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# Trends in sea-ice cover within bowhead whale habitats in the Pacific Arctic

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ABSTRACT

The range of the Bering-Chukchi-Beaufort (BCB) population of bowhead whales (*Balaena mysticetus*) extends across the seasonally ice-covered waters of the Pacific Arctic region. The majority of whales summer in the eastern Beaufort Sea and winter in the Bering Sea, migrating across the Chukchi Sea in fall and spring. As arctic sea-ice extent rapidly diminishes, the increasing length and variability of the open water season is changing bowhead habitat substantially, with many areas now regularly ice-free when whales are present. This study examines changes in the number of open water days (OWD) between 1979 and 2014 within annual bowhead whale core-use areas as defined by satellite tagging data, and within the western Beaufort Sea (140–157°W; to 72°N) sampled by fall aerial surveys. Ice cover has decreased more in the core-use areas in the northern extent of the range than in core-use areas in the southern extent. The numbers of OWD within the core-use areas near Point Barrow and along the northern Chukotka Coast during peak use have increased by 13 and 10 days/decade, respectively. The most dramatic reductions in sea-ice cover have taken place in the western Beaufort Sea where the number of OWD on the shelf and slope have increased by 20 and 25 days/decade, respectively. In contrast, sea-ice cover has not significantly changed within the winter core-use area near the Gulf of Anadyr. Using aerial survey data, we found that bowheads in the Beaufort Sea during the fall migration have a preference for being closer to shore than to the ice edge, and that their distance to shore decreases as the fraction of open water increases. This distribution may be due to increased feeding opportunities closer to shore as a result of greater upwelling along the shelf break when the ice cover is farther from shore. Furthermore, the aerial survey data also revealed a substantial shift westward toward Point Barrow in the whales' use of the western Beaufort Sea during fall in the period 1997–2014 compared to 1982–1996. The extent and timing of sea-ice coverage has changed relatively little over time in the Bering Sea. Bowheads typically migrate north prior to spring ice melt and retreat; therefore, large changes in the timing of the spring migration are not expected. We anticipate that bowheads will spend increasingly more time within summer and fall feeding areas, delaying their arrival to wintering areas in the Bering Sea. Reduced ice coverage and thickness in the southern Chukchi Sea may make wintering there more common in the future. Summer and fall movements may be more variable as productivity and zooplankton aggregations in existing feeding areas are altered in response to sea ice thinning and retreat, and as new areas become available.

## 1. Introduction

Sea ice is important for the ecology and evolution of arctic marine mammal species. These species exhibit a range of adaptations for living in ice-covered waters, such as thick blubber, no dorsal fin (beluga—*Delphinapterus leucas*, narwhal—*Monodon monoceros*, and bowhead whales—*Balaena mysticetus*), or cryptic coloration as seen in young seals (i.e. white lanugo) or the white pelage of polar bears (*Ursus maritimus*). Sea ice, due to its roles both as a structural element in the Arctic environment and as an ecological driver of prey populations, is also thought to be an important factor for determining the seasonal range of arctic marine mammals. For pinnipeds, such as ice seals and walruses (*Odobenus rosmarus*), sea ice provides a platform for resting, pupping, molting, and feeding. For polar bears, sea ice provides the

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substrate on which they hunt. For cetaceans, sea ice may provide refuge from predators, such as killer whales (*Orcinus orca;* e.g. Shelden et al., 2003; Higdon and Ferguson, 2009). However, too much sea ice may also pose a risk of entrapment for cetaceans (e.g. beluga whales; Heide-Jørgensen et al., 2002; Ivashin and Shevlyagin, 1987) or limit gene flow between populations (e.g. Dyke et al., 1996; Alter et al., 2012). In contrast, the presence of sea ice may foster connectivity between populations for species that travel on the ice, such as the Arctic fox (e.g. *Alopex lagopus*; Geffen et al., 2007).

The spatial extent of arctic sea ice has declined at a rate of 14% per decade since the beginning of the satellite record in 1979 (Stroeve et al., 2014). This decline has been especially evident in recent years with the ten lowest September minimum ice extents having all occurred in the last ten years (2007–2016). Furthermore, the Arctic has experienced over a 60% reduction in annual mean sea-ice thickness over the last 30–40 years (Lindsay and Schweiger, 2015). There are several identified causes of the recent arctic sea-ice decline, including warming trends (Overland et al., 2008), atmospheric circulation and wind patterns (Nghiem et al., 2007), a thinner more mobile ice cover (Maslanik et al., 2007), increased inflow of warm water (Woodgate et al., 2006), and the ice albedo feedback (Perovich, 2011). Given that most of these drivers are either projected to continue (e.g. warming trends) or are positive feedback mechanisms (e.g. increased ice mobility and the ice albedo feedback), it is unlikely that the current declining trends in sea-ice extent will abate before a nearly ice-free Arctic Ocean is observed in summer.

In this paper, we examine how sea ice has changed the habitat of the Bering-Chukchi-Beaufort (BCB; aka Western Arctic) stock of bowhead whales. Bowheads have long been considered ice-associated whales (e.g. Haldiman and Tarpley, 1993; Moore and Reeves, 1993; George, 2009) that have a range restricted to areas with seasonal ice cover, seek refuge within pack-ice from predators, migrate through seasonal flaw lead systems in spring, and have a protruding rostrum capable of breaking ice up to 60 cm thick to breathe (George et al., 1989). The majority of the BCB stock spends summers in the Beaufort Sea (Moore and Reeves, 1993; Harwood et al., 2010) and winters in the Bering Sea, migrating through the Chukchi Sea in both fall and spring. The most recent abundance estimate for the stock was approximately 17,000 whales in 2011 (Givens et al., 2013). Whales that summer in the eastern Beaufort Sea have been observed in deep waters beyond the continental shelf (Moore et al., 2000); however, the majority feed in shallower waters over the continental shelves (e.g. Moore and Reeves, 1993; Moore et al., 2000; Ashjian et al., 2010; Harwood et al., 2010; Citta et al., 2015) where summer sea ice has substantially diminished over recent decades. In a typical year, the majority of bowheads remain in the eastern Beaufort Sea until late summer or early fall, when they begin their fall migration across the western Beaufort Sea and Chukchi Sea. Most whales arrive at, and pass by, Point Barrow from late August through mid-October. By mid to late fall, bowhead whales are well into the Chukchi Sea, where their migration is broadly distributed (Quakenbush et al., 2010; Clarke et al., 2016). Most whales linger along the northern Chukotka coast before arriving in the Bering Sea, where they remain from December to April.

Our understanding of how sea ice is thought to affect the distribution of bowhead habitat has changed over the last several decades, concurrently with diminishing arctic sea ice. Researchers initially believed that bowheads in winter were largely restricted to polynyas—areas of open water usually formed downwind from land masses (Niebauer and Schell, 1993)—because polynyas provided open water for surfacing (e.g. Bogoslovskaya et al., 1982; Brueggeman et al., 1987) and because bowheads targeted the ice edge for feeding. Recent studies indicate that bowhead whales are much less limited by sea ice than originally thought, although this assertion is confounded by lighter ice conditions in recent years. Satellite tagging has shown that most bowheads do not rely on polynyas in winter (Citta et al., 2012) and that they are capable of migrating through very heavy sea ice in spring (Zeh et al., 1993; Quakenbush et al., 2012). Genetic studies indicate that the dispersal of bowheads is not as limited by sea ice as previously believed (Alter et al., 2012). Although bowheads may sometimes target the ice edge for feeding, many feeding areas are completely devoid of sea ice when whales are present (Moore et al., 1995; Ashjian et al., 2010; Walkusz et al., 2012; Citta et al., 2015; Okkonen et al., this issue). Bockstoce et al. (2005) summarized catch data from historical whaling ship logs indicating that thousands of bowheads summered in the Bering Sea in the 1850s, which was presumably ice-free, at least in some years (e.g. see Mahoney et al., 2011). This does not mean that bowhead habitat is independent of sea-ice conditions; rather, that the relationship between bowheads and ice is more subtle.

The current decline in sea ice is thought to have had a positive influence on bowhead whale habitat in the Pacific Arctic region (Moore and Stabeno, 2015). Declining sea ice is associated with an increase in net primary productivity due to more photosynthetically active radiation entering the ocean (e.g. Arrigo et al., 2008) and a longer growing season (e.g. Arrigo and van Dijken, 2011, 2015). These changes may translate into enhanced secondary production, including faster growth rates of zooplankton (Matsuno et al., 2011; Ershova et al., 2015) that bowhead whales consume. George et al. (2015) found that sub-adult whales in particular gain more mass, an indicator of improved body condition, during years with less sea ice. Improved body condition, however, may be linked to other factors as well, including prey aggregation through increases in upwelling favorable winds (Pickart et al., 2013) or increased transport of zooplankton through Bering Strait (Woodgate et al., 2012; Ershova et al., 2015). Despite these mechanisms for advantage, it is unclear if continued rapid declines in sea ice will remain advantageous for bowhead whales. For example, bowhead whales are known to target large zooplankton, yet warming may favor smaller-sized species, which appears to be the case in the Bering Sea where bowheads winter (Eisner et al., 2014). Declining sea-ice habitat may expose bowhead whales to more competition as sub-arctic species of whales, such as humpback whales (*Megaptera novaeangliae*), or predators, such as killer whales (*Orcinus orca*), expand into the bowhead whales' summer and fall range.

In this paper, we examine sea-ice conditions within known bowhead whale habitats by analyzing long-term (1979–2014) changes in sea-ice concentration and timing within the areas of the Alaskan Beaufort Sea where whales are counted via aerial surveys during the fall migration (Clarke et al., 2015) and within core-use areas delineated by satellite telemetry studies (e.g. Citta et al., 2015). Within the aerial survey zone, we examine how the presence and location of sea ice influence the observed locations of bowhead whales relative to the coast. We then synthesize this information to discuss how the distribution of bowhead whales and the timing of their migration may change as sea ice continues to decline.

## 2. Methods

This section describes the three primary datasets used in this study, each corresponding to a different period. The sea-ice data span 1979–2014 (see Section 2.1) and begin at the start of the satellite record; thus providing consistency with most studies of long-term changes in arctic sea-ice concentration. Due to our focus on long-term changes in the ice cover, we did not constrain the years of sea-ice data to align with the period of either the aerial survey data (1982–2014; see Section 2.2) or the satellite tagging data (2006–2012; see Section 2.3).

### 2.1. Satellite-derived sea-ice coverage (1979–2014)

We derived values for the open water fraction (OWF; 1 minus the sea-ice fraction) within the whale core-use areas and over the western Beaufort Sea shelf and slope using the daily and monthly averaged passive microwave datasets from the Nimbus-7 Scanning Multi-channel Microwave Radiometer (SMMR) and the Defense Meteorological