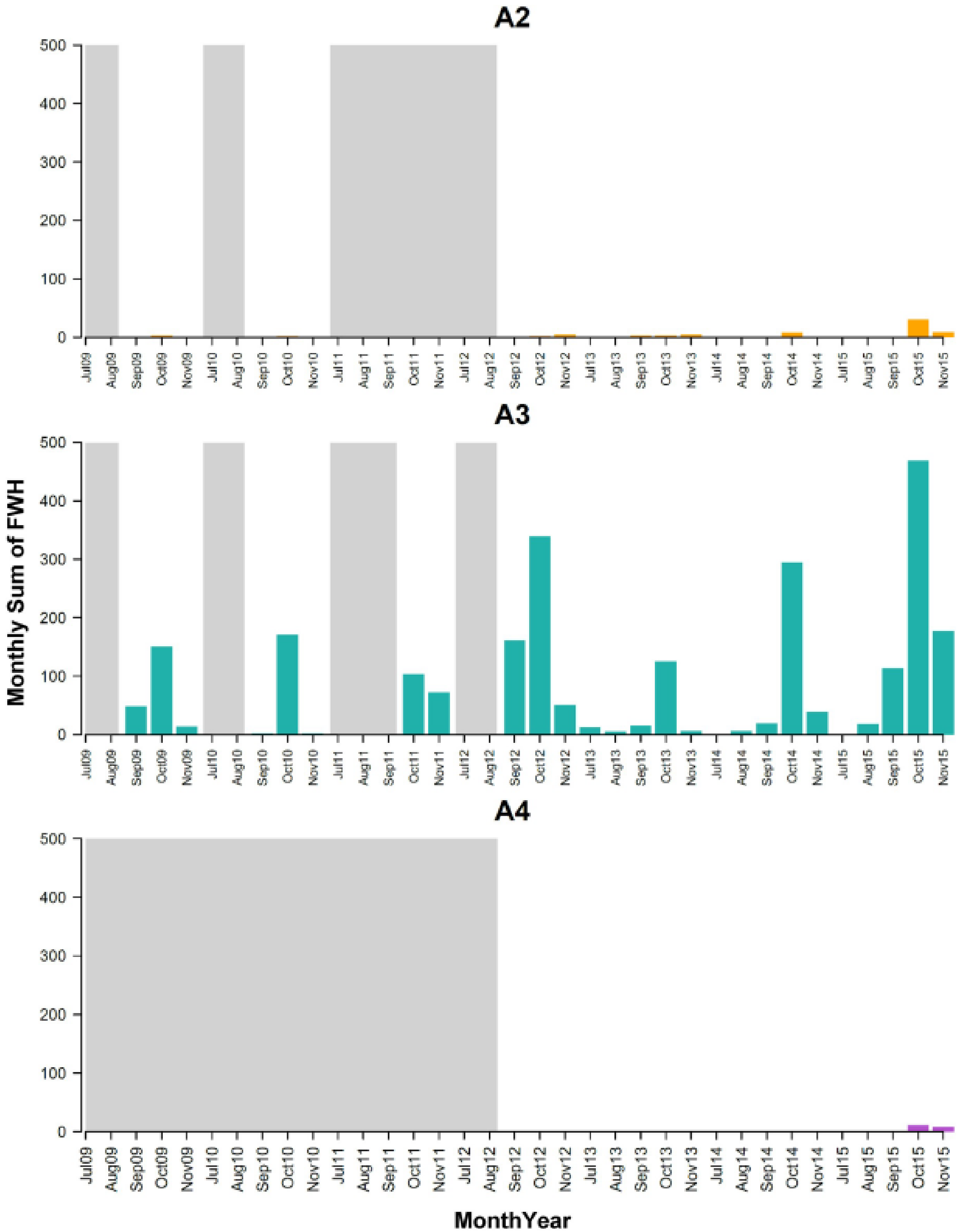

Fig. 2. Histograms of monthly sum of hours with fin whale calls ('FWH') recorded at the three mooring sites (A2, A3, and A4) within the Bering Strait region from 2009 to 2015. The gray-shaded boxes indicate periods when the hydrophones were not recording.

occurrence of FWH across all sites (68.4%), and given the hydrophones all had data from October, we restricted our statistical tests to this month. Wilcoxon rank-sum tests revealed statistically significant differences in the distribution of FWH in October at the three mooring sites (A2 and A3: W = 5259.5, $p < 0.001$, $n = 186$ days; A2 and A4: W = 8423, $p = 0.006$, $n = 124$ days; A3 and A4: W = 1709, $p < 0.001$, $n = 124$ days). The earliest detection of fin whale calls across all sites and years occurred on 23 July 2013 at A3, and the latest fin whale detection occurred on 20 November 2015 at A3 (Table 2). Annual fin whale departure dates using the 95% quantile were only calculated for A3 given the lack of data at A2 and A4 (see Supplemental Fig. S4 for the cumulative distribution of days with fin whale calls at A3). Fin whale departure dates at A3 did not show any statistically significant trend ($R^2 = 0.20$, $p = 0.311$; Fig. 3).

Table 2
Fin whale detection data for the three moorings, including the dates of the first and last detection, and total number of days with fin whale calls present ('FW Days'). The '.' indicates periods when the hydrophone was not actively recording.

	A2			A3			A4		
Year	First Detection Date	Last Detection Date	FW Days	First Detection Date	Last Detection Date	FW Days	First Detection Date	Last Detection Date	FW Days
2009	1 Oct	5 Nov	4	23 Sep	8 Nov	33	.	.	.
2010	14 Oct	17 Oct	2	29 Sep	5 Nov	22	.	.	.
2011	.	.	.	1 Oct	18 Nov	28	.	.	.
2012	28 Oct	2 Nov	3	1 Sep	7 Nov	52	None	None	0
2013	22 Sep	15 Nov	7	23 Jul	9 Nov	28	None	None	0
2014	17 Oct	19 Oct	3	9 Aug	13 Nov	37	2 Nov	2 Nov	1
2015	30 Sep	19 Nov	14	8 Aug	20 Nov	71	11 Oct	8 Nov	7

At A3, fin whale calling activity was highest in 2012 and 2015 (52 and 71 days with at least one FWH, respectively), while calling activity was the lowest in 2010 (22 days) followed by 2011 and 2013 (28 days). The Wilcoxon tests comparing FWH in October between years at A3 show significant differences in the distributions fin whale detections across years, with significant values ($p < 0.01$) between all consecutive years except 2009 and 2010 ($p = 0.736$) and 2010 and 2011 ($p = 0.463$; Table 3). Wilcoxon tests comparing FWH in 2012 and 2015 to the other years detected significantly different distributions ($p < 0.01$), except for the test between 2012 and 2014 ($p = 0.614$; Table 3).

Fin whale calls were less common at A2, though 2015 had relatively higher call activity with 40 h with fin whale calls compared to 2–10 h in each of the other six years. At A4, fin whale calls were only detected in 2014 (1 h) and 2015 (19 h). Insufficient sample sizes precluded any statistical comparisons of fin whale vocal activity between years for A2 and A4.

Table 3
Wilcoxon rank-sum test results comparing fin whale hours (FWH) recorded at A3 in October of each year. The *p*-values are listed in the upper section above the diagonal, and the gray shaded area below the diagonal are the W statistics from the Wilcoxon rank-sum tests (**bold** W values indicate significant results). Significant *p*-values ($p < 0.05$) are in **bold*** and indicate that the distribution of FWHs significantly differed between the two years.

Year	2009	2010	2011	2012	2013	2014	2015
2009	.	0.736	0.147	**0.002***	0.42	**0.026***	**0.000***
2010	174.5	.	0.463	**0.002***	0.554	0.062	**0.000***
2011	186	220	.	**0.002***	0.566	**0.003***	**0.000***
2012	**69**	**77**	**76**	.	**0.003***	0.614	**0.007***
2013	223	185	98.5	**399.5**	.	**0.004***	**0.000***
2014	**96**	120.5	**57.5**	257.5	**47.5**	.	**0.006***
2015	**30**	**14**	**14.5**	**110**	**21**	**106**	.

3.2. Sea-ice conditions and analyses

Sea-ice conditions within the study area were highly variable from year to year. Melt-out dates ranged from as early as 27 April (2011) to as late as 20 May (2010; Table 4). The number of days between the initiation of melting (<80% concentration) and ice-free conditions in the study area (<15% concentration) ranged from 21 days (2015) to 41 days (2013; Table 4). The study area was typically ice-free starting in late May to early June, with the earliest ice-free date occurring on 24 May 2015 and the latest on 17 June 2010. On average, freeze-up dates (≥80% concentration) occurred in early to mid-December, with the earliest freeze-up on 28 November 2009 and the latest on 25 December 2010.

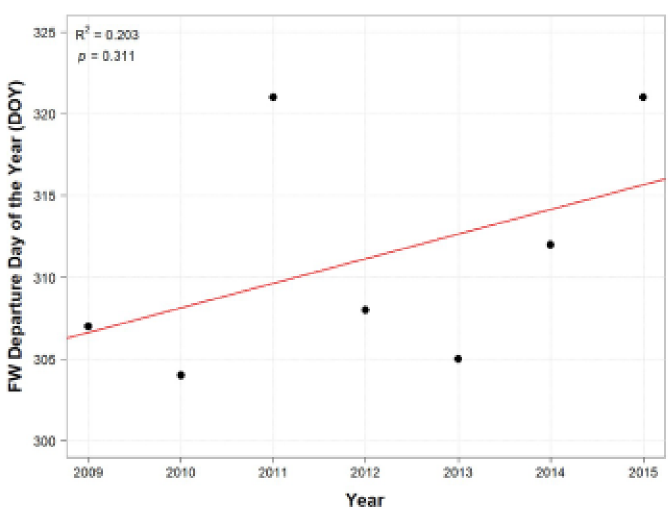

Fig. 3. Fin whale departure day of the year (DOY) for each year at the A3 mooring site, north of the Bering Strait, along with the line of best fit ($R^2 = 0.203$, $p = 0.311$).

The freeze-up periods for each year were typically much shorter than the melt periods, with the number of days between the ice-free date and freeze-up initiation ranging from five days (2014) to 23 days (2010 and 2012; Table 4).

Fin whale departure dates for each year at A3 were compared to the sea ice freeze-up date for the study area and the Chukchi Sea, as well as the day of the year when the daily mean near-surface and near-bottom temperatures first reached ≤0 °C (Fig. 4). Two-sided Pearson correlation tests indicated no significant correlation between fin whale departure date and sea ice freeze-up date for the study area ($t = -1.046$, $p = 0.344$) or the Chukchi Sea ($t = -0.308$, $p = 0.771$). The latest fin whale departure date occurred on 17 November 2011 and 2015 when the mean sea ice concentrations were ~0.8% and 4.9% in the study area, and 21.0% and 18.2% in the Chukchi Sea, respectively (Table 4).

3.3. Environmental conditions at the moorings

Environmental data at the three mooring sites exhibited strong interannual and spatial variation. The highest temperatures and lowest salinities on average were seen at A4 (e.g. 2013 October near-surface mean temperature = 3.5 °C, SD = 0.7 °C; near-surface mean salinity = 30.3 psu, SD = 1.3 psu). Conversely, A2 and A3 had lower temperatures and higher salinities than A4 (A2: 2013 October near-surface mean temperature = 3.3 °C, SD = 0.7 °C, near-surface mean salinity = 31.1 psu, SD = 1 psu; A3: 2013 October near-surface mean temperature = 2.9 °C, SD = 0.8 °C, near-surface mean salinity = 31.7 psu, SD = 0.8 psu; Fig. 5). This spatial structure, with warm fresh waters near the Alaskan Coast, typically indicates the presence of the Alaskan Coastal Current (see discussion in Woodgate et al., 2015). There were also significant interannual differences across all three sites. The lowest near-surface and near-bottom temperatures occurred in 2012 while the highest

Table 4
Sea ice statistics calculated for 2009–2015 for the study area and Chukchi Sea. Statistics for the study area include: melt initiation date ('Melt-Out Date'), melt period (number of days between 80% and 15% sea ice conc.), date when the study area was ice-free (<15% conc.; 'Ice-Free Date'), freeze-up period (number of days between 15% and 80% sea ice conc.), and mean sea ice concentration (%) in the study area on the last date fin whale calls were recorded ('Last FW'). Statistics for the Chukchi Sea include mean sea ice concentration (%) on the last date fin whale calls were recorded ('Last FWH').

	Study Area							Chukchi Sea
Year	Melt-Out Date	Ice-Free Date	Melt Period (# of days)	Freeze-up Date	Freeze-up Period (# of days)	Mean Nov. sea ice conc.	Last FW mean sea ice conc.	Last FW mean sea ice conc.
2009	14 May	5 June	23	28 Nov	12	30.2%	0.9%	1.5%
2010	20 May	17 June	29	25 Dec	23	3.4%	1.3%	4.5%
2011	27 April	30 May	34	4 Dec	12	13.3%	0.8%	21.0%
2012	16 May	10 June	25	11 Dec	23	21.3%	1.9%	18.8%
2013	5 May	14 June	41	18 Dec	19	6.3%	3.1%	12.8%
2014	1 May	31 May	31	17 Dec	5	5.4%	4.1%	7.07%
2015	4 May	24 May	21	10 Dec	17	20.1%	4.9%	18.2%

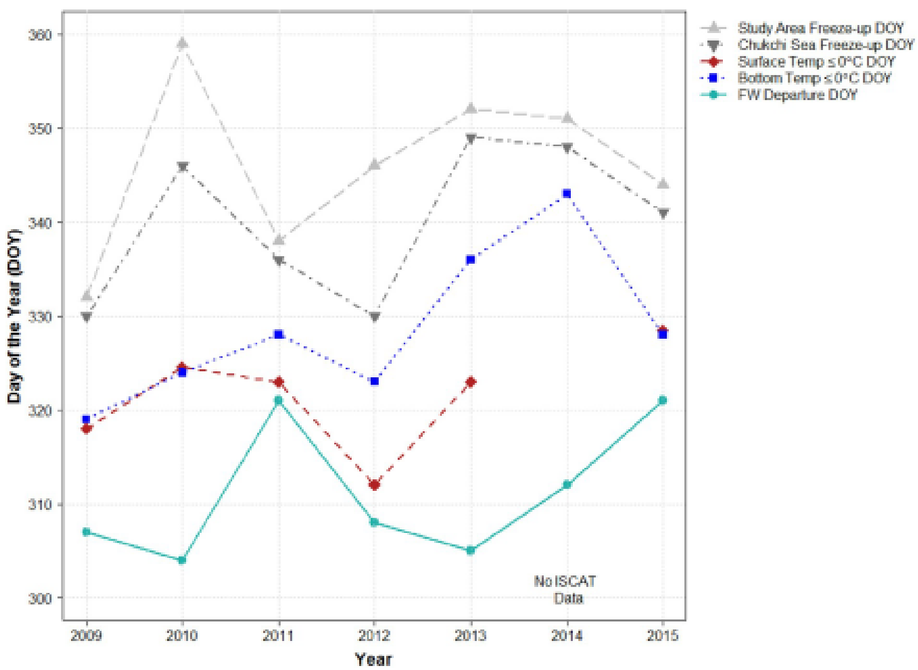

Fig. 4. Calculated fin whale departure days for each year at site A3 (light blue, solid line) with other non-solid lines indicating the day of the year (DOY) when the daily mean near-surface (ISCAT; red, medium-dashed line) and near-bottom (SBE; blue, dotted line) temperatures first reached ≤ 0 °C at the A3 mooring site. The light gray, long-dashed line represents the DOYs when sea ice concentration in the study area first reached ≥15% in each year, and the dark gray, dot-dashed line represents when sea ice concentration in the Chukchi Sea reached ≥15%. See Fig. 1 for boundaries of study area. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

temperatures occurred in 2015 (Fig. 5; Woodgate, 2018).

Northward water velocities were on average the highest at sites A2 and A4 during the open-water season (Fig. 6), consistent with known seasonality in the flow due to weaker opposing southward winds in summer (Woodgate et al., 2005b). The year 2012 had the weakest northward water velocity throughout the open-water season while 2014 had sustained high northward velocities throughout the season (Fig. 6; Woodgate, 2018). Overall, northward water velocities weakened over the period between July and November with the slowest northward water velocities occurring in November, except in 2012 and 2014 when the seasonal minimum velocities were seen in September and October (Fig. 6). Direction of flow at all three sites was primarily northward during the open-water season (see Supplemental Fig. S5–S11 for plots of the water and wind velocity vectors along with fin whale acoustic presence at A3 during the open-water season). For a more detailed overview of variation in Bering Strait transport through 2015, see Woodgate (2018).

Due to low fin whale detections at A2 and A4, we focused our wind analysis on site A3 and used wind data from the grid point closest to the mooring (67.5°N, 190°W, ~140 km to the northwest of A3). On average, along-channel winds were mainly southward during the month of October, with the strongest mean winds occurring in 2013 (October $\bar{x}$ = −6.2 m/s, SD = 5.4 m/s) and the weakest mean winds in 2012 (October $\bar{x}$ = −0.4 m/s, SD = 8.1 m/s; Table 5). Note that the negative sign indicates a southward direction.

3.4. Environmental analyses

We focused our environmental analyses on the A3 mooring site due to the relative lack of fin whale detections at A2 and A4. The Kendall's rank correlation tests between FWH on days with fin whale calls (i.e. FWH >0) and the environmental variables produced statistically significant ($p < 0.05$) though small correlations for daily mean water speed, and along-channel wind and water velocities pooled for all seven years (2009–2015; Table 6). We ran a second test using October data only and found similar results, as well as the addition of significant correlations between FWH and near-surface temperature and SST at site A3 (Table 6).

Days with fin whale calls mostly had southward mean wind velocities while days without calls (i.e. FWH = 0) mostly had northward overall mean winds (Table 5; Fig. 7). The Wilcoxon test comparing the overall mean along-channel wind velocity for October of each year against the means for days with and without FWHs revealed that days without FWH and days with FWH ≥6 h and 12 h had statistically significant differences in along-channel wind velocities in 2011 and 2014 only (Table 5). Insufficient data precluded any tests for days with FWH

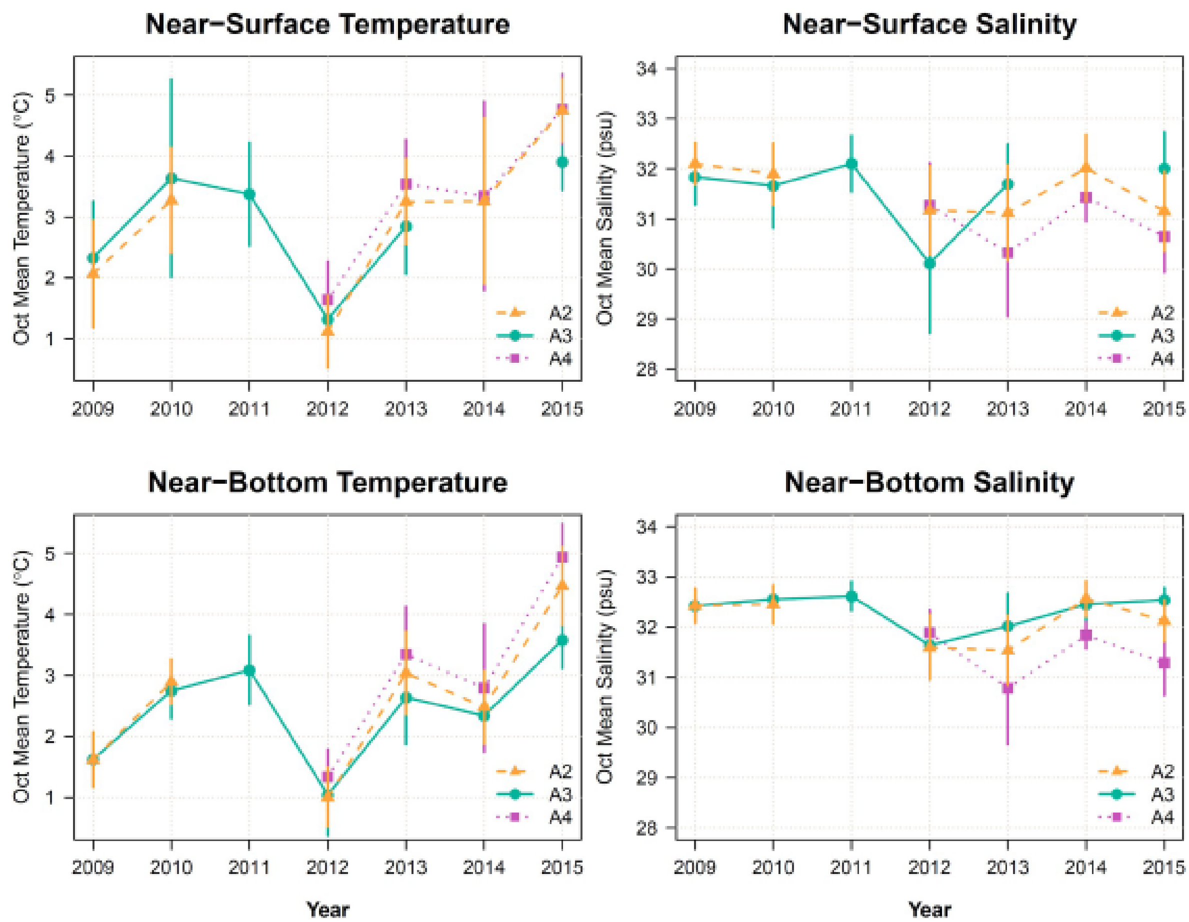

Fig. 5. Plots of the mean temperatures (°C) and salinities (psu) for October of each year for both the near-surface and near-bottom levels of the water column at each mooring site in the study area (A2, A3, and A4; see key for colors, symbols, and line styles). The vertical lines represent the standard deviation of the monthly means. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

≥18 h.

3.5. Water mass composition at the moorings

Water mass composition at A2 and A3 during the open water season was dominated by the presence of the Bering Chukchi Summer Water (BCSW) at both the near-surface (>70% of days at both sites) and near-bottom levels (>90% of days at both sites) for all recording years (see Supplemental Figs. S12–S14 for plots with the water mass composition at the three sites during the open water season). The water mass composition at A4 was similarly dominated by BCSW at the near-bottom (73% of days in July–November) and to a lesser extent in the near-surface (51% of days in July–November). The cold and salty Bering Chukchi Winter Water (BCWW) appeared in both levels in the water column in November at all three sites, when it is assumed that fin whales are beginning their migration south. A fresher, colder signal, that falls within the Melt Water (MW) category as defined by Danielson et al. (2017), appeared in the near-surface at all three sites in September and October 2012 and 2013, with the strongest signal in 2012. However, since the sea-ice edge is far away from the mooring sites in September and October, the freshening observed in 2012 and 2013 was likely due to fresh waters from either the Alaskan Coastal Current (ACC) or the Siberian Coastal Current (SCC). The SCC is a cold, fresh current present seasonally in the Chukchi Sea only in some years (Weingartner et al., 1999). Also noteworthy was a warm Alaskan Coastal Water (ACW) signal in the near-surface at A2 in 2013, 2014, and 2015 and at A3 in 2010 and 2015.

We conducted a side-by-side comparison of the daily water mass designations for A2 and A3 and noted the number of days when at least one of the water mass designations at A2 did not match those from A3. Out of 726 days when both moorings were recording and had data for both instruments, 14 days (~2% of total days) had different water mass composition in the near-bottom water and 69 days (~10% of total days) for the near-surface water. In contrast, A2 and A4 had different water mass compositions on 203 days (~39%) for the near-surface and 127 days (24%) for the near-bottom. The comparison between A3 and A4 yielded 311 days (60%) with different water mass composition at the near-surface and 136 days (26%) at the near-bottom. These results indicate that despite close spatial proximity, A2 and A4 had very different water mass composition while A2 and A3 had similar water mass composition.

3.6. Water mass analyses

The chi-squared tests of independence between the pooled FWH and the near-surface/near-bottom water mass designations at site A3 suggest that the occurrence of fin whale calls during the study period was statistically dependent on the occurrence of water masses (both tests using near-surface and near-bottom water mass designations: $p < 0.001$). We repeated the tests of independence for each recording year at A3, using the Fisher's Exact Test to compare the daily near-surface and near-bottom water mass designations to the total FWH for each day. The results show a significant relationship for 2009, 2011, 2012, and 2015 (all $p < 0.02$), signifying that fin whale presence was statistically dependent on water mass presence for these years. We were unable to execute the Fisher's Exact test for 2013 (near-bottom water mass) and

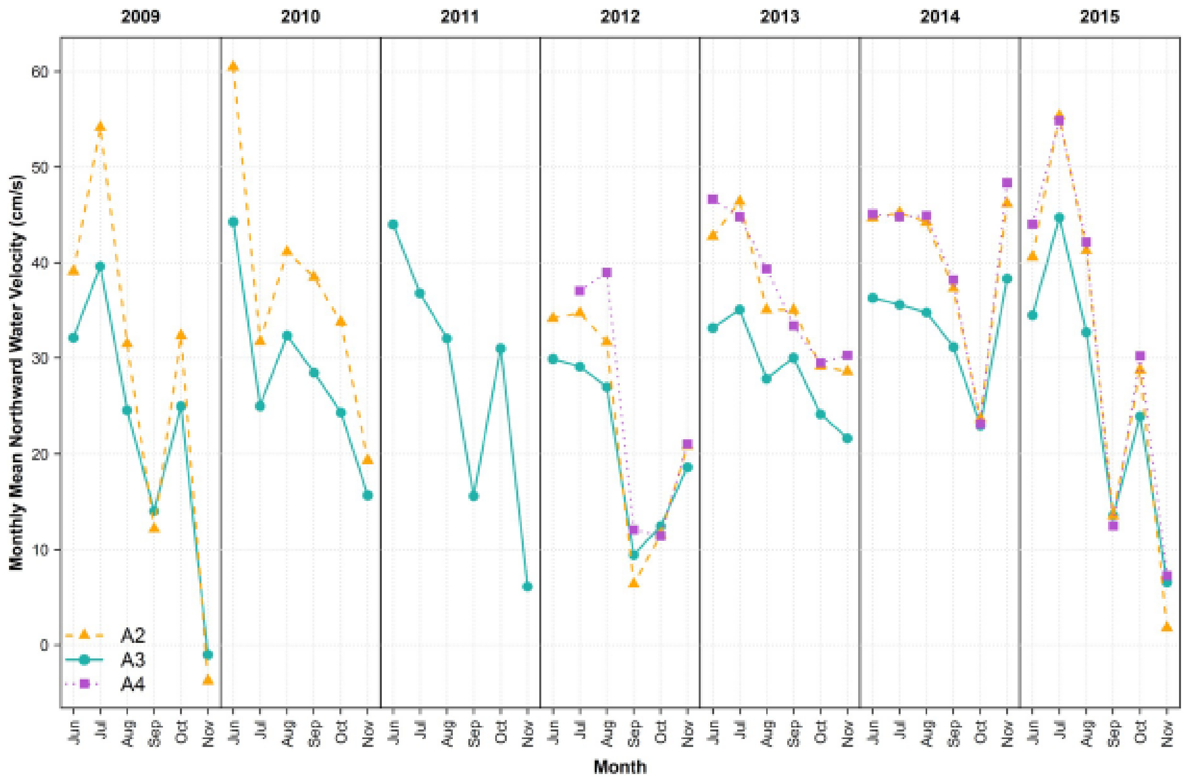

Fig. 6. Monthly mean northward water velocity (cm/s) for the June through November at each mooring site in the Bering Strait region (A2, A3, and A4; see key for colors, symbols, and line styles). See Fig. 1 for mooring locations. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 5
Summary of the overall monthly mean along-channel wind velocities (m/s) for October along with overall means for days with and without fin whale hours (FWH) in October. Wind velocities were measured at the data point at 67.5° N and 190° W. Values in parentheses are the Wilcoxon rank-sum p-values for the comparison between the overall October mean for each year (**bold***: significant $p < 0.05$).

Year	All October (m/s)	Days without FWH (m/s)	Days with ≥1 FWH (m/s)	Days with ≥6 FWH (m/s)	Days with ≥12 FWH (m/s)	Days with ≥18 FWH (m/s)
2009	−2.7	**2.5 (0.03*)**	−5.2 (0.19)	−6.2 (0.07)	−6.6 (0.21)	NA
2010	−5.1	−3.2 (0.46)	−6.2 (0.58)	−7.3 (0.37)	−7.9 (0.25)	−9.5 (NA)
2011	−2.1	0.6 (0.12)	−4 (0.21)	**−6.1 (0.04*)**	**−8.7 (0.02*)**	NA
2012	−0.4	1.3 (0.97)	−0.5 (0.99)	−2.5 (0.45)	−3 (0.33)	−5.8 (NA)
2013	−6.2	−5.8 (0.88)	−6.7 (0.88)	−5.8 (0.84)	−7 (0.82)	NA
2014	−4.8	**0.2 (0.04*)**	−6.2 (0.35)	−6.8 (0.25)	−7.9 (0.14)	−9.2 (NA)
2015	−4.0	5.5 (0.18)	−4.3 (0.86)	−4.7 (0.68)	−6 (0.255.3)	−7.1 (NA)

Table 6
Summary table of the Kendall's rank correlation test results for site A3. Correlation tests were conducted between the number of fin whale hours (FWH) recorded on days with fin whale calls (FWH > 0) and the daily means of: near-surface and near-bottom temperatures, along-channel wind and water velocities, water speeds, and SST. Two sets of tests were carried out: pooled data for all months for all years (2009–2015), and on October data only for all years at A3 (2009–2015).

Environmental Variable (Daily Means)	Pooled data - all months ($n = 271$)		Oct only - all years pooled ($n = 156$)	
	p	τ	p	τ
Near-surface Temperature	0.674	0.019	**0.012***	0.151
Near-surface Salinity	0.053	−0.087	0.851	−0.011
Near-bottom Temperature	0.82	0.01	0.129	0.084
Near-bottom Salinity	0.29	−0.044	0.507	0.037
Water Speed	**< 0.001***	−0.167	**< 0.001***	−0.28
SST	0.202	−0.054	**0.044***	0.111
Along-channel water velocity	**< 0.001***	−0.15	**< 0.001***	−0.207
Along-channel wind velocity	**< 0.001***	−0.194	**< 0.001***	−0.231

2014 (both near-surface and near-bottom) due to the fact that only one water mass (BCSW) was present at both levels in the water column, resulting in zeros in both the expected and observed columns of the test's contingency tables.

We were unable to perform a chi-squared test for independence for A2 and A4 due to the presence of small expected values ($E_{i,j} < 5$) in the

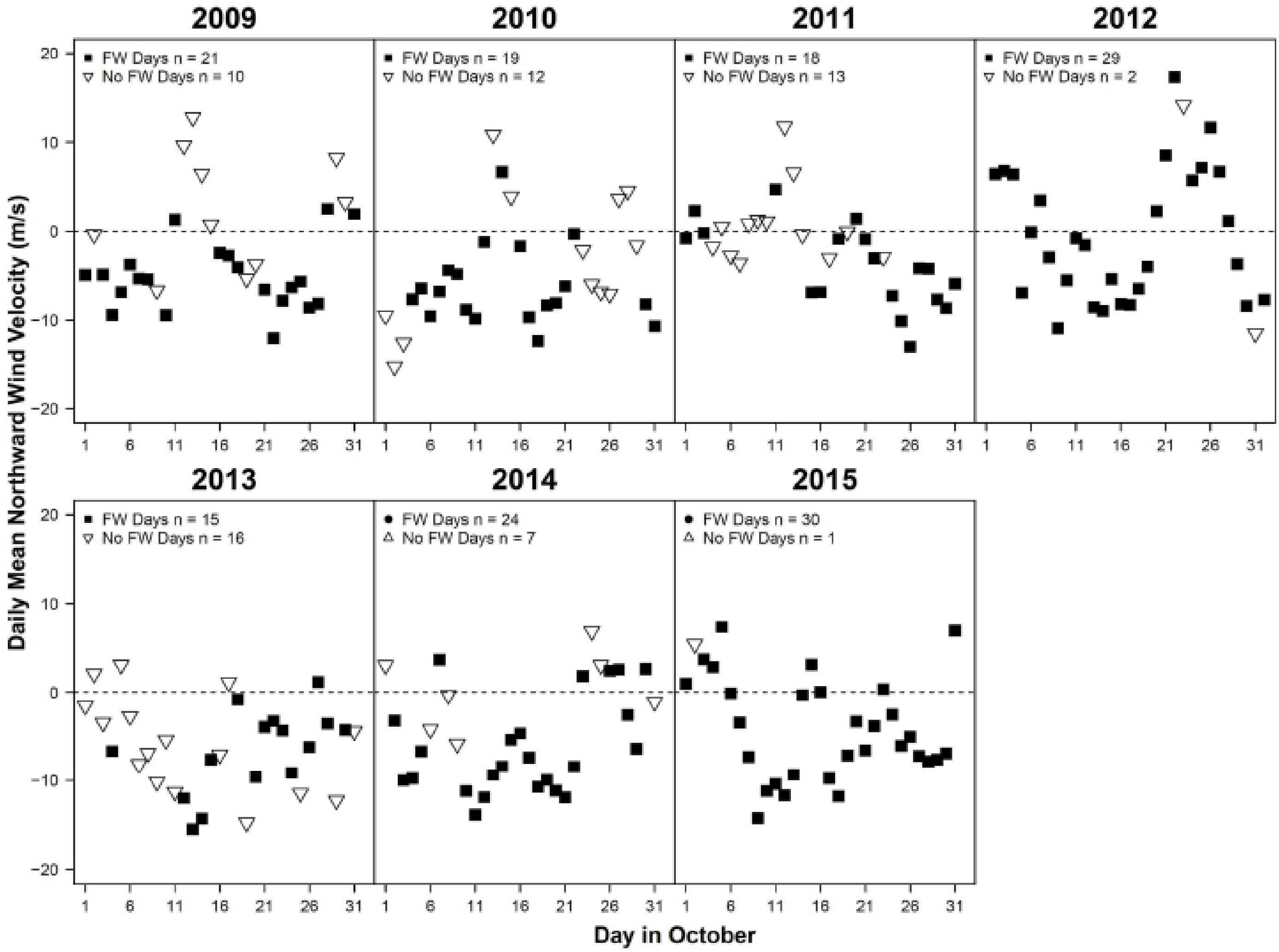

Fig. 7. Daily mean northward wind velocity for days with fin whale calls at site A3 ('FW Days', black squares) and days without fin whale calls ('No FW Days', white triangles) in October. Note that negative values signify southward wind velocities. The number of FW Days and No FW Days is included for reference.

contingency tables generated by the test. At A4, fin whale calls were only heard on days when the BCSW was present at both levels of the water column. Calling fin whales were only heard at A2 on days when the BCSW was present in the near-bottom waters. We applied a Fisher's Exact Test to the A2 near-surface water mass designations and found that fin whale calls and water mass occurrence in the near-surface waters were statistically independent of each other ($p = 0.48$).

4. Discussion

The results of this study show a pattern of interannual and spatial variation in the presence of acoustically-active fin whales in the Bering Strait region. Across all three sites, the year 2015 had the most fin whale detections followed by 2012, though these years had contrasting temperatures and salinities, sea-ice conditions, water velocity and wind patterns. Site A3, where the Anadyr Water (AW) and Bering Shelf Water (BSW) were most prevalent, had the most hours with fin whale calls, supporting our hypothesis that water masses may affect the occurrence of fin whales. We found small but significant correlations between FWH and northward wind and water velocities, near-surface temperatures and SST at site A3. However, our *p*-values for the correlation tests were potentially too low and likely overestimated the real significance of the tests given that days with fin whale calls were likely not independent of each other. In addition, the statistically significant correlations between FWH and environmental variables were small (<0.25). Thus, we conclude that it is not possible to prove a strong relationship between individual environmental parameters and FWH with our data. More data and greater spatial coverage are necessary to prove any significant association between days with fin whale calls and environmental factors in the Bering Strait region.

Most fin whale calls were heard in October, potentially due to fact that fin whale 20-Hz pulses primarily serve a reproductive purpose (Watkins et al., 2000; Croll et al., 2002; Stafford et al., 2007), and thus, tend to be heard closer to the winter mating season (Stafford et al., 2007). Consequently, fin whale vocalizations may not be a reliable indication of when fin whales first pass northwards through the Bering Strait. Additionally, the dates of departure from the Bering Strait region presented here only apply to vocal fin whales since we could not detect non-vocal whales, which could have remained in the area beyond these dates. Due to this inherent bias, the departure dates presented in this study only provide an approximation for when fin whales leave the region. The departure dates from the A3 mooring site did not exhibit a significant trend (Fig. 3), therefore it is not possible to determine whether fin whales are extending their residence time in the Chukchi Sea from our data. Perhaps this is not surprising given that we only have seven years of data, and interannual variability is substantial. In general, the fin whale departure dates at A3 occurred in early November, ranging from 31 October (2010) to 17 November (2011 and 2015). What signaled the fin whales to leave the Chukchi Sea is not clear. Sea-ice concentrations in the study area around the last detection dates were well below ‘ice-free levels (15%; Table 4), indicating that the Bering Strait was still navigable and free of sea ice. It is possible, though, that fin whales respond to cooling water temperatures since all departure dates occurred before near-surface and near-bottom water temperatures at A3 reached below 0 C (Fig. 4).

The overwhelming majority of fin whale calls were detected at site A3, where calling fin whales were heard every year. There are multiple possible explanations for the spatial variability observed in fin whale detections. First, site A3 is situated at the confluence of two productive water masses, the AW and BSW, which likely provide better feeding opportunities for fin whales. The dominant water mass detected at A3 was the Bering Chukchi Summer Water (BCSW), which is composed of the AW and BSW, and thus has high nutrient levels and larger zooplankton (Eisner et al., 2013; Ershova et al., 2015; Danielson et al., 2017). Though fin whale calls were also detected on days when other fresher water masses were present at A3, including days in 2015 when Alaskan Coastal Water (ACW) was present in the near-surface (Fig. S13). Fin whale calls were also detected on days in September 2012 when a fresh, cold signal appeared in the near-surface waters at A3, possibly indicating the presence of the Siberian Coastal Current (SCC).

The SCC occasionally flows into the Bering Strait during periods with strong or persistent southward winds (Weingartner et al., 1999). Ershova et al. (2015) detected the presence of the SCC in the central Chukchi Sea in September 2012, therefore it is possible that the reach of the SCC extended to the A3 site that month. Fig. S8 shows that winds measured in September 2012 were predominantly southward, which has been shown to cause the ACW to deviate away from the Alaskan coast and towards the western Chukchi Sea (Woodgate et al., 2015; Pisareva, 2018; Morris, 2019). Often the presence of the cold and fresh SCC creates a front (Weingartner et al., 1999), which could isolate and cluster prey. In 1992 1993, Moore et al. (1995) observed bowhead whales (*Balaena mysticetus*) feeding in close association with salinity and thermal fronts along the Chukotka coast. Moreover, *Thysanoessa inermis*, a common fin whale prey (Nemoto, 1959; Witteveen and Wynne, 2016), was found to be the dominant zooplankton species collected from a dense prey patch near a front, lending support to the potential importance of the SCC in creating favorable feeding conditions for fin whales at A3.

In addition to its proximity to productive water masses, A3 may be situated close to oceanographic features created by currents, such as island wake eddies, that are known to create favorable foraging opportunities for baleen whales (Johnston et al., 2005a; Chenoweth et al., 2011). Eddies create upwelling zones which promote phytoplankton blooms (Hasegawa et al., 2009) and have been shown to be important feeding habitat for auklets and other planktivores in the Bering and Chukchi seas (Piatt and Springer, 2003). In the Bay of Fundy, Canada, island wake eddy systems were found to be important feeding grounds for fin whales as well as minke whales (*B. acutorostrata*) and harbor porpoises (*Phocoena phocoena*; Johnston et al., 2005a,b). Currents moving past the Diomede Islands generate island wake eddies (Coachman et al., 1975; Woodgate et al., 2015) that are then carried northwards towards A3, according to satellite SST data (Woodgate, pers. comm.). The island wake eddies may create opportune feeding conditions for fin whales at A3.

In contrast, site A2 had fin whale detections in all recording years but in lower abundance, while fin whale calls were largely absent from site A4. Given its position in the less-productive ACC, A4 may present lower quality feeding areas for fin whales than the other two sites. Though A2 had similar water mass composition as A3, water velocities were higher at A2, potentially transporting prey out of the area. Therefore, fin whales may be less inclined to stay at in the region around A2 due to fewer feeding opportunities. Also, the position of site A3 north and towards the middle of the Bering Strait gives it an advantage over A2 in capturing the calls of fin whales migrating through the western strait. Whereas A2 and A4 can only record the calls of fin whales passing through the east channel of the strait, A3 can potentially record calling whales migrating through both channels.

While the spatial variability in fin whale detections may be explained, the exact environmental mechanisms for the observed temporal variability are less clear. Both 2012 and 2015 stand out as years with the highest number of fin whale detections at A3, yet the two years had very different environmental conditions. The year 2012 had the coldest October mean temperatures (near-bottom October mean at A3 1.0 C), late sea ice breakup (16 May), anomalously low flow (Woodgate, 2018), and weak mean northward wind velocities in the fall. On the other hand, 2015 had a very warm annual mean temperature (near-bottom October mean at A3 3.6 C), earlier sea ice breakup (4 May), high flow (Woodgate, 2018), and variable northward wind velocities. Our results suggest that at A3, the occurrence of fin whale calls is more strongly related to southward winds than northward winds, but this relation does not hold for all years (Table 5). Thus, we cannot attribute interannual variation in the acoustic presence of fin whales to any one environmental predictor. Instead, we believe that a combination of conditions not only in the Chukchi Sea, but also in the Bering Sea, contributes to the abundance of fin whales in the study area. We hypothesize a series of ‘push and ‘pull factors below that may have influenced the observed interannual variation in the presence of acoustically-active fin whales.

Pull factors imply that conditions in the Chukchi Sea were favorable for zooplankton and other fin whale prey in 2012 and 2015, thus drawing more fin whales into the area to feed. The abundance of hours with fin whale calls at A3 in 2012 may point to the fact that the year was particularly cold, and thus, productive. Colder temperatures are more favorable for the secondary production of *Calanus* copepods (Kimmel et al., 2018), a prominent constituent of the Chukchi Sea zooplankton. Cold years in the Bering and Chukchi seas have been also found to have higher zooplankton biomass and abundance (Ohashi et al., 2013; Ershova et al., 2015; Pinchuk and Eisner, 2017), and thus stronger recruitment for walleye pollock (*Gadus chalcogrammus*) and Pacific cod (*G. macrocephalus*; Stabeno et al., 2012), which are zooplankton predators like fin whales. Friday et al. (2013) observed twice as many fin whales along the eastern Bering Sea shelf in 2008 and 2010 when temperatures were cold than they did in 2002, a warm year. In their August September 2012 sampling of the Chukchi Sea, Danielson et al. (2017) observed an abnormally high biomass of large copepods as well as a predominance of the BCSW in the bottom water at multiple sampling stations. During the same sampling period, Pinchuk and Eisner (2017) report a high abundance of *Calanus glacialis* and widespread distribution of Pacific-origin zooplankton in 2012, adding evidence to our hypothesis that 2012 was a favorable year for fin whale prey.

Conversely, 2015 was a warm year with high salinities. High salinities are usually indicative of high AW content and thus are typically associated with high nutrient levels (Danielson et al., 2017). Consequently, 2015 may have had higher zooplankton abundance due to a nutrient-rich environment. Pinchuk and Eisner (2017) found a strong correlation between the biomass of Pacific-origin zooplankton and high salinities associated with the BCSW, which was the dominant water mass at A3 in 2015 (Supplementary Figs. S12 S14). It is also possible that the earlier sea-ice retreat and warmer water temperatures observed in 2015 created better conditions for Pacific-origin copepods and euphausiids. Matsuno et al. (2011) found that Pacific copepod species (e.g. *Eucalanus bungii*) expanded into the Chukchi Sea in 2007, a year with relatively early sea-ice retreat and abnormally high sea surface temperatures, similar to 2015. A notable pull factor for 2015 could also have been the strong water velocities measured in the Bering Strait. Strong velocities likely led to higher transport of both nutrients and zooplankton from the Bering Sea into the Chukchi Sea, creating better feeding opportunities for summer migrant fin whales.

In contrast to pull factors, potential push factors consist of poorer conditions in other reaches of the fin whale range, thereby sending fin whales into the Chukchi Sea in search of better conditions. Such areas include the Bering Sea and Gulf of Alaska, where fin whales are known to occur in the summer months (Moore et al., 1998, 2000; Stafford et al., 2007). Both 2014 and 2015 were significantly warmer years in comparison to historical records for the Bering Sea (Duffy-Anderson et al., 2017). Warm years in the Bering Sea result in poor recruitment in walleye pollock due to the prevalence of small, lipid-poor copepods (Kimmel et al., 2018). In 2015, an anomalously warm water mass, nicknamed the Blob, pervaded the North Pacific, leading to declines in krill and to northward distribution shifts of multiple marine species (Cavole et al., 2016). Concurrent with the appearance of the Blob were reports of a mass mortality event of common murres (*Uria aalge*) in the Gulf of Alaska (Piatt et al., 2018). Additionally, 12 fin whales stranded on Kodiak Island, AK, between May and June 2015 (Savage, 2017). Though the causes of death for the whales were not determined, ecological conditions rather than anthropogenic factors (e.g. ship strikes) are thought to be the culprit (Savage, 2017). Warmer temperatures observed in 2015 may have affected prey availability in other fin whale summer feeding grounds, pushing fin whales into the Chukchi Sea in search of better feeding opportunities.

Another possible explanation for the increased observation of fin whale calls in 2015 is that the North Pacific population of fin whales is increasing (Zerbini et al., 2006), and thus may be reclaiming portions of its previous range (Clarke et al., 2013; Brower et al., 2018). An increased number of fin whales observed during annual surveys conducted by the Aerial Surveys of Arctic Marine Mammals Project (ASAMM) from 2008 2016 in comparison to 1982 1991 supports this theory (Brower et al., 2018). Brower et al. (2018) report seeing the most fin whales in the south-central Chukchi Sea in 2014 (44% of observations) and in 2015 (27%). However, it is difficult to evaluate habitat reclamation of fin whales using their calls alone given that only males are thought to produce the 20-Hz pulse and we could only detect vocal fin whales.

Limitations of the present study include limited spatial coverage of the study area with hydrophones located in only the east channel and north of the Bering Strait. Since there are no recent surveys on the western side of the Bering Strait or Chukchi Sea, our knowledge of fin whale habitat use in this region is limited. Given that the productive AW is typically found mainly in the west channel of the Bering Strait, it is possible that most fin whales may traverse through the strait on the western side. However, without adequate observation platforms covering both sides of the strait, the exact migration path of fin whales in the region remains unknown.

The results of this study corroborate patterns of interannual variation in fin whale presence observed by previous studies. Like the present study, Delarue et al., 2013 noted low fin whale detections in the northeast Chukchi Sea in 2009 and 2010, attributing diminished vocal activity to poorer feeding conditions. In contrast, more fin whales were heard in 2007, a particularly warm year in the Chukchi Sea with early ice retreat and low sea-ice extent, as well as high transport through the Bering Strait (Woodgate et al., 2010; Delarue et al., 2013). The conditions in 2007 described by Delarue et al. (2013) are very similar to those we observed in 2015, when fin whale calls were the most abundant.

Our results present a preliminary examination of how environmental variations in the Bering Strait and southern Chukchi Sea may lead to interannual variability in the acoustic presence of fin whales. Though we were unable to identify a single environmental driver that explained the variation, differences in temperature, salinity, wind and water velocities likely played a role. There are potentially numerous combinations of environmental variables that create preferential feeding opportunities for fin whales. Delarue et al. (2013) hypothesize that perhaps the combination of environmental variables observed in 2007 (warm SSTs, low sea-ice concentrations, and high transport) created favorable conditions for fin whale prey. However, the abundance of calling fin whales in 2012, a period with colder water temperatures, low transport, and high spring sea-ice concentrations, suggests that alternative environmental drivers are also favorable for fin whale feeding.

Conditions in the Bering Sea may also be an important factor in determining fin whale occurrence in the Chukchi Sea. Comparing fin whale detections in the southern Chukchi Sea with those in the Bering Sea could help indicate whether fin whale presence in one region results in higher fin whale presence in the other. Also, examining environmental conditions in the Bering Sea for 2009 2015 could shed light on the patterns of fin whale occupation found in the present study. Continued monitoring of fin whale presence in the southern Chukchi and Bering seas in relation to oceanographic features is necessary for composing a more complete picture of how fin whale presence in the Pacific Arctic is changing in response to environmental shifts over time.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Erica Escajeda: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Data curation, Writing - original draft, Writing - review & editing. **Kathleen M. Stafford:** Conceptualization, Validation, Supervision, Resources, Data curation, Project administration, Funding acquisition, Writing - review & editing. **Rebecca A. Woodgate:** Data curation, Validation, Resources, Project administration, Funding acquisition, Writing - review & editing. **Kristin L. Laidre:** Supervision, Resources, Writing - review & editing.

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Appendix A. Supplementary data

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