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JASA ARTICLE

Marine mammal detections on the Chukchi Plateau 2009–2020[a)]

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ABSTRACT:

The Arctic Ice Monitoring (AIM) observatory has been maintained on the Chukchi Plateau at 75.1° N 168.0° W nearly continuously since 2003. The AIM site consists of a submerged mooring that, since October 2008, has been instrumented with a passive acoustic recorder to sample ambient sound, with a focus on marine mammal detections in the High Arctic. Year-long data sets for 2009, 2012, and 2014–2020 were analyzed for the presence of signals from Arctic species including bowhead and beluga whales, bearded seals, and walrus. Calls from subarctic ribbon seals were commonly detected in autumn months, suggesting they have expanded their distribution much further northward. Killer whale calls were detected in recent years providing evidence that they have moved further north into the Pacific Arctic. No other subarctic cetaceans were heard. Year-round passive acoustic sampling of sounds produced by marine mammals over a decadal timescale has enhanced our understanding of how climate-driven changes in biodiversity are affecting even the very High Arctic. https://doi.org/10.1121/10.0010208

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I. INTRODUCTION

Climate change is altering the underwater acoustic environment of the Pacific Arctic as loss of sea ice results in higher levels of environmental, biological, and anthropogenic noise (e.g., Halliday *et al.*, 2021). Many of the locations in the Arctic that have been monitored with year-round passive acoustic instruments are in near shore environments and/or regions that have oceanographic programs to monitor freshwater and heat fluxes into and out of the Arctic (Simon *et al.*, 2010; Hannay *et al.*, 2013; Woodgate *et al.*, 2015; Ahonen *et al.*, 2017; Heimrich *et al.*, 2021). Since 2008, a long-term, passive acoustic recorder has been moored at 75.1° N on the northern Chukchi Plateau in the Pacific Arctic in a region of annual and multi-year pack ice (Fig. 1). The Arctic Ice Monitoring (AIM) installation is a submerged mooring operating year-round to monitor the creation and deterioration of sea ice. Prior to 2000, this site was dominated by thick multi-year ice but since 2003 it has been almost continuously within the first-year-ice domain (Rivas *et al.*, 2018). The AIM site is also on one pathway of Pacific water inflow to the Arctic (Shi *et al.*, 2003; Danielson *et al.*, 2020). Although its location has experienced a large decrease in sea-ice presence and appreciable surface-water warming during late summer and autumn, it is still ice-covered for much of the year.

The combination of sea-ice loss and warmer seawater has influenced ecological processes in the Pacific Arctic region (e.g., Duffy-Anderson *et al.*, 2019). In most areas, primary production is initiated earlier in spring, with an overall 57% increase in Arctic Ocean net productivity between 1998 and 2018 (Lewis *et al.*, 2020). Changes in productivity vary at regional and local scales, with levels of primary and secondary production in the Chukchi Sea, some of the highest in the Pacific Arctic region (Grebmeier *et al.*, 2006; Waga and Hirawake, 2020). These large-scale environmental changes can be reflected in changes in the seasonal and spatial distribution of upper trophic level consumers, such as marine mammals (Moore, 2008; Moore and Kuletz, 2019).

The routine inclusion of marine mammal call detection in ocean acoustic observations, from both fixed and mobile platforms, has been a goal of many bioacousticians (e.g., Moore *et al.*, 2007). Over the past two decades, year-round passive acoustic sampling of sounds produced by marine mammals, as well as other natural and anthropogenic sources, has enhanced our understanding of ocean and ecological processes (Howe *et al.*, 2019). During the International Polar Year (IPY) 2008–2009, a recorder was added to the AIM site to sample the underwater sound field, with a focus on marine mammal calls. A study of the first year of passive acoustic data (October 2008–October 2009) detected four Arctic endemic species: bowhead (*Balaena mysticetus*) and

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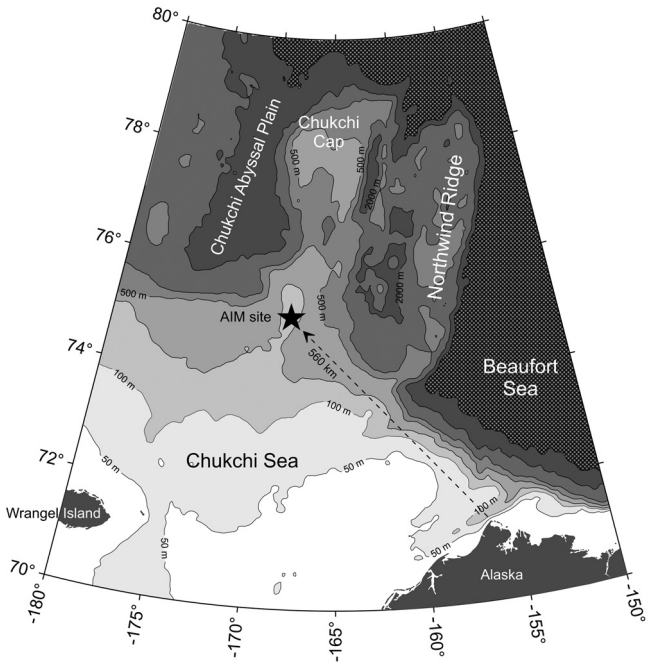

FIG. 1. AIM mooring location (star) in the Pacific Arctic.

beluga (*Delphinapterus leucas*) whales and bearded seals (*Erignathus barbatus*), and one subarctic species: ribbon (*Histriophoca fasciata*) seals (Moore *et al.*, 2012). Overall, sound sources included wind and waves during the open water and shoulder season (August through early November), Arctic marine mammals from May into September or October, airguns primarily from seabed mapping efforts (August through October), and sounds associated with ice failure, ridge building and blowing snow during the months with heavy ice cover (usually late October through early August). Here, we present data from the decade following the IPY to examine changes in the seasonal presence of marine mammals on the Chukchi Plateau in the high Pacific Arctic.

II. METHODS

Starting in 2003, the AIM mooring been deployed at 75.1° N, 168.0° W, 500 km to the northwest of Utqiaġvik, Alaska (Fig. 1). A long-term, passive acoustic recorder (Multi-Electronique Aural M2) was added to the mooring in 2008, with annual recovery and re-deployment each October (except for 2012–2013 when ice conditions prevented servicing of the mooring). The recorder sampled acoustic data at 8192 Hz on a duty cycle of either 9 min every 20 min or 8 min every 30 min. Recording duration varied by year due to battery life (Table I).

Upon recovery, each acoustic data file was displayed as a spectrogram and sound sources in each file were identified both visually and aurally by trained analysts (KMS, EKB, AMB, BMK). Biological sources included bowhead (calls and song notes), beluga (whistles), and killer whales (*Orcinus orca*, pulsed calls), walrus (*Odobenus rosmarus*, knocks, bells and grunts), and bearded (trills), and ribbon seals (downsweeps and grunts). These sounds are all distinct from each other (Fig. 2) and the presence of at least one sound from any of these sources was tallied by hour.

The total number of hours per week in which each species was heard were plotted by year to examine seasonal and inter-annual variability in sound detections and to determine if there were long-term changes in the phenology of occurrence near Chukchi Plateau region. The acoustic detection ranges of the marine mammal calls are at most 30 km, and for beluga whales, likely less than 5 km (Cleator *et al.*, 1989; Simard *et al.*, 2010; Bonnel *et al.*, 2014; Frouin-Mouy *et al.*, 2019).

To examine the fraction and thickness of sea ice over the mooring location, we used sea ice thickness and sea ice fraction data from the Arctic Reanalysis neXtSIM sea ice model with 12.5 km resolution (Rampal *et al.*, 2019) provided by the Copernicus Marine Environmental Monitoring Service (Copernicus Marine Environmental Monitoring Service, 2021). These data were available up until December 2019 (Fig. 3). Additionally, the ice-profiling sonar (IPS) on the mooring was used to calculate the submerged depth of sea ice (draft) at intervals of 1–3 s as the difference between the depth of the IPS and its distance from the ice bottom. The IPS was used in combination with Doppler sonar (ADCP), which measured ice-drift velocity. Together, the instruments provided data from which a detailed (1-m resolution) ice thickness of the pack ice drifting over the mooring could be constructed [Fig. 3(b), Melling *et al.*, 1995].

TABLE I. Deployment dates, recording dates, duty cycle and sample rate for all deployments.

Year	Deployment dates	Data collection	Duty cycle (min/min)	Sample rate (Hz)
2009-2010	20 Oct 09–10 Oct 10	20 Oct 09–11 Apr 10	9/20	8192
2011-2012	15 Oct 11–14 Oct 13	15 Oct 11–26 Jul 12	9/20	8192
2013-2014	14 Oct 13–4 Oct 14	14 Oct 13–10 Sep 14	8/30	8192
2014-2015	4 Oct 14–2 Oct 15	4 Oct 14–30 May 15	8/30	8192
2015-2016	2 Oct 15–9 Oct 16	3 Oct 15–9 Oct 16	8/30	8192
2016-2017	10 Oct 16–6 Oct 17	10 Oct 16–6 Oct 17	8/30	8192
2017-2018	6 Oct 17–15 Oct 18	6 Oct 17–15 Oct 18	8/30	8192
2018-2019	16 Oct 18–7 Oct 19	16 Oct 18–7 Oct 19	8/30	8192
2019-2020	7 Oct 19–4 Oct 20	7 Oct 19–4 Oct 20	8/30	8192

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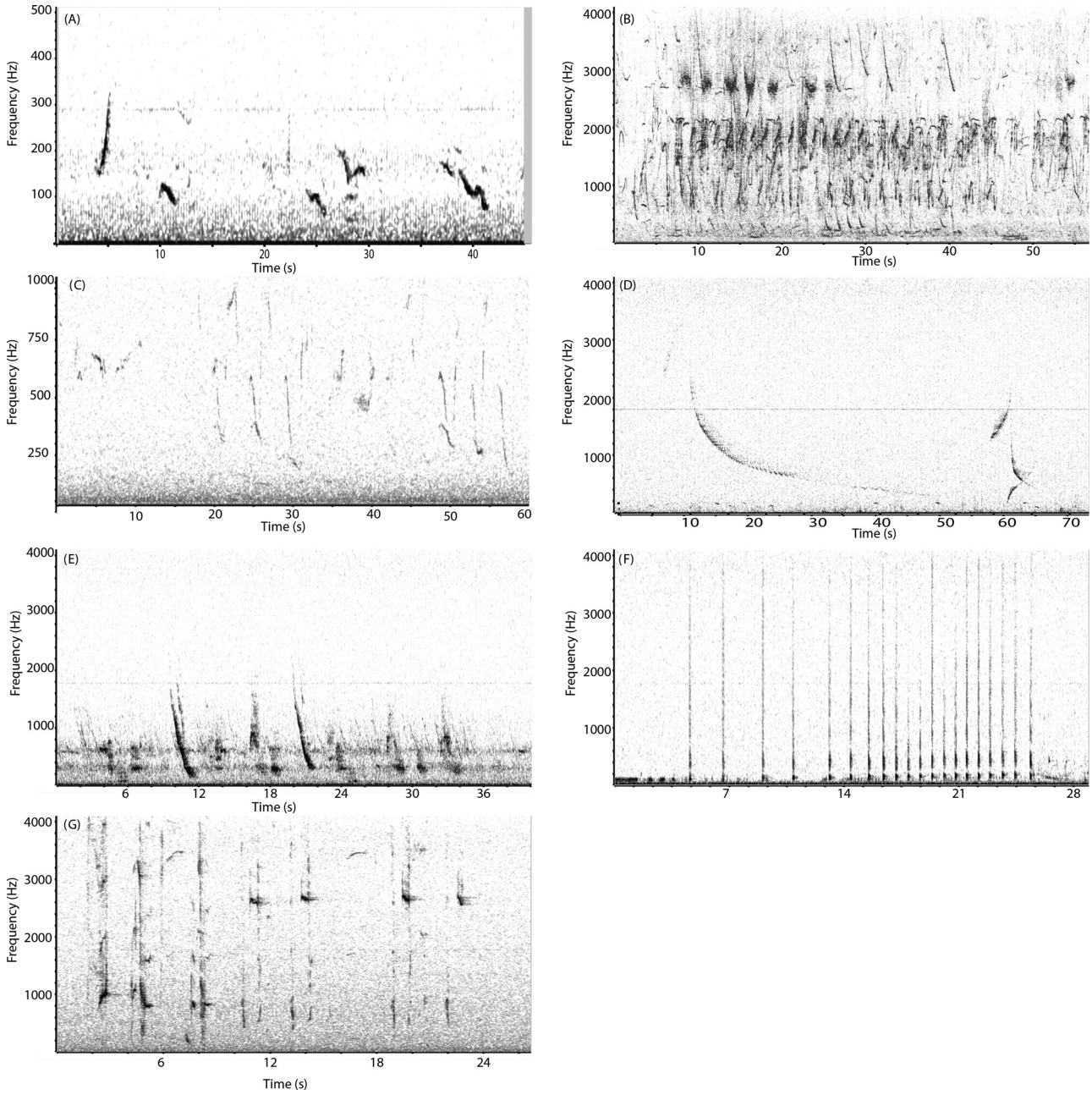

FIG. 2. Spectrograms (1024 pt fast Fourier transform, FFT, 50% overlap, Hann window) of exemplar acoustic sounds; note differences in time and frequency scales. (A) Bowhead whale calls recorded 5 July 2019; (B) Beluga whale sounds recorded 10 June 2016; (C) Bowhead whale song recorded 10 December 2016; (D) Bearded seal trills recorded 19 April 2017; (E) Ribbon seal sounds recorded 5 November 2016; (F) Walrus knock series recorded 4 March 2016; (G) Killer whale calls recorded 1 Aug 2016.

III. RESULTS

A. Cetaceans

Bowhead and beluga whales were detected in every year in which there was acoustic sampling at the AIM site. The cetaceans were remarkably consistent in the week in which they were first detected. Calls from both bowhead and beluga whales were detected in early- to mid-May, with the exception of 2016 when both species were detected in early April (Fig. 4). Both species were detected to varying levels into late August through 2014. From 2015-onward, both bowhead and beluga whales had secondary pulses in occurrence extending their presence on the Chukchi Plateau into late November, with bowhead whales heard until late December in 2016 and 2019 (Fig. 4). The greatest variation in occurrence in the detection of these species occurred in the months (July through December) with the greatest variability in the fraction of sea ice over the mooring [Figs. 3(a) and 4].

The only subarctic cetacean detected was killer whales. Killer whales were detected infrequently on the Chukchi Plateau and only in the last five years: 2016, 2018, 2019, and 2020 (Fig. 4). In 2016, 2018, and 2020, these occurred only during one hour each year. In 2019, they were heard during three consecutive week in August.

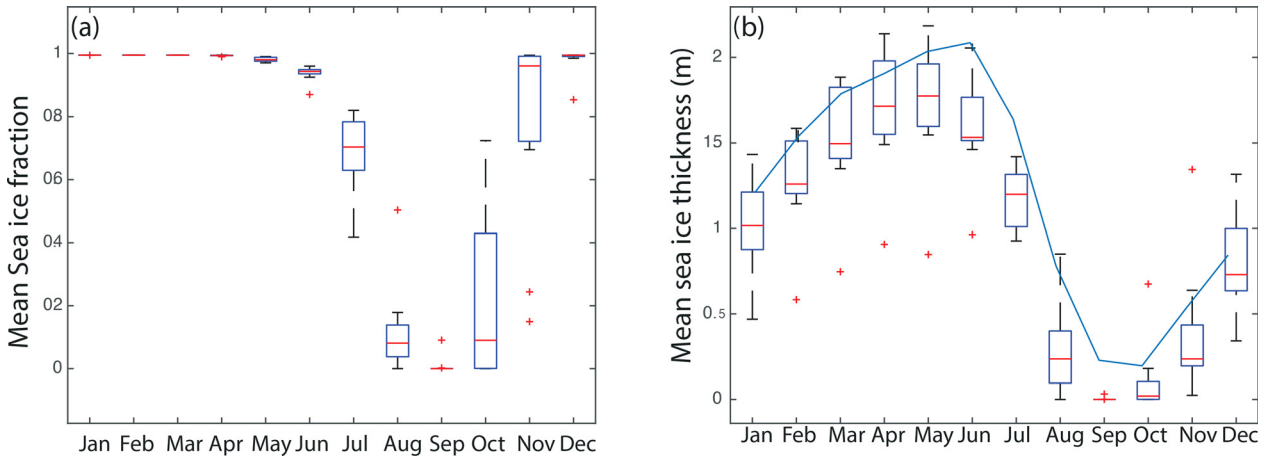

FIG. 3. (Color online) (a) Median monthly fraction of sea ice over the AIM mooring from 2009 to 2019. (b) Median monthly sea ice thickness (m) over the AIM mooring from 2009 to 2019. The blue line shows the mean thickness (m) measured by the IPS on the mooring. The bottom and top edges of the box-plots represent the 25th and 75th percentiles, respectively.

B. Pinnipeds

Bearded seals were recorded every year at the AIM site in late May or June and seldom thereafter (Fig. 5). Their acoustic residency on the Chukchi Plateau spanned ~8 weeks in 2009 and 2012 but only 3–4 weeks from 2014-onward.

Walrus were first detected on one day in 2015 and then in 2016 in early March and at low levels through June of 2016 (Fig. 5). There were a few acoustic detections of walrus in 2017 and 2018, but these were rare, and no walrus were heard in 2019 or 2020.

Ribbon seals showed the greatest interannual variability in presence on the Chukchi Plateau (Fig. 5). 2014 was the first year in which they were detected in the present dataset with the highest occurrence in 2016 when they were heard from early August to the end of the year. In 2018, they were detected briefly in early May and then from August until early November. There were few detections in 2019 but in 2020 for the first time, ribbon seals were heard over a month in the spring, albeit at relatively low levels.

IV. DISCUSSION

The AIM marine observatory has provided, for the first time, underwater sound recordings over a decade timescale from a location in the high Pacific Arctic. The over ten-year time span (2009–2020) of passive acoustic data from the Chukchi Plateau has shown consistent occupation of this region by Arctic endemic cetaceans, bowhead and beluga whales, and the occasional presence of ice seals and walrus. More strikingly, the acoustic data have revealed changes in the presence of sub-arctic species, including killer whales, which are a potential predator of endemic Arctic species. Changes over the decade from the first deployment in 2008–2009 (Moore *et al.*, 2012) to 2020 include decreasing occurrence of bearded seals.

A. Cetaceans

Bowhead whales were the most commonly recorded marine mammal at the AIM site. This species overwinters in the Bering Sea and migrates north through Bering Strait in spring on its way to foraging grounds in the Canadian Beaufort Sea. Many head westward to Chukotka in autumn or through the central channel in the Chukchi Sea, and then return south for winter (Citta *et al.*, 2021). Their presence on the Chukchi Plateau through much of the summer and autumn was a surprise when they were first recorded at such a high latitude in 2008 because this location was well outside known spring and autumn migratory corridors (Moore *et al.*, 2012). Of the 46 bowhead whales instrumented with satellite tags from 2006-present, only one has taken a route over the Chukchi Plateau during its autumn migration towards Chukotka (Quakenbush *et al.*, 2010; Citta *et al.*, 2018). Nevertheless, the acoustic data here that now span over a decade show that bowhead whales regularly inhabit the Chukchi Plateau region from late spring into autumn. Bowhead whale calls roughly display a bimodal distribution in later years (Fig. 3) with the first mode extending from spring into summer and the second, shorter mode, in autumn. This is similar to long term data from the western Beaufort and eastern Chukchi Seas (Stafford *et al.*, 2021) that mirror the population's migration through the US Beaufort into the Canadian Beaufort Sea and then back west in autumn. This could be a similar situation on the Chukchi Plateau.

Supporting Indigenous Knowledge of bowhead whale migratory patterns (Huntington *et al.*, 2021), Stafford *et al.* (2021) found that bowhead whales migrate north in spring under high sea ice concentrations and that the timing of their spring migration has not changed significantly over the past decade. However, the timing of autumn migration has been delayed by ~1 week per year (Stafford *et al.*, 2021). On the Chukchi Plateau, the mean sea ice fraction over the mooring showed little interannual variation from December through the following May with nearly 100% ice concentration but varied considerably from July into November [Fig. 3(a)]. Sea ice thickness, on the other hand, varied by month [Fig. 3(b)]. Sea ice over the mooring as determined by the IPS increases in thickness starting in December and is thickest from April to June [Fig. 3(b)]. Towards the end of winter,

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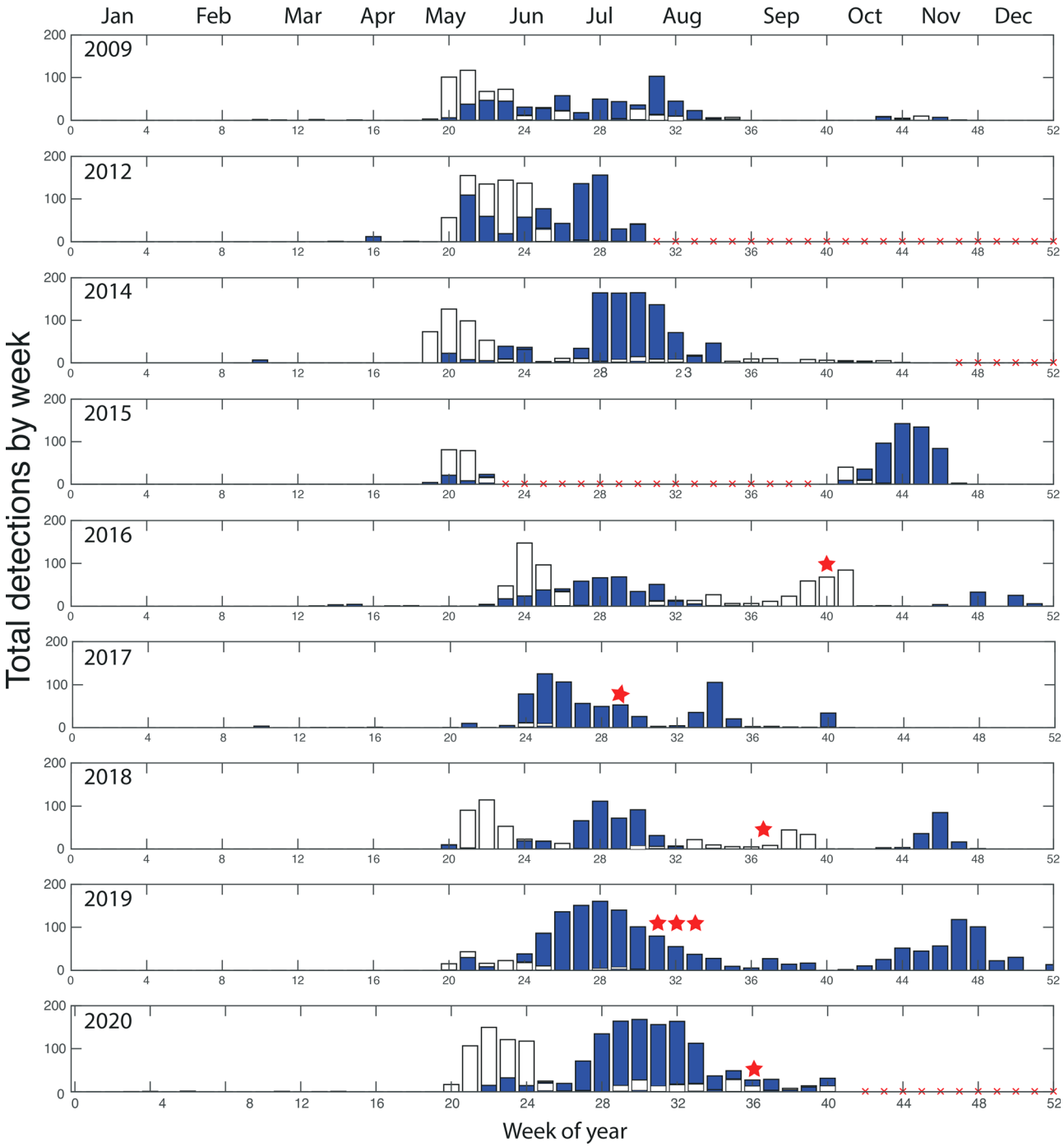

FIG. 4. (Color online) Total number of hours by week with acoustic detections of cetaceans. Bowhead whales are shown as dark blue bars, beluga whales as white bars and killer whales shown as red stars.

the combination of ~100% ice cover and maximum sea ice thickness may constrain the bowhead's mobility until the pack opens up as the fraction of ice declines (George *et al.*, 1989). This suggests that increasing ice thickness may mitigate when bowhead whales can reach the Chukchi Plateau in spring. Ellison *et al.* (1987) suggested that the reflections of bowhead whale calls off sea ice can provide them a rough idea as to the thickness and age of ice in their migratory pathway allowing them to make decisions about the navigability of the ice. At the Chukchi Plateau, spring migration timing may be a combination of date and sea ice thickness but is also likely influenced by sea ice conditions further south. In November, the fraction of sea ice over the mooring declined over time from 100% from 2010 to 2015 to less than 20% by 2019. From August through November almost all the ice above the mooring is thinner than 0.5 m. In most years, bowheads have left the Chukchi Plateau before sea ice begins to thicken, although the higher numbers of detection of bowheads by week in November and into December from 2015 onwards suggests that a

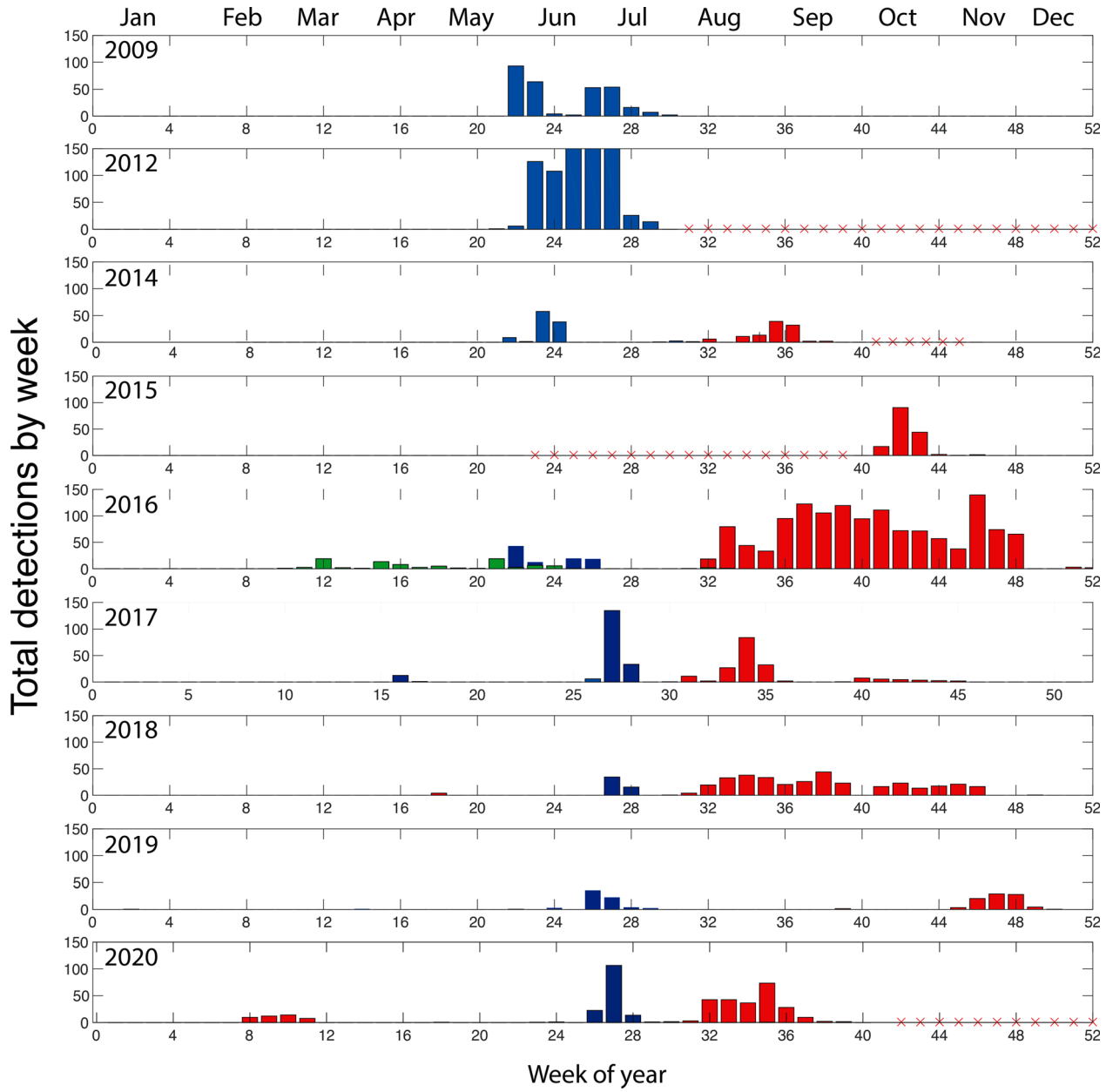

FIG. 5. (Color online) Total number of hours by week with acoustic detections of bearded seals (blue bars), walrus (green bars), and ribbon seals (red bars). Xs indicate no data available.

combination of ice thickness and extent may be driving autumn migratory behavior.

Two populations of beluga whales inhabit the Pacific Arctic seasonally, migrating north in spring from winter grounds in the Bering Sea and spending the summer in the eastern Beaufort Sea or in the western Beaufort Sea/Barrow Canyon region (Frost and Lowry, 1990; Richard *et al.*, 2001; Suydam *et al.*, 2001). The beluga whales heard on the Chukchi Plateau are most likely those from the eastern Beaufort Sea population based on information from satellite telemetry (Suydam *et al.*, 2001; Hauser *et al.*, 2014). However, as with bowhead whales, this area is well outside the known migratory corridor and summering area for this species (Moore *et al.*, 2012) and has only been identified as a "core-use" area in September (Hauser *et al.*, 2014). Nevertheless, as with bowhead whales, belugas were recorded every year, although over fewer months than bowheads. In general, the spring arrival of both bowhead and beluga whales at the Chukchi Plateau occurred at the same time while in the autumn, beluga whales appeared to depart by the end of September annually (Fig. 4).

The detection of killer whales on the Chukchi Plateau is perhaps the most evocative indicator of cetaceans responding to Arctic change. This species was detected in only a one hour on a single day in each of 2016, 2018, and 2020, but during 1–8 h over six days during the first half of August in 2019. Killer whale acoustic detections and sightings have become increasingly common over the last decade in the Chukchi Sea (Stafford, 2019). The presumed ecotype of the animals recorded is that of transient, or mammal-eating

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killer whales (Madrigal *et al.*, 2021). As in the eastern Canadian Arctic, killer whales in the Pacific Arctic may become major predators in a region and during seasons from which they were previously excluded due to heavy ice (Ferguson *et al.*, 2010; Higdon *et al.*, 2012; Breed *et al.*, 2017). Additional evidence of this species' impact comes from increases in bowhead whale carcasses with evidence of killer whale depredation and increases in rake marks on bowhead whale flukes (George *et al.*, 2017; Willoughby *et al.*, 2020). The increase in killer whale detections in the Pacific Arctic is likely due to multiple, potentially interacting, effects including increasing open-water habitat as sea ice continues to decline, an increase in their prey source as some subarctic cetaceans and the Arctic bowhead whale populations increase, and/or increases in the numbers of killer whales in the Arctic. Indigenous peoples, commercial whalers, and numerous studies propose that bowhead whales, in particular, retreat into the sea ice as a mechanism for avoiding predation by killer whales (see George and Thewissen, 2021, and references therein). This protection may be waning as sea ice retreats further to the north.

Other subarctic cetacean species that have been seen and heard increasingly in the Chukchi Sea (Clarke *et al.*, 2013; Delarue *et al.*, 2013; Brower *et al.*, 2018) but that have not yet been detected on the Chukchi Plateau include fin (*Balaenoptera physalus*), humpback (*Megaptera novaeangliae*), and minke (*B. acutorostrata*) whales.

B. Pinnipeds

Both bearded seals and walrus are ice-obligate pinnipeds that rely on sea ice as a platform for resting, pupping, and breeding (Burns, 1981a; Moore and Huntington, 2008). Both of these species tend to forage in relatively shallow water on primarily benthic prey (Jay *et al.*, 2001; Olnes *et al.*, 2020), although bearded seals forage throughout the water column (Stirling *et al.*, 1983, Sheffield and Grebmeier, 2009) and both species are capable of diving several hundred meters (Garde *et al.*, 2017; Hamilton *et al.*, 2018; Olnes *et al.*, 2020).

Walrus will use sea ice floes as resting platforms and as transportation in between foraging dives, and the lack of sea ice in much of the Chukchi Sea over the past decade has resulted in thousands of walrus hauling out on shore on the northwest coast of Alaska (Jay *et al.*, 2012). It is feasible that the infrequent walrus detections we recorded in 2017 and 2018 were the result of only a few animals being swept north on sea ice. The greater occurrence of walrus in 2016 could indicate that some animals did not migrate south during the late autumn and overwintered in the northern Pacific Arctic on drifting sea ice. In the northeastern Chukchi Sea, south of our study area, walrus were commonly detected from June through September, with the earliest detections in mid-May (Hannay *et al.*, 2013).

The acoustic behavior of bearded seals is closely linked with the presence of high concentrations of sea ice (MacIntyre *et al.*, 2015) and the decline of sea ice fraction and thickness above the mooring from June to July may have resulted in less bearded seal occupation of the Chukchi Plateau region. When compared to acoustic studies to the south of the Chukchi Plateau in the western Beaufort and northeastern Chukchi Seas, bearded seals were heard relatively infrequently, suggesting that the Chukchi Plateau is at the extreme end of their northern distribution in the Pacific Arctic (MacIntyre *et al.*, 2013, 2015; Jones *et al.*, 2014).

Ribbon seals are generally considered a subarctic species based on their distribution in the Bering Sea throughout most of the year. They are ice-associated however, and like bearded seals and walrus, use sea ice for pupping, resting, mating, and molting during the spring and early summer although they can breed and molt on beaches (Burns, 1970; Moore and Huntington, 2008; Boveng *et al.*, 2020). In the summer months, ribbon seals disperse into open water regions that include the Bering and Chukchi Seas and recent acoustic data have documented them in the nearshore western Beaufort Sea in October and November (Jones *et al.*, 2014; Frouin-Mouy *et al.*, 2019). Their acoustic presence in the northeastern Chukchi Sea was much more sporadic. Their regular occurrence on the Chukchi Plateau reported here represents, we believe, a far northward expansion of their summer and autumn range. The many months in which they were heard in 2016 and, in particular, in both 2018 and 2020 in late autumn into winter suggest that this species is moving further north as the edge of the pack ice continues to move north under a changing climate. The Chukchi Plateau region may be more favorable to foraging ribbon seals than the southern Chukchi Sea as the Plateau juts out into much deeper water (up to 2000 m), which is preferred habitat for ribbon seal foraging (Burns, 1981b; Boveng *et al.*, 2020).

V. CONCLUSIONS

Like much of the Arctic, the ecology of the Chukchi Plateau is changing rapidly, largely driven by reductions in sea ice extent and thickness which are fostering increased occupation by subarctic marine mammals. Passive acoustic data are providing evidence of change in the far north of the Pacific Arctic where Arctic endemic bowhead whales are heard into December, ribbon seals have expanded their distribution northwards, and subarctic killer whales are being heard further north and with increasing regularity. Presently, the Chukchi Plateau region remains largely ice-covered for nearly nine months. If sea ice continues to decline there, certainly we expect continued expansion of subarctic species into the very high North. This paper joins others in this volume to advance our understanding of a changing Arctic Ocean through passive acoustic observations of changes in biodiversity (i.e., Miloslavich *et al.*, 2018).

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