ARCTIC
VOL. 73, NO. 4 (DECEMBER 2020) P. 485–498
https://doi.org/10.14430/arctic71592

Abundance of the Eastern Chukchi Sea Stock of Beluga Whales, 2012–17

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(*Received 8 November 2019; accepted in revised form 10 July 2020*)

ABSTRACT. Aerial line transect surveys were conducted during 19 July–20 August in each of the years 2012–17, with onshore–offshore transects covering a study area of approximately 110 000 km^2, from 140˚ W to 157˚ W longitude and from shore to 72˚ N latitude. These data were used to estimate abundance of the eastern Chukchi Sea (ECS) stock of beluga whales. The data were stratified based on bathymetry to reflect strong large-scale gradients in beluga density. A half-normal key function was used to model detection from a dataset of 999 sightings of 2465 belugas. The detection function was found to depend significantly on sky condition and ice coverage. For the years 2012 through 2017, respectively, the estimated numbers of ECS belugas in the study area during the study period were 7355 (CV = 0.17), 6813 (CV = 0.18), 16 598 (CV = 0.21), 6456 (CV = 0.21), 6965 (CV = 0.23) and 13 305 (CV = 0.27). There is no statistically significant trend. These estimates do not correct for belugas outside the study region. Indeed, diverse data indicate that belugas venture far outside the study region and their distribution varies interannually due to prey availability and other factors. Recently reviewed tagging data suggest that correcting for whales outside the study area would approximately double our abundance estimates. These results provide no indication that the stock has substantially declined during these six years due to the impact of subsistence hunting, industrial activity or climate change, although interannual variation and estimated CVs are both large, thereby potentially masking small-scale impacts.

Key words: *Delphinapterus leucas*; aerial survey; line transect; distance sampling; abundance; Beaufort Sea

RÉSUMÉ. Des levés aériens de transects en ligne ont été effectués entre le 19 juillet et le 20 août des années 2012 à 2017, les transects côtiers et extracôtiers couvrant une aire d'étude d'environ 110 000 km^2, de 140˚ à 157˚ de longitude ouest, et de la côte jusqu'à 72˚ de latitude nord. Ces données ont été utilisées pour estimer l'abondance du stock de bélugas de l'est de la mer des Tchouktches (ECS). Les données ont été stratifiées en fonction de la bathymétrie afin de tenir compte des gradients prononcés à grande échelle en matière de densité de bélugas. Une fonction clé demi-normale a été employée pour modéliser la détection à partir d'un ensemble de données de 999 observations de 2 465 bélugas. Il s'est avéré que la fonction de détection dépendait énormément de l'état du ciel et de la couverture de glace. Pour les années 2012 à 2017, respectivement, les nombres estimés de bélugas de l'ECS dans l'aire et la période étudiées s'élevaient à 7 355 (CV = 0,17), 6 813 (CV = 0,18), 16 598 (CV = 0,21), 6 456 (CV = 0,21), 6 965 (CV = 0,23) et 13 305 (CV = 0,27). Il n'y a pas de tendance statistiquement significative. Ces estimations ne comprennent pas de corrections pour les bélugas à l'extérieur de l'aire étudiée. En effet, diverses données indiquent que les bélugas s'aventurent loin en dehors de l'aire étudiée et que leur distribution varie d'une année à l'autre en fonction de la disponibilité des proies et d'autres facteurs. Selon des données de marquage examinées récemment, une correction visant à tenir compte des baleines en dehors de l'aire étudiée aurait pour effet de doubler approximativement nos estimations d'abondance. Ces résultats ne fournissent aucune indication selon laquelle le stock de bélugas a diminué considérablement pendant ces six années en raison des incidences de la chasse de subsistance, de l'activité industrielle ou du changement climatique, bien que la variation interannuelle et les estimations de CV soient toutes deux considérables, ce qui risque de dissimuler les incidences à petite échelle.

Mots clés : *Delphinapterus leucas*; levé aérien; transect en ligne; échantillonnage à distance; abondance; mer de Beaufort

Traduit pour la revue *Arctic* par Nicole Giguère.

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INTRODUCTION

Beluga whales or white whales (*Delphinapterus leucas*) occur throughout the Arctic and sub-Arctic (NAMMCO, 2018). In Alaska there are five currently recognized stocks, which are named after where the stocks occur for at least part of the year: Cook Inlet, Bristol Bay, eastern Bering Sea, eastern Chukchi Sea, and the Beaufort Sea (Frost and Lowry, 1990; O'Corry-Crowe et al., 1997, 2002). The stocks in Cook Inlet and Bristol Bay are non-migratory while the eastern Bering Sea stock migrates a relatively short distance within the Bering Sea. The eastern Chukchi Sea (ECS) and eastern Beaufort Sea (BS) stocks are highly migratory (Richard et al., 2001; Suydam et al., 2001; Hauser et al., 2014). Subsistence harvests from all of these stocks have been or are important for meeting the cultural and nutritional needs of many communities in western and northern Alaska (Frost and Suydam, 2010). Roughly 50–60 ECS belugas are harvested annually (Frost and Suydam, 2010). Additionally, industrial activities, including oil and gas, commercial shipping, and potentially commercial fishing, occur or are increasing in the range of many of these stocks (Reeves et al., 2014). Finally, climate change is also affecting beluga whale habitat and behavior (Hauser et al., 2016, 2018).

Because belugas help meet subsistence needs, are subject to potential impacts from industrial activities, and occupy habitat that is experiencing rapid ecological changes, it is important that whale populations and harvests are routinely monitored to ensure sustainability of the hunts. The Alaska Beluga Whale Committee (ABWC) has been supportive and involved in obtaining data for both harvest levels and population size and trend (Adams et al., 1993). The population size and trend of the ECS stock has been particularly difficult to monitor. Belugas gather annually near Kasegaluk Lagoon in the northeastern Chukchi Sea in late June and early July. Thus the ABWC flew coastal surveys in this area from about 1990 to 2003 (Lowry and Frost, 2002, 2003) but were only successful at obtaining a minimal population estimate of 3710 belugas in 1992 (Frost et al., 1993). Satellite tracking data showed that many animals from the Chukchi Sea stock were outside the area covered by the coastal survey (Suydam et al., 2001), thus that estimate appeared to be substantially negatively biased. Satellite-tracking data also showed that ECS belugas moved from the northeastern Chukchi Sea to the Beaufort Sea, especially along the shelf break and near Barrow Canyon in the western Beaufort Sea (Suydam et al., 2001; Suydam, 2009; Hauser et al., 2014). This information led to the development of a different approach for counting belugas from the ECS.

Lowry et al. (2017) provided an estimate of the size of the ECS stock of 20 752 (CV = 0.70). That estimate was based on a 2012 survey conducted across the Alaskan Beaufort Sea by the Aerial Surveys of Arctic Marine Mammals (ASAMM) program (see Clarke et al., 2013). ASAMM is operated by the U.S. National Marine Fisheries Service's Marine Mammal Laboratory, primarily with funding from the Bureau of Ocean Energy Management. The 2012 estimate was so much larger than the previous minimal estimate from 1992 that verification was needed about the population size of ECS belugas. Analyzing ASAMM data from subsequent years is the primary purpose of our paper. It is also important to obtain a time series of abundances to evaluate effects of subsistence hunting, industrial activity, or climate change on stock status. Thus, the objective of this paper is to estimate population size and possibly trend from 2012 to 2017 for eastern Chukchi belugas using consistent analytical methods across years.

METHODS

Surveys

Our analysis uses aerial survey data collected during the ASAMM project, from 19 July–20 August 2012–17. The survey was a visual line transect survey with onshore–offshore transects covering a study area of approximately 110 000 km^2, from 140° W to 157° W longitude, from shore to 72° N latitude (Fig. 1). These spatiotemporal parameters are necessary to isolate the ECS beluga stock from other beluga stocks in the ASAMM dataset (Lowry et al., 2017). Roughly, this region includes waters extending from the Beaufort Sea coast and inner shelf to the Arctic Ocean basin, between Utqiaġvik (formerly known as Barrow) and the Canadian border (Fig. 1). While the ranges of the ECS and BS beluga stocks are known to overlap spatially, especially during migration (Richard et al., 2001; Hauser et al., 2014), satellite telemetry indicates that the 95% probability contour of the utilization distributions for the two stocks in July and August are nonoverlapping (Hauser et al., 2014). During these months, the eastern boundary of the ASAMM survey area at 140° W longitude effectively divides the two stocks. Our western boundary was taken as 157° W longitude because, while there is considerable survey effort west of that boundary in the eastern Chukchi Sea (Clarke et al., 2018a), few belugas were seen (0.3% to 17.3% of total annual sightings, or 8.3% over all years). Belugas present in the Chukchi Sea prior to 19 July are likely available to be counted in the 140°–157° W region during summer. These temporal and spatial boundaries for the data we analyzed match those made by Lowry et al. (2017).

Transects were systematically spaced every one-half degree of longitude, oriented perpendicular to the coastline to cross major bathymetric features, such as Barrow Canyon, the Beaufort Sea shelf and slope, and bowhead and beluga migration paths. From 2012 to 2016, a new set of transects was generated prior to each flight, and the longitudes of the southern and northern endpoints were randomly generated, independent of each other, within 0.5-degree bins. In 2017, one set of transects was generated at the beginning of the field season and repeatedly flown

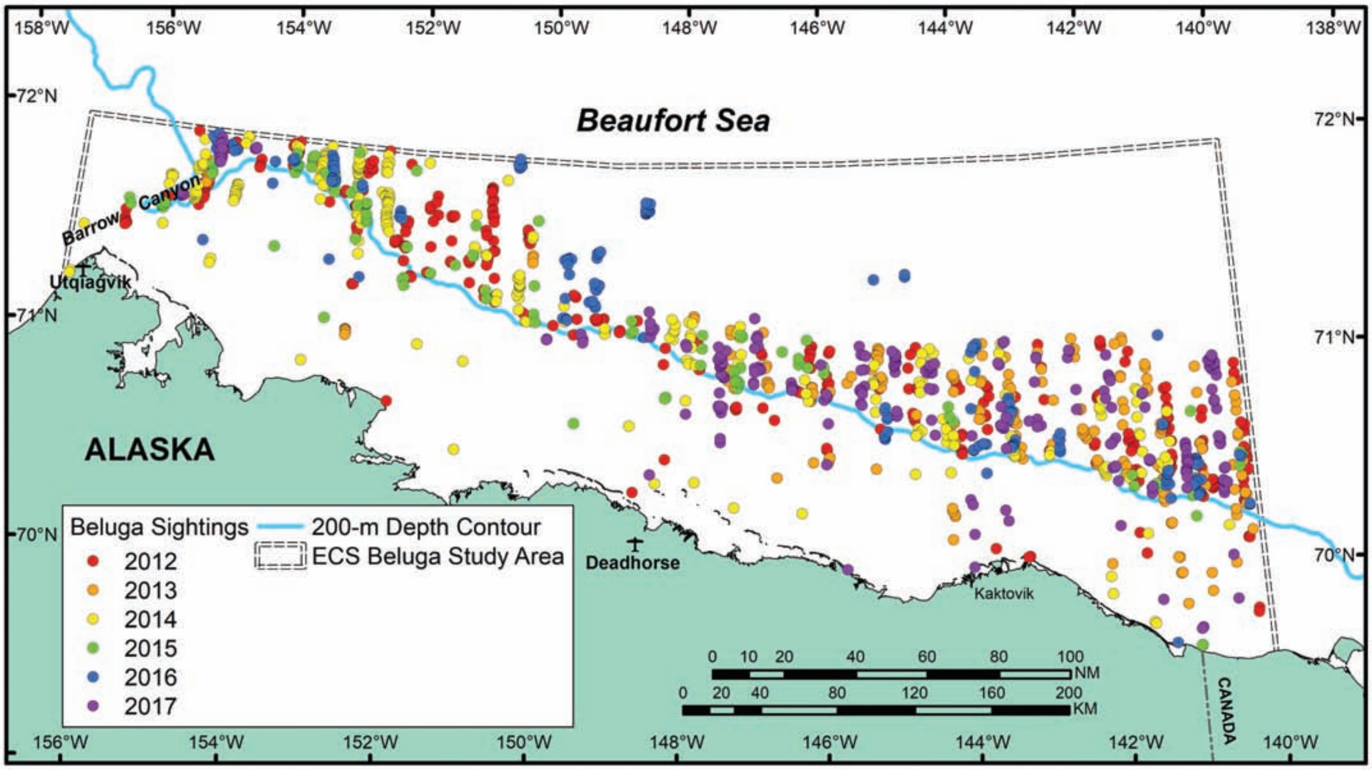


FIG. 1. Map of the study area. Each dot represents one sighted beluga group used in our analysis. The 200 m bathymetric contour is shown to illustrate Barrow Canyon and the preferred habitat of belugas.

throughout the year. The longitude of the northern and southern endpoints for the easternmost transect in the study area was randomly generated between 140˚ and 140.5˚ W. Using this transect as an anchor, the remaining transects were uniformly distributed every 0.5 degrees longitude. Thus, the transects from 2012–16 were oriented approximately north–south, whereas the transects in 2017 were oriented directly north–south. Transects extended up to 215 km northwards from the Alaskan coast. The area to be covered by a survey flight was nonrandom, dependent on reported or observed weather conditions, avoidance of recently surveyed areas, other aerial operations, and subsistence use areas. Weather permitting, effort was distributed fairly evenly across the entire study area, with the exception of the area north of about 71.3˚ N between 140˚ W and 150˚ W, which was surveyed less frequently, as explained further below.

The aircraft used was a high-wing Rockwell Aero Commander 690A twin turboprop equipped with bubble windows. Target survey altitude was 365–457 m above sea level. Target airspeed was 204–213 km/h. Single-observer line-transect methods were used. Primary observers measured the declination angle from the horizon to the sighting using handheld clinometers during level flight when the sighting was abeam. All marine mammals sighted were recorded. Transect flying was often interrupted by closing-mode circling to confirm species identification or group sizes (for large cetaceans but usually not for belugas); the times and positions of starting and ending the circling were recorded. Survey conditions that were recorded at the start of transects and when conditions changed included Beaufort sea state, sky conditions, impediments to visibility, visibility range (km) perpendicular to the aircraft, glare, and ice cover. Visibility and glare were recorded separately for the two sides of the aircraft (Clarke et al., 2018a).

The survey was focused on bowhead whales, which is evident in both the survey design and, to a lesser extent, field protocols. The survey was designed to focus effort over the distribution of bowhead whales in the Beaufort Sea, resulting in less effort in areas over slope and Arctic basin habitats (where belugas are expected to be found) in the eastern portion of the study area, and substantial effort in other areas where belugas are scarce. Physical characteristics of belugas are distinct from any other marine species encountered in the study area. Therefore, beluga sightings were often not circled to confirm species identification. Lastly, to further maximize survey effort dedicated to large cetaceans, beluga sightings often were not circled to estimate group size; hence, group size was typically estimated without breaking away from the transect line. Further details of the survey are given by Clarke et al. (2018a) and Lowry et al. (2017).

Data

We stratified the study region based on bathymetry in order to reflect strong large-scale gradients in beluga density (Thomas et al., 2007). This stratification should improve precision and reduce bias. Stratum boundaries were defined at depths of 0, 20, 50, 200, 2000 and 2500 m and at 72˚ N. The study area was further subdivided (at 154˚ W) into an east (E) and west (W) portion, to isolate the unique habitat associated with Barrow Canyon. Figure 2 shows the bathymetric stratification, along with (qualifying) transect effort flown during the analysis period each year. Our strata differ from those of Lowry et al. (2017), and our analysis region is about 4.5% larger than theirs, because the deepest stratum used in our analysis (2000 – 2500E) extends farther north than their strata in the east portion of the survey area.

We limit analysis to survey effort occurring in acceptable survey conditions. Beluga detectability depends on sea state (DeMaster et al., 2001), and we required Beaufort sea state 3 (wind 13 – 19 km/h; large wavelets, crests begin to break) or lower, as have past beluga abundance analyses in the western Arctic (Harwood and Kingsley, 2013; Lowry et al., 2017). As with Lowry et al. (2017), we also required that the visibility was at least 2 km (average of left and right sides). Flight segments with poorer sea state or visibility or both were treated as no effort, and sightings during those conditions were excluded. Moreover, we included only sightings made by primary observers during transect effort and with an associated clinometer angle, ignoring sightings during other types of effort (e.g., circling or search) and those from non-primary observers or lacking a clinometer angle (Clarke et al., 2018a).

It is clear from Figure 2 that there was scant coverage of the deepest portion of the study area. For the purpose of abundance estimation, we excluded all areas deeper than 2500 m. (However, for estimating the detection function, we included the few sightings in those areas to increase sample size.)

Detection Function

To estimate the detection function, we eliminated three sightings of large groups (45, 100, and 140) because they were anomalous, probably not representative of the main sighting process, and potentially influential in the estimation process. (These sightings were included in the abundance estimation.) Another group of 45 was omitted when truncating the data (see below). Our final dataset comprised 999 sightings, 99% of which had 15 or fewer animals. Group size is discussed further below. The total number of belugas seen in these 999 sightings was 2465.

We used both left and right truncation when estimating the detection function. Buckland et al. (2001) recommend truncating 5% – 10% of the largest observations or those for which detection probability is less than about 0.15. The 95th and 90th percentile distances were 1.42 and 1.19 km, respectively. We took the approach of fitting an approximate detection function (half-normal key function with no adjustments, fit to data initially truncated at 1.5 km) and determining the distance for which the estimated detection probability was less than 0.15. Based on this exploratory fit, sightings with distances at the left edge of the sighting distribution were also eliminated and the right-truncation point adjusted slightly to follow the Buckland et al. (2001) guideline. Figure 3 shows a histogram of all sighting distances before left and right truncation. Our decision was to omit sightings with distances less than 0.2 km or greater than 1.2 km. We subtracted 0.2 km from all retained sighting distances and then treated zero as if it were the centerline using standard detection function estimation methods. We believe that reduced sighting rates at less than 0.2 km from the centerline are primarily due to the narrow field of view close to the trackline and the rate of travel—although observers have an unobstructed view from the trackline to the horizon, view time directly beneath the plane is brief. We have no explanation for the slightly anomalous number of sightings at about 1.3 km and no reason to consider it anything other than random variability or clumping on a round clinometer reading of 20.

We applied standard distance sampling models (Buckland et al., 2001) to the truncated data, using the Distance (version 0.9.7) and mrds (version 2.2.0) packages in the R statistical environment (Miller, 2017; Laake et al., 2018; R Core Team, 2018). The single observer protocol required us to adopt the common assumption that $g(0) = 1$ (i.e., 100% detection of available whales at 0.2 km from the trackline). We compared half-normal and hazard rate key functions with up to four cosine adjustment terms, using AIC to assess which models best fit. We considered the best model to be the simplest one that cannot be improved upon by at least 2.0 AIC units when adding terms (Burnham and Anderson, 2010). Initial findings indicated that a half-normal model with no adjustments was preferred for modeling the combined data (all years, with no covariates). Therefore, we adopted this key function subsequently to investigate the importance of covariates that might significantly affect sighting rates. The effects of covariates were modeled as linear contributions to the log-scale parameter of the half-normal key function (Marques and Buckland, 2004). After such effects were evaluated, significant covariates were included in the model to reconfirm that the half-normal key function remained preferred and no cosine adjustment terms were needed.

Covariates examined included size of sighted group, observer name, survey year, ice conditions, sky conditions, Beaufort Sea state, longitude, and latitude. These latter two variables were tested solely as surrogates to evaluate whether there was any significant unexplained spatial variation in the detection function. Sky condition was rated as “clear,” “partly cloudy,” or “overcast,” however only the “overcast” category had a significant effect on detection, so the former two categories were pooled for simplicity. The sequence in which variables were retained in our model matters and is discussed in the Results.

Ice conditions were reported as a coverage percentage ranging from 0% to 93%. We used a recursive binning approach to simplify these data. Initially, a categorical ice coverage variable was defined with the following 13 bins:

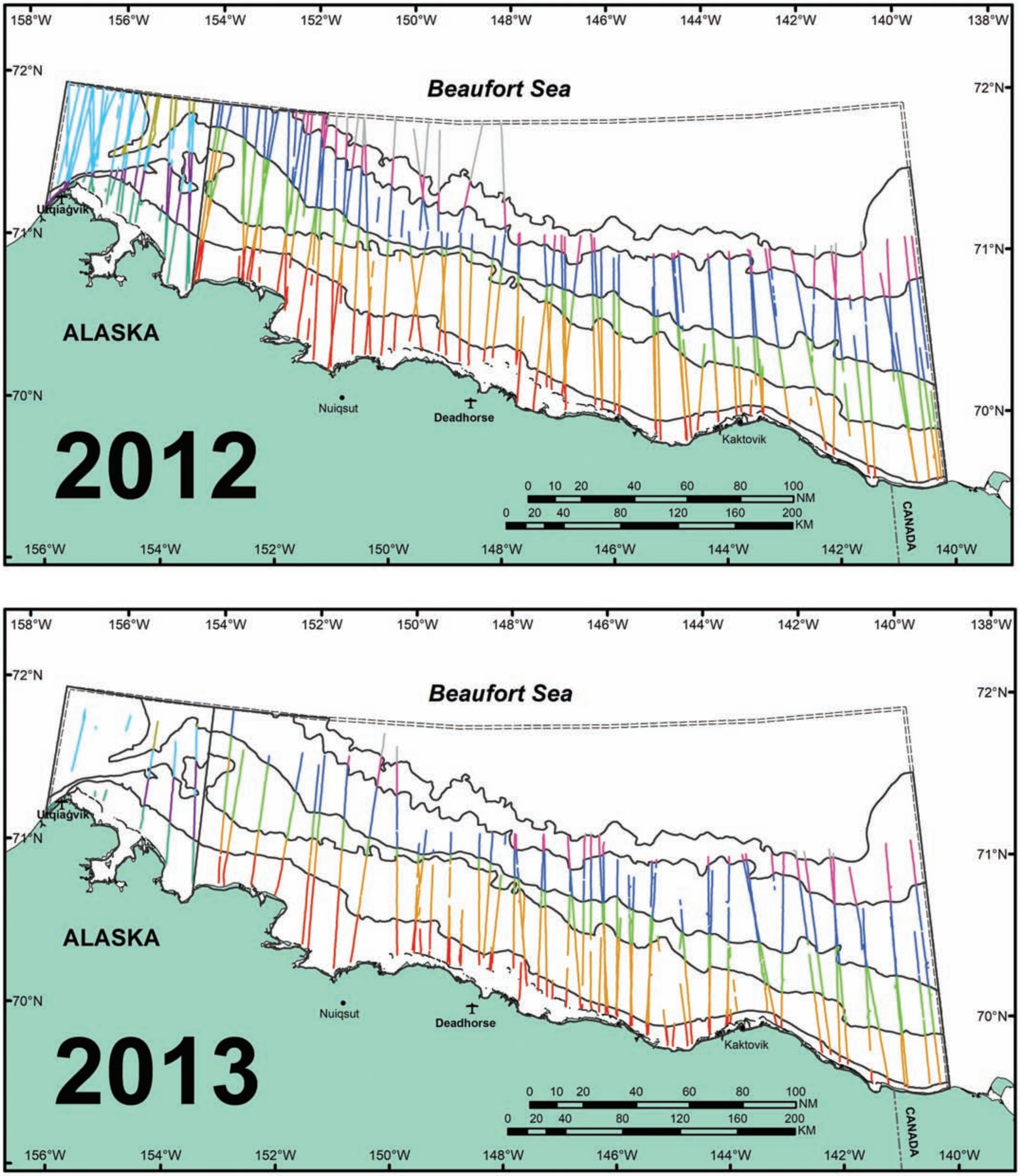


FIG. 2. Transects included in analyses, colored by strata. The colors and depth (m) stratum labels are as follows: 0–20E (red), 0–20W (dark green), 20–50E (orange), 20–50W (dark purple), 50–200E (light green), 50–200W (cyan), 200–2000E (blue), 200–2000W (olive), 2000–2500E (magenta), 2500–72˚ N (gray, not used in analysis).

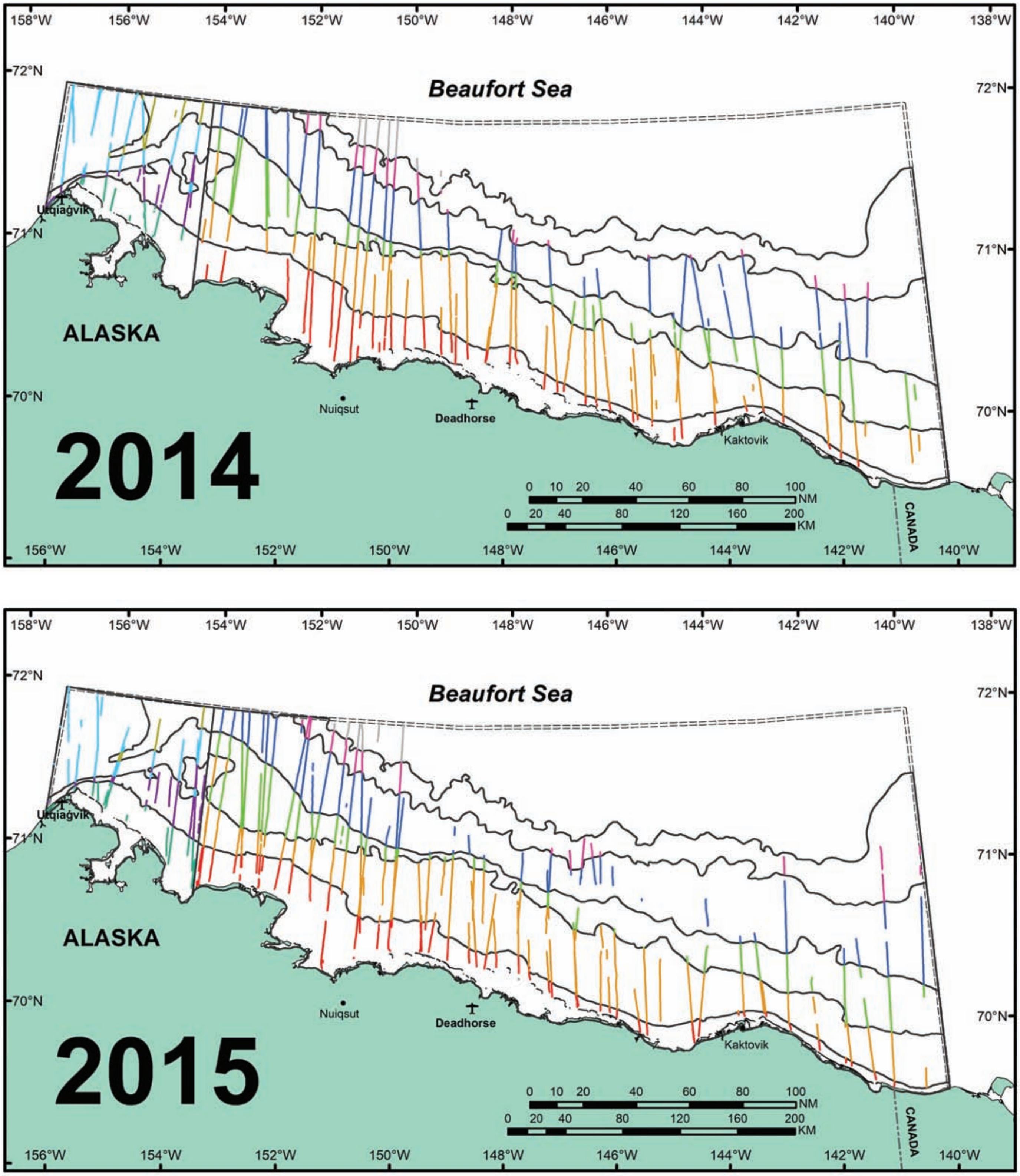
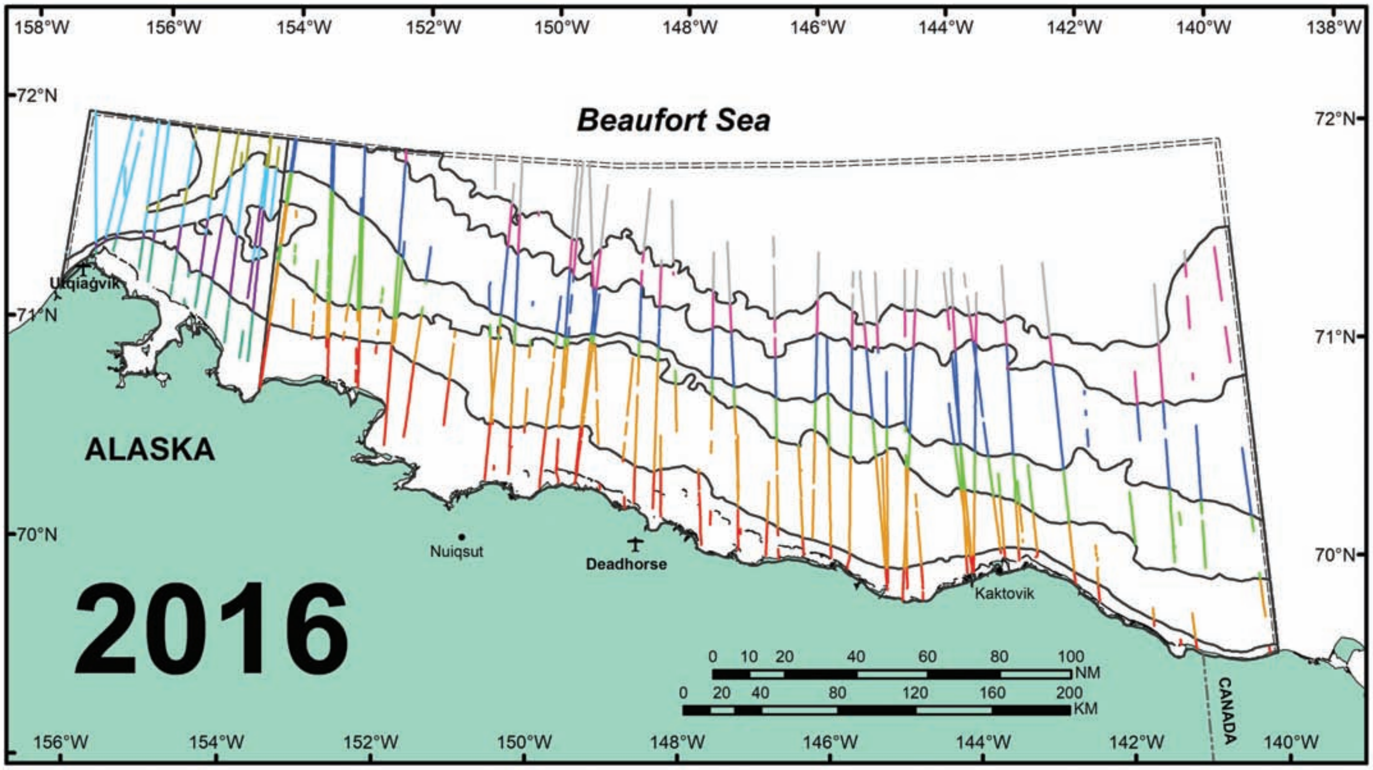


FIG. 2 – *continued*: Transects included in analyses, colored by strata. The colors and depth (m) stratum labels are as follows: 0–20E (red), 0–20W (dark green), 20–50E (orange), 20–50W (dark purple), 50–200E (light green), 50–200W (cyan), 200–2000E (blue), 200–2000W (olive), 2000–2500E (magenta), 2500–72° N (gray, not used in analysis).



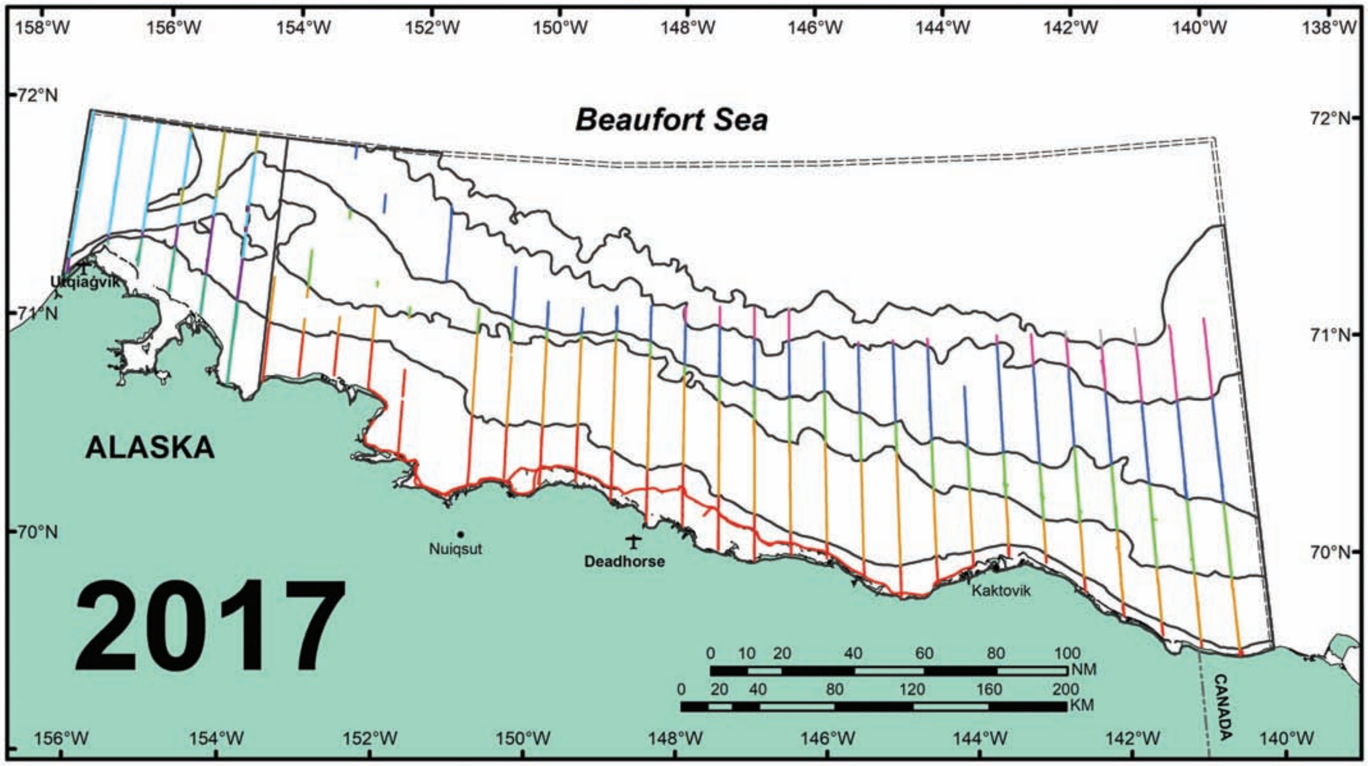


FIG. 2 – *continued*: Transects included in analyses, colored by strata. The colors and depth (m) stratum labels are as follows: 0–20E (red), 0–20W (dark green), 20–50E (orange), 20–50W (dark purple), 50–200E (light green), 50–200W (cyan), 200–2000E (blue), 200–2000W (olive), 2000–2500E (magenta), 2500–72° N (gray, not used in analysis).

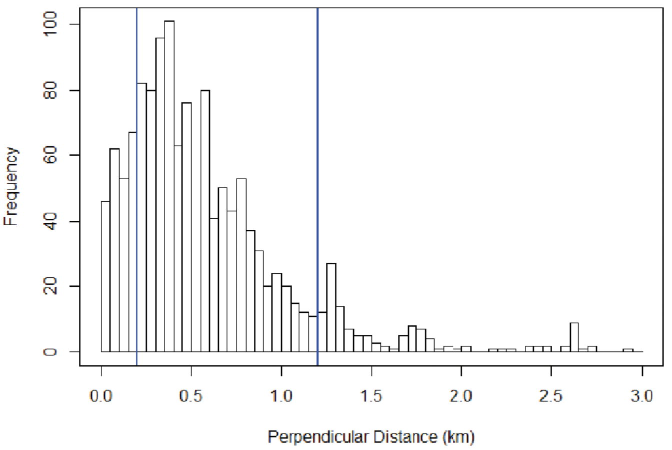


FIG. 3. Histogram of sightings distances for the analyzed dataset, all years combined. Vertical blue lines indicate the truncation used for estimating the detection function. A small number of distances exceeding 3 km are not shown.

0, 1–4, 5–9, 10–14, 15–19, 20–24, 25–29, 30–34, 35–39, 40–49, 50–59, 60–74, 75–100. After fitting the detection function model with this variable, we tried 12 simpler alternative binnings achieved by pooling two adjacent bins from the original variable. The best of these (according to AIC) was chosen. Then the process was repeated, trying 11 ways to pool the best 12-bin variable. This process was repeated until no further simplification improved AIC. At the end of the process (at which point only three bins remained), we reconfirmed that several other alternatives (such as keeping 0% ice in a separate bin) were also inferior to our result.

Abundance Estimates

As noted above, we used a reduced dataset that excludes the deepest (exceeding 2500 m) stratum because there was virtually no survey effort there (Fig. 2). To the remaining transects, we fit standard Horvitz-Thompson-like abundance estimates independently for each year (Buckland et al., 2001), including accounting for the group size of each sighting. All these abundance estimates employed the same detection function estimate obtained from the full data as described above. Estimates were fit using the *dht()* function in the Distance package (version 0.9.7) in R (Miller, 2017; R Core Team, 2018). The resulting estimates pertain to the number of belugas visible from the aircraft; an availability correction is presented next.

Lowry et al. (2017) provide information about dive behavior. They reported that 19 tagged belugas spent an average proportion of 0.54 (CV = 0.45) of their time in 0–10 m depths when they are assumed to be visible from the plane. For consistency, we retain this definition of visibility. However, we note that even if a beluga is not visible at 10 m depths, it is probably still visible to the observers in the sense that it either just surfaced or will surface within a few seconds.

Unfortunately, the data table of Lowry et al. (2017) lists only 18 whales, not 19. Furthermore, they appear to have used the standard deviation rather than the standard error of the mean when estimating uncertainty for the abundance estimate. We have chosen to use the standard error of the mean, so the CV for 0.54 is taken to be $0.45/\sqrt{18}$. Defining the estimated total number of belugas in the survey area in a year as $\hat{N} = \hat{Y}/0.54$ where $\hat{Y}$ is the estimate from the preceding paragraph, we can calculate the corresponding CV by pooling variances as $\mathrm{CV}\{\hat{N}\} = \sqrt{\mathrm{CV}\{\hat{Y}\}^2 + 0.45^2/18}$.

RESULTS

Detection Function

In total, 999 beluga group sightings were used in the detection function analysis, comprising 2465 individuals. Table 1 summarizes the sequence of candidate models fit. This process led to a single chosen model, having greatest possible parsimony while retaining the best AIC in the sense explained above. Table 2 shows the parameter estimates for the chosen model. Figure 4 shows the estimated detection function.

In Table 1, the null model used a half-normal key function with no cosine adjustments; alternative starting options had inferior AIC. Next, we investigated group size effects. There was no indication that larger groups were sighted relatively more often (compared to smaller groups and single animals) at larger distances. Using a non-parametric scatterplot smoother and ordinary linear regression to assess average group size as a function of

TABLE 1. Model selection proceeded from top to bottom. Better models have lower AIC values, and the best model (Ice+Overcast) is the simplest one that incorporates significant covariate effects and cannot be improved upon by at least 2.0 AIC points.

Model	AIC	Notes
Null	−311.25	Half-normal key function with no cosine adjustments.
Group size	−309.22	Best of several binnings; inferior to null model.
Year	−313.93	Improved AIC is attributed to ice effects; see below.
Ice	−342.61	Best categorical: 0%–9%, 10%–59%, 60%–100%.
Ice+Year	−335.59	After controlling for ice, no year effect should be included.
Ice+Overcast	−348.82	Significant effect for overcast. Our best model.
Ice+Overcast+Observer	−337.83	No observer effect.
Ice+Overcast+Longitude	−348.97	No spatial component.
Ice+Overcast+Latitude	−348.19	No spatial component.

TABLE 2. Estimated terms in the log-linear model for the half-normal scale parameter in the detection function. Effects for 60%–100% ice and clear to partly cloudy skies are subsumed in the intercept.

Model term	Parameter estimate	Standard error
Intercept	−1.256	0.094
Ice 0–9%	0.688	0.105
Ice 10–59%	0.419	0.106
Overcast	−0.187	0.065

sighting distance revealed that mean group size slightly decreased (statistically non-significantly) as distance increased. We also fit detection functions that included several binnings of the group size variable, and these models all showed non-significant group size effects and inferior AIC compared to the null model (Table 1).

Table 1 shows that incorporating a year effect in the detection function modestly improved AIC. It turns out, however, that this is primarily because 2015 was a heavier ice year in the western Beaufort Sea in late July through August, and ice coverage has a very strong influence on detection. Using our recursive binning approach, we found that the best ice coverage categories were 0%–9%, 10%–59% and 60%–100%. Incorporating this categorized ice coverage variable yielded a substantial improvement in AIC. Moreover, once ice coverage was used in the model, there was no significant improvement to be achieved by adding year (Table 1). A model term for overcast sky conditions also significantly improved the detection function. This variable was binary, with the alternative being clear or partly cloudy.

We found no observer effects. Also, after accounting for ice and sky condition, the model was not significantly

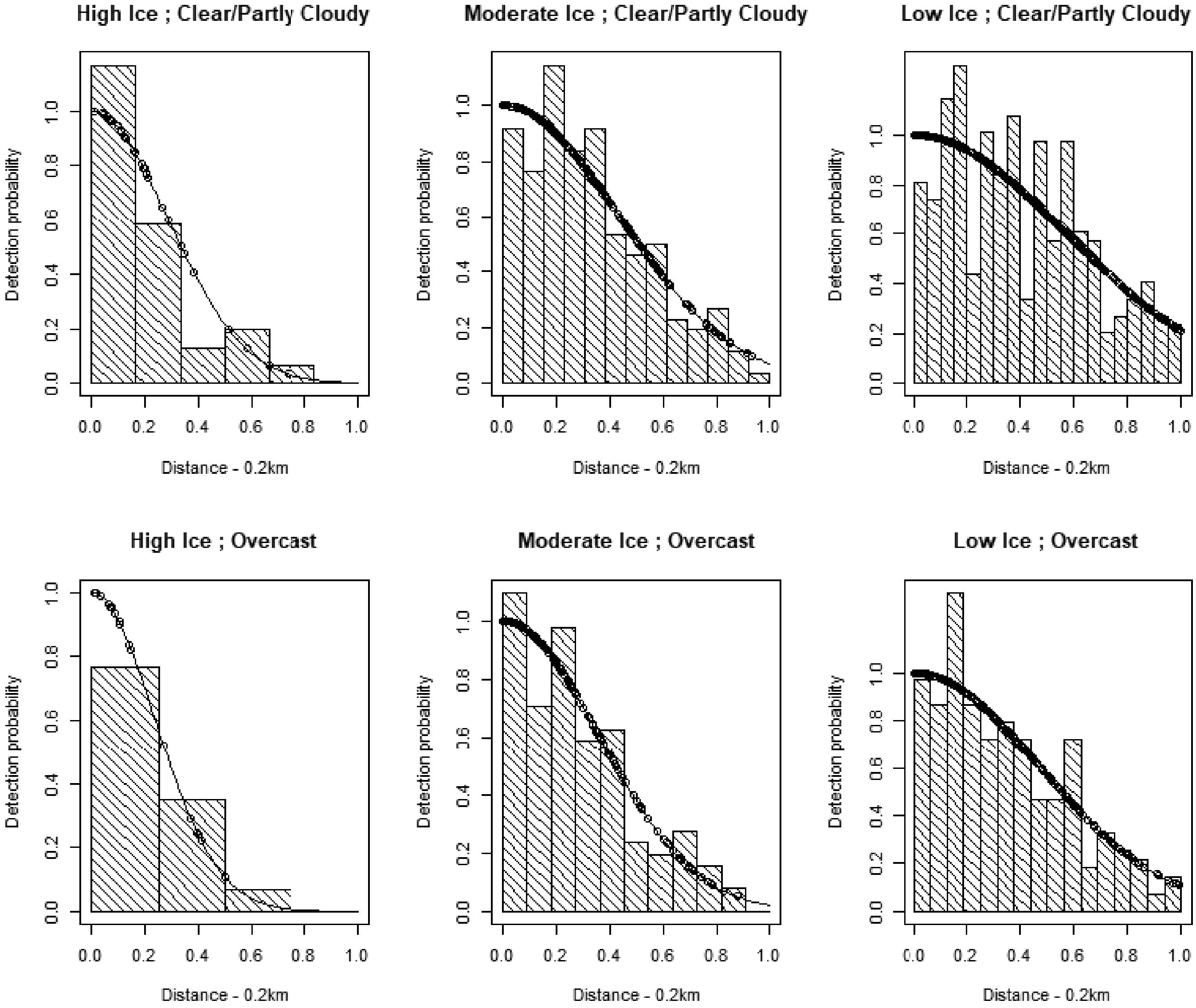


FIG. 4. Histograms of sighting distances (after subtracting 0.2 km as described in text) and fitted detection functions (curves). The dots correspond to individual sightings. Ice and sky conditions are given in the figure panel titles.

improved by adding terms for longitude or latitude. We interpret this result as a lack of evidence for unexplained spatial variation in the detection function. An unweighted Cramer-von Mises test using 10 distance classes indicates no lack-of-fit for our final model ($p = 0.81$).

The parameter estimates in Table 2 can be interpreted as follows. The half-normal key function scale parameter, or equivalently the effective strip width (ESW), is significantly greater for low and moderate ice coverage, compared to high ice. Overcast skies are associated with a significant decrease in ESW. These results are also illustrated in Figure 4.

Abundance

Table 3 shows the strata areas, qualifying survey effort, and numbers of individuals sighted in each year. Table 4 provides our abundance estimates and related results. The estimated number of belugas 0 – 10 m below surface is denoted $\hat{Y}$, and the estimated total number in the survey area after correcting for diving whales is denoted $\hat{N}$. We also show corresponding CVs and 95% confidence intervals for the total abundances in the survey area, using the log approach (Burnham et al., 1987:211 – 213; Buckland et al., 2001:116).

DISCUSSION

The area covered by ASAMM did not include the entire summer range of ECS belugas (Suydam et al., 2001; Hauser et al., 2014; Lowry et al., 2017). Tagging data show that Chukchi Sea and Beaufort Sea belugas travel much farther north during the summer (Richard et al., 2001; Suydam et al., 2001; Suydam, 2009; Hauser et al., 2014). In general, ECS belugas occupy habitat in the Beaufort Sea that tends to include deep water, have a steep slope, and ice cover (Moore, 2000; Clarke et al., 2018b). Although sea ice cover likely does not directly impact beluga abundance, it probably has an impact through effects on prey availability (Clarke et al., 2018b; Hauser et al., 2018).

Furthermore, Clarke et al. (2018b) and O'Corry-Crowe et al. (2016) report significant interannual variation in range and habitat selection, suggesting that the portion of the population present in the study area may fluctuate substantially within a year and vary between years. Indeed, Clarke et al. (2018b) observed a more than tenfold difference in beluga relative density in summer and fall in the western Beaufort Sea from 2009 to 2016 (0.0055 belugas/km surveyed in 2010; 0.0652 belugas/km surveyed in 2014). Factors impacting distribution and thus abundance estimates may include the proportion of the ECS beluga stock that occurs in the eastern Beaufort Sea each summer, the proportion of the ECS stock that uses the study area, the possible presence of BS belugas in the study area, timing of the onset of the westward migration, foraging opportunities, possible impacts from industrial activities (e.g., oil and gas activities, commercial shipping), and presence of potential predators. In particular, prey, which are influenced by water depth, slope and ice cover, likely have a strong influence on beluga distribution (Stafford et al., 2013, 2018; Hauser et al., 2015). The variable nature of prey distribution likely results in differing levels of use of the study region in different years.

Thus, our abundance estimates do not constitute estimates of the entire ECS stock, merely the portion present in the study region during each year of the analysis period. This may explain why, in 2014 and 2017, the estimated abundance in the survey area is roughly double that in other years, which seems unrelated to survey coverage or total sightings. It is possible that ECS belugas simply inhabited the survey area more preferentially in these years than others. Unfortunately, very few data from tagged belugas, beluga stomach samples from this area, and prey sampling are available to explain the abundance variation we found in the 2012 – 17 period. The available stomach samples from ECS belugas are from the eastern Chukchi Sea prior to when the whales arrive in the Chukchi Sea (Quakenbush et al., 2015) and no samples are available for ECS belugas harvested in the Beaufort Sea. One of the primary prey of BS belugas in the Beaufort Sea is Arctic cod (Loseto et al., 2009); cod are likely primary prey for ECS belugas in this area as well. Thus, beluga distribution is subject to potentially substantial interannual variation of their prey (Bluhm and Gradinger, 2008; Logerwell et al., 2011). Hauser et al. (2017) suggested that belugas may track oceanographic eddies north of the Beaufort Sea in the Canadian Basin (Llinás et al., 2009), which are outside the study area and likely entrain prey. Because eddies can be ephemeral, beluga distribution may change substantially with variable oceanographic conditions therefore influencing the presence of belugas within the study area. Indeed, many of the tagged ECS belugas spent time far to the north of the study area presumably in search of prey (Suydam et al., 2001; Hauser et al., 2015).

Our analysis is based on an assumption that the ECS and BS stocks of belugas are separated in July and August by a boundary at 140° W longitude. This simplifying assumption facilitates modeling, analysis, and comparison with Lowry et al. (2017), but may not be entirely true. First, the lack of stock overlap during this period within the Alaskan Beaufort Sea is based upon data from satellite tags that are rather old. In the last decade, animal distribution may have changed, particularly in response to changes in habitat and climate. Second, the tagged belugas were not randomly sampled from their respective populations: the ECS belugas were tagged near Point Lay in July, and the BS belugas were tagged in the Mackenzie Delta in July (mostly) and August. Hence, there is almost no way that tagged animals could overlap in July simply because the tagging locations are so far apart. However, this is not proof that the populations do not overlap during July and August, merely that belugas tagged in these locations do not overlap then. Third, genetic evidence from harvested belugas indicates

TABLE 3. Strata, their area (km^2), and annual amounts of survey effort (E, in km) and individuals sighted (n) in each.

		2012		2013		2014		2015		2016		2017	
Stratum	Area	E	*n*	E	*n*	E	*n*	E	*n*	E	*n*	E	*n*
0−20E	12076.952	1135.062	2	836.523	0	660.062	7	644.413	2	770.710	0	1715.830	0
0−20W	3411.625	366.815	0	107.875	0	108.749	1	194.498	0	181.426	0	357.841	0
20−50E	19611.210	2614.911	24	2311.783	33	1621.009	6	1808.202	2	1898.529	0	2258.005	50
20−50W	1933.316	367.456	0	105.972	0	169.629	4	237.849	3	212.243	0	251.690	0
50−200E	12056.012	1629.175	36	1151.034	27	839.739	24	906.196	28	958.162	9	953.126	32
50−200W	4576.867	1043.930	50	151.873	0	381.450	41	338.557	3	492.072	2	721.767	0
200−2000E	18994.676	2429.545	362	1541.044	190	1070.031	371	1014.809	136	1317.884	201	1345.514	247
200−2000W	1152.930	225.150	40	25.702	6	99.404	33	48.846	25	135.603	16	111.829	44
2000−2500E	10432.706	719.323	39	434.067	31	192.619	22	243.929	7	547.595	43	318.872	83
Total	84246.294	10531.267	553	6665.873	287	5142.692	509	5437.299	206	6514.224	271	8034.474	456

TABLE 4. Estimated number of belugas 0–10 m below surface ($\hat{Y}$) and total numbers in the survey area after correcting for diving whales ($\hat{N}$), corresponding CVs, and 95% confidence intervals for total abundance in the survey area.

	2012	2013	2014	2015	2016	2017
$\hat{Y}$	3972	3679	8963	3486	3761	7185
CV$\{\hat{Y}\}$	0.135	0.140	0.182	0.175	0.205	0.245
$\hat{N}$	7355	6813	16598	6456	6965	13305
CV$\{\hat{N}\}$	0.171	0.176	0.211	0.205	0.231	0.267
95% CI	5268, 10268	4837, 9595	11934, 24966	4339, 9606	4456, 10885	7960, 22239

that BS belugas are sometimes found in the Chukchi Sea in late July (O'Corry-Crowe et al., 2018).

The intrusion of BS belugas into our ECS analysis area could be enough to substantially affect our abundance estimates. This intrusion is one potential explanation for the large interannual variation in our estimates. However, it is also true that some ECS belugas occur outside the study area during summer, thereby impacting our estimates in the opposite direction. Further study of stock structure and distribution during summer is warranted.

Our 2012 abundance estimate uses mostly the same data as that of Lowry et al. (2017), however the estimates are not directly comparable for several reasons, including (1) our chosen study region differs slightly from theirs, and (2) we do not correct for belugas outside the study region. Of course, our analyses also differ in other ways whose impact and comparability are less clear: (1) we stratify bathymetrically rather than longitudinally, and (2) we use a simpler, more standard detection function model that includes left truncation. The proportion of days that tagged belugas were located within the Lowry et al. (2017) study area was 0.64 (females) and 0.35 (males), which means that if we ignore the different study area boundaries, correcting our estimates for this factor would roughly double the abundances. It is possible to derive a somewhat comparable estimate from the Lowry et al. (2017) results by removing their correction factors for whales outside the study region. This changes their 2012 estimate to 10 272 (CV 0.50), compared to our estimate of 7355 (CV 0.17).

Our stratification choice could be debated. In particular, since most belugas are seen in depths of 200 m or more, perhaps shallower strata could have been pooled. Since the contributions to our estimates from these strata are relatively small, this choice would have a quite limited impact on our abundance estimates or their overall precision. The E/W stratification is potentially important since the Barrow Canyon region provides quite a different habitat than the shallower, flatter coastal regions to the east.

Three anomalous sightings were set aside when estimating the detection function (although they were included in the abundance step). To investigate the impact of this choice, we re-ran the analyses retaining those cases throughout. We found that this choice was important. Table 5 provides alternative estimates for the impacted years, when these few sightings of huge groups were included in all parts of the analysis. We recommend the results in Table 4.

TABLE 5. Estimated number of belugas 0–10 m below surface ($\hat{Y}$) and total numbers in survey area after correcting for diving whales ($\hat{N}$), corresponding CVs, and 95% confidence intervals for total abundance in the survey area, for an alternative analysis that includes the few very large groups at all stages of analysis.

	2012	2013	2014	2015	2016	2017
$\hat{Y}$	4913	3682	10923	3490	3764	10515
CV$\{\hat{Y}\}$	0.181	0.140	0.282	0.175	0.205	0.389
$\hat{N}$	9099	6819	20228	6463	6971	19471
CV$\{\hat{N}\}$	0.210	0.176	0.302	0.205	0.231	0.404
95% CI	6060, 13659	4842, 9604	11344, 36067	4343, 9618	4460, 10896	9094, 41691

As noted above, we used the standard error of the mean when incorporating uncertainty from the dive tag data analysis of Lowry et al. (2017). If we had taken their results at face value, the estimates of CV$\{\hat{N}\}$ would have been 0.470, 0.471, 0.485, 0.483, 0.494, and 0.512 for 2012 through 2017, respectively. The point estimates of abundance would have been unchanged.

Our series of abundance estimates show no time trend (log regression estimated annual increase rate of 6.1%, with 95% CI = (−13.4%, 30.2%), $p = 0.59$). There is therefore no reason to infer from our analysis that the abundance of eastern Chukchi Sea beluga is changing, but there are two important caveats to this claim. First, our CVs are quite high, so only a strong population trend would be detectable from our data. Second, it remains possible that a population trend due to a combination of climate change, industrial activity, food availability, hunting, or other factors is masked by a counteracting trend in the extent to which beluga choose to inhabit the study region during the study period. In summary, our estimates provide the most comprehensive longitudinal look at ECS beluga abundance to date and provide evidence of an abundant population without apparent major decline over the study period.

ACKNOWLEDGEMENTS

Funding for and co-management of the Aerial Surveys of Arctic Marine Mammals project was provided by the Bureau of Ocean Energy Management (BOEM), Alaska OCS Region, under Interagency Agreement Nos. M11PG00033, M16PG00013, and M17PG00031. In 2012, the ABWC also provided funding. The North Slope Borough provided funds for the analyses of data, with additional contributions from the ABWC using marine mammal co-management funds from the National Oceanic and Atmospheric Administration (grant NA17NMF4390131). We thank John Citta and two anonymous reviewers for helpful comments that improved the manuscript. We thank BOEM staff including Cathy Coon, Jeffrey Denton, Carol Fairfield and Dee Williams. We also thank Clearwater Air, Inc. and flight followers from the USDOI Aviation Management Division and the Bureau of Land Management Anchorage Interagency Dispatch Center. Finally, we thank the dedicated and highly skilled ASAMM observers and pilots without whom this valuable dataset would not exist.

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