Spatiotemporal Patterns and Habitat Preferences of Bowhead Whales in the Eastern Beaufort Sea, Arctic Ocean

Nikoletta Diogou[1,2], William D. Halliday[1,2], Stan E. Dosso[2], Xavier Mouy[3,4], Andrea Niemi[5], Stephen J. Insley[1,6]

[1] *Wildlife Conservation Society Canada, Whitehorse, Yukon, Canada.*
[2] *School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia (BC), Canada.*
[3] *JASCO Applied Science Ltd, Victoria, BC, Canada.*
[4] *Integrated Statistics, Inc., under contract to National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northeast Fisheries Science Center, Woods Hole, MA, United States*
[5] *Fisheries and Oceans Canada, Freshwater Institute, Winnipeg, Manitoba, Canada*
[6] *Department of Biology, University of Victoria, Victoria, BC, Canada*

ABSTRACT

The Arctic is warming four times faster than the rest of the globe. The shrinking sea ice causes cascading effects throughout the ecosystem. While cetaceans experience climate-driven changes in the ocean, their adaptation mechanisms include spatially and/or temporally shifting their habitat occupancy, or even permanently altering their migration phenology. The urgent need for monitoring Arctic cetaceans, combined with the challenge of long-term studies in the Arctic, was addressed with passive acoustics. During 2014-2021, ten sites in the Beaufort Sea were equipped with fixed acoustic recorders, monitoring the ocean soundscape for 1-12 months. Combined manual and automated bioacoustic analysis with statistical analysis allowed quantifying the variability of bowhead whale (*Balaena mysticetus*) presence through time and space. The bowhead is the only Arctic endemic mysticete and a species of high cultural and nutritional value for the Inuit people. Results indicate a large variation in bowhead presence over the years and across the stations. However, a clear seasonal pattern is dominant throughout the data. These spatiotemporal patterns, combined with in-situ and remotely-sensed environmental variables in multivariate models allowed identifying the conditions that affect the bowhead distribution. Understanding these responses is key for predicting the impact of environmental change while the ocean is warming.

Keywords: *Bowhead whales, Canadian Arctic, foraging grounds, passive acoustic monitoring, habitat preferences.*

1. INTRODUCTION

The Arctic region is undergoing rapid changes, with substantial loss of sea ice extent and thickness over the past decades due to ocean warming. These environmental shifts can have far-reaching impacts on the entire ecosystem (Cooper and Grebmeier, 2022; Frey et al., 2021; Lefebvre et al., 2022; Moore et al., 2022), producing a suite of cascading effects that can alter ecological processes and affect the wellbeing and survival of many species. Monitoring and understanding these changes are fundamental for addressing mitigation efforts and should be a priority for conservation managers and policy makers.

The Bering-Chukchi-Beaufort (BCB) stock of bowhead whales (*Balaena mysticetus*) is particularly vulnerable to the impacts of these changes. These whales, endemic to the Arctic, are the longest-living mammals on the planet and are culturally significant to the Inuit people. The BCB stock is listed under Canada's Species At Risk Act (SARA) and is considered of Special Concern under the management plan for BCB bowhead whales (COSEWIC, 2009). Bowheads are distinctively vocal and use sound for multiple biological functions, including reproduction, group cohesion, socializing and navigating (Stafford et al., 2017). In addition to bowhead calls, the Arctic soundscape consists of a variety of sounds including: (a) calls from other animals such as bearded seals, ringed seals, beluga whales, and fish; (b) ice sounds, and (c) shipping noise (see examples of these signals in Fig. 1).

**Corresponding author*: niki.diogou@gmail.com.

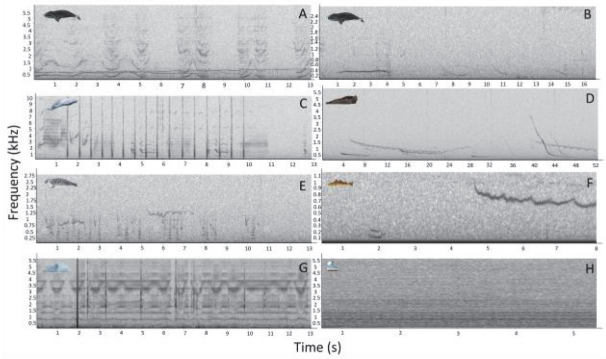

Figure 1. Spectrogram examples from site CB50 of (A) bowhead whale song, (B) bowhead whale moans, (C) beluga whale calls, (D) bearded seal calls, (E) ringed seal barks, (F) fish call, (G) ice sounds, and (H) shipping noise. Note the differences in x and y axes scalings between spectrograms. (A), (E), and (F) also contain parts of bearded seal calls. The images of bowhead whale and bearded seal are publicly available from NOAA website (www.fisheries.noaa.gov). The Arctic cod image was taken from the DFO website (www.dfo-mpo.gc.ca) and the beluga whale photo belongs to Javier Yaya Tur. The ringed seal illustration belongs to Pieter Folkens, the ice and ship images were modified from photos by Annie Spratt and Tobias Bjorkli respectively from Pexels.

BCB bowhead whale migration patterns are strongly influenced by the sea-ice state (Clark et al., 2015) and the episodic nature of feeding hotspots. The whales spend winters in the ice-free Bering Sea for breeding, and summers ranging from the Chukchi Sea to the eastern Beaufort Sea foraging.

The western Canadian Arctic is an under-studied area in the distribution range of BCB bowhead whales, and data on their distribution, temporal patterns, and habitat preferences are scarce, particularly for areas far from shore. Passive acoustic monitoring (PAM) provides a highly effective and cost-efficient means of studying marine mammal distributions, especially in remote and inaccessible areas with harsh environmental conditions (Moore et al., 2006). Autonomous archival acoustic recorders can be effectively used to continuously monitor vocal species day and night over long periods (i.e., 1 year).

In the paper, we combined acoustic recordings collected by Wildlife Conservation Society Canada (WCS Canada) (Halliday, Têtu, et al., 2018; Halliday et al., 2019) to provide complete information on the presence of BCB bowheads at their foraging grounds in the western Canadian Arctic. By analyzing these recordings, we attempt to identify the drivers of whale presence at different years and sites, and explain their relationship with a variety of environmental conditions, including sea-ice cover, water temperature, and other oceanographic features, using statistical modeling. Such knowledge fills important gaps for BCB bowhead ecology as the Arctic Ocean is rapidly changing. These findings have significant implications for conservation and management of the whales, as well as for understanding the impacts of climate change on Arctic ecosystems as a whole.

2. MATERIALS AND METHODS

The western Canadian Arctic, especially the Amundsen Gulf, represents core habitats for the summer foraging of the BCB stock (Citta et al., 2015). Here, during 2014-2021, ten sites were equipped with archival fixed acoustic recorders (Fig. 2), monitoring the ocean soundscape for 1-12 months. A combination of SoundTrap ST500 and ST300 (Ocean Instruments, New Zealand) were deployed through the years across the bowhead distribution in the western Canadian Arctic. The recorders are set at 24-48 kHz sampling rate with a minimum duty cycle of 5 minutes of recording every hour, and 16-bit depth. In all cases, the frequency range of the bowhead vocalizations were within the recording frequency range.

Figure 2. Map of the study area at the Western Canadian Arctic indicating the locations of the acoustic stations and the recording periods.

The moorings consisted of a heavy anchor, tandem acoustic releases, sub-surface floats, and a short vertical line from the releases to the floats where the acoustic recorders were attached. The water depth at the deployment sites varied from 12.2 to 351 m, and the recorders were attached to the mooring line 1 to 10 m above the bottom. In some cases, moorings also included other instruments, such as conductivity-temperature-depth (CTD) loggers and acoustic zooplankton fish profilers (AZFP) which provided additional data used for subsequent analysis. Moorings deployment and recovery were carried out from a ship provided by partners from Fisheries and Oceans Canada (DFO) during the ice-free summer (August to October) of each year.

Bioacoustic analysis included a combination of manual and automated methods to detect bowhead whale calls in each file analyzed. Based on stereotyped bowhead calls (Clark and Johnson, 1984; Stafford et al., 2018), an existing detector/classifier was used to automatically identify bowhead acoustic signals (Spectro Detector JASCO Applied Science Ltd, Victoria, British Columbia, Canada, as reported in Mouy et al., 2013). All files with an automated detection were manually assessed for bowhead calls, through visual and aural inspection using spectrograms produced using Raven Pro version 1.5 (Bioacoustics Research Program, 2017). For each deployment, an additional 10-100% of the files was manually examined for any false negatives.

To examine the environmental conditions at the bowhead habitats, remotely-sensed environmental data were used. We extracted satellite data in a grid large enough to fit the entire study area and all acoustic stations including a buffer zone of about 2° (68.3° to 73° latitude, −142° to −114° longitude) for the period 1 January 2014 to 1 January 2022. Data were downloaded at the finest temporal and spatial scales available, and ranged from daily to 5-days temporal resolution, and 1-25 km spatial resolution. Data were downloaded into NetCDF format, then converted to raster format, and finally were cropped into buffers of five different scales (5, 10, 25, 50, and 100 km) centered on each acoustic station. The mean was computed for all grid cells inside each buffer for each variable and then averaged into 5-day bins. The following remotely-sensed variables were downloaded directly from the ERDDAP website (http://coastwatch.pfeg.noaa.gov/erddap/index.html; Simons, 2016): sea surface temperature/salinity/height anomaly, ice concentration, ice concentration/thickness, wind speed/direction, and Ekman upwelling (wind stress).

For the assessment of the spatiotemporal patterns in bowhead whale acoustic occurrence, and the habitat preferences assessment, we used generalized linear mixed models (GLMM, lme4 R package; Bates et al., 2015). For the seasonal patterns, the models included *station*, *month*, and their interaction as fixed effects, and *week* as a random effect to control for temporal autocorrelation in the data. For the habitat preferences, models also included all the environmental variables as explanatory variables. All statistical analyses were performed in the R programming language (R Core Team, 2017), and models with the same distribution family were compared using Akaike's information criterion for small samples (AICc) from the MuMIn R package (Barton, 2018).

3. CONCLUDING REMARKS

The utilization of an eight-year time series encompassing bowhead whale data has proven to be immensely valuable in detecting environmental variability within the vulnerable Arctic region. Through the application of passive acoustic monitoring, we were able to collect extensive marine-mammal data from otherwise inaccessible environments, enabling us to enhance our understanding of bowhead whale ecology in the western Canadian Arctic. This study serves as a testament to the rapid changes occurring within the Arctic marine ecosystem, particularly at high trophic levels. The findings quantified the occurrence patterns of bowhead whales in the eastern Beaufort Sea and their associations with various environmental conditions. By deepening our understanding of the dynamics between whales and their changing environment, we can develop effective strategies to ensure their long-term survival.

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