Representation of the Pacific Arctic seabird community within the Distributed Biological Observatory array, 2007-2015

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ABSTRACT

An array of eight Distributed Biological Observatory (DBO) sites serve as long-term monitoring areas for three geographic regions: the northern Bering, eastern Chukchi, and Beaufort seas. The locations of the DBO sites were largely determined based on abundance and diversity of benthic invertebrates. It is not clear how well these fixed sampling sites can detect changes in processes and populations that operate over spatial scales that are 1–3 orders of magnitude greater than the areas sampled by the DBO sites. In this paper, we examine whether the DBO array provides a reasonable method by which to describe and monitor the distribution and community composition of seabirds in the eastern Pacific Arctic, and if it captures areas of high seabird abundance. We used vessel-based survey data totaling ~115,860 km of transects within the study area from July-October, 2007-2015. We compared species richness, diversity, abundance, and community composition of seabirds among DBO sites and to the broader geographic regions. In general, the avifauna of DBO sites were representative of their respective surrounding region, although sampling effort in the Beaufort was limited. Species richness (totaling 63 species) was highest in the Bering region and lowest in the Beaufort region. Species diversity indices were similar among DBO sites and regions, except for exceptionally low diversity in the two easternmost DBO sites of the Beaufort region. Total seabird abundance was highest in and near Bering Strait, and dropped abruptly northward and eastward of Point Barrow. We used K-means cluster analysis to identify six community types across the entire study area, with five community types identified as having at least one numerically dominant species, and one community type defined by very low densities of a variety of species. Several community types were associated with major current systems (e.g. Anadyr Current, Alaska Coastal Current), and for two community types, breeding colony locations were also influential. Short-tailed shearwaters were the most abundant species in five of the eight DBO sites, and they were the numerically dominant species in a community that was represented from DBO 1 through DBO 6. Overall, variance in abundance was much greater by DBO site (or region) than by year for total birds and for seven of eleven taxa. Taxa with greater interannual variance than spatial variance were shearwaters and phalaropes (among regions), and murrelets (among DBO sites), all of which are late summer migrants to the study area, and glaucous gulls, a circumpolar species. The consistency in species' abundance by site indicates that DBO sites will be useful for monitoring seabirds in each region. As an array, the DBO sites captured major hotspots of seabird abundance as well as the seabird communities, except for the fulmar-dominated community in the outer Bering Shelf. However, all DBO sites will need to be surveyed to capture the full range of seabird communities in this study area. The Beaufort DBO sites require more survey coverage than currently achieved to fully evaluate their effectiveness to monitor changes in seabirds for that region.

Keywords: Distributed Biological Observatory, Pacific Arctic, Seabird communities, Seabird distribution, Seabird species richness, Bering Sea, Chukchi Sea, Beaufort Sea

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1. INTRODUCTION

A rapidly changing Arctic requires monitoring of ecological processes and biological components at large spatial and temporal scales, which can be difficult to maintain over time (Moore et al., 2018).

Starting in 2010, five Distributed Biological Observatory (DBO) regions were identified as sites for long-term monitoring to track biological responses to rapid biophysical changes occurring from the northern Bering Sea to the northeastern Chukchi Sea. In 2012, the five sites were expanded to eight, to include three sampling regions in the Beaufort Sea (Moore and Grebmeier, 2018). The five original sites were established primarily on the basis of benthic diversity and abundance. Seabirds are among the upper trophic level groups that can be used to detect change in the Pacific Arctic marine system (Moore et al., 2014). In contrast to the benthic organisms and even many fishes, seabirds are highly mobile in their distribution and abundance, which complicates sampling and interpretation of observed distribution patterns with respect to the DBO array (Moore and Kuletz, 2018). In addition, seabird communities change dramatically throughout the year in the Pacific Arctic, and include locally breeding birds as well as migrants that move into the area during summer to feed (Gall et al., 2017; Kuletz et al., 2015).

Seabirds are predators that have shown phenological, dietary, and distributional changes coincident with rapidly changing Arctic and Subarctic conditions (Divoky et al., 2016; Gall et al., 2017; Renner et al., 2016). Seabird population sizes and breeding success can be monitored at their breeding colonies, but they can also be counted at sea, where they spend the majority of their time when foraging and migrating. Seabirds of the Pacific Arctic include species that eat zooplankton, fish, benthic organisms, and combinations of these. Bottom-up biological and physical processes that operate at hierarchical scales influence seabird distribution, as seabirds respond to seasonal and annual changes in climate and lower trophic levels (Hunt and Schneider, 1987; Piatt et al., 2007).

At the broadest spatial scales (>1000 km), seabirds are associated with oceanographic habitats and to variable extent, by distribution of prey within those habitats (Hunt and Schneider, 1987). At small scales (<100 km), seabirds are patchily distributed, with the highest densities typically found in areas with high prey availability (Hunt and Schneider, 1987; Benoit-Bird et al., 2011, 2013). Hunt and Schneider (1987) proposed that meso scale processes (100–500 km), combined with prey patchiness, result in distinct seabird communities associated with particular physical habitats. In addition, breeding birds are constrained to foraging within range of their colonies (10–100 km) while they incubate eggs and raise chicks (Coulson, 2002). Nonetheless, seabirds can range over huge areas, begging the question of whether at-sea surveys within the DBO array provide a useful representation of the greater region, or of seabird communities therein.

Seabird surveys have been conducted in and near the DBO sites annually from 2007 to 2015, although not with consistency in space and time. In addition to the DBO sampling stations, we were able to combine surveys conducted as part of a variety of projects, including industry-based studies, the Arctic Marine Biodiversity Observing Network (AMBON), and other vessel-based programs. Using these combined data, we questioned whether the samples collected within the DBO polygons are representative of the seabird communities in their respective regions, and if they captured areas of high seabird abundance for the entire study area. In this paper, we describe the distribution and abundance of seabirds of the Pacific Arctic in the context of the DBO array and surrounding waters. In doing so, we provide a step towards application of DBO sites to upper trophic levels.

2. METHODS

2.1. Study area

The main study area (Fig. 1) includes the northern Bering, eastern Chukchi, and Beaufort seas, from 60°N to 73°N. The eastern and western boundaries in the northern Bering Sea extend from 179°W, at the northwestern edge of Bering Sea continental shelf, eastward to 162°W, at Norton Sound. In the Chukchi and Beaufort seas, the longitude extends from 169°W, at the international dateline, eastward to 126°W, at the west end of Amundsen Gulf in the Canadian Arctic. We considered three major geographic regions: the northern Bering (north of 60°N to Bering Strait), which contains DBO sites 1 and 2; the eastern Chukchi (Bering Strait to Pt. Barrow), containing DBO sites 3, 4, and 5; and the Beaufort (east of Pt.

Barrow), containing DBO sites 6, 7, and 8. Hereafter we refer to the regions, respectively, as the Bering, Chukchi, and Beaufort regions.

2.1.1. Physical properties

The Pacific Arctic is hydrographically and biologically distinct from the southern Bering Sea, and is generally defined as beginning at ~60°N, with seasonal variations (Stabeno et al., 2010; Sigler et al., 2011). The continental shelf ecosystem of the northern Bering and southern Chukchi Sea is influenced by salinity and temperature characteristics of three major water masses and their associated currents: Anadyr Water, Bering Shelf Water, and Alaska Coastal Water (Coachman et al., 1975; Weingartner et al., 1999; Fig. 2). These water masses advect nutrients, heat, and plankton northward from the Bering Sea, resulting in high productivity in the Bering Strait region, i.e. the Chirikov Basin (between St. Lawrence Island and Bering Strait; Fig. 2) and Hope Basin (north of Bering Strait), and throughout the Chukchi Sea (Springer and McRoy, 1993; Grebmeier et al., 2006). Both Anadyr Water and Bering Shelf Water are relatively cold, saline, and nutrient rich (Coachman and Shigaev, 1992; Weingartner et al., 2013). North of Bering Strait, Anadyr Water and Bering Shelf Water merge and become Bering Sea Water, which then bifurcates towards the Arctic Basin and branches around the shallow (40 m depth) plateau known as Hanna Shoal (Coachman et al., 1975; Dunton et al., 2017; Fig. 2).

Alaska Coastal Water, transported in the Alaska Coastal Current (Fig. 2), is heavily influenced by river input from the Bering Sea coast. It is relatively warm, fresh, and nutrient poor (Springer et al., 1984; Coachman and Shigaev, 1992) compared to water masses found farther offshore. The Alaska Coastal Current flows roughly parallel to mainland Alaska, until reaching Pt. Barrow, where it branches to the west or continues east along the Beaufort coast. The Beaufort and northern Chukchi seas are also influenced by deep Atlantic water flowing eastward near the shelf edge and the westerly flowing Beaufort Gyre in the Arctic Basin (Fig. 2). These water masses vary seasonally and interannually in their physical characteristics, spatial extent, and degree of mixing, due to changes in atmospheric circulation, regional wind patterns, and sea-ice extent and timing of retreat (Weingartner et al., 1999, 2005; Woodgate et al., 2015; Pickart et al., 2009, 2013).

Sea-ice cover changes seasonally and dramatically in the Pacific Arctic, with direct and indirect consequences for upper trophic level organisms (Grebmeier et al., 2010; Stabeno et al., 2018), including seabirds (Hunt et al., 2018). Sea ice cover expands southward from the Beaufort and Chukchi seas in late fall and typically extends into the middle of the Bering Sea by March (Stabeno et al., 2010). Within the pack ice, open water areas (polynyas) persist throughout winter and spring, providing habitat for those species of birds and mammals that remain (Stringer and Groves, 1991). Sea ice retreats in spring, generally reaching Bering Strait by mid-June, although in recent years it has retreated north of the Strait by early June (NSIDC, 2010; Okkonen et al., 2018). Sea ice continues to retreat in the Arctic throughout summer and early fall, with minimal ice coverage in late September or early October. Wind direction and storms affect the extent of winter sea ice (Okonnen et al., 2018) and the timing of sea-ice spring or summer retreat affects water mass properties and subsequent productivity throughout the open water period, roughly June through October (Weingartner et al., 2005; Arrigo et al., 2008; Blanchard et al., 2017; Stabeno et al., 2018), which is the seasonal period of this study.

2.1.2. Lower trophic levels

During summer, the zooplankton and pelagic fish communities of the northern Bering and eastern Chukchi seas reflect the underlying hydrography, with strong gradients operating nearshore to offshore, and from south to north (Sigler et al., 2017). Zooplankton densities are generally highest just north of Bering Strait, although their distribution and abundance vary seasonally and interannually (Hopcroft et al., 2010; Eisner et al., 2013). Zooplankton communities tend to be associated with specific water masses, e.g. large copepods are found primarily in cold, high salinity Anadyr Water and small copepod species in warmer, low salinity Alaska Coastal Water (Eisner et al., 2013). Species composition of zooplankton communities also show a latitudinal gradient, ranging from Subarcticspecies in the northern Bering and southern Chukchi seas, to primarily Arctic species in the northern Chukchi Sea (Piatt and Springer, 2003; Hopcroft et al., 2010; Eisner et al., 2013). The majority of plankton and particle biomass primarily sinks to the benthos in the Chukchi, but there is flow from Barrow Canyon eastward along the Beaufort Shelfand shelf break, and minimal advection off shelf into the Arctic basin (Ashjian et al., 2005). The zooplankton community in the Beaufort Sea consists primarily of *C. glacialis*, an arctic species with circumpolar distribution (Daase and Falk-Petersen, 2013).

The principal prey of piscivorous seabirds are structured primarily along a latitudinal gradient and secondarily with water masses (Eisner et al., 2013, Norcross et al., 2013). Capelin (*Mallotus villosus*) are most abundant in the northern Bering and southern Chukchi seas. Juvenile saffron cod (*Eleginus gracilis*), juvenile Arctic cod (*Boreogadus saida*), and Pacific sand lance (*Ammodytes hexapterus*) are most abundant in the central and northern Chukchi Sea, and walleye pollock (*Theragra chalcogramma*) is common. Both diversity and biomass of fishes decrease with latitude, and high diversity and biomass are associated with Alaska Coastal Water (Piatt and Springer, 2003; Eisner et al., 2013). The Beaufort Sea has low fish abundance overall, although less is known about fishes in this region (Rand and Logerwell, 2011, Logerwell et al., 2015). By far the most abundant fish in the Beaufort is Arctic cod (Logerwell et al., 2015), a species known to be a key prey for Arctic seabirds (Hobson, 1993; Hop and Gjøsæter, 2013). Other common demersal fishes in the Beaufort include eelpouts (*Lycodes* spp), Bering flounder (*Hippoglossoides robustus*), and walleye Pollock; the latter may be increasing in numbers in the Beaufort Sea, albeit in much lower densities than in the Chukchi and Bering seas (Rand and Logerwell, 2011).

2.1.3. Seabirds

The study area supports approximately 60 species of seabirds, including: 1) species that nest along the study area's coastlines; 2) populations that breed elsewhere in Alaska and use the study area during other portions of their annual cycle, typically post-breeding; and 3) southern migratory species that forage in Alaskan waters only during the northern hemisphere summer. The term 'seabirds' typically refers to those species that feed primarily in the marine environment and that nest on coastal cliffs or islands, often in colonies (e.g. fulmars, shearwaters, gulls, murres, puffins). For this study, we also include other marine-associated species as 'seabirds', including loons, seaducks, and phalaropes (Table 1). These species-groups spend portions of their lives at sea during which they forage in the marine environment.

The coastal bluffs and islands of the Bering and Chukchi seas have some of the largest seabird breeding populations in the world (Stephensen and Irons, 2003), with large colonies in the northern Bering Sea and the southern Chukchi Sea (Fig. 1). Approximately 12 million seabirds nest at colonies on either side of Bering Strait (USFWS, 2014). On the Chukchi Sea coast, the largest colonies are near Cape Thompson and Cape Lisburne. Farther north, the coast has no habitat suitable for cliff-nesting birds, and only small scattered colonies or breeding pairs occur there and farther eastward along the Beaufort coast (Stephensen and Irons, 2003; USFWS, 2014). Seaducks and phalaropes nest in scattered coastal and inland locations throughout the study area (Johnson and Herter, 1989).

Offshore, seabird densities in the study area range from among the highest recorded in the North Pacific and Atlantic (i.e. Bering Strait) to among the lowest (i.e. the Beaufort) (Humphries and Huettmann, 2014; Wong et al., 2014; Kuletz et al., 2015). Localized 'hotspots' of high seabird density occur near large seabird colonies (e.g. Chirikov Basin; Piatt and Singer, 2003) but also in offshore waters far from colonies (e.g. Hanna Shoal; Gall et al., 2013; Kuletz et al., 2015). Areas with high offshore seabird abundance often include high proportions of migrants from the southern hemisphere, primarily short-tailed shearwater (*Ardenna tenuirostris*), which at times may equal or exceed the abundance of locally breeding birds (Gall et al., 2013; Kuletz et al., 2015).

2.2. Data collection

The seabird survey data came from two sources, the U.S. Fish and Wildlife Service (FWS; 2007-2015) and ABR, Inc. (ABR; 2008-2015). The FWS surveys were conducted in collaboration with a variety of vessel-based research projects that operated throughout the study area (Kuletz and Labunski, 2017). The ABR surveys focused primarily in oil and gas lease sale areas of the northeastern Chukchi Sea (DBO 4) but also included transits and surveys in other areas of the eastern Chukchi Sea. The FWS surveys were conducted during transits between stations or ports. The ABR surveys had dedicated sampling time and followed parallel lines spaced ~ 4 km apart within three primary study regions of the eastern Chukchi Sea, approximately 100-230 km offshore of Wainwright, Alaska (see Gall et al., 2013 for details). For all projects, survey vessels ranged in length from 35 m (115 ft) to 128 m (420 ft). Total survey effort (Fig. 1) was thus highest in the DBO 4 site and in proximity to Bering Strait, the latter being the route between the Bering and Chukchi seas.

All data were collected following similar protocols for visual observations and modified strip transects (Tasker et al., 1984; Kuletz et al., 2008) while underway during daylight hours. The observer, stationed inside the bridge, recorded all seabirds within 300 m and a 90° arc from the center line of travel. Transect width was occasionally reduced to 200 m or 100 m depending on visibility conditions, and surveys were discontinued if visibility was <100 m (i.e. due to fog), or if seas were Beaufort scale > 6. Birds on the water were recorded continuously and flying birds were recorded during quick 'scans' of the transect window at intervals of approximately 1 min^{-1} (depending on vessel speed) to avoid overestimating the density of flying birds (Tasker et al., 1984; Gould and Forsell, 1989). Birds actively foraging from the air, such as surface plunging or touching the water surface, were recorded as 'on water' (i.e. continuously). Birds were counted on first observation and thereafter ignored to avoid double counting birds following the vessel.

Data were entered directly into a laptop computer connected to the ship's Global Positioning System (GPS) or a Garmin 60CSx handheld GPS unit, using survey software DLog3 (A.G. Ford, Inc., Portland, OR; FWS, 2007-2015 and ABR, 2008) or TigerObserver (TigerSoft, Las Vegas, NV; ABR 2009-2014). Each entry was stamped with time and location (latitude and longitude), which were also recorded automatically at 20 sec intervals to track survey effort. Binoculars (10 x) were used to aid in species identification, and if necessary, a digital camera was used for later confirmation of identification. A geometrically marked wooden dowel was used to estimate distance from the line of travel to the bird, and verified when possible with a laser rangefinder. The observer recorded species, number of individuals, and behavior (on water, on ice, foraging, or in air). Birds were identified to the lowest taxonomic level possible. For details see Kuletz et al. (2008) and Gall et al. (2013).

2.2.1. Data selection

We extracted all survey data from 2007-2015 for the months of July through October. We subdivided transect lines (which varied in length) into continuous ~ 3-km segments (n = 34,521) and then calculated density (birds•km^{-2}) for each segment based on transect width (typically 300 m), using the latitude and longitude of the segment centroid as the location. We did not correct for detection because our primary goal was to describe distribution and relative abundance, and comparisons among DBO sites and regions should not be affected by biases from detection probabilities. Survey effort differed between regions, with 9404, 21,393, and 3724, 3-km segments available in the Bering, Chukchi, and Beaufort regions, respectively. For community cluster analysis we generated a 30-km hexagonal grid over the study area and averaged the density values for each species using all 3-km segments within each grid cell. We retained hexagon grid cells that had five or more 3-km segments, considered a minimum to obtain a representative sample within each cell while still providing sufficient spatial coverage of all DBO sites; the minimum 15 km of transects per cell is similar in scale to that used in Kuletz et al. (2015).

Our analyses included 11 bird families: Podicipedidae (grebes), Scolopacidae (phalaropes), Stercorariidae (jaegers), Alcidae (auks), Laridae (gulls, terns), Gaviidae (loons), Diomedeidae (albatross), Procellariidae (fulmars, shearwaters), Hydrobatidae (storm-petrels), Phalacrocoracidae (cormorants), and marine species of Anatidae (eiders, scoters, other seaducks). From these families, 11 species or species groups (Table 1) were selected for further analysis, because they together comprised about 95 % of all recorded birds (for some analyses, the two murre species were combined into a 'total murres' taxa). 'Total birds' refers to all species combined, including those not identified to the species level (but within the families above). Where possible, birds identified only to family or genus were incorporated into data analyses. This was accomplished using two separate methods; the first was used in analysis of species richness and the second was used in analyses and visualizations of species densities (see below).

2.2.2. Data analysis

For each DBO site or region, and for the entire study area, we endeavored to characterize three aspects of the seabird community; 1) species richness and diversity, 2) distribution and abundance, and 3) patterns of community composition. To address the issues of unequal sampling among regions, we compared species richness among locations using rarefaction, a method that facilitates comparisons among groups with different numbers of samples, and also used an index of diversity to examine evenness of species. We used a statistical modeling approach to evaluate spatial and temporal variation in seabird abundance. Finally, we used cluster analysis and data visualizations to examine spatial patterns of community composition.

2.2.3. Species richness and diversity

To examine seabird species richness for the each region we used rarefaction curves, which depicted the number of species observed as a function of the number of 3-km segments sampled, generated through random resampling of the data. This approach addresses the issue of variable sample size and of uneven distribution of birds, which affects estimates of species richness (Magurran and McGill, 2011). We assessed species richness using the combined data across years for each region (Bering, Chukchi, Beaufort), creating rarefaction curves by randomly sampling (with replacement) 3-km segments within each region. We calculated 95% confidence intervals using quantiles from 2000 random draws for each sample size along the rarefaction curve. We also determined observed species richness for each DBO site using combined years of data collected within each site.

Not all birds were identified to species level. To address this issue, we incorporated higher-order taxa into our analyses of species richness by counting them as a unique species if no corresponding lower-order taxa were present in the sample. In other words, if, and only if, no thick-billed murres or common murres were present in a sample (i.e. either a random draw of 3-km segments, or all segments within a DBO site), then an unidentified murre was counted as a species.

Finally, we compared seabird diversity among regions and DBO sites using the Shannon Index (Shannon, 1948; MacArthur and MacArthur, 1961), which incorporates the number of species and the evenness of abundance values.

2.2.4. Abundance and distribution

To examine the potential for latitudinal or longitudinal influence on overall distribution across the entire study area, we first used Generalized Additive Models (GAM) to examine spatial variation in abundance of seabirds. The GAM used the centroid of each 3-km segment as location, a smooth term (thin plate regression spline), a maximum basis dimension of 100, and a likelihood defined by the Tweedie distribution with a log link and estimated scale parameter (Wood, 2017). We examined various choices of maximum basis dimension to ensure that our choice did not influence the final smooth, based on an approximation to cross validation (Wood, 2017). Model fit diagnostics were examined and found reasonable for all but a few extreme high-density observations. The above model was also compared to alternatives using Poisson, quasi-Poisson, and negative binomial likelihoods. These alternatives had worse model fit diagnostics than that using the Tweedie likelihood. We compared various basis specifications for the smooth term (Gaussian process models, a smooth on the sphere, and an adaptive smooth where the amount of smoothing depends on geographic locations; all documented in the R package mgcv; Wood, 2017). All models gave similar general patterns, except an adaptive smooth model where the uncertainty was extreme in areas with sparse data (high latitudes >70˚N). The model estimates predict seabird density as a function of latitude at 168˚W longitude (directly through the Bering Strait) and as a function of longitude at 71˚N latitude (to bisect both the Chukchi and Beaufort regions).

Second, we examined spatial variation of seabird density in each region or DBO site using the same GAM model but with location (DBO site or region) defined as a random effect (bs=”re” option of the mgcv smooth specification), instead of a smooth based directly on latitude and longitude. The modeled estimated densities were constructed for total birds and the 1o species or species groups (Table 1). We plotted the estimates in rank order of the DBO site number, which are aligned south (DBO 1) to north (DBO 4) and west (DBO 4) to east (DBO 8).

Finally, to examine the relative influence of spatial (DBO site or region) and temporal (year) variation in seabird density we fit the model with the location and year factors as random effects. We report the estimates of the standard error (with 95% confidence intervals) for year and DBO site or region. We performed each analysis above using total seabirds and for each of the same 10 taxa used for the GAM model.

2.2.5. Community composition and distribution

We took two complementary approaches to the community analysis. First, we illustrated community composition within DBO sites using waffle charts (square pie charts), which depict both species composition and density values using rectangular grids (Rudis and Gandy, 2017). This allowed comparisons among DBO sites. Second, to understand how the DBO sites fit into the broader regional context, we evaluated the major patterns of seabird community composition for the entire study area. We used K-means cluster analysis (Hartigan and Wong, 1979) to describe patterns of community composition across the study area (all three regions) by grouping 30-km hexagonal grid cells based on similarity in densities and species of birds. We included all 30-km grid cells with centroids ≥ 60˚N and ≤ 74˚N, and log-transformed densities prior to performing the cluster analysis. Clustering was based on species densities only, not geographic coordinates of the grid cells. The optimal clustering was determined by comparing the inflection point of within-group sums of squares to the number of clusters (Hartigan and Wong, 1979). We then used waffle charts to compare species composition of each identified cluster type. We also evaluated spatial patterns of community composition by mapping the identified clusters of cells back onto the 30-km hexagonal grid.

Prior to these analyses, we apportioned all higher-order taxa to species using a two-step approach. First, we prorated higher-order taxa to species based on the corresponding species ratios within each grid cell. For example, if higher-order taxon A could be species B or C, we allocated the density of A among B and C based on their proportional density in that grid cell. In some cases, a higher-order taxon was present, but there were no corresponding species in a given grid cell. Therefore, in a second step, we prorated the remaining values to species based on spatial interpolation of species ratios; for this, we used kriging, with a distance cutoff of 60 km (~ 2 grid cells).

All analyses were done using R functions and scripts (R Core Team, 2015). Kriging of species ratios used function *krige* in package gstat (Pebesma, 2004). The General Additive Model used function *gam* in the package mgcv (Wood, 2017). Cluster analysis was performed using the R function *kmeans* (Hartigan and Wong, 1979). Waffle charts made use of the R package waffle (Rudis and Gandy, 2017).

3. RESULTS

3.1.1 Species richness and diversity

The estimated species richness was highest for the Bering region (asymptote at ~ 50 species), followed by the Chukchi region (~ 40 species), and lowest for the Beaufort region (~ 35 species) (Fig. 3). In most cases, the rarefaction curve indicated that the observed richness within the DBO sites was within the expected bounds of regional species richness, given the sampling effort. The exception was DBO 4, which had extremely high sampling (>5500 segments) and an observed 34 species, whereas ~ 40 species was predicted for the region at that sampling level. For most DBO sites, however, actual sampling effort was not sufficient to reach the asymptote, particularly for the three DBO sites in the Beaufort region (Fig. 3). Among DBO sites, DBO 3 had the highest observed species richness (35 species). The lowest species richness was recorded in DBO 8, where glaucous gull was the only species recorded on transect.

The Shannon Index (H´) was 2.47 for the entire study area. Diversity was highest in the Bering region followed closely by the Chukchi region, and was lowest for the Beaufort region (Table 2). Among DBO sites, there was little difference in H´, with most DBO sites ranging from 1.46 to 2.15. Despite high seabird abundance, two of the Chukchi DBO sites (4 and 5) had lower diversity indices than Beaufort DBO sites 6 and 7, indicative of the numerical dominance of a few species in the Chukchi. DBO 8 had an extremely low H´ (near zero) because only one species was recorded on transect there.

3.2. Abundance and distribution

Seabirds occurred in nearly all surveyed areas, with the exception of a few cells in Norton Sound, areas of the Beaufort shelf, and most of the Arctic basin (Fig. 4). Seabird abundance was highest along the outer shelf of the Bering Sea, the Chirikov Basin through Bering Strait and parts of Hope Basin, and near Pt. Barrow (Fig. 4).

For total seabirds, modeled abundance by latitude (with longitude held constant), which highlights DBO sites 1 – 4, dipped between the shelf edge (~60°N) to ~61°N, then increased northward and peaked at ~65°N (near Bering Strait) and then declined gradually continuing north to ~70.5°N (Hanna Shoal area) (Fig. 5, top). Abundance then declined sharply near the Arctic shelf break at ~72°N, with greater uncertainty in the estimated values, reflecting low sampling effort in the far north (Fig. 1) as well as low encounter rates of birds. From the Chukchi to the Beaufort and moving west to east, which highlights DBO sites 4 – 8, peaks in abundance are evident at ~172°W (west of Hanna Shoal) and ~162°W near Pt. Barrow. Abundance declines farther eastward to ~140°W, with a slight increase west of DBO 8, but with higher uncertainty in estimates (Fig. 5, bottom). Overall, expected densities were above 1 bird•3-km segment (log zero) with respect to latitude except at the far northern latitudes, where error in estimates were high. In contrast, expected densities fall below 1 bird•3-km segment over a wide range of longitudes, starting near DBO 7. The highest expected densities were near Pt. Barrow, at ~55 birds•3-km segment (Fig. 5, bottom) and near Bering Strait, at ~32 birds•3-km segment (Fig. 5, top). There were, however, a variety of species-specific distribution patterns in modeled abundance with respect to latitude and longitude (Appendix A).

The modeled abundances of total seabirds for the DBO sites were in most cases similar to those of their respective regions (estimates for regions did not include 3-km segments inside DBO polygons) (Fig. 6). However, abundance in DBO 2 was higher than the greater Bering region, while DBO sites 7 and 8 were much lower than the Beaufort region. Among sites, abundance estimates generally declined moving north (to DBO 4) and eastward (from DBO 5 to 8). Abundance declined sharply in the Beaufort, with estimates below 1 bird•3-km segment (below log zero) for DBO sites 7 and 8 (Fig. 6).

The patterns in abundance were more complicated for individual taxa (Fig. 7). For species that were more evenly dispersed (black-legged kittiwakes, glaucous gull) or of low abundance (murrelets), estimates were similar between DBO sites and regions. Taxa that tended to be more aggregated (phalaropes, shearwaters) or with large local colonies (crested and least auklets, murres, puffins) had DBO site estimates either higher or lower than the respective region. Overall, for all 30 taxa-site comparisons, there were 16 equivalent estimates between DBO sites and the respective region, 8 with lower DBO site estimates and 6 with higher DBO site estimates. Four of 10 taxa (northern fulmars, black-legged kittiwakes, murres, and puffins), showed a roughly linear decline in abundance from south to north and west to east; these species are all primarily piscivorous. Shearwaters (which are omnivorous) declined abruptly at DBO sites 7 and 8. Phalaropes, least auklet, and crested auklet (all planktivores) peaked between DBO sites 2–4, encompassing Bering Strait, Hope Basin, and Hanna Shoal. Glaucous gull and murrelets (primarily piscivores, but also consume invertebrates and krill) varied little among DBO sites (Fig. 7), except that murrelets were absent in DBO 8.

Total seabird density had higher spatial variance (i.e. among regions or sites) than it did among years (Fig. 8), indicating that seabird abundance was more consistent among years than among locations. Most of the taxa examined also showed higher variance among sites than years. Among regions, however, shearwaters, phalaropes, and glaucous gulls had temporal variance that was similar to or higher than spatial variance (Fig. 8), indicating that their abundance varies more by year than by location. Among DBO sites, only murrelets had higher temporal variance, although both values were very low for this taxa.

3.3. Species composition and seabird communities

The seabird community within the study area clustered into six community types. Of the six community types identified, five had a species composition predominated by one species that composed > 25% of total seabird density (Fig. 9). Although other species were part of each community type, we hereafter refer to the community types by their predominate species (Appendix B). The 'least auklet community' had the highest total density (34.9 birds•km^2), and included short-tailed shearwaters, crested auklet, black-legged kittiwake, both murre species, northern fulmar, phalaropes, and 34 other species. Three community types (northern fulmar, short-tailed shearwater, thick-billed murre) had similar total densities, ranging from 11.7 to 17.3 birds•km^{-2} (Fig. 9, Appendix B). The 'crested auklet community' had the lowest total density of the species-identified community types (Fig. 9), with a total of 9.7 birds•km^{-2} (Appendix B). The 'low density community' included 52 species, with a total density of 1.6 birds•km^{-2}, and no numerically dominant species.

Mapping the community types revealed the distribution of the six primary seabird communities throughout the study area (Fig. 10), with all six community types occurring in Hope Basin (with DBO 3). Three communities showed clear geospatial aggregations. The northern fulmar community was found mostly in the outer Bering Sea shelf, south of DBO 1; the least auklet community occurred in the Chirikov Basin (with DBO 2) and Bering Strait (between DBO 2 and 3); and the crested auklet community occurred in the Hanna Shoal area, including most of DBO 4. Three communities were more spatially dispersed; these included communities dominated by thick-billed murre, short-tailed shearwater, and the low-density community.

The thick-billed murre community type occurred across a large area in the Bering region's central shelf (with a small number of cells in DBO 1) and in a smaller patch near the Siberian coast (outside of DBO 2). It also occurred in the Chukchi region near Cape Thompson to Cape Lisburne, with portions in DBO 3 (Fig. 10). The short-tailed shearwater community type was the most dispersed of the communities that were dominated by one species; it stretched in a band across the Bering Shelf south of St. Lawrence Island (DBO 1), and northward along the eastern Bering region (partially captured by DBO 2), through Bering Strait and northward along the Chukchi coast (partially in DBO 3), with high densities from Wainwright to the mouth of Barrow Canyon (DBO 5), and into the western Beaufort Sea (partially in DBO 6; Fig. 10). The low density community was widely dispersed, particularly in the Beaufort (DBO sites 6, 7, 8) as well as the northernmost waters of the Chukchi and most inshore waters of all regions (Fig. 10).

Within DBO sites, species composition was typically numerically dominated by one or two species, with shearwaters the most abundant in five of eight DBO sites (Fig. 11), in which they represented 43 – 76 % of total birds in a given DBO site (Appendix C). DBO 1 included high proportions of shearwaters, thick-billed murre, and northern fulmar. DBO 2 had the highest mean total density (32.5 birds•km^{-2}), with least auklet composing 40% of the total (Fig. 11, Appendix C). DBO 3 had high proportions of shearwaters, least auklet, and phalaropes. In DBO 4, crested auklet was numerically dominant, composing 58% of total density. DBO 5 had the highest proportion of shearwaters, which composed 78% of total density. The Beaufort DBO sites had much lower densities than other sites, ranging from 2.5 birds•km^{-2} (DBO 6) to 0.1 birds•km^{-2} (DBO 8), with shearwaters still predominate in DBO 6, composing 63% of total birds. Seaducks (mainly long-tailed ducks and king eiders) composed 54% of total density in DBO 7, but at low density (0.3 birds•km^{-2}, combined). (See Appendix D for species-specific distribution maps).

4. DISCUSSION

The Distributed Biological Observatory seeks to leverage multiple research campaigns to build and maintain long-term data sets in the Pacific Arctic, with the goal to address ecological and management issues in the dynamic regions of the northern Bering, eastern Chukchi, and Beaufort seas. By combining 10 years of at-sea surveys derived from a variety of vessel-based programs, our study is the first to use the DBO array to describe the seabird communities of these contiguous marine ecoregions. We also put the DBO sites in context of the broad-scale patterns of seabird distribution, and found that the DBO sites have captured most, but not all, of the areas of high seabird abundance for the study area.

4.1. Species richness and diversity

We found differences in species richness among the three marine regions, with distinctly low values in the Beaufort region. Although predicted values indicated higher species richness overall in the Bering than the Chukchi, the highest observed values were in Chukchi DBO sites, perhaps partly due to higher sampling effort there (Fig. 1). For most DBO sites, observed species richness was consistent with values predicted by the regional rarefaction curves, given their respective sampling efforts. Two exceptions were DBO sites 1 and 4, which had lower than predicted species richness; both of these sites are farther offshore than the others. In DBO 1, seabird abundance was high but species richness was low due to the predominance of shearwaters (Fig. 11). DBO 4 is far from land or suitable breeding habitat, thus breeding birds would be less likely to frequent the area, as indicated by the low numbers of coastal species observed there (Appendix C). Species diversity among DBO sites was similar, but generally lower than that of their respective regions; this is likely a consequence of the smaller spatial scale and in some cases (e.g. DBO sites 1, 7, 8), lower survey effort within DBO sites, both of which can reduce measures of diversity (Willig and Presley, 2017).

In the Bering, DBO 2 had relatively high species richness (Fig. 3), consistent with Santora et al. (2018), which found an increase in seabird species richness with latitude that culminated in the Chrikov Basin, based on a biogeographic analysis of the entire Bering Sea. As a transitional zone between the southern Bering and Chukchi seas (Sigler et al., 2011, Stabeno et al., this issue), the northern Bering might be expected to have higher seabird species richness and diversity overall (Table 2), as was predicted had there been greater sampling effort (Fig. 3). Seabird species that breed in the northern Bering Sea are joined by post-breeding and non-breeding seabirds from the south. In comparison, smaller populations of fewer species breed in the Chukchi Sea, and even fewer in the Beaufort Sea (USFWS, 2014).

4.2. Seabird abundance and species composition in DBO sites

We found clear evidence of latitudinal and longitudinal gradients on total seabird abundance which the DBO array, in most cases, appears to represent fairly well. For total seabirds, locations of high seabird abundance stand out, particularly the south side of Bering Strait and near Pt Barrow at the mouth of Barrow Canyon. The abundance of birds in the outer Bering shelf, Chirikov Basin, and near Pt. Barrow is likely a function of high nutrient flow and high zooplankton abundance, concentrated by strong physical forcing in these areas (Piatt and Springer, 2003; Grebmeier et al, 2006; Ashjian et al., 2010; Danielson et al., 2017). The high proportion of shearwaters and northern fulmar in DBO 1 partly reflects the proximity to the shelf break, sites of upwelling and fronts (Springer et al., 1996), where these birds tend to feed (Schneider et al., 1987, 1990). Species abundant in and around DBO 1, including northern fulmars and thick-billed murre, nest at large colonies on St. Matthew Island, located between DBO sites 1 and 2 (Fig. 1).

The abundance of seabirds within ~ 100 km either side of Bering Strait (Fig. 4), which is captured by DBO sites 2 and 3, partly reflects the effect of birds moving through a narrow bottleneck connecting two high-nutrient areas. In addition, the area is in proximity to large seabird breeding colonies on islands in the northern Bering region, and on the mainland in the Chukchi region (Fig. 1). Within foraging range of these colonies, strong currents through the ~82 km wide strait advect nutrients and lower trophic organisms (Sigler et al., 2011) and create predictable prey aggregations (Hunt, 1997; Grebmeier et al., 2006; Eisner et al., 2013). Piscivorous murres, puffins, kittiwakes, and other species also nest on these islands (Stephensen and Irons, 2003; USFWS, 2004), but the high seabird abundance in DBO 2 was driven primarily by least auklets (Fig. 11), which often feed near the Anadyr Current (Hunt, 1997; Sheffield-Guy et al., 2009). The nutrient rich waters of the Anadyr Current, and associated eddies, bring copepods and euphausiids within foraging range of > 5 million nesting planktivorous auklets (Elphick and Hunt, 1993; Piatt and Springer, 2003), as well as high numbers of shearwaters pursuing euphausiids (Nishizawa et al., 2017).

The northern gateway to Bering Strait, DBO 3, with the second highest seabird abundance, encompasses the slopes of Hope Basin and diverging currents flowing northward, and is within foraging range of birds nesting on the Diomede islands (as evidenced by high proportions of least and crested auklets). In the Chukchi, > 600,000 piscivorous seabirds, primarily murres and black-legged kittiwakes, nest at Cape Thompson and Cape Lisburne (Dragoo et al., 2017). However, these locally nesting species composed low proportions of the birds observed offshore, with both murre species combined contributing ~ 12 % and kittiwakes < 4 % of total birds. Rather, the abundant species in DBO 3 were migratory shearwaters and phalaropes, as well as northern fulmars and least and crested auklets, none of which nest in the Chukchi region. Notably, our analysis pooled all summer and fall months (July – October), whereas recent surveys conducted in June 2017 and 2018 found that locally nesting murres, kittiwakes, and puffins predominated in offshore waters of DBO 3 in early summer (KJK, unpubl. data).

Far from large seabird colonies, DBO 4 had lower total densities of seabirds than DBO sites farther south, but high densities of crested auklets. DBO 4 includes Hanna Shoal, a shallow (~ 40 m) plateau of high productivity surrounded by nutrient rich Bering Sea Waters (Schonberg et al., 2014; Weingartner et al., 2017) with high copepod and euphausiid biomass (Grebmeier et al., 2006; Ashjian et al., 2017). Late season plankton blooms and stratification of the water column make copepods available and aggregated into late summer (Weingartner et al., 2013; Danielson et al. 2017), which appears to attract non-breeding or post-breeding crested auklets > 600 km northward from the nearest auklet colonies. In addition, crested auklets fitted with geolocators at nest sites in the Aleutian Islands also traveled to the Chukchi Sea after breeding (Will et al., 2017). Perhaps because those birds complete chick rearing several weeks earlier than auklets in the northern Bering Sea, auklets are relatively abundant in the area throughout summer and fall (Gall et al., 2013; Kuletz et al., 2015), a phenomena clearly represented by DBO 4.

The DBO 5 site encompasses the mouth of Barrow Canyon, where easterly-flowing Beaufort Water and Arctic Basin Water is upwelled onto the Chukchi shelf (Pickart et al., 2013), periodically resulting in a zone of high nutrients and zooplankton biomass that attract piscivorous belugas (Stafford et al., 2013). Under certain conditions (i.e. a relaxation of the Alaska Coastal Water and increased influence of the Beaufort Gyre), large zooplankton are 'trapped' near the canyon mouth, drawing foraging aggregations of feeding whales (Ashjian et al., 2010; Okkonen et al., 2011), along with shearwaters and other seabirds (Kuletz et al., 2015). This highly dynamic set of conditions may at times extend into the westernmost Beaufort site, DBO 6, where shearwaters remained the predominate species.

Overall, the lack of seabirds we found in the Beaufort region is similar to other accounts of low seabird abundance in offshore waters of the Beaufort Sea (Sigler et al., 2011; Wong et al., 2014), and is consistent with observations of low prey availability and smaller prey species there (Sigler et al., 2011). The extremely low values we found for species richness, diversity, and abundance in the Beaufort region, particularly in DBO sites 7 and 8, must be considered in the context of low survey effort in that region, but are also likely an accurate reflection of the region's coastal and marine habitats. The Beaufort coastline has no suitable nesting habitat for most seabird species. However, the coastal waters which we rarely surveyed support a variety of birds, including terns, gulls, loons, seaducks, waterfowl, and shorebirds (Johnson and Herter, 1989; Fischer and Larned, 2004). Farther offshore, where most of our surveys occurred, the shelf and slope is dominated by nutrient poor waters of the Beaufort Gyre, subsurface Atlantic waters, and Alaska Coastal Water (Pickart et al., 2013). Consequently, the Beaufort has low abundance and diversity of benthic, invertebrate, and fish taxa, compared to the Chukchi and Bering seas (Rand and Logerwell, 2011; Sigler et al., 2011; Iken et al., 2018). Among the individual taxa, the gradual decline in piscivorous species from south to north and west to east (Fig. 7), may reflect gradients in fish abundance as well as absence of nesting habitat. In contrast, planktivorous birds peaked in abundance between DBO sites 2 – 4, indicative of highly aggregated zooplankton in those regions. Thus, while the individual DBO sites may have been established to track changes in benthic hotspots, together they also appear to capture the broad-scale gradients in seabird communities of the regions.

4.3. Spatial and interannual variance

For total seabirds and most examined taxa, interannual consistency in abundance was a contrast to the high regional or DBO site variance (Fig. 8), which indicates both the potential usefulness of the DBO array for monitoring seabirds (because in general, species tended to go to the same large-scale locations), and that the entire array is necessary to capture the variety of seabird communities. There was slightly higher variance among years than among regions for shearwaters, phalaropes, and glaucous gulls, which can be linked to their life history. Shearwaters and phalaropes are not tied to breeding sites during this time of year, and can more readily respond to changes in location of prey. For example, the short-tailed shearwater appears to track euphausiids from the Bering Sea into the Chukchi Sea in late summer and fall, resulting in strong seasonal shifts in distribution (Suryan et al., 2016; Nishizawa et al., 2018). Phalaropes (mainly red phalaropes) nest in scattered locations inland and gather at sea following breeding, to replenish fat reserves prior to migrating south (Taylor et al., 2011). Although individual glaucous gulls may breed locally in scattered locations, this circumpolar species is wide-ranging, omnivorous, and forages in a variety of habitats (Petersen et al., 2015).

Variance in seabird abundance was even higher at the smaller scale of DBO sites. Among DBO sites, only murrelets (primarily ancient murrelet, and lower numbers of Kittlitz’s murrelet) showed slightly greater variance among years than among sites. Ancient murrelets breed from British Columbia to the Aleutian Islands and have only recently been common in the Pacific Arctic (Day et al., 2013). Kittlitz’s murrelets nest on coastal mountains from the northern Gulf of Alaska to the Aleutian Islands, with small populations in northwestern Alaska (Day et al., 1999). Both of these species have been shown via birds fitted with satellite tags to migrate to the Chukchi Sea after breeding.

While interannual variability in seabird abundance and species composition in this study area has been shown previously (e.g. in DBO 4; see Gall et al., 2013), our study indicates that within the northern Bering to Beaufort seas, meso-scale patterns of seabird distribution are generally consistent. Habitat features (including location of breeding colonies) attracted a distinct community of seabirds that differed among DBO sites, and was fairly consistent over our time frame of eight years. However, at a greater temporal scale of decades, seabird communities may exhibit long-term ecosystem changes. Recent examples include the shift in offshore waters of the northeast Chukchi Sea from primarily piscivorous seabirds to planktivorous seabirds (Gall et al., 2017), and evidence of southern Bering Sea species shifting their distribution northwards, including murrelets (Day et al., 2013), northern fulmar (Renner et al., 2013) and albatrosses (Kuletz et al., 2014).

4.4. Community Composition

The six seabird community types that we identified within our study area were sometimes associated with specific bathymetric or oceanographic characteristics, including currents, shoals, and underwater canyons. The fulmar-dominated community type, which included other pelagic seabird species that prefer shelf-edge sites, occupied the northern extent of the ‘green belt’ that stretches along the length of the Bering Sea outer shelf (Springer et al., 1996), but which was not captured by the nearest DBO site (DBO 1). Northern fulmars nest on St. Matthew Island, south of DBO 1, and although they are far-ranging, colony location is the key factor influencing their offshore distribution in Alaska (Renner et al., 2013). The thick-billed murre community type included a high proportion of other species, with distinct but disjunct patches across the study area south of 70˚N. Murres typically forage within 100 km of their colonies (Coulson, 2002), which is likely why this community type was closely associated with colony sites. Most of this community type was outside the DBO array, although it had some representation in DBO sites 1 and 3. In contrast, the least auklet-dominated community type was well represented by DBO 2 and to lesser extent, by DBO 3; it extended from the Chirikov Basin through Bering Strait, and reflected proximity to auklet breeding sites and known forage areas (Hunt 1997, Gall et al., 2006; Sheffield-Guy et al., 2009).

The extent of the shearwater-dominated community type throughout the study area explains how shearwaters dominated DBO sites 2 - 6. Shearwaters are omnivorous and feed both on and under the water surface (Weimerskirch and Sagar, 1996; Burger, 2001), and they track changes in prey over large regions (Nishizawa et al., 2017). Although shearwaters were temporally variable among regions (Fig 8), this community occurred throughout the study area and thus was well represented by the DBO array. In contrast, the restricted extent of the spatially well-defined crested auklet community type was only represented in DBO 4, and was uniquely disconnected from breeding sites. Anecdotal observations during at sea surveys (AEG, KJK) suggest that at least some of these auklets were undergoing post-breeding molt in this area, thus access to dependable, high densities of zooplankton would be essential.

The low density community type extended throughout the eastern side of most of the study area, and throughout most of the Beaufort region and Arctic shelf and basin (Fig. 10). The occurrence of this community type in more inshore waters and northern portions of the Chukchi and Beaufort regions was coincident with low survey coverage, yet even when accounting for that effect (i.e. GAM models of abundance), the relative paucity of seabirds in these areas is striking. Furthermore, our results were consistent over multiple surveys and years in this study, and this pattern has been noted in other studies (Wong et al., 2014) and in earlier overviews (Piatt and Springer, 2003). The Beaufort DBO sites were primarily composed of the low density community type, and the near absence of this community in other DBO sites indicates that Bering and Chukchi DBO sites are located in areas of high seabird abundance, relative to the entire study area.

5. Conclusion

Overall, we conclude that the DBO sites can be used to characterize the seabird community of the Pacific Arctic, although only when examined in their entirety, because each site captured a different community type. The unique composition of seabirds among DBO sites reflect the diversity of marine habitats throughout the DBO array. Although short-tailed shearwaters were numerically dominant throughout much of the study area, the DBO array also captured areas of high abundance for a variety of species. In particular, DBO sites 2 and 3, and surveys between, highlight the importance of the northern Bering Sea seabird colonies, which stand in the path of increased vessel activity and potential pollution issues as traffic through Bering Strait increases (Humphries and Huettmann, 2014).

The DBO array does, however, have limitations. For example, the northern fulmar-dominated community type was found primarily south of DBO 1, illustrating that the current DBO array does not capture the 'green belt' of seabird activity on the outer Bering shelf. Notably, unlike the planktivorous auklets, most piscivorous colonial species (murres, puffins, kittiwakes) are not as well covered by the DBO array. A sampling site west of St. Matthew Island that straddles both the northern fulmar and thick-billed murre communities could help to address this gap.

Our results suggest that most DBO sites are high-use areas for seabirds, albeit of different community types, and therefore should be useful for integration with other disciplines. For example, in DBO 2, there should be strong links between planktivorous auklets and zooplankton. Near DBO 3, based on prey collected from kittiwakes and murres at the Cape Lisburne colony (1975-2015), a wide variety of fishes and in some years high proportions of invertebrates are consumed, including Gadidae (primarily Arctic cod), Osmeridae, Ammodytidae, Pleuronectiformes, Cottidae, and others (Drummond, 2016); these species were also found in regional fish surveys (Rand and Logerwell, 2011; Logerwell et al., 2015), providing a trophic link within the region.

Because seabirds are highly mobile, particularly non-breeding birds, sampling over large areas is necessary, but in some locations the level of effort required may not be achievable. For example, because of extremely low seabird abundance, an order of magnitude increase in sampling effort would be necessary to adequately describe the seabird communities of DBO sites 7 and 8. Effort might be better spent improving coverage within foraging range of large colonies of piscivorous seabirds. With the predicted dramatic changes in sea ice, which will alter ocean properties and thereby seabird prey in the

Pacific Arctic (Gerbmeier et al., 2010, 2018; Stabeno et al., 2018), it may be necessary to concentrate efforts where impacts to seabirds could be greatest.

To fully realize the potential for understanding seabirds and their trends in these three regions, several gaps need to be addressed: 1) coverage would need to be spatially expanded to capture the northern Bering outer shelf, and increased if the goal is to capture the Beaufort coastal areas; 2) broader seasonal coverage would be needed to capture shifts in seabird communities during early summer in the Chukchi Sea, particularly now that ice retreats earlier in the year and returns later (Frey et al., 2015; Stabeno et al., 2018), and; 3) a more equal distribution of effort among DBO sites would strengthen the spatial comparisons in seabird abundance and species composition. Combining efforts across organizations and science programs has provided spatial and temporal data on seabirds not otherwise possible for this large and remote ecosystem. The data acquired are possibly unique, particularly for this area, and critical at a time when the Arctic is changing so rapidly. We conclude that the DBO array will be a good tool for monitoring offshore habitat use of seabirds in the Pacific Arctic.

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Figure Captions

Fig. 1. The study area, showing survey effort (km surveyed) in 30-km hexagonal cells. Stars mark locations of major seabird colonies, with numbered DBO site polygons outlined in black.

Fig. 2. Major currents and oceanographic features of the northern Bering, Chukchi, and Beaufort seas. Map is by EAL, based on Dunton et al., 2017.

Fig. 3. Rarefaction curves of predicted species richness based on a random selection of transects from seabird surveys in the Bering (red), Chukchi (green), and Beaufort (blue) regions. Solid lines indicate the mean, with shading representing 95% confidence intervals. Numbers in circles are the observed species richness and sample size within the DBO site.

Fig. 4. Total seabird densities for the study area, showing the DBO polygons outlined in black. Densities (birds•km^{-2}) are means of 3-km segments within each 30-km hexagonal cell. White cells indicate sampling effort but no birds observed. Dark dashed lines indicate boundaries of shelf slopes in the Bering, Chukchi, and Beaufort regions.

Fig. 5. Modeled total seabird density (log expected count per 3-km segment ± 2 SE) by latitude, holding longitude constant at 168˚W (top), and by longitude, holding latitude constant at 71˚N (bottom). Arrows highlight locations of major features along the latitudinal gradient (top; approximate locations of Bering Strait and DBO sites 1 – 4, south to north) and longitudinal

gradient (bottom; showing approximate locations of Point Barrow and DBO sties 4 – 8, west to east).

Fig. 6. Modeled density (log expected count per 3-km segment ± 2 SE) for total seabirds, for DBO sites (circles) and surrounding region (squares). The X-axis is arranged by DOB site number and regions aligned with their respective sites. Regions are Bering (red), Chukchi (green) and Beaufort (blue).

Fig. 7. Modeled density (log expected count per 3-km segment ± 2 SE) for selected species and species groups, for DBO sites (circles) and surrounding region (squares). DBO sites are in numerical order along the X-axis, and regions aligned with their respective sites. Regions are Bering (red), Chukchi (green) and Beaufort (blue).

Fig. 8. Standard deviation of log expected density (estimate ± 95% CI) for location and year for total seabirds and for 11 taxa, among three regions (top) and among eight DBO sites (bottom).

Fig. 9. Species composition and relative abundance of the six communities identified with cluster analysis, using data from 2007 - 2015. Each cell in the waffle graph represents 0.1 birds•km^{-2}. See Appendix B for mean densities of all species within each community type.

Fig. 10. Mapped results of K-means Cluster Analysis using a 30-km hexagonal grid. The colors represent six community types, referred to by their most abundant species, or for Cluster F, by low density and lack of a dominant species.

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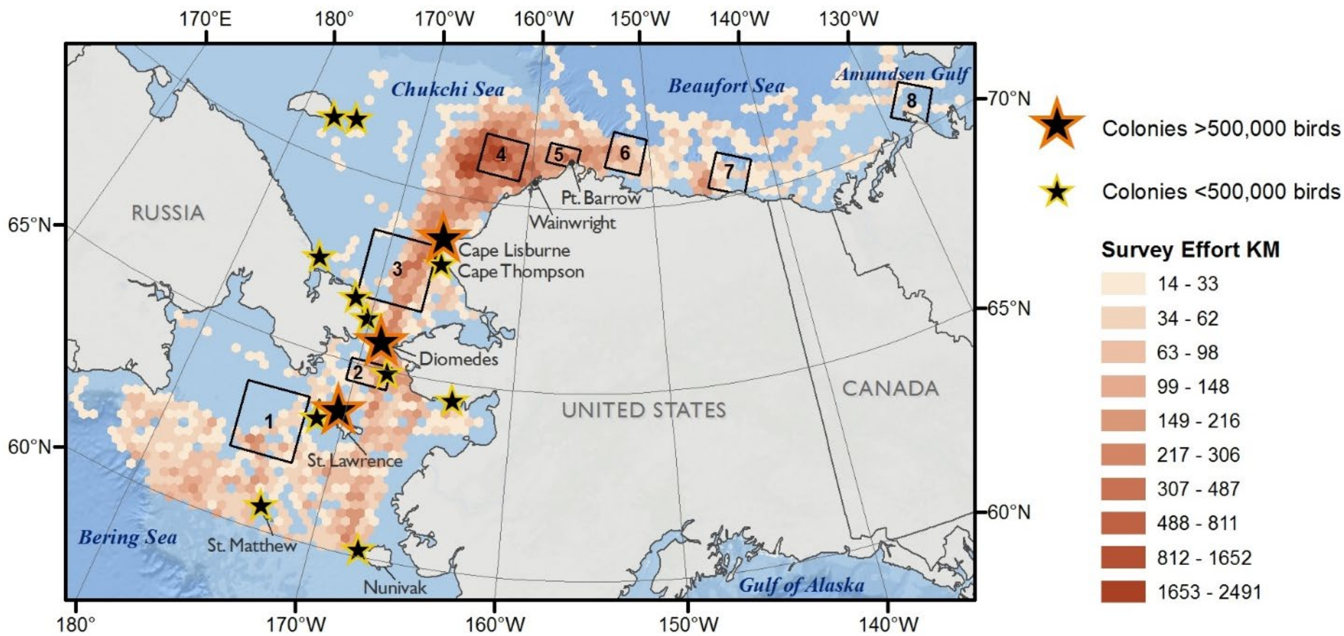

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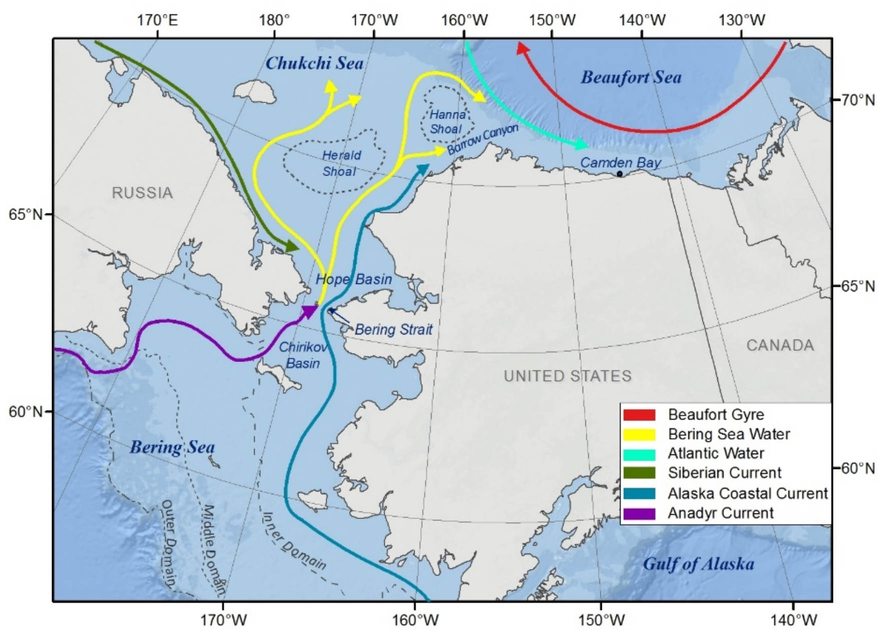

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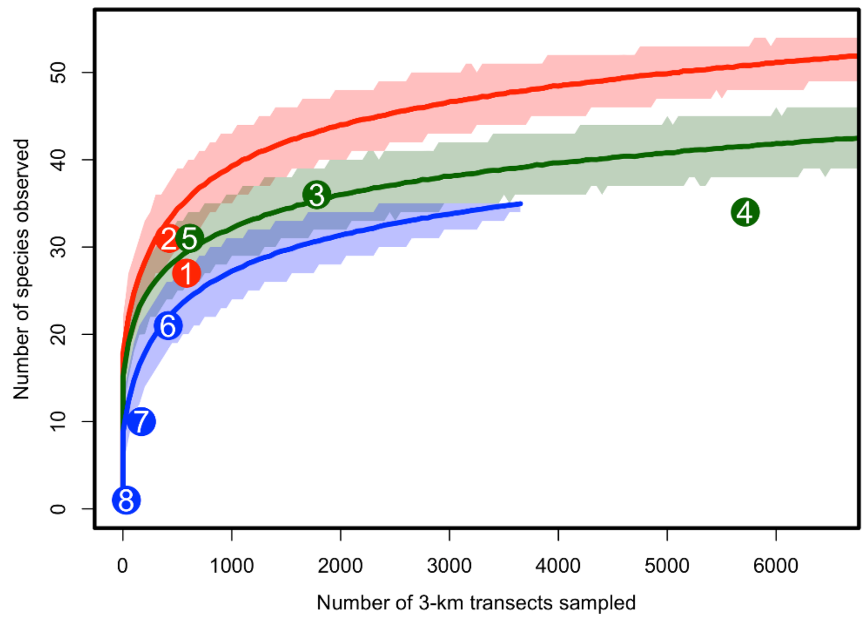

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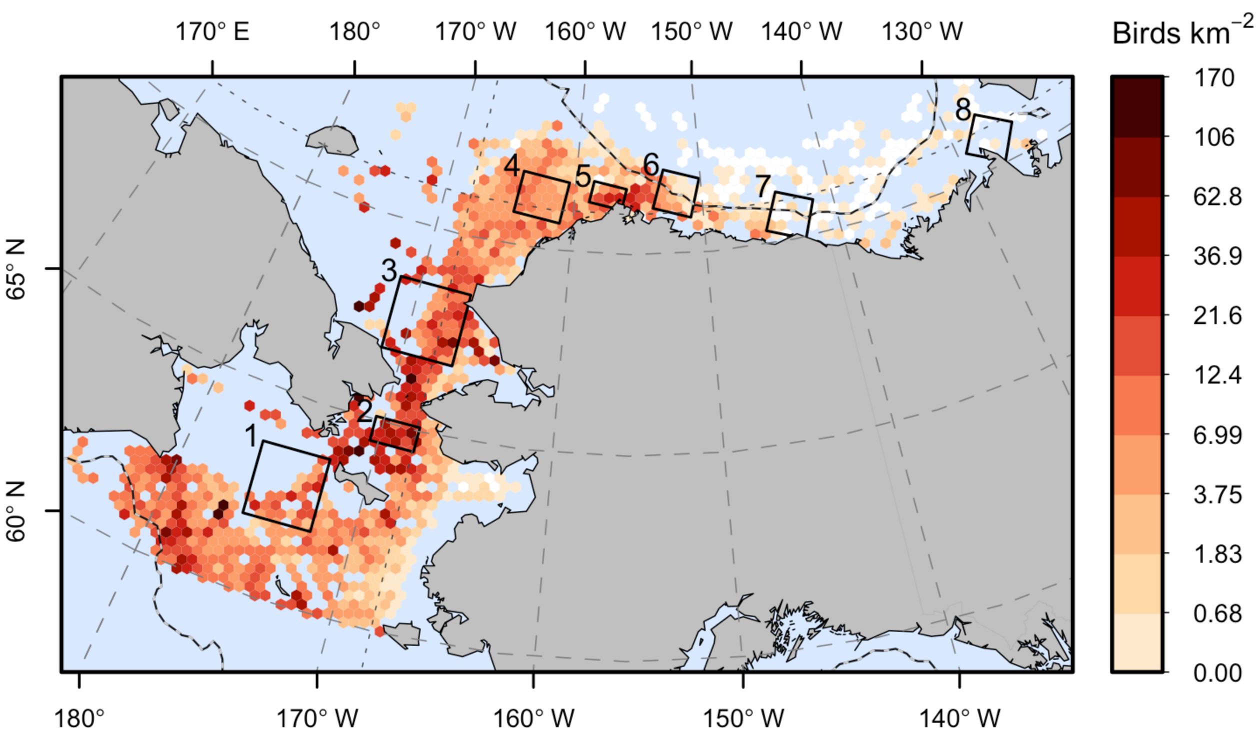

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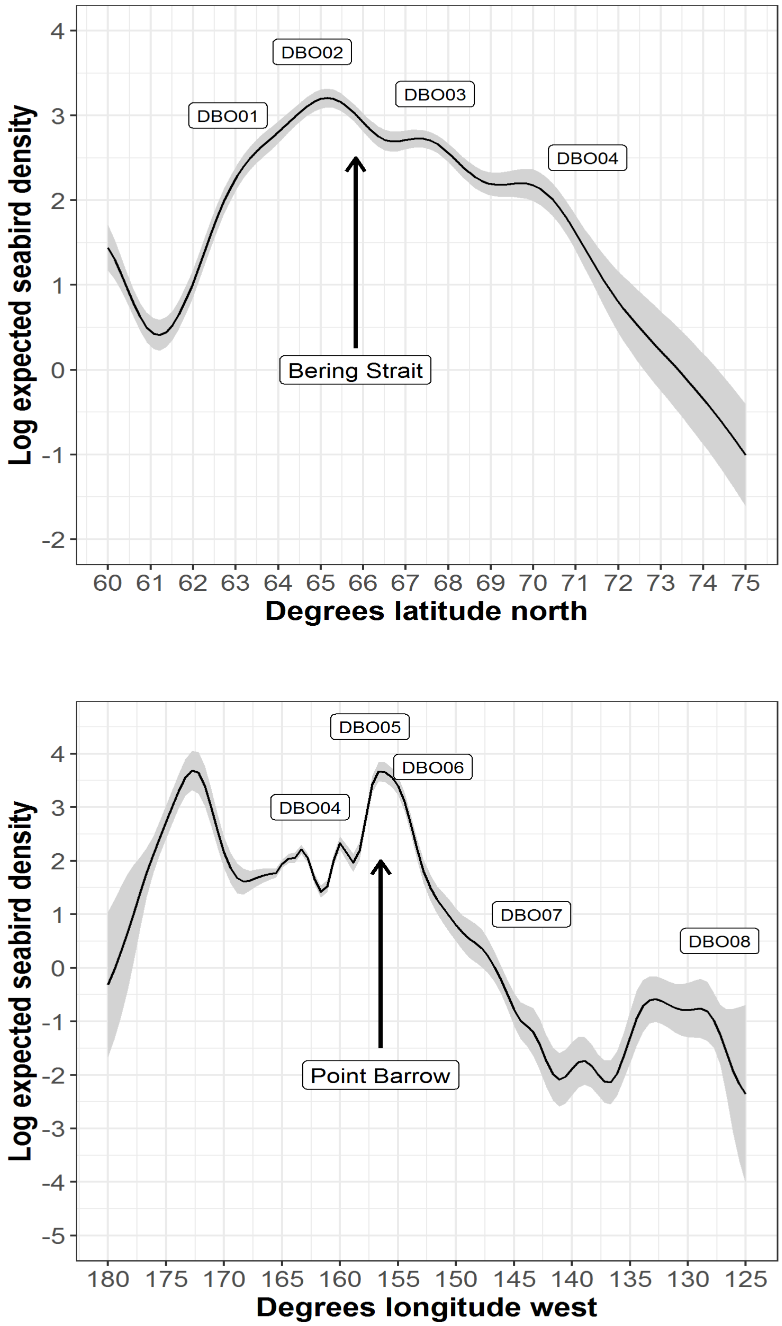

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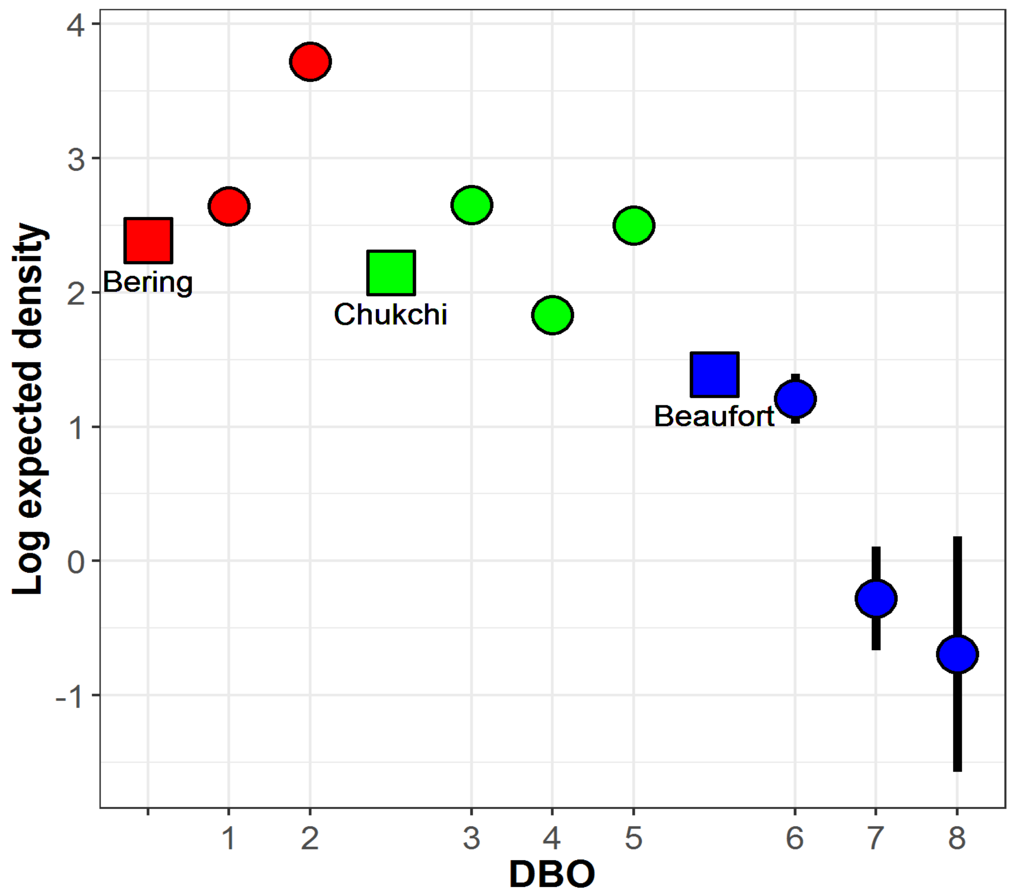

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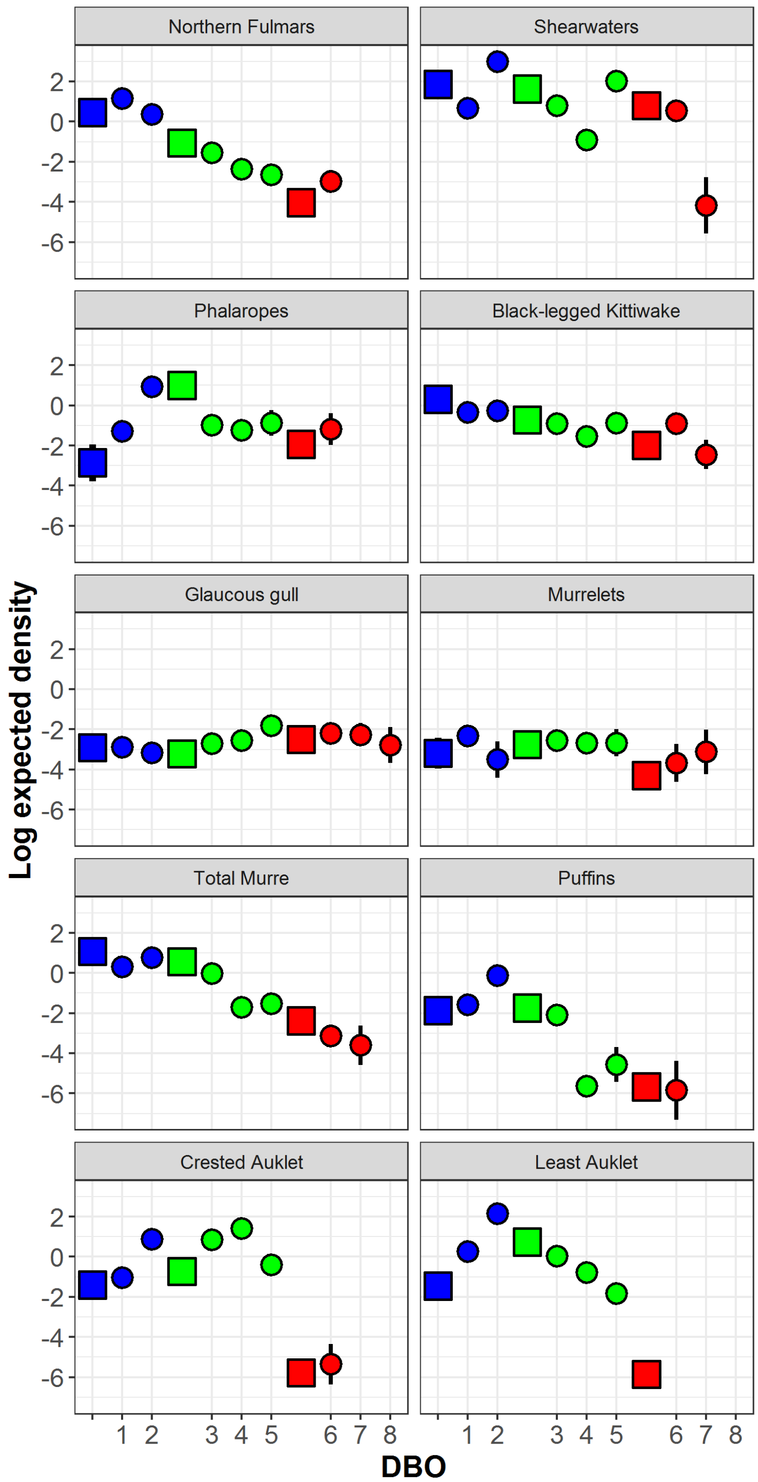

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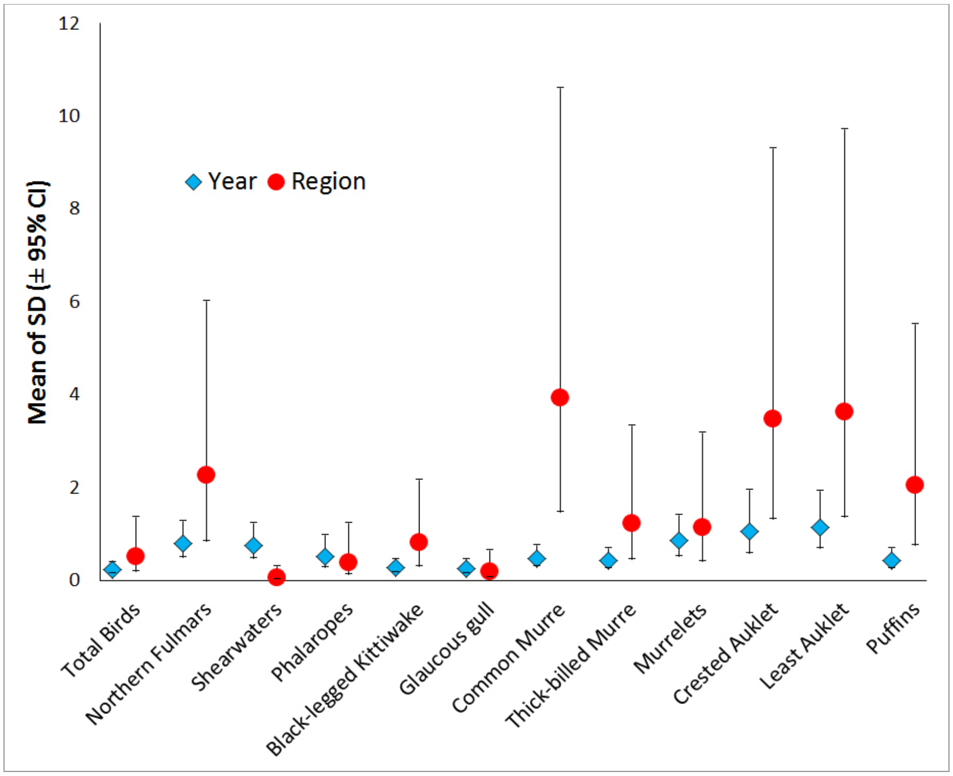

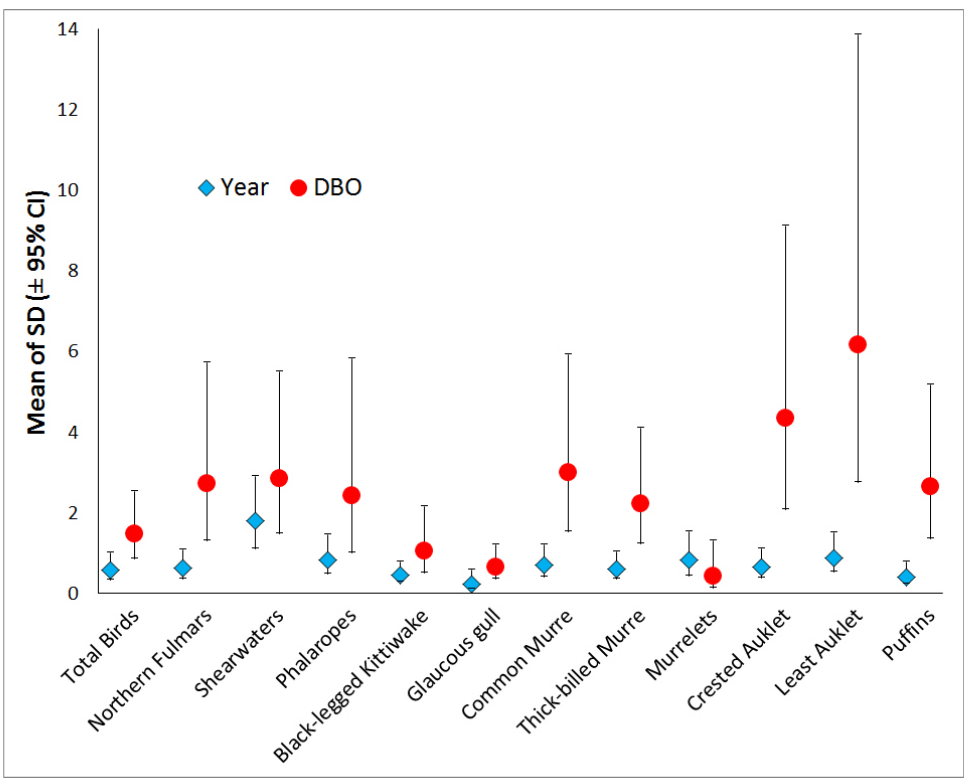

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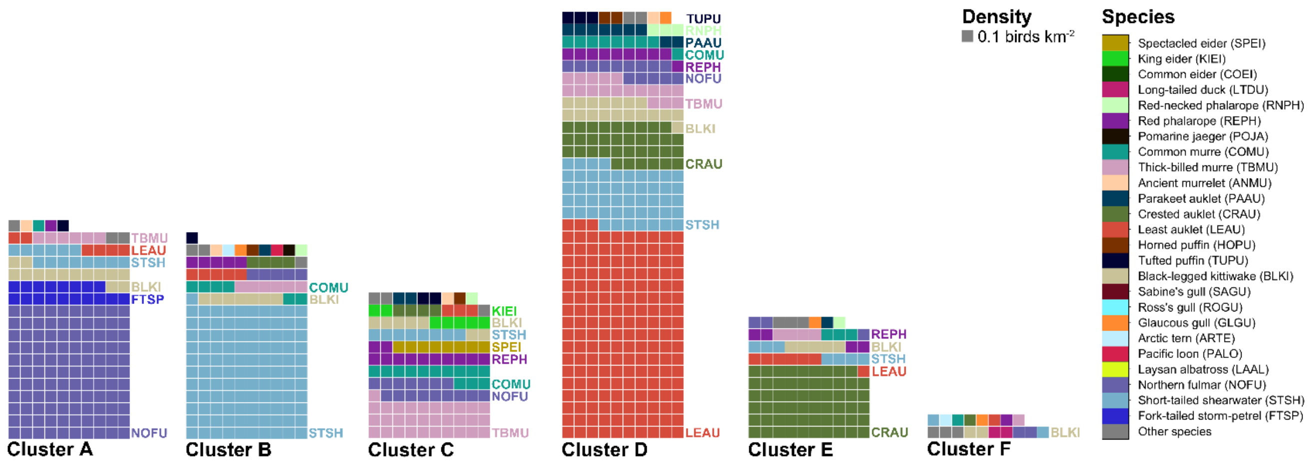

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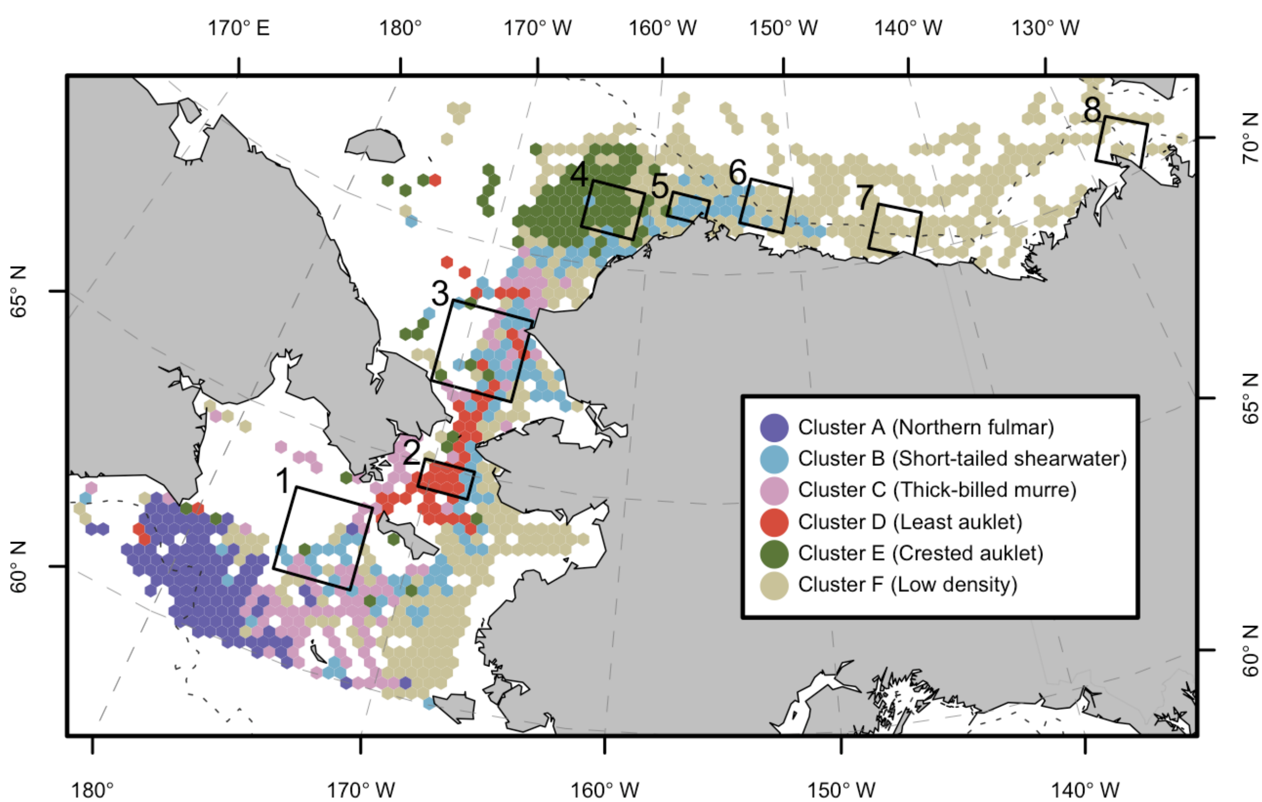

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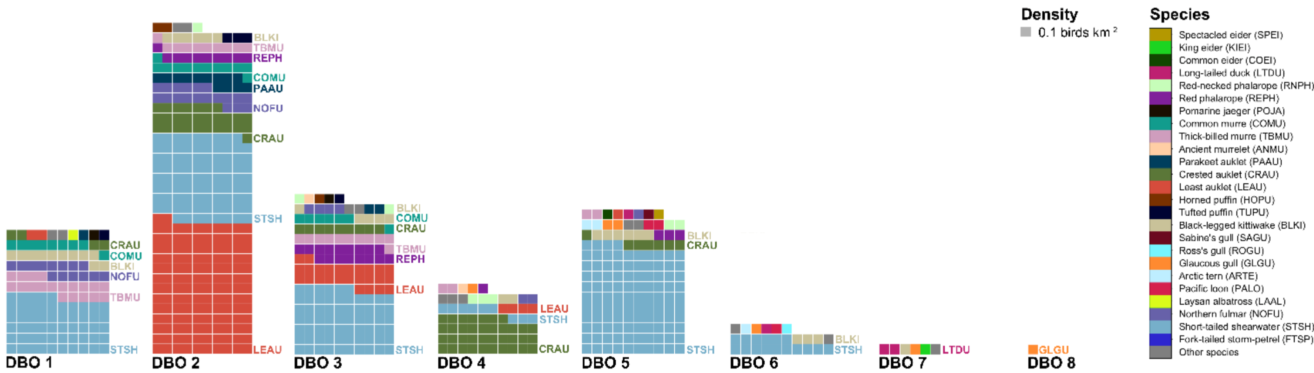


Fig. 11. Species composition and densities for the eight DBO sites, based on surveys from 2007-2015. Each cell in the waffle graph represents 0.1 birds•km^{-2}. See Appendix C for mean densities of all species within each DBO site.

Table 1. Species observed in the study area, their foraging mode, primary diet, and nesting or migratory status. Species with names in bold were selected for GAM analyses (see Methods), with some species combined as a single taxa (see footnotes).

Family	Common Name	Latin name	forage mode	primary diet	Colonies in study area	Other nesting areas
Anatidae	Steller's Eider	*Polysticta stelleri*	benthic	crustacea, mulluscs		lagoons & inland
	Spectacled Eider	*Somateria fischeri*	benthic	crustacea, mulluscs		lagoons & inland
	King Eider	*Somateria spectabilis*	benthic	crustacea, mulluscs		lagoons & inland
	Common Eider	*Somateria mollissima*	benthic	crustacea, mulluscs		lagoons & inland
	Harlequin Duck	*Histrionicus histrionicus*	benthic	crustacea, mulluscs		lagoons & inland
	Surf Scoter	*Melanitta perspicillata*	benthic	crustacea, mulluscs		lagoons & inland
	White-winged Scoter	*Melanitta fusca*	benthic	crustacea, mulluscs		lagoons & inland
	Black Scoter	*Melanitta americana*	benthic	crustacea, mulluscs		lagoons & inland
	Long-tailed Duck	*Clangula hyemalis*	benthic	crustacea, mulluscs		lagoons & inland
	Common Merganser	*Mergus merganser*	diver	fish		lagoons & inland
	Red-breasted Merganser	*Mergus serrator*	diver	fish		lagoons & inland
Podicipedidae	Red-necked Grebe	*Podiceps grisegena*	diver	fish		lagoons & inland
Scolopacidae	**Red-necked Phalarope**[1]	***Phalaropus lobatus***	surface	zooplankton		lagoons & inland
	Red Phalarope[1]	***Phalaropus fulicarius***	surface	zooplankton		lagoons & inland
Stercorariidae	Pomarine Jaeger	*Stercorarius pomarinus*	surface	fish & scavenger		lagoons & inland
	Parasitic Jaeger	*Stercorarius parasiticus*	surface	fish & scavenger		lagoons & inland
	Long-tailed Jaeger	*Stercorarius longicaudus*	surface	fish & scavenger		lagoons & inland
Alcidae	Dovekie	*Alle alle*	diver	zooplankton	yes	mainly Atlantic
	Common Murre[2]	***Uria aalge***	diver	fish	yes	Bering & GOA
	Thick-billed Murre[2]	***Uria lomvia***	diver	fish & krill	yes	Bering & GOA
	Black Guillemot	*Cepphus grylle*	diver	fish	yes	Bering Sea only
	Pigeon Guillemot	*Cepphus columba*	diver	fish		Bering & GOA
	Marbled Murrelet[3]	***Brachyramphus marmoratus***	diver	fish		Bering & GOA
	Kittlitz's Murrelet[3]	***Brachyramphus brevirostris***	diver	fish		Bering & GOA
	Ancient Murrelet[3]	***Synthliboramphus antiquus***	diver	fish		Bering & GOA
	Cassin's Auklet	*Ptychoramphus aleuticus*	diver	fish		Bering & GOA
	Parakeet Auklet	*Aethia psittacula*	diver	fish & zooplankton	yes	Bering & GOA
	Least Auklet[4]	***Aethia pusilla***	diver	zooplankton	yes	Bering Sea only
	Whiskered Auklet	*Aethia pygmaea*	diver	fish & zooplankton		Bering Sea only
	Crested Auklet[5]	***Aethia cristatella***	diver	zooplankton	yes	Bering Sea only
	Horned Puffin[6]	***Fratercula corniculata***	diver	fish	yes	Bering & GOA
	Tufted Puffin[6]	***Fratercula cirrhata***	diver	fish	yes	Bering & GOA
Laridae	**Black-legged Kittiwake**[7]	***Rissa tridactyla***	surface	fish	yes	Bering & GOA
	Red-legged Kittiwake	*Rissa brevirostris*	surface	fish		Bering Sea only
	Ivory Gull	*Pagophila eburnea*	surface	fish & scavenger		Beaufort & Atlantic

Table 1. Species observed in the study area, their foraging mode, primary diet, and nesting or migratory status. Species with names in bold were selected for GAM analyses (see Methods), with some species combined as a single taxa (see footnotes).

Family	Common Name	Latin name	forage mode	primary diet	Colonies in study area	Other nesting areas
	Sabine's Gull	*Xema sabini*	surface	fish & scavenger		Atlantic/circumpolar
	Black-headed Gull	*Chroicocephalus ridibundus*	surface	fish & scavenger		Beaufort & Atlantic
	Ross's Gull	*Rhodostethia rosea*	surface	fish		Atlantic/circumpolar
	Mew Gull	*Larus canus*	surface	fish & scavenger		Bering & GOA
	Herring Gull	*Larus argentatus*	surface	fish & scavenger		Bering & GOA
	Iceland Gull	*Larus glaucoides*	surface	fish & scavenger		Beaufort & Atlantic
	Slaty-backed Gull	*Larus schistisagus*	surface	fish & scavenger		Western Bering
	Glaucous-winged Gull	*Larus glaucescens*	surface	fish & scavenger		Bering & GOA
	Glaucous Gull[8]	***Larus hyperboreus***	surface	fish & scavenger	yes	lagoons & inland
	Aleutian Tern	*Onychoprion aleuticus*	surface	fish		Bering & GOA
	Arctic Tern	*Sterna paradisaea*	surface	fish	yes	lagoons & inland
Gaviidae	Red-throated Loon	*Gavia stellata*	diver	fish		lagoons & inland
	Pacific Loon	*Gavia pacifica*	diver	fish		lagoons & inland
	Common Loon	*Gavia immer*	diver	fish		lagoons & inland
	Yellow-billed Loon	*Gavia adamsii*	diver	fish		lagoons & inland
Diomedeidae	Laysan Albatross	*Phoebastria immutabilis*	surface	squid, fish		central Pacific*
	Short-tailed Albatross	*Phoebastria albatrus*	surface	squid, fish		central Pacific*
Procellariidae	**Northern Fulmar**[9]	***Fulmarus glacialis***	surface	fish, squid		Bering & GOA
	Mottled Petrel	*Pterodroma inexpectata*	dive & surface	fish, squid, krill		southern hemisphere*
	Short-tailed Shearwater[10]	***Ardenna tenuirostris***	dive & surface	fish, squid, krill		southern hemisphere*
	Sooty Shearwater[10]	***Ardenna grisea***	dive & surface	fish, squid, krill		southern hemisphere*
Hydrobatidae	Fork-tailed Storm-Petrel	*Oceanodroma furcata*	surface	zooplankton		Bering & GOA
Phalacrocoracidae	Red-faced Cormorant	*Phalacrocorax urile*	diver	fish	yes	Bering & GOA
	Pelagic Cormorant	*Phalacrocorax pelagicus*	diver	fish	yes	Bering & GOA

* Indicates species is migratory only, and does not nest in Alaska.

[1] combined as 'Phalarope', with Red Phalarope comprising 80% of this taxa

[2] combined as 'Murre' for some analyses, with 40% Common and 60% Thick-billed murres in this taxa.

[3] combined as 'Murrelets', with 7% Marbled, 25% Kittlitz's, and 68% Ancient murrelets in this taxa

[4] a single species taxa, Least Auklet

[5] a single species taxa, Crested Auklet

[6] combined as 'Puffins', with 34% Horned and 66% Tufted puffins in this taxa.

[7] a single species taxa, Black-legged Kittiwake

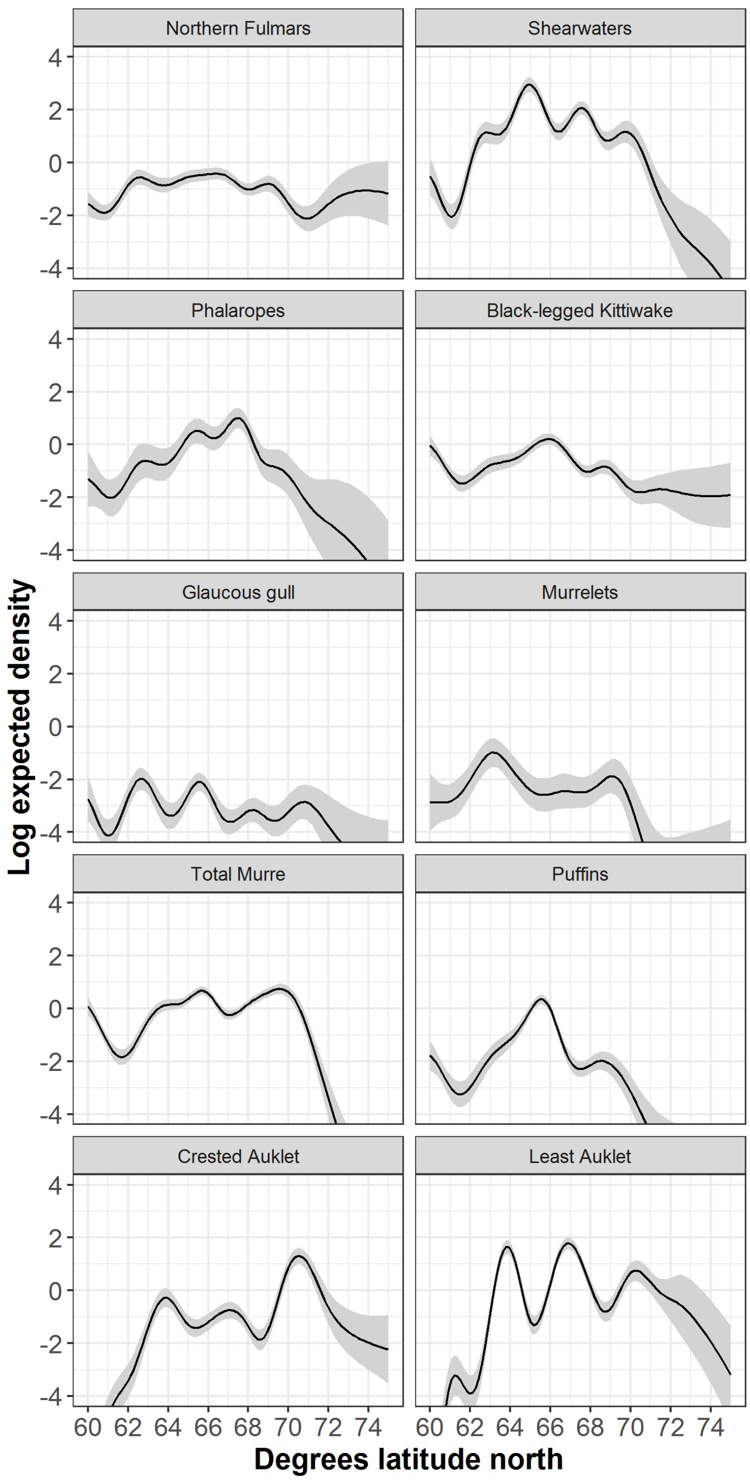
[8] a single species taxa, Glaucous Gull

[9] a single species taxa, Northern Fulmar

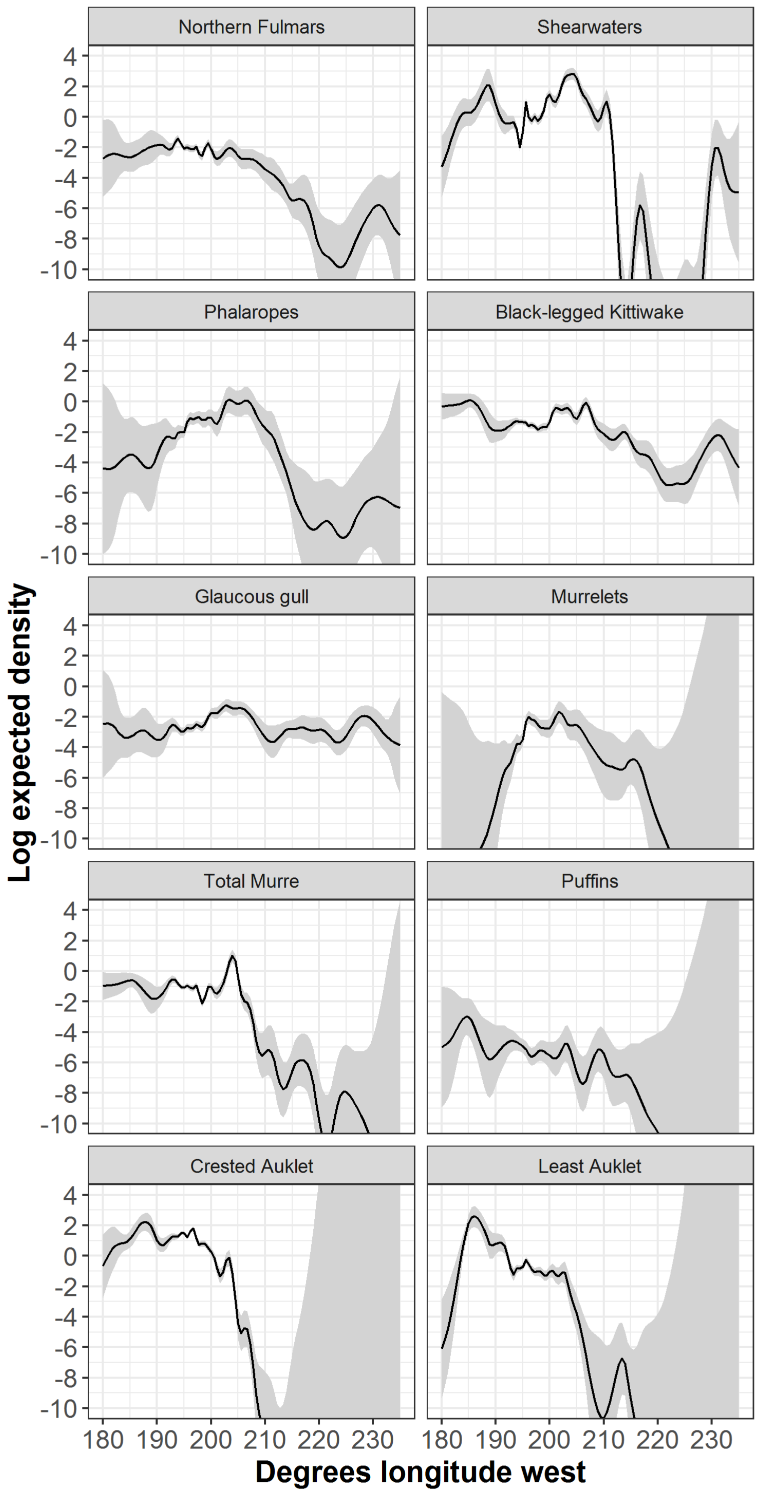
[10] combined as 'Shearwaters', with Short-tailed Shearwater being >99% of this taxa

Table 2. Shannon Diversity Indices (H´) for each region (excluding DBO sites) and within each DBO site. Sample units were 3-km transect segments from surveys conducted July – October, 2007 – 2015.

Region	H'	DBO Site	H'
Bering	2.44	1	1.82
		2	1.74
Chukchi	2.30	3	2.15
		4	1.46
		5	1.53
Beaufort	1.74	6	1.72
		7	2.13
		8	0



Appendix A. Modeled total seabird density (log expected count per 3-km segment ± 2 SE) for 10 taxa, by latitude, holding longitude constant at 168˚W. The large error estimates (shading) in the far north are indicative of both low sampling effort and low encounter rates of birds in those areas.



Appendix A. Modeled total seabird density (log expected count per 3-km segment ± 2 SE) for 10 taxa, by longitude, holding latitude constant at 71°N. The very large error estimates (shading) are indicative of low sampling effort and low encounter rates of birds in those areas.

Appendix B. Mean densities for each community identified by cluster analysis. Data is from 2007-2015, July-Oct. Densities within communities used average density of 30-km grid cells. Species not identified to species were prorated within grid cells using ratio of identified birds. The numerically dominate species for each community is given in parentheses, and color coded headings match communities in Figure 13.

Common Name	Latin name	Cluster A (N. Fulmar)	Cluster B (Shearwater)	Cluster C (TB Murre)	Cluster D (L. Auklet)	Cluster E (C. Auklet)	Cluster F (Low Density)
Steller's Eider	*Polysticta stelleri*	0.000	< 0.001	< 0.001	0.004	0.000	0.002
Spectacled Eider	*Somateria fischeri*	0.000	0.008	0.775	0.001	0.002	0.008
King Eider	*Somateria spectabilis*	0.000	0.025	0.732	0.003	0.007	0.022
Common Eider	*Somateria mollissima*	0.000	0.048	0.015	0.005	0.001	0.020
Harlequin Duck	*Histrionicus histrionicus*	0.001	0.000	0.009	0.000	0.000	0.001
Surf Scoter	*Melanitta perspicillata*	0.000	< 0.001	0.000	0.000	0.000	< 0.001
White-winged Scoter	*Melanitta fusca*	0.001	0.001	0.004	0.009	< 0.001	0.003
Black Scoter	*Melanitta americana*	0.000	< 0.001	0.000	0.000	0.000	< 0.001
Long-tailed Duck	*Clangula hyemalis*	0.000	0.037	0.006	0.001	0.025	0.161
Common Merganser	*Mergus merganser*	0.000	< 0.001	0.000	0.001	0.000	0.000
Red-breasted Merganser	*Mergus serrator*	0.000	0.000	0.000	0.000	0.000	< 0.001
Red-necked Grebe	*Podiceps grisegena*	0.000	< 0.001	< 0.001	0.000	0.000	< 0.001
Red-necked Phalarope	*Phalaropus lobatus*	0.003	0.078	0.052	0.269	0.109	0.044
Red Phalarope	*Phalaropus fulicarius*	0.063	0.454	1.221	1.016	0.364	0.081
Pomarine Jaeger	*Stercorarius pomarinus*	0.040	0.059	0.035	0.035	0.023	0.013
Parasitic Jaeger	*Stercorarius parasiticus*	0.013	0.023	0.008	0.008	0.005	0.004
Long-tailed Jaeger	*Stercorarius longicaudus*	0.010	0.004	0.002	0.003	0.002	0.004
Dovekie	*Alle alle*	0.000	0.002	0.000	0.002	0.001	< 0.001
Common Murre	*Uria aalge*	0.131	0.635	1.292	0.894	0.259	0.106
Thick-billed Murre	*Uria lomvia*	0.568	0.623	3.087	1.815	0.441	0.091
Black Guillemot	*Cepphus grylle*	0.000	0.013	< 0.001	0.001	0.005	0.010
Pigeon Guillemot	*Cepphus columba*	0.002	0.001	0.028	0.017	< 0.001	< 0.001
Marbled Murrelet	*Brachyramphus marmoratus*	0.000	< 0.001	0.005	0.001	0.000	0.001
Kittlitz's Murrelet	*Brachyramphus brevirostris*	0.000	0.020	0.010	0.002	0.011	0.008
Ancient Murrelet	*Synthliboramphus antiquus*	0.053	0.116	0.084	0.051	0.032	0.036
Cassin's Auklet	*Ptychoramphus aleuticus*	0.000	0.000	0.002	0.001	0.000	< 0.001
Parakeet Auklet	*Aethia psittacula*	0.041	0.143	0.155	0.895	0.050	0.035

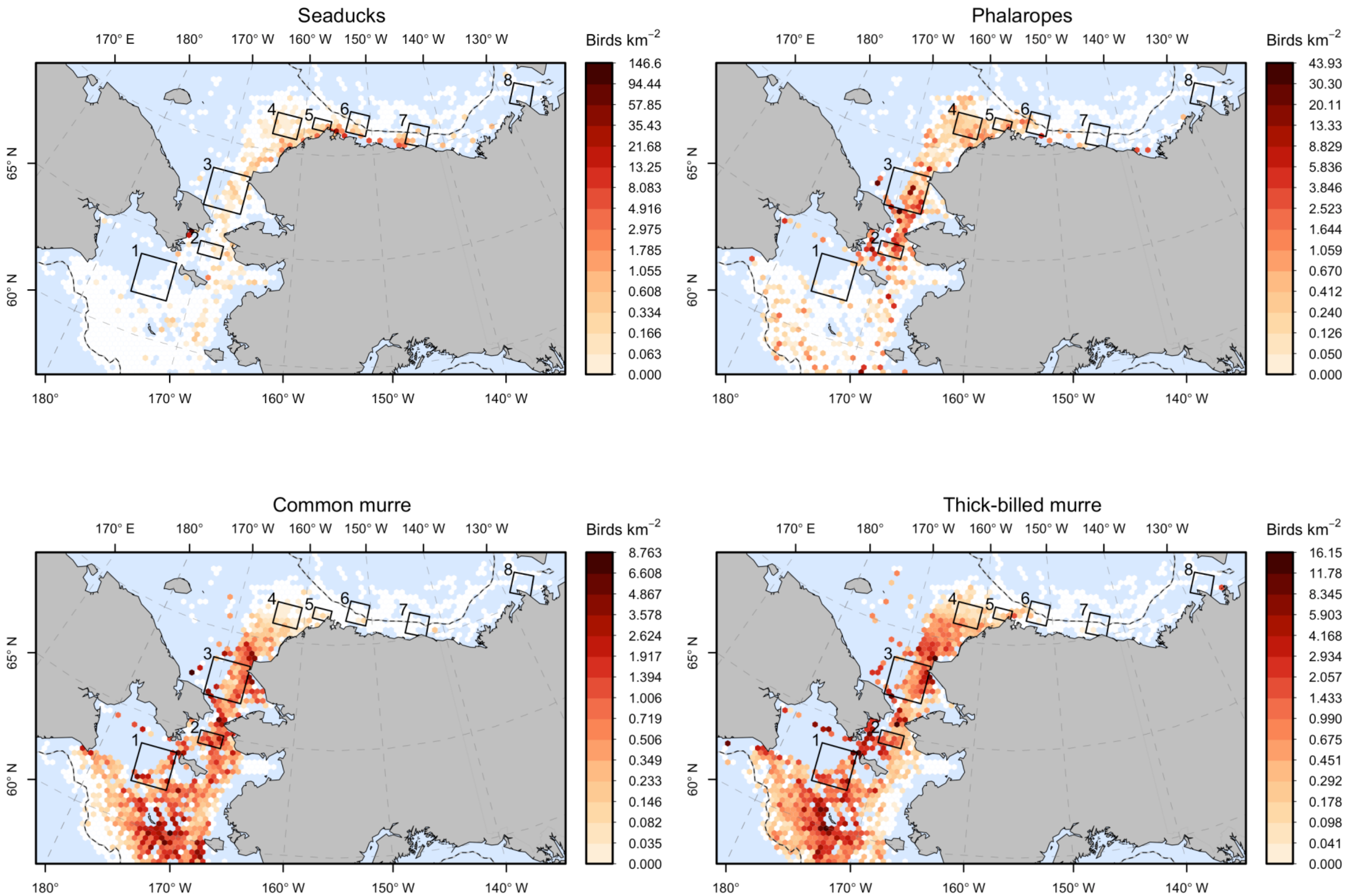
Least Auklet	*Aethia pusilla*	0.581	0.537	0.327	17.316	0.725	0.051
Whiskered Auklet	*Aethia pygmaea*	0.000	0.000	0.001	0.000	0.000	0.000
Crested Auklet	*Aethia cristatella*	0.030	0.427	0.403	3.540	5.940	0.081
Horned Puffin	*Fratercula corniculata*	0.019	0.086	0.148	0.154	0.019	0.011
Tufted Puffin	*Fratercula cirrhata*	0.129	0.094	0.157	0.348	0.030	0.018
Black-legged Kittiwake	*Rissa tridactyla*	1.387	0.720	0.698	1.822	0.459	0.235
Red-legged Kittiwake	*Rissa brevirostris*	0.005	0.004	0.010	0.001	0.000	0.001
Ivory Gull	*Pagophila eburnea*	0.000	0.000	0.000	0.000	0.001	< 0.001
Sabine's Gull	*Xema sabini*	< 0.001	0.027	0.004	0.008	0.010	0.020
Ross's Gull	*Rhodostethia rosea*	0.000	0.010	0.000	0.000	0.024	0.019
Mew Gull	*Larus canus*	0.000	0.000	0.000	< 0.001	0.000	0.000
Herring Gull	*Larus argentatus*	0.042	0.004	0.026	0.018	0.006	0.005
Iceland Gull	*Larus glaucoides*	0.000	0.000	< 0.001	0.000	0.000	< 0.001
Slaty-backed Gull	*Larus schistisagus*	0.047	< 0.001	0.003	0.017	0.001	< 0.001
Glaucous-winged Gull	*Larus glaucescens*	0.010	0.013	0.008	0.009	0.002	0.009
Glaucous Gull	*Larus hyperboreus*	0.031	0.076	0.035	0.087	0.057	0.062
Aleutian Tern	*Onychoprion aleuticus*	0.000	0.000	0.000	0.000	0.000	< 0.001
Arctic Tern	*Sterna paradisaea*	0.002	0.075	0.002	0.006	0.007	0.059
Red-throated Loon	*Gavia stellata*	0.000	0.002	0.002	< 0.001	0.001	0.003
Pacific Loon	*Gavia pacifica*	0.000	0.076	0.013	0.005	0.030	0.023
Common Loon	*Gavia immer*	0.000	0.001	0.000	0.000	0.000	0.001
Yellow-billed Loon	*Gavia adamsii*	0.000	0.001	< 0.001	0.002	0.001	0.002
Laysan Albatross	*Phoebastria immutabilis*	0.012	0.008	0.012	0.000	0.001	< 0.001
Short-tailed Albatross	*Phoebastria albatrus*	0.001	0.000	0.000	0.000	0.000	0.000
Northern Fulmar	*Fulmarus glacialis*	10.962	0.549	1.578	1.374	0.324	0.162
Mottled Petrel	*Pterodroma inexpectata*	0.002	0.000	< 0.001	0.000	0.000	0.000
Short-tailed Shearwater	*Ardenna tenuirostri*	1.356	11.072	0.754	5.127	0.718	0.191
Sooty Shearwater	*Ardenna grisea*	< 0.001	< 0.001	0.001	0.000	0.000	< 0.001
Fork-tailed Storm-Petrel	*Oceanodroma furcata*	1.799	0.022	0.012	0.020	0.000	0.007
Red-faced Cormorant	*Phalacrocorax urile*	0.000	0.007	< 0.001	0.000	0.000	< 0.001
Pelagic Cormorant	*Phalacrocorax pelagicus*	0.001	0.006	0.005	0.003	0.012	0.002
Total Birds		17.340	16.106	11.719	34.892	9.705	1.611

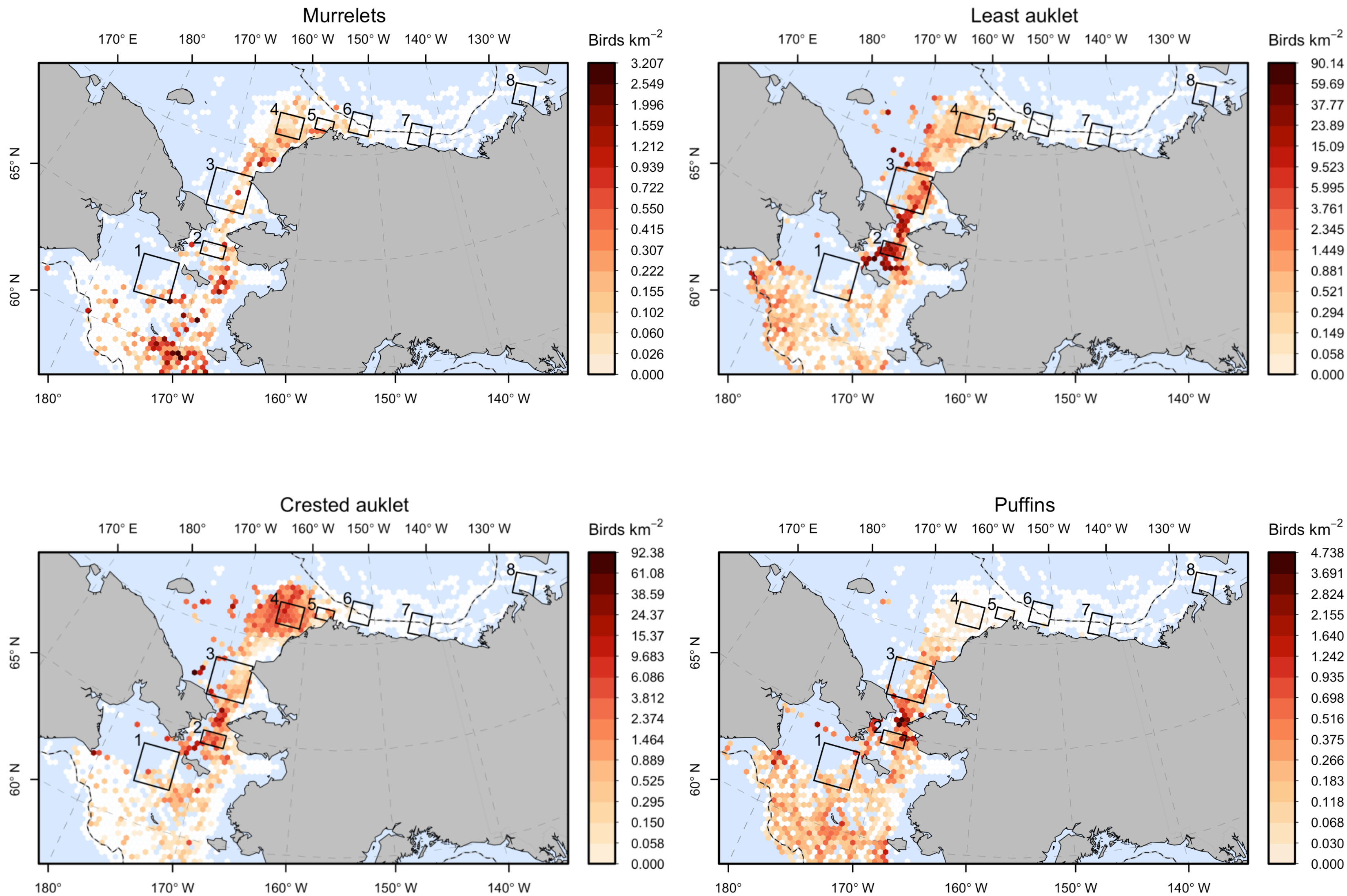
Appendix C. Mean densities (birds•km^{-2}) for each DBO site, using data from 2007-2015, July-Oct. Birds not identified to species were prorated based on identified birds within 30-km hexagonal cells, and grid cell densities were averaged to obtain DBO mean densities.

Common Name	Latin name	DBO 1	DBO 2	DBO 3	DBO 4	DBO 5	DBO 6	DBO 7	DBO 8
Steller's Eider	*Polysticta stelleri*	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.000
Spectacled Eider	*Somateria fischeri*	0.000	0.000	0.004	< 0.001	0.092	0.000	0.000	0.000
King Eider	*Somateria spectabilis*	0.000	0.000	0.016	0.031	0.046	0.039	0.062	0.000
Common Eider	*Somateria mollissima*	0.000	0.010	0.030	0.001	0.106	0.004	0.000	0.000
Harlequin Duck	*Histrionicus histrionicus*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Surf Scoter	*Melanitta perspicillata*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
White-winged Scoter	*Melanitta fusca*	0.000	0.022	0.003	0.001	0.000	0.000	0.000	0.000
Black Scoter	*Melanitta americana*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Long-tailed Duck	*Clangula hyemalis*	0.000	0.000	0.034	0.042	0.118	0.065	0.193	0.000
Common Merganser	*Mergus merganser*	0.000	0.003	0.001	0.000	0.000	0.000	0.000	0.000
Red-breasted Merganser	*Mergus serrator*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Red-necked Grebe	*Podiceps grisegena*	< 0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Red-necked Phalarope	*Phalaropus lobatus*	0.000	0.094	0.163	0.320	0.249	0.012	0.000	0.000
Red Phalarope	*Phalaropus fulicarius*	0.027	0.970	1.654	0.084	0.307	0.028	0.000	0.000
Pomarine Jaeger	*Stercorarius pomarinus*	0.093	0.031	0.078	0.010	0.021	0.012	0.000	0.000
Parasitic Jaeger	*Stercorarius parasiticus*	0.011	0.009	0.019	0.004	0.003	0.008	0.006	0.000
Long-tailed Jaeger	*Stercorarius longicaudus*	0.000	0.000	0.005	0.001	0.003	0.002	0.005	0.000
Dovekie	*Alle alle*	0.000	0.005	0.000	0.001	0.000	0.000	0.000	0.000
Common Murre	*Uria aalge*	0.948	1.249	0.696	0.042	0.019	0.011	0.000	0.000
Thick-billed Murre	*Uria lomvia*	1.918	1.005	1.109	0.173	0.154	0.026	0.002	0.000
Black Guillemot	*Cepphus grylle*	0.000	0.000	0.001	0.004	0.012	0.000	0.000	0.000
Pigeon Guillemot	*Cepphus columba*	0.001	0.000	0.001	< 0.001	0.000	0.000	0.000	0.000
Marbled Murrelet	*Brachyramphus marmoratus*	0.020	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Kittlitz's Murrelet	*Brachyramphus brevirostris*	0.000	0.000	0.003	0.012	0.043	0.014	0.000	0.000
Ancient Murrelet	*Synthliboramphus antiquus*	0.033	0.020	0.054	0.066	0.027	0.000	0.000	0.000
Cassin's Auklet	*Ptychoramphus aleuticus*	0.000	0.005	0.000	0.000	0.000	0.000	0.000	0.000
Parakeet Auklet	*Aethia psittacula*	0.053	1.258	0.185	0.018	0.004	0.000	0.000	0.000
Least Auklet	*Aethia pusilla*	0.169	13.231	2.603	0.442	0.063	0.000	0.000	0.000
Whiskered Auklet	*Aethia pygmaea*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Crested Auklet	*Aethia cristatella*	0.373	2.755	0.882	3.733	0.661	0.003	0.000	0.000
Horned Puffin	*Fratercula corniculata*	0.021	0.153	0.090	0.005	0.000	0.000	0.000	0.000
Tufted Puffin	*Fratercula cirrhata*	0.139	0.313	0.083	0.001	0.004	0.000	0.000	0.000

Black-legged Kittiwake	*Rissa tridactyla*	1.120	0.629	0.543	0.247	0.578	0.321	0.070	0.000
Red-legged Kittiwake	*Rissa brevirostris*	0.004	0.000	< 0.001	0.000	0.000	0.000	0.000	0.000
Ivory Gull	*Pagophila eburnea*	0.000	0.000	0.000	< 0.001	0.000	0.000	0.000	0.000
Sabine's Gull	*Xema sabini*	0.005	0.011	0.002	0.008	0.074	0.002	0.000	0.000
Black-headed Gull	*Chroicocephalus ridibundus*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ross's Gull	*Rhodostethia rosea*	0.000	0.000	0.000	0.031	0.032	0.078	0.000	0.000
Mew Gull	*Larus canus*	0.000	0.000	< 0.001	0.000	0.000	0.000	0.000	0.000
Herring Gull	*Larus argentatus*	0.033	0.000	0.003	0.000	0.000	0.000	0.000	0.000
Iceland Gull	*Larus glaucoides*	0.000	0.000	< 0.001	0.000	0.000	0.000	0.000	0.000
Slaty-backed Gull	*Larus schistisagus*	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Glaucous-winged Gull	*Larus glaucescens*	0.002	0.002	0.000	0.001	0.000	0.003	0.006	0.000
Glaucous Gull	*Larus hyperboreus*	0.029	0.012	0.040	0.069	0.159	0.126	0.085	0.056
Aleutian Tern	*Onychoprion aleuticus*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Arctic Tern	*Sterna paradisaea*	0.009	0.001	0.003	0.003	0.156	0.113	0.000	0.000
Red-throated Loon	*Gavia stellata*	0.000	0.001	0.004	0.002	0.012	0.000	0.000	0.000
Pacific Loon	*Gavia pacifica*	0.000	0.036	0.028	0.049	0.229	0.053	0.044	0.000
Common Loon	*Gavia immer*	0.000	0.000	0.000	0.000	0.008	0.000	0.000	0.000
Yellow-billed Loon	*Gavia adamsii*	0.001	0.000	0.000	0.004	0.016	0.000	0.000	0.000
Laysan Albatross	*Phoebastria immutabilis*	0.051	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Short-tailed Albatross	*Phoebastria albatrus*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Northern Fulmar	*Fulmarus glacialis*	1.445	1.856	0.362	0.180	0.052	0.034	0.000	0.000
Mottled Petrel	*Pterodroma inexpectata*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Short-tailed Shearwater	*Ardenna tenuirostris*	5.495	8.746	6.569	0.861	10.362	1.591	0.006	0.000
Sooty Shearwater	*Ardenna grisea*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Fork-tailed Storm-Petrel	*Oceanodroma furcata*	0.031	0.022	0.001	0.002	0.000	0.000	0.000	0.000
Red-faced Cormorant	*Phalacrocorax urile*	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pelagic Cormorant	*Phalacrocorax pelagicus*	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000
Total for DBO		12.033	32.451	15.271	6.449	13.612	2.546	0.488	0.056

Appendix D. Distribution for species groups maps using data from July - October, 2007 – 2015 in the northern Bering, Chukchi and Beaufort seas.




Murrelets
170° E
180°
170° W
160° W
150° W
140° W
130° W
Birds km^{-2}
3.207
2.549
1.996
1.559
1.212
0.939
0.722
0.550
0.415
0.307
0.222
0.155
0.102
0.060
0.026
0.000
65° N
60° N
180°
170° W
160° W
150° W
140° W
1
2
3
4
5
6
7
8
Least auklet
Birds km^{-2}
90.14
59.69
37.77
23.89
15.09
9.523
5.995
3.761
2.345
1.449
0.881
0.521
0.294
0.149
0.058
0.000
Crested auklet
Birds km^{-2}
92.38
61.08
38.59
24.37
15.37
9.683
6.086
3.812
2.374
1.464
0.889
0.525
0.295
0.150
0.058
0.000
Puffins
Birds km^{-2}
4.738
3.691
2.824
2.155
1.640
1.242
0.935
0.698
0.516
0.375
0.266
0.183
0.118
0.068
0.030
0.000

DSR2_2018_91_Kuletz et al., 3.28.19