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Basin-Wide Shift in Bowhead Whale Migration in the Pacific Arctic

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Key Points:

- Acoustic data reinforce known delay in bowhead fall departure from the western Beaufort Sea and overwintering in the southern Chukchi Sea
- Increased presence in the western Beaufort Sea and Chukchi Plateau suggests these regions are becoming more favorable for bowhead feeding
- Whales are adapting to a rapidly changing Arctic, but changes and emerging threats may impact them and communities south of Bering Strait

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract In a rapidly changing Arctic, multiple lines of evidence suggest that bowhead whale migration is changing. To explore these changes further, we used passive acoustic data to examine bowhead whale presence in the western Beaufort Sea (12 years) and Chukchi Plateau (11 years) spanning 2008 to 2022. Departure from the western Beaufort Sea shifted 45 days later over the 12-year period. Summer presence increased at both sites, suggesting feeding areas within the Chukchi Sea are becoming more favorable. Likewise, findings from the Bering Strait suggest that some whales are remaining north of the Bering Strait for the winter instead of in the Bering Sea. These Pacific Arctic-wide changes to migration have occurred over only one decade. Questions remain about prey availability in the Chukchi Sea, implications of migratory changes, such as a northward shift in the core overwintering area, and impact to communities south of the Bering Strait.

Plain Language Summary Bowhead whales are an important top predator in the Pacific Arctic. With increasing temperatures and decreasing sea ice, changes are occurring in the migration patterns of this "ecosystem sentinel" throughout the Pacific Arctic. We analyzed passive acoustic data from the western Beaufort Sea and Chukchi Plateau from 2008 to 2022. Whales are delaying their fall departure from the western Beaufort Sea and spending more time in the western Beaufort Sea and Chukchi Plateau, which, along with increased habitat use on the Chukchi Shelf, suggests that conditions there are becoming more favorable for feeding. Combined with previous data from the Bering Strait, which showed that some whales are spending winter in the southern Chukchi Sea rather than in the northern Bering Sea, these findings suggests that changes are occurring over a short period of time throughout the Pacific Arctic. A northward shift could put bowhead whales in the direct path of ships, especially along the western side of the Chukchi Sea, and impact whaling communities south of the Bering Strait.

1. Introduction

As average air temperatures rise four times faster than the global average (Rantanen et al., 2022) and sea ice undergoes substantial transformation (Meier, 2021; Schweiger et al., 2011), it is evident that the Arctic is changing. Multiple lines of evidence suggest extraordinary change in the Pacific Arctic from 2017 to 2021, including unparalleled lack of sea ice formation in the Bering Sea in the winters of 2017 and 2018, with open water areas and southern ice edge positions surpassing 2030–2044 projections (Ballinger & Overland, 2022; Wang et al., 2018). In addition to an increasing frequency of major sea-ice loss events and associated impacts (Ballinger & Overland, 2022), these large-scale environmental changes are being reflected in changes in the distribution and movement patterns of marine mammals (Hauser et al., 2017; Stafford, Farley, et al., 2022; Stafford, Melling, et al., 2022; van Weelden et al., 2021).

After spending winter in the northern Bering Sea, Bering-Chukchi-Beaufort (BCB) bowhead whales (*Balaena mysticetus*) migrate northward through the Bering Strait then east toward the Canadian Beaufort Sea for the summer. In the fall, they migrate west toward the Chukotka Peninsula, southward through the Bering Strait, and back into the northern Bering Sea. Traditional Knowledge has long documented changes to bowhead whale migration (George et al., 2013; Huntington et al., 2021; Noongwook et al., 2007). Szesciorka and Stafford (2023) used passive acoustic monitoring data to track bowhead whale migration from 2009 to 2021 and found that some whales are remaining in southern Chukchi Sea rather than moving into the Bering Sea for the winter. This was corroborated by biologging data spanning 2009–2019, which found that in 2018 and 2019, tagged whales wintered north of their historical range southwest of St. Lawrence Island in the northwestern Bering Sea (Citta et al., 2023).

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BCB bowhead whales are considered a conservation success story (Thewissen & George, 2021). While hunted to near-extinction by commercial whaling from 1700 to early 1900s (Thewissen & George, 2021), the most recent abundance estimates from ice-based (14,025 whales; Givens et al., 2021) and aerial (17,175 whales; Ferguson et al., 2022) surveys in 2019 indicate that the population has nearly quadrupled since 1978 and may have reached or surpassed abundance prior to commercial whaling (Citta et al., 2023). Although bowhead whales are not the sole subsistence prey for the Iñupiat and Siberian Yup'ik, Native hunters have expressed concern about changes in migration in the Bering Strait region, specifically the impact of the loss of whales during the spring harvest on nutrition and culture (Pennington, 2023). And while the threat of commercial whaling is gone, new potential threats have emerged including ship strikes, entanglement in fishing gear, pollution and noise from offshore oil development, and predation by killer whales (George et al., 2017).

Multiple lines of evidence indicate that bowhead whale winter ranges are shifting northward and summer ranges are expanding (Citta et al., 2023; Ferguson et al., 2021; Heide-Jørgensen et al., 2012; Stafford et al., 2021a). Passive acoustic data have been used to document bowhead whale overwintering on summer feeding grounds in the eastern Beaufort Sea (Insley et al., 2021). And as late as 9 January 2023, at least two bowhead whales were heard calling on a hydrophone deployed by North Slope Borough residents off the ice off Utqiaġvik, AK (formerly Barrow; J. C. George personal communication as told to K.M.S.). Given these findings, including changes documented by Szesciorka and Stafford (2023), we wondered if we could corroborate the known changes in migration using passive acoustic monitoring data in other Pacific Arctic regions. Here we explore trends in bowhead whale presence along their migration route in the western Beaufort Sea (12 years) and Chukchi Plateau (11 years) spanning 2008–2022.

2. Materials and Methods

2.1. Deployment Locations

Sites assessed in this study, including the southern Chukchi Sea/Bering Strait boundary site (see Szesciorka & Stafford, 2023), were in the western Beaufort Sea (71.4°N, 152°W) and Chukchi Plateau (75.1°N, 168°W; Figure 1). The western Beaufort Sea hydrophone is part of a year-round mooring on the Beaufort slope along the migratory corridor of BCB bowhead whales (Lin et al., 2016). The Chukchi Plateau hydrophone is part of the Arctic Ice Monitoring observatory's (Department of Fisheries and Oceans, Canada) year-round mooring on the continental margin where bowhead whale presence was first documented in 2008 (Moore et al., 2012). Both sites benefit from the advection of zooplankton and nutrients (Gosselin et al., 1997; Springer & McRoy, 1993; Springer et al., 1996) resulting from the northward flow of three distinct water masses through the Bering Strait (Coachman & Aagaard, 1966). Combined with the Bering Strait, these sites largely cover passage points along the full BCB bowhead whale migration, the exception being the northern coast of Chukotka.

2.2. Acoustic Data and Analysis

Passive acoustic data were collected by AURAL-M2 (Multi-Électronique, Inc.) recording packages. Stafford et al. (2021a) provide deployments details for the western Beaufort Sea from 2008 to 2018 (deployed at 90–168 m, 8 or 16 kHz sampling rate, 5–20 min/hr duty cycle). We include one additional deployment from 5 November 2018 to 23 July 2020 sampled at 16 kHz on a 9/30 min duty cycle. There were not enough data for 2015, therefore the year was excluded from analysis. Stafford, Farley, et al. (2022) and Stafford, Melling, et al. (2022) provide deployments details for the Chukchi Plateau from 2009 to 2020 (deployed at ∼166 m, 8 kHz sampling rate, 9/20 or 8/30 min duty cycle). We include two additional deployments from 4 October 2020 to 23 February 2022 and 20 September 2021 to 11 October 2022 sampled at 16 kHz on a 9/30 min duty cycle. There were not enough data for 2010 or 2013, therefore those years were excluded from analysis. Szesciorka and Stafford (2023) provide deployments details for the southern Chukchi Sea/Bering Strait boundary from 2009 to 2021 (deployed at ∼50 m, 8 or 16 kHz sampling rate, 10–25 min/hr duty cycle). There were no data for the winter of 2016–2017 which was excluded from analysis.

Each acoustic file was displayed as a spectrogram and assessed visually by trained analysts for the presence of at least one bowhead whale signal per file to produce a timeseries of hourly bowhead whale presence. Methods on the migration timing metric estimation are detailed in Szesciorka and Stafford (2023). Briefly, call onset was defined as the first day with more than 15% of call hours (day with more than 3 hr with calls) and call cessation

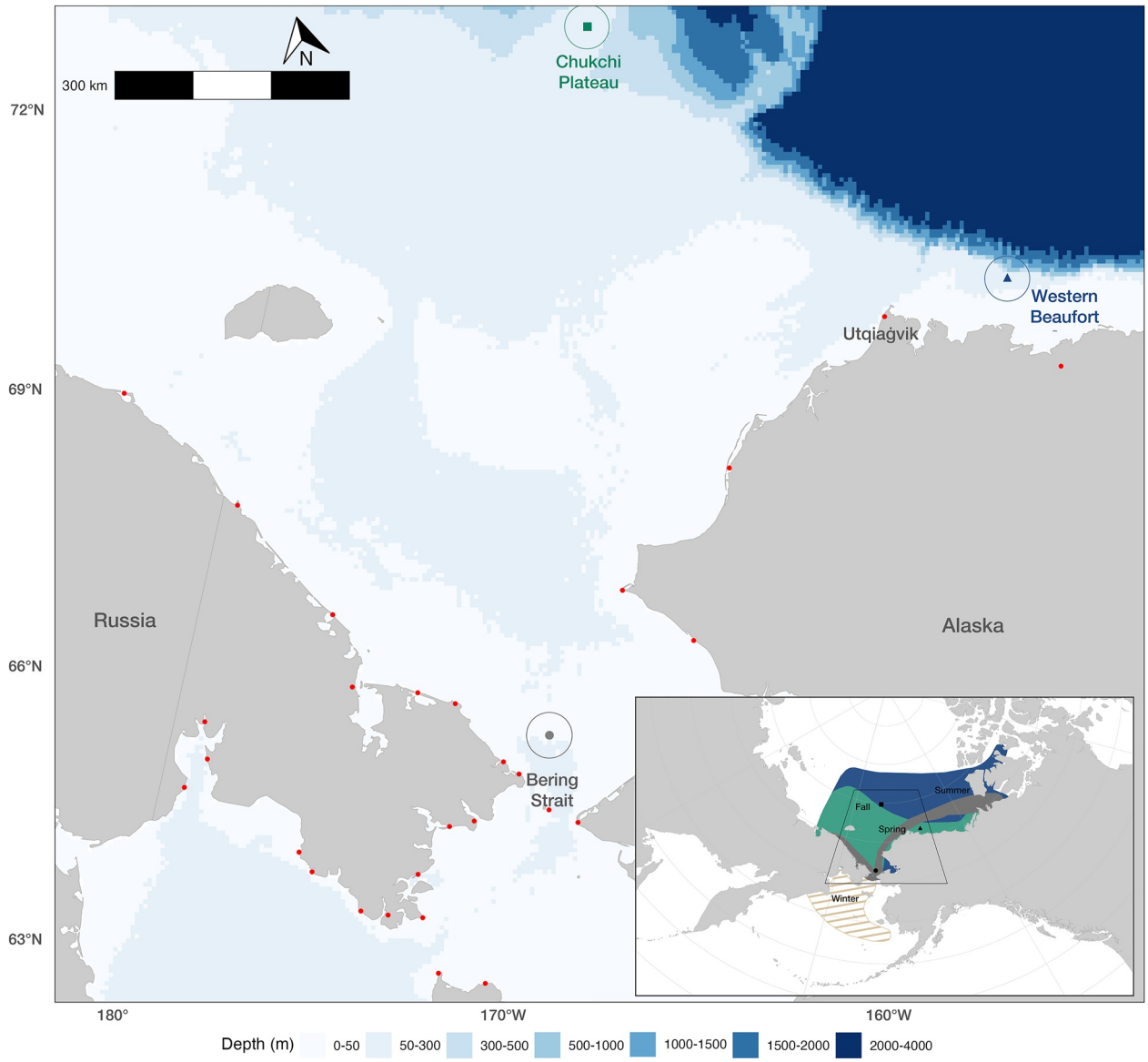

Figure 1. Hydrophone deployment locations in the western Beaufort Sea (blue circle), Chukchi Plateau (green circle), and southern Chukchi Sea/Bering Strait boundary (gray circle). Open circles indicate nominal maximum detection radius of hydrophones (~30 km; see Bonnel et al., 2014). Red dots indicate whaling communities along coastal Alaska and coastal Russia. Inset indicates broader global region and seasonal migration regions (modeled after Quakenbush et al., 2018).

was defined as the last day with more than 15% of call hours. The ratio of days with calls relative to days of effort was also calculated. Linear models were used to assess long-term trends with the base "stats" package in R (v 4.3.0; R Core Team, 2022). Figures made in R with the "ggplot2" (v 3.4.2; Wickham, 2016), "ggOceanMaps" (v 1.0.9; Vihtakari, 2021), and "sf" (v 1.0–13; Pebesma, 2018) packages.

3. Results

3.1. General Trends

The western Beaufort Sea hydrophones recorded for ~12 years from the fall of 2008 through mid-2014 and the fall of 2016 through the summer of 2020 (Table 1; Figure S1). The mean annual timeframe with bowhead whale calls was 10 April through 22 November. The earliest onset was 28 March and the latest was 21 April. There was one March onset. The remaining onsets occurred in April (n = 9), spanning 23 days. Cessation dates ranged 100 days (~3.3 months), including October (n = 1), November (n = 6), December (n = 2), and January (n = 1).

Table 1
Annual Migration Metrics in the Western Beaufort Sea and Chukchi Plateau

	Western Beaufort Sea			Chukchi Plateau			
Year	Onset	Cessation	Ratio call days	Onset	Cessation	Ratio call days	Overlap range (days)
2008	nd	307	0.48	nd	nd	0.01	nd
2009	105	308	0.51	135	315	0.28	May–August (84)
2010	92	286	0.40	nd	nd	0.06	nd
2011	87	315	0.52	nd	322	0.05	nd
2012	107	327	0.48	142	nd	0.31	April–July (60)
2013	111	324	0.53	nd	nd	0.06	nd
2014	105	nd	0.48	133	234	0.27	May–July (46)
2015	nd	nd	nd	133	318	0.26	nd
2016	nd	385	0.75	152	346	0.27	nd
2017	98	322	0.49	145	278	0.27	April–October (74)
2018	94	363	0.55	139	322	0.19	May–September (49)
2019	101	325	0.61	140	354	0.42	May–December (128)
2020	95	nd	0.58	146	340	0.45	May–July (54)
2021	nd	nd	0.48	151	246	0.22	nd
2022	nd	nd	0.51	132	nd	0.31	nd

Note. Metrics include onset and cessation Julian date, ratio of call days relative to number of effort days, and the range and number of days of overlap at both sites (nd indicates insufficient data to determine the onset, cessation and/or ratio of call days). See Szesciorka and Stafford (2023) for migration metrics from the southern Chukchi Sea/Bering Strait boundary.

The earliest cessation was 13 October and the latest was 19 January (2016), the only instance where whales remined into the next calendar year. In 2017, call cessation occurred mid-November, but in 2018 and 2019 whales stayed late into December.

The Chukchi Plateau hydrophones provided data for ~11 years, including 2009, the spring of 2012, and 2014–2022 (Table 1; Figure S1). Mean bowhead whale call presence was 20 May through 3 November. All onsets occurred in May within a 23-day range. The earliest onset was 10 May and the latest was 31 May. Cessation dates ranged 121 days (~4 months), including August ($n = 1$), September ($n = 1$), October ($n = 1$), November ($n = 4$), and December ($n = 3$). The earliest cessation was 22 August and the latest was 20 December. Cessation dates from 2017 through 2020 appeared to be increasing (i.e., whales staying later), but calling in 2021 ended earlier (3 September) due to an early freeze-up, and the greatest sea-ice extent in 20 years (Bhatt et al., 2022). Calling in 2022 appeared to end 29 August; however, effort ended 11 October. Bimodal distributions were evident 2017–2020, especially in 2018, which suggested whales visited the Chukchi Plateau multiple times each year (Figure S1).

In years with simultaneous effort at the western Beaufort Sea and Chukchi Plateau (Table 1; Figure S1), whales were present at both sites 13%–35% of the time, with 46–128 days ($\overline{x}$ 70 days) of overlap throughout the year. The overlaps occurred from April to December ($\overline{x}$ 5 months). There was no long-term trend in overlap at the two sites; however, overlap in 2017 spanned April–October and overlap in 2019 spanned May–December suggesting that more months (although not always more days) were spent at both sites in later years.

3.2. Long-Term Trends

Bowhead whales are remaining later in the western Beaufort Sea (Figure 2a). Departure shifted by >45 days from 2008 to 2019 ($p < 0.01$, $r^2 = 0.58$). There was no long-term trend in arrival or departure at the Chukchi Plateau nor the southern Chukchi Sea/Bering Strait boundary (Szesciorka & Stafford, 2023). In the western Beaufort Sea ($p < 0.06$, $r^2 = 0.30$) and Chukchi Plateau ($p < 0.01$, $r^2 = 0.40$), the number of days with calls relative to the number of days with effort increased, suggesting an increased presence across 12 and 14 years, respectively

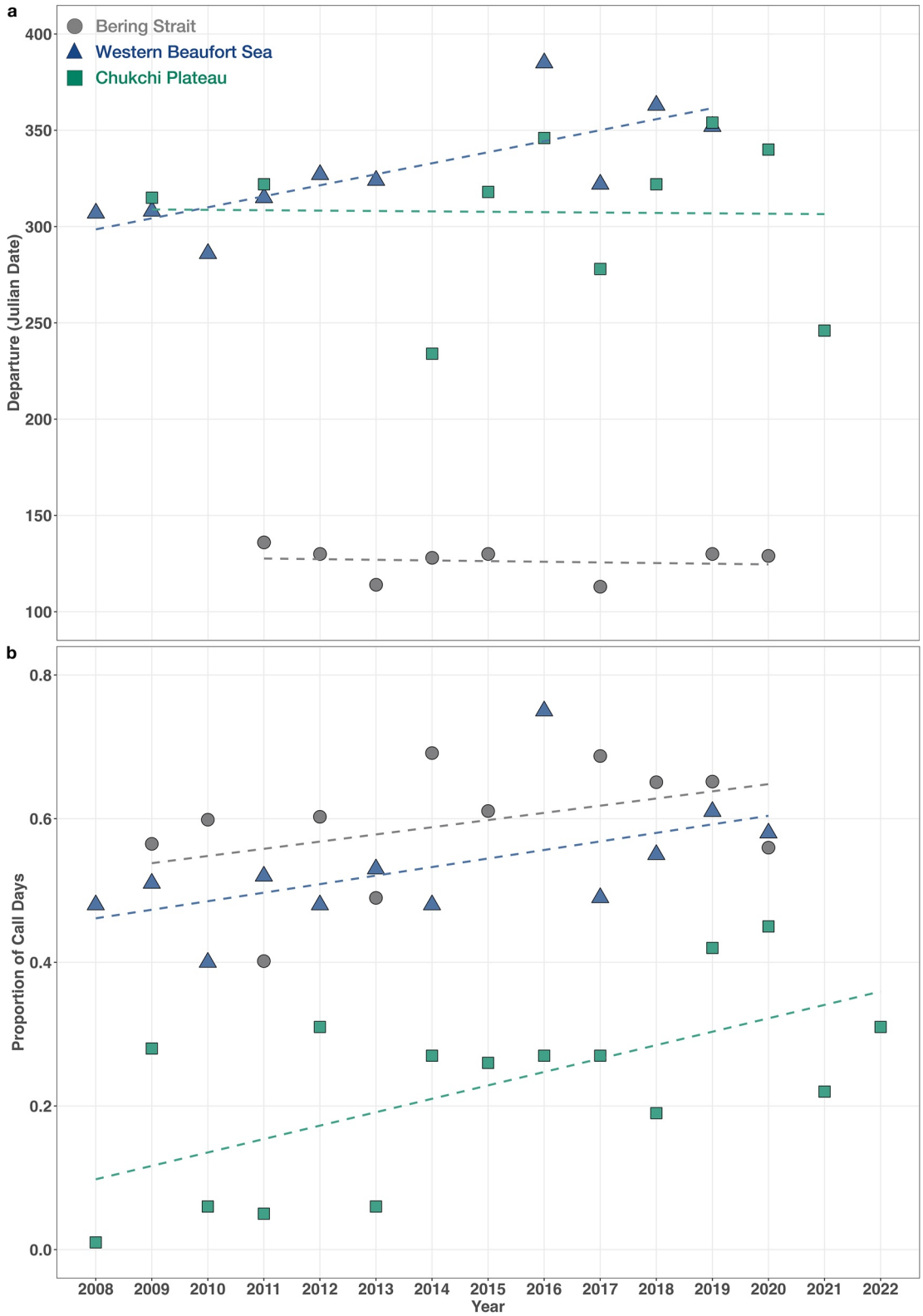

Figure 2. Bowhead whale migration metrics from 2008 to 2020. (a) Departure Julian dates and (b) number of days with bowhead whale calls relative to number of days with effort for the western Beaufort Sea, Chukchi Plateau, and southern Chukchi Sea/Bering Strait boundary.

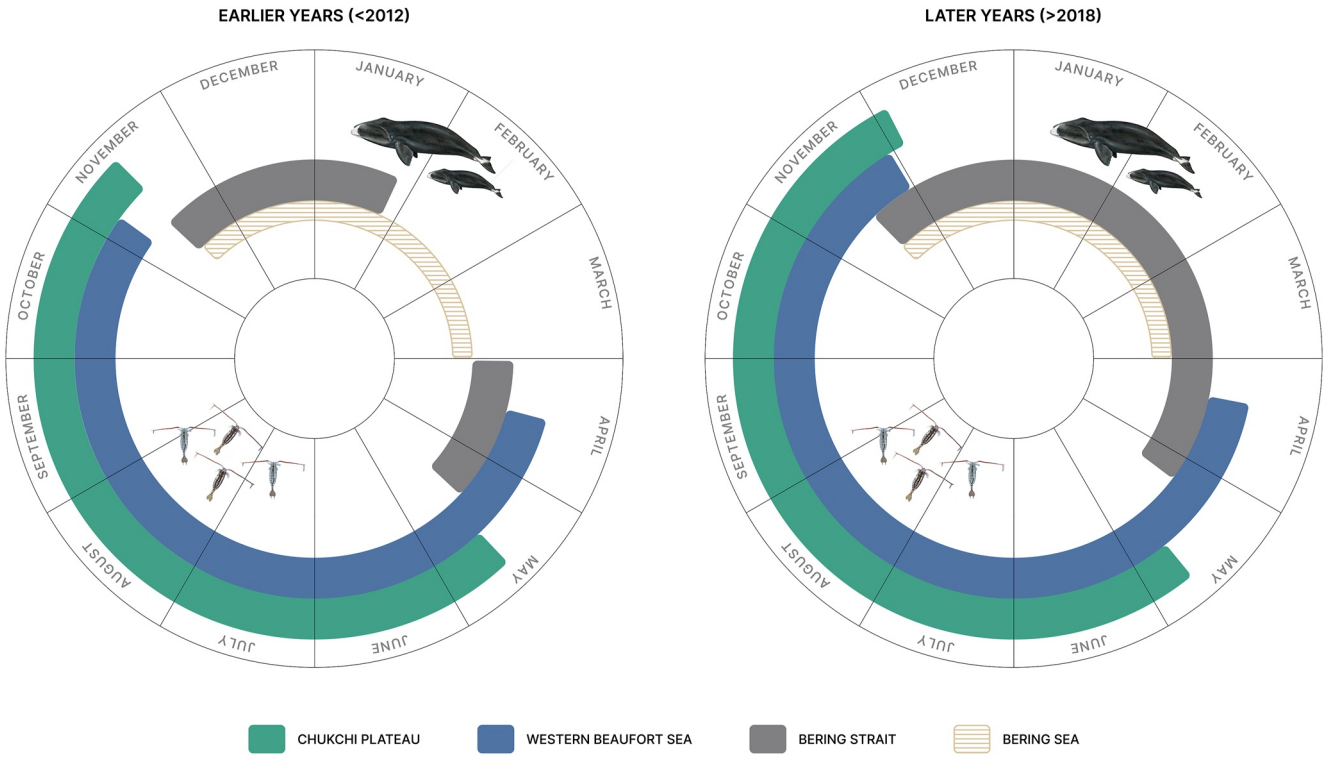

Figure 3. Schematic of changes to bowhead whale migration from earlier years (<2012) to later years (>2018) at migratory destinations throughout the Pacific Arctic. Chukchi Plateau (green) and western Beaufort Sea (blue) are assessed in this study, Bering Strait was assessed in Szesciorka and Stafford (2023). The Bering Sea (tan lines) is included for reference based on Citta et al. (2012).

(Figure 2b). At the southern Chukchi Sea/Bering Strait boundary, the proportion of call days across 12 years was increasing but non-significant.

4. Discussion

4.1. Rapid Broad Scale Changes

As the best studied of the four bowhead whale populations, basin-wide changes to the BCB migration have been documented from tagging studies and aerial surveys, including a delayed arrival at wintering areas in the Bering Sea (Druckenmiller et al., 2018) and increased overwintering in the Chukchi Sea (Citta et al., 2023). The results from this passive acoustic monitoring study, with Szesciorka and Stafford (2023), corroborate basin-wide changes to bowhead whale migration in the Pacific Arctic even over just one decade (Figure 3). Despite a paucity of long-term hydrophone data from the Canadian Beaufort Sea, with the delayed fall departure from the western Beaufort Sea we can infer that whales might be lingering in their summer feeding grounds. As a result, whales are likely delaying arrival at the northern Bering Sea winter grounds and some whales are spending the winter in the southern Chukchi Sea instead of the northern Bering Sea. Whales may be transiting from the eastern Canadian Beaufort Sea through the western Beaufort Sea to access the Chukchi Plateau throughout the feeding season.

Bowhead whales are thought to feed primarily on copepods in the Amundsen Gulf and along the eastern Beaufort Sea shelf (Walkusz et al., 2012). The presence of bowhead whales along the western Beaufort Sea migratory corridor suggests some animals are transiting to/from their Canadian Beaufort Sea foraging grounds throughout the feeding season (Stafford et al., 2021a). Movement between the eastern Canadian Beaufort and the western Alaskan Beaufort and Chukchi Sea throughout the summer has been documented in tagged whales for nearly two decades (Citta et al., 2023; Olnes et al., 2020). Higher use by tagged whales along the outer Chukchi Shelf corresponded to years (2009, 2012, 2014, 2015, 2017, and 2018) with a higher proportion of calls at the Chukchi Plateau and lower use corresponded to years (2008 and 2010) with a lower proportion of calls at the Chukchi Plateau (Figure 3; Citta et al., 2021).

In addition to using the northern Chukchi shelf (spring–fall) to feed, whales may be transiting to the krill trap on the Beaufort Sea shelf near the eastern side of Barrow Canyon, an intermittent prey source for migrating whales if conditions are right (Ashjian et al., 2010; Okkonen et al., 2011, 2020) and/or southward to the southern Chukchi Sea/Bering Strait gateway (late fall), where there have been reports of gray whales feeding on euphausiids (Bluhm et al., 2007) and increased bowhead whale presence during periods of high abundance of zooplankton (Tsujii et al., 2016, 2021).

4.2. Habitat Use at the Chukchi Plateau

Bowhead whales were first documented at the Chukchi Plateau in 2008, much further north than their previously defined spring/fall migratory corridor (Moore et al., 2012). The persistent annual overlap between the western Beaufort Sea and Chukchi Plateau spanning the spring to late fall suggests that the Chukchi Plateau, and areas along the Chukchi Shelf, are at times favorable feeding areas for bowhead whales. The Chukchi Sea is a pathway for krill from Bering Strait (Ashjian et al., 2021; Berline et al., 2008) on which bowhead whales are thought to feed in the Chukchi Sea (Ashjian et al., 2010; Moore et al., 1995). Copepods have also been found in high abundance in the summer at the Chukchi Plateau (Ashjian et al., 2003). Therefore, it is likely that bowhead whales are feeding on krill and/or copepods at the Chukchi Plateau, and may favor some areas along the Chukchi Shelf for feeding. Prey-driven migration could explain why bowhead whale presence was truncated in some years (2014, 2022) while extended in others (2016, 2018–2020).

Migration timing in BCB bowhead whales is partitioned, with mother-calf pairs migrating later than adults without calves (Braham et al., 1980; George et al., 2013; Koski & Miller, 2009). If migration timing is partitioned, it is likely that feeding is partitioned as well. Aerial surveys have documented partitioning in the Beaufort Sea based on age class (Koski & Miller, 2009; Richardson et al., 1987). As the population grows, potentially exceeding pre-whaling abundances, it is possible that whales are partitioning feeding across the broader Pacific Arctic basin. We do not know how many animals are visiting the Chukchi Plateau or if there is a demographic division such as age- or sex-specific segregation. However, satellite tag data suggested that most whales that make these mid-season, long-distance movements are adults (Citta et al., 2021, 2023).

4.3. Impacts of Changes to Migration

We do not know how many whales are overwintering in the southern Chukchi Sea rather than the Bering Sea or if the entire population will shift northward as the Pacific Arctic continues to warm. It remains to be seen if and how these changes impact the location and timing of feeding and breeding behaviors. Stomach content analysis from harvested whales (Sheffield & George, 2021) and dive behavior from tagged whales (Citta et al., 2021) indicate that bowhead whales feed year-round. With increased northward transport and advection of krill into the Chukchi Sea (Huntington et al., 2020; Woodgate, 2018), a northward shift would not likely impact foraging opportunities. Mating, which occurs mid-March to mid-April (Reese et al., 2001) and birth appear unlikely to be impacted by a northern shift of the population as birth and nursing would likely occur in the southern Chukchi Sea during the spring migration.

Remaining north of Bering Strait may offer additional protection (i.e., sea ice as a refuge) from the growing risk of killer whale predation on calves (Citta et al., 2023; George et al., 2017; Stafford, Farley, et al., 2022; Stafford, Melling, et al., 2022). And although entanglement risk in the Bering Sea is largely driven by lost gear rather than overlap with commercial fisheries and crabbing gear (Citta et al., 2014; George et al., 2017), a shift north will not increase risk of entanglement, as the Russian commercial fishery for pollock in the Chukchi Sea uses trawls, which doesn't pose entanglement risk to bowhead whales.

Halliday et al. (2022) found little overlap between bowhead whales and vessel traffic from July through October along the western Chukchi Sea. However, if over-wintering areas shift northward, this may put whales in the direct path of additional shipping traffic, especially the western side of the Chukchi Sea, where it has increased 12.5% since 2009 (Berkman et al., 2022).

Importantly, changes to migration could impact traditional whaling communities south of the Bering Strait. We do not expect that whales will stop over-wintering in the Bering Sea. However, if core areas shift northward, there may be fewer whales available around communities in the northern Bering Sea. Conversely, a northward shift

could benefit communities along northwestern Alaska if bowhead whales spend additional time north of Bering Strait.

Long-term changes in arrival and departure, as determined by passive acoustic monitoring, revealed large-scale changes to bowhead whale migration. But because of staggered spring migration—subadult whales, then large adults of both sexes, pregnant females, and lastly mothers with calves (George et al., 2021)—onset and cessation of migration may be useful at some sites but not others. And as whales remain longer, arrival and departure dates will be more difficult to pinpoint. Additional call metrics (i.e., absences and proportion of call days) revealed unexpected trends like the shift to overwintering north of the Bering Strait (see: Szesciorka & Stafford, 2023) and the increased presence in the western Beaufort Sea and Chukchi Plateau despite no long-term trend in arrival or departure in some cases. This underscores the need for metrics that might reveal behavior or relative abundance, to better understand the basin-wide changes to bowhead whale migration it the Pacific Arctic.

5. Conclusions

Although BCB bowhead whales are considered a conservation success story, like other whale species, they face growing anthropogenic and climate-driven threats. Bowhead whale migration patterns are changing as rapidly as the Arctic environment is changing. Phenotypic plasticity may outweigh potential costs (e.g., location and timing of life history events) and have additional benefits such as reduced predation pressures. However, there may come a time when basin-wide changes to the Arctic ecosystem, such as shifts in prey distribution and abundance, negatively affect the BCB bowhead whale population. Additionally, the impact (whether positive, negative, or neutral) to traditional whaling communities in Alaska remains to be seen. Finally, questions remain about the location and timing of life history events and prey availability on the Chukchi shelf. As top predators relying on finding aggregated prey, bowhead whales are considered "ecosystem sentinels" (Moore & Kuletz, 2019). Changes to migration timing and habitat use that this study has documented add to the growing body of literature providing evidence of on-going extreme change (e.g., Huntington et al., 2020; Rantanen et al., 2022) and reflect fundamental changes in structure and function of the biophysical environment and underlying marine food webs in the Pacific Arctic.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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Data Availability Statement

Acoustic data sets are available in the Arctic Data Center at Stafford (2014, 2017). Bowhead whale detection data for the western Beaufort Sea are available from Stafford et al. (2021b).

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