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Evaluation of LGL visual aerial survey data for estimating narwhal abundance in Eclipse Sound during the open-water season 2013–2015

Cory J.D. Matthews, Claire A. Hornby,
Steven H. Ferguson, and Marianne Marcoux

Freshwater Institute
Fisheries and Oceans Canada
501 University Crescent
Winnipeg, MB, R3T 2N6

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The Eclipse Sound narwhal (*Monodon monoceros*) stock is one of several summering aggregations of the Baffin Bay narwhal population. LGL Environmental Research Associates were enlisted by Baffinland Iron Mines Corporation to conduct aerial surveys of narwhals in Eclipse Sound during the open-water season (early August to mid-October) from 2013-2015 to assess shipping impacts of the Mary River Project on their distribution. Baffinland provided the three years of aerial survey data to DFO to evaluate for the purpose of estimating Eclipse Sound narwhal stock abundance. The spatiotemporal coverage of the surveys differed among the three years, and only the 2014 surveys spanned the entire range of Eclipse Sound narwhals during the early to late August period when narwhals are assumed to be resident to their summering stocks. The 2013 data in particular excluded portions of the Eclipse Sound narwhal summering range during the period of peak occupancy, and were therefore not analysed. Histograms of the number of detections with perpendicular distance revealed a large number of detections were missed within the defined strip width during all survey years. Although distance sampling analysis can account for such declines in detections with increasing distance from the track line, the high proportion of observations missing perpendicular distances posed problems for this analysis. In particular, assumptions that missing distances did not occur on the track line or occurred randomly with respect to perpendicular distance could not be evaluated. Other limitations included the single midline transects of fiord strata, which violated distance sampling assumptions and did not span a sufficient range of covariate values to estimate abundance using density surface modelling. Validity of the abundance estimates for calculating hunt quotas is therefore uncertain. However, estimates may be potentially useful as indices of relative abundance throughout the survey period and among years for the areas that were surveyed consistently.

INTRODUCTION

The Baffin Bay narwhal (*Monodon monoceros*) population is the largest of Canada's two narwhal populations, numbering approximately 140,000 individuals (Doniol-Valcroze et al. 2015a). During summer, Baffin Bay narwhals are distributed in fiords and inlets of northeastern Canada and western Greenland, with individuals typically showing site fidelity to a given region during the post-calving period (Dietz et al. 2001, Heide-Jørgensen et al. 2002, Heide-Jørgensen et al. 2003, Dietz et al. 2008, Watt et al. 2012). These regional summer aggregations form the basis of independently managed stocks in Canada and Greenland, where narwhals are subject to subsistence hunts. In Canadian waters, there are four defined Baffin Bay narwhal stocks, Somerset Island, Admiralty Inlet, Eclipse Sound, and East Baffin Island, and two putative stocks, Smith and Jones Sound (Richard 2010).

The Eclipse Sound narwhal stock was surveyed by Fisheries and Oceans Canada (DFO) in 2004 and 2013, resulting in abundance estimates of 20,225 (Coefficient of Variation [CV] = 0.36) and 10,489 (CV = 0.24) respectively (Richard et al. 2010, Doniol-Valcroze et al. 2015a). In contrast, the 2013 estimate for the neighboring Admiralty Inlet stock (35,043; CV = 0.42; Doniol-Valcroze et al. 2015a) was higher than the previous estimate in 2010 (18,049; CV = 0.23; Asselin and Richard 2011), which has raised questions about mixing of animals between the two adjacent summering stocks (Doniol-Valcroze et al. 2015a). Supporting evidence has been inconclusive because, while most narwhals tagged in the Eclipse Sound area typically remain in the region throughout the summer and return after overwintering in Baffin Bay (Dietz et al. 2001, Heide-Jørgensen et al. 2002, Watt et al. 2012), Watt et al. (2012) reported that one narwhal tagged in Tremblay Sound in 2010 summered in Admiralty Inlet in 2011, and nearly half of the narwhals tagged in Eclipse Sound in 2009 and 2010 left the area in late August and traveled into areas occupied by the Admiralty Inlet and Somerset Island stocks further west.

Additional abundance estimates of Eclipse Sound narwhals are required for assessment of interannual variation in abundance, and to provide additional data for modelling stock abundance trajectory (Witting 2015, Watt et al. 2019). To that end, DFO conducted a third aerial survey of the stock in August 2016, with a resulting abundance estimate of 12,039 (CV = 0.23; Marcoux et al. 2019). DFO has also been provided aerial survey data collected by the environmental consulting company LGL Environmental Research Associates in 2013, 2014, and 2015. LGL was hired by the mining company Baffinland Iron Mines Corporation to assess potential impacts of shipping iron ore from Baffinland's Mary River Project on narwhals in the area. Aerial surveys in 2013 and 2014 were conducted primarily to collect baseline data before operational shipping began in 2015, when research efforts were focused on documenting potential impacts on narwhals (Thomas et al. 2015a). Although the surveys were designed to detect changes in overall spatiotemporal distribution patterns of narwhals in response to large vessel traffic, they were conducted using similar protocols and covered a similar area as DFO surveys designed to assess abundance.

The time series of survey data across three consecutive years (two of which were not surveyed by DFO) is potentially valuable for modelling trends in Eclipse Sound narwhal abundance (Witting 2015, Watt et al. 2019), and advancing DFO's efforts to manage this stock using a precautionary approach framework (Stenson and Hammill 2008, Stenson et al. 2012). We assess here whether the spatiotemporal coverage and data quality of the LGL surveys can be used to derive abundance estimates comparable to those of DFO surveys.

METHODS

SURVEY AREA AND DESIGN

Aerial surveys were conducted roughly bi-weekly over much of the open-water season (early August to mid-September or later), and covered most, if not all, of the summer range of narwhals in Eclipse Sound. Details of the 2013, 2014, and 2015 aerial surveys, which differed somewhat in their timing and spatial coverage, are presented in Elliott et al. (2015), Thomas et al. (2015a), and Thomas et al. (2015b), respectively.

In 2013, eight surveys were conducted from August 31 to October 18. Two surveys were carried out on adjacent days roughly every two weeks (Table 1). The first four surveys in late August and mid-September included Navy Board Inlet, the western third of Eclipse Sound, Milne Inlet, and Tremblay Sound (Figure 1). Coverage of the fifth and sixth surveys was extended eastward to include the rest of Eclipse Sound (late September). The seventh survey covered the entire area including Pond Inlet in mid-October (Figure 1). The spatial coverage of the final (eighth) survey conducted over the following two days was similar, but omitted Koluktoo Bay and Tremblay Sound (Table 1). Navy Board Inlet, Eclipse Sound, Milne Inlet, Koluktoo Bay, and Pond Inlet were surveyed using systematic transects, while Tremblay Sound was surveyed using a single non-linear transect run down the middle of the sound.

In 2014, 12 surveys were conducted from the beginning of August to the end of October. Similar to 2013, two surveys were carried out on adjacent days roughly every two weeks, resulting in six survey periods (Table 1). The first survey of each two-week period covered the entire summering range of Eclipse Sound narwhals, including the fiords off southern Eclipse Sound (Figure 1). Fiords were omitted from the second of each paired survey conducted on the subsequent day.

In 2015, surveys were conducted just once every two weeks from August 1 to September 17 (Table 1). As in 2014, Eclipse Sound, Milne Inlet, Koluktoo Bay, and Pond Inlet were surveyed using systematic transects (Figure 1), while Tremblay Sound was surveyed with one non-linear transect flown in the center of the sound (Figure 1). The Navy Board Inlet and fiord strata were excluded in all 2015 surveys.

SURVEY PROTOCOL

Surveys were flown using the same aircraft model and flight parameters during all three years (Elliott et al. 2015, Thomas et al. 2015a,b). A DeHavilland DHC-6 Series 300 Twin Otter fitted with four bubble windows and an optical glass-covered ventral camera port at the rear of the plane was flown at an altitude of 1,000 ft (305 m) above sea level at a ground speed of 120 knots (222 km/h). Surveys were conducted with a dual-platform observer design with four observers seated at bubble windows, two on each side of the aircraft. However, data from just the primary observers at the front of the aircraft were provided to DFO. Observers recorded narwhal group sizes within a ~1,000 m strip that extended from 135.7 m to 1,137.9 m from the aircraft, although they also scanned for narwhals beyond the defined strip width at a reduced level of effort when none were observed close to the aircraft (Elliott et al. 2015). The perpendicular declination angle to each observation was measured using a clinometer, although observers failed to do so when high narwhal densities overwhelmed their capacity to both record group size and measure angles (Elliott et al. 2015). The two primary observers also recorded ice cover, ice type, sea state (Beaufort scale), ‘sightability’, and sun glare every 2-minutes on-transect, and at any point noticeable changes in these conditions occurred. Flight data (latitude, longitude, and altitude) were recorded continually at 1 second intervals by a Garmin GPS receiver that was connected to a notebook computer onboard the aircraft.

DATA ANALYSIS

Survey Assessment

Initial assessments of the temporal and spatial coverage of the LGL surveys led to the exclusion of the 2013 data from subsequent analysis because of incomplete spatial coverage. The only surveys to cover the entire area in 2013 were conducted in mid-October, after Eclipse Sound narwhals (and stocks further west that may pass through Eclipse Sound) have begun their eastward migration to Baffin Bay (Watt et al. 2012). Therefore, the 2013 surveys would not provide comparable abundance estimates to previous DFO surveys conducted in early to mid-August, and were not considered further.

Survey coverage in 2014 was largely similar to that of DFO surveys in terms of spatial extent, and the first four surveys occurred during early to mid-August, which is when DFO conducts its surveys (based on when the Eclipse Sound narwhal stock occupy their summer range; Watt et al. 2012). While the 2015 survey omitted Navy Board Inlet and the eastern fiord strata, these strata have had no or few narwhals in previous (Doniol-Valcroze et al. 2015a) or subsequent surveys (Marcoux et al. 2019). Bearing that caveat in mind, survey data from both 2014 and 2015 were further assessed for the purpose of estimating abundance.

Non-fiord Strata

Although surveys were conducted using a strip design, initial examination of data clearly indicated detections were missed over the strip width (see ‘Results’). Survey data from 2014 and 2015 were therefore treated as a line transect design, which allows for detection probability to decrease with increasing distance from the transect (Buckland et al. 2001, 2004). Data were analysed using distance sampling, which models detection probability as a function of distance from a line (or point) to estimate the effective strip half width (ESHW; see Thomas et al. 2010), which is used to estimate density ($\widehat{D}$) as:

$$\widehat{D} = \frac{n \cdot \hat{E}(s)}{2 * L * ESHW}$$

with variance calculated as:

$$var(\widehat{D}) = \widehat{D}^2 \times \left\{ \frac{var(n)}{n^2} + \frac{var(ESHW)}{ESHW^2} + \frac{var(\hat{E}(s))}{\hat{E}(s)^2} \right\}$$

where n is the number of detected groups, $\hat{E}(s)$ is the expected group size, and L is the summed transect length making up the survey (Buckland et al. 2001). Abundance ($\widehat{N}$) can then be estimated as:

$$\widehat{N} = \widehat{D} * A$$

where A is the area surveyed.

The 2014 and 2015 survey data had an unusually large number of detections lacking declination angle measurements (57% and 53% of all observations in 2014 and 2015, respectively) required to calculate perpendicular distances, which posed a problem for distance sampling analysis that is typically dealt with using one of two approaches. The more conservative of the two is to simply exclude all detections with missing distances from the analysis, as distance sampling produces unbiased estimates provided the omitted detections were not at zero distance (Thomas et al. 2010). However, this approach excludes data that would otherwise contribute to estimates of encounter rate and cluster size, and in this particular case, would eliminate the majority of survey data. The second approach, which has been employed in previous analyses of DFO surveys (albeit ones with smaller proportions of missing distance data), is to fit the detection function to observations with distances to estimate the average detection probability, which is then applied in an analysis of the entire dataset to estimate cluster size and encounter rate (Doniol-Valcroze et al. 2015a, Matthews et al. 2017).

The primary assumption of distance sampling is that all objects on the track line are detected (Buckland et al. 2001, Laake and Borchers 2004). Failure of this assumption typically occurs in aerial surveys because the area beneath the aircraft can be obstructed from view, and objects closer to the track line appear to pass by faster than those more distant (Becker and Quang 2009). Histograms of detections with perpendicular distance showed the LGL surveys clearly missed sightings at the track line (see ‘Results’), which likely reflected the survey protocol to focus on a strip offset from the track line (as reported in Elliott et al. 2015). To satisfy the assumption that detection probability at zero distance equals 1 ($g(0) = 1$), aerial survey data are typically left-truncated, which effectively shifts the track line to the perpendicular distance where maximum detections occurred. However, data truncation poses a problem for inclusion of observations with missing distances to estimate density after the detection function has been fit, as they cannot be assumed to have occurred within the truncated data range. We therefore opted to fit gamma detection functions, which, unlike the half-normal and hazard-rate key functions that have a probability of detection of 1 at zero distance, are non-shouldered with a probability of detection of 0 at zero distance (Becker and Quang 2009). Detection functions were fit to non-binned perpendicular distances pooled from all strata surveyed within a given year, since many of the individual surveys did not have a sufficient number of observations to fit detection functions separately. Data were right-truncated at 1000 m, and observations with missing perpendicular distances were excluded prior to model fitting using the conventional distance sampling (CDS) and multiple covariate distance sampling (MCDS) engines using the package mrds 2.1.14 (Laake et al. 2015) in the statistical software R, version 3.1.3 (2015). MCDS allows for the inclusion of additional covariates that can impact the scale of the detection function. Covariates, including observer, Beaufort sea state, sun glare, and ‘sightability’, which was a subjective assessment of overall conditions, were modeled individually and in combination. Potentially related covariates (e.g., sightability and glare or Beaufort sea state) were not included in the same model. Best fit models were assessed using Akaike information criterion (AIC).

For final density (and abundance) estimates, the average probability of detection (p) and its SE from the best-fit model were input as multipliers in a final analysis using Distance 7.1 software (Thomas et al. 2010) that applied a uniform function with no expansions to all observation data. We assumed all observations with missing perpendicular distances occurred within the truncated range (0-1,000 m) since there were very few detections with measured perpendicular distances greater than 1,000 m. Density, cluster size, and encounter rate estimates were computed at the stratum level. Mean cluster size was used in density estimates, since regressions of cluster size against probability of detection (using only observations with perpendicular distances) showed there was no bias in cluster size with respect to perpendicular distance (Buckland et al. 2001). Encounter rate and its variance were estimated using a post-stratification scheme (variance estimator ‘S2’), which has been shown to reduce bias in variance estimation for systematic designs (Fewster et al. 2009).

Fiord Strata

Tremblay Sound and the other fiord strata were surveyed using single, non-linear transects that typically ran down the middle of each stratum. This design violates several assumptions of distance sampling (e.g., unequal coverage probability), and narrow portions of the stratum can impact the detection function when the coastline truncates the observation distance

(Doniol-Valcroze et al. 2015b). For this reason, non-linear transects in fiord strata were analysed using both MCDS and Density Surface Modeling (DSM; Miller et al. 2013a, Doniol-Valcroze et al. 2015 a, b). Koluktoo Bay, which was surveyed using systematic saw-tooth transects, was analysed using distance analysis as outlined above. DSM models line transect data using a Generalized Linear approach, and provides spatially-explicit estimates of animal abundance from either distance sampling, presence/absence, or strip transect field methods (Miller et al. 2013a). This method goes beyond typical distance sampling by accommodating environmental covariates, such as depth, and can model covariate effects on count data, improving interpretation of results. Following the same approach that Doniol-Valcroze et al. (2015b) used to estimate narwhal abundance in fiord strata surveyed by DFO in 2013, we estimated the detection probability/ESHW of fiord transects by fitting a gamma detection function that incorporated the covariates observer, sightability, and Beaufort sea state to survey data grouped by year. Observations along transects were summarized into 1-km long segments. Generalized Additive Models (GAM; Wood 2006) were then constructed with per-segment counts as the response variable (with segment areas corrected for detectability) and distance to shore and distance to the mouth of the fiord as explanatory variables (Doniol-Valcroze et al. 2015b). DSM analyses were done using the package ‘dsm’ version 2.2.15 (Miller et al. 2013b) in the statistical software R, version 3.1.3 (R Core Team 2015). MCDS was also performed as outlined above for the non-fiord strata using average detection probabilities from gamma functions fit separately to non-fiord observations.

Abundance Estimates

Surface abundance was estimated for each stratum for each survey. These estimates were adjusted for availability bias, which refers to the proportion of animals that were submerged at unobservable depths during the survey (Marsh and Sinclair 1989), using correction factors determined from dive profiles of Eclipse Sound and Admiralty Inlet narwhals satellite tagged from 2009-2012 (Watt et al. 2015). The correction factor for the 0-2 m bin, 3.18 ± 0.107 (Watt et al. 2015), was applied to all strata based on a study that showed narwhal-shaped models at depths greater than 2 m could not be detected by observers (Richard et al. 1994). Perception bias, which refers to animals that were available for detection but were missed, could not be estimated using mark recapture distance sampling (MRDS) because only front observer data were provided to DFO. Narwhal abundance for each survey was estimated by summing the surface-only and availability bias-corrected estimates (and their associated variances) of the individual strata. 95% confidence intervals were calculated assuming a log-normal distribution (Buckland 2001).

RESULTS

DETECTION FUNCTION

Histograms of the distribution of perpendicular distances of the straight-line transects from the non-fiord strata indicated the greatest numbers of detections occurred around 200-300 m in both 2014 and 2015, and that fitting gamma detection functions was appropriate (Figure 2). ‘Observer’ and ‘sightability’ were included in the best-fit model for the pooled 2014 survey data, with an average detection probability of 0.362 (Standard Error [SE] = 0.013) and an ESHW of 361.9 m. The CDS model (including perpendicular distance as the only covariate) was the best-fit model for the pooled 2015 data, with an average detection probability of 0.403 (SE = 0.031) and an ESHW of 403.1 m (Table 2).

Histograms for Tremblay Sound and other fiord strata differed from those of the non-fiord strata, as well as between the two years (Figure 3). ‘Observer’ was included in the best-fit model for the pooled 2014 survey data, with an average detection probability of 0.505 (SE = 0.0559) and an ESHW of 505.3 m. Re-fitting the detection function with right data truncation at 800 m, where a smaller spike in detections occurred, resulted in little change, with an average detection probability of 0.510 (SE = 0.161) and an ESHW of 509.8 m. The MCDS model with 'sightability' was the best-fit model for the pooled 2015 data, with an average detection probability of 0.422 (SE = 0.0289) and an effective strip (half) width of 275.8 m (Table 3). The shorter ESHW in 2015 was not due to the fact that the 2014 function included fiord strata not surveyed in 2015 because all but one of the perpendicular distances used in fitting the 2014 detection function were from Tremblay Sound.

ABUNDANCE ESTIMATES

Surface abundance estimates differed greatly among strata, between surveys conducted on adjacent days, throughout the survey period, and between survey years (Table 4, Figure 4). Encounter rate variance (see Table 5) contributed > 90% of overall estimated variance, while variance in cluster size and detection probability were negligible components of overall variance. The density surface models provided poor fits to observation data and nonsensical abundance estimates for the fiord strata, which likely reflected the sparse spatial coverage and detections in the fiord survey (data not shown). All subsequent abundance estimates were calculated using distance sampling, which is equivalent to the naïve models used by Doniol-Valcroze et al. (2015b) when density surface models provided similarly poor results. Note that this prevented incorporation of encounter rate variance into the associated variance estimates, which are small relative to the other strata as a result (Tables 5 and 6). Total availability-bias adjusted abundance estimates summing all strata ranged from 2,296-40,074 narwhals in 2014 and from 3,603-13,200 in 2015 (Table 7, Figure 4).

There were general shifts in abundance among strata that likely reflect shifts in narwhal numbers and/or distribution throughout the survey area. For example, in 2014, Pond Inlet and Eclipse Sound had higher numbers of narwhals at both the beginning and end of the open-water season than throughout it, while the Milne Inlet, Koluktoo Bay, and Tremblay Sound strata showed the opposite trend (Table 6). Although the 2015 surveys were not carried out as far into the season as 2014, the same general pattern occurred in the Eclipse Sound, Milne Inlet, and Tremblay Sound strata (Table 6). The Navy Board Inlet strata (surveyed only in 2014) had no to very few narwhals until mid-September/early October.

DISCUSSION

While the LGL survey data were originally collected for purposes other than estimating abundance, they represent a potentially valuable addition to the time series of Eclipse Sound narwhal abundance estimates necessary to model stock abundance and trajectory (Witting 2015, Watt et al. 2019). Published estimates of Eclipse Sound narwhal abundance include only two years (2004 and 2013), an insufficient number of data points to sufficiently understand trends. DFO's objective under its Precautionary Approach (PA) framework (Stenson and Hammill 2008, Stenson et al. 2012) is to collect the data required to develop population models for marine mammal stocks that are currently considered to be Data Poor and managed using potential biological removal (PBR). Under the model-based approach, harvest advice would instead be based on long-term population trends derived from time series of abundance estimates and harvest removals. Unfortunately, abundance estimates derived from the LGL survey data were deemed to be inappropriate for extending the DFO survey time series because of the high proportion of data missing perpendicular distances. It cannot be determined if detections missing perpendicular distance from the track line were randomly distributed with respect to perpendicular distance, or if they were biased in some way. Missing distances occurred primarily when high density narwhal aggregations overwhelmed observer ability to measure declination angles (Elliott et al. 2015, Thomas et al. 2015a,b) required to calculate perpendicular distances. Since objects nearer the aircraft pass the observer's field of view more quickly relative to those farther away, missing distances may have occurred with greater frequency closer to the track line.

It is common practice to model global detection functions based on pooled data from surveys conducted using the same aircraft and observers in similar conditions (e.g., Doniol-Valcroze et al. 2015a, Matthews et al. 2017), as we have done here. Another option is to fit detection functions to observation data from each individual survey. The surveys conducted on August 1 or 2 in both 2014 and 2015 are missing perpendicular distances for less than 10% of observations (Table 1), which is similar to previous DFO surveys (e.g., Matthews et al. 2017). However, these two surveys were conducted earlier than previous DFO surveys, which took place over August 18-19 in 2013 (Doniol-Valcroze et al. 2015) and August 7-21 in 2016 (Marcoux et al. 2019). The estimates derived from the LGL data are higher later in August, suggesting surveys conducted at the beginning of the month excluded a portion of the stock. Other surveys with lower proportions of missing distance data also occur late in the season (Table 1), but well after narwhals have begun moving out of Eclipse Sound (and perhaps into Eclipse Sound from stocks further west). Another consideration for detection functions fit to the relatively small number of observations for individual surveys is the sample size would likely be inadequate to model covariates that were revealed to have significant impact on detection probability in our analysis of pooled data.

In addition to missing perpendicular distances, the single center-line transects of fiord strata do not satisfy the equal probability of detection assumption of distance sampling (Thomas et al. 2002). Density surface modelling proved to be a poor alternative, as models were poor predictors of narwhal density and abundance. Density surface models require large amounts of spatially referenced data that span a sufficient range of values of modeled covariates. With just one transect and often few detections, data were insufficient to inform models. In particular, transects running down the center of the fiords were equidistant to the coastline, and therefore did not sample a range of the covariate 'distance to shore'. In contrast, Doniol-Valcroze et al. (2015b) and Marcoux et al (2019) successfully used density surface models to estimate narwhal densities in the same fiords, but their analysis was based on multiple transects of each fiord. Comparisons of fiord strata abundance estimates derived from traditional distance sampling and DSM indicate the two differ, with higher estimates produced by distance sampling in recent analyses of narwhal abundance (Doniol-Valcroze et al. 2015b, Marcoux et al. 2019). Therefore, distance sampling analysis may have produced positively biased narwhal abundance estimates in Tremblay Sound and fiord F6, which would in turn have biased total estimates (particularly for surveys for which counts in those surveys were high). Having said this, however, it is interesting that most of the surveys produced estimates that were comparable to or lower than those derived from DFO surveys of Eclipse Sound narwhals.

For the reasons explained above, we recommend that the abundance estimates derived from the LGL survey data not be used to provide management advice. However, provided any biases are consistent across survey estimates, the estimates produced here may be useful as indices of relative variation in narwhal abundance between replicates and throughout the open-water season. The time series of roughly bi-weekly survey estimates display a similar pattern across the open-water season in both 2014 and 2015, revealing general shifts in distribution among the survey strata, as well as the timing of such shifts. Narwhals overwinter in Baffin Bay and begin their spring migration into the Canadian Arctic after ice break up in late June and July (Finley and Gibb 1982). Presumably, Eclipse Sound narwhals enter prior to August and stay in Eclipse Sound through August. The highest numbers of narwhals were observed in Milne Inlet, Koluktoo

Bay, and Tremblay Sound during the August surveys, while the lowest density was observed in the Eclipse Sound and Pond Inlet strata. The higher numbers in the Eclipse Sound and Pond Inlet strata earlier in the season were likely narwhals moving into the area that had yet to redistribute among other strata, while higher numbers in Eclipse Sound, Pond Inlet, and one of the eastern fiords during the September and October surveys were likely animals on their fall migration returning to Baffin Bay. The higher numbers of narwhals observed in Navy Board Inlet towards the end of the survey period in 2014 may have been narwhals migrating from the Admiralty Inlet or Somerset Island stocks

CONCLUSION

The impact of high proportions of missing distance data on final abundance estimates cannot be evaluated, so using them for the purpose of providing management advice is not recommended. However, estimates may serve as indices of relative abundance throughout the open-water period and between survey years.

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REFERENCES CITED

Asselin, N.C., and Richard, P.R. 2011. Results of narwhal (*Monodon monoceros*) aerial surveys in Admiralty Inlet, August 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2011/065. iv + 26 p.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Brochers, D.L., and Thomas, L. 2001. Introduction to distance sampling, Estimating abundance of biological populations. Oxford University Press, New York. 432 p.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Brochers, D.L., and Thomas, L. 2004. Advanced distance sampling, Estimating abundance of biological populations. Oxford University Press, New York. 416 p.

Dietz, R., Richard, P.R., and Acquarone, M. 2001. Summer and Fall Movements of Narwhals (*Monodon monoceros*) from Northeastern Baffin Island towards Northern Davis Strait. Arctic 54(3): 244–261.

Dietz, R., Heide-Jørgensen, M.P., Richard, P., Orr, J., Laidre, K.L., and Schmidt, H.C. 2008. Movements of narwhals (*Monodon monoceros*) from Admiralty Inlet monitored by satellite telemetry. Polar Biol. 31: 1295–1306.

Doniol-Valcroze, T., Gosselin, J.F., Pike, D., Lawson, J., Asselin, N., Hedges, K., and Ferguson, S. 2015a. Abundance estimates of narwhal stocks in the Canadian High Arctic in 2013. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/060. v + 36 p.

Doniol-Valcroze, T., Gosselin, J.-F., Pike, D., and Lawson, J. 2015b. Spatial modelling of narwhal density in fiords during the 2013 High Arctic Cetacean Survey (HACS). DFO Can. Sci. Advis. Sec. Res. Doc. 2015/059. v + 31 p.

Elliott, R.E., Raborn, S., Smith, H.R., and Moulton, V.D. 2015. Marine mammal aerial surveys in Eclipse Sound, Milne Inlet, Navy Board Inlet, and Pond Inlet, 31 August – 18 October 2013. Final LGL Report No. TA8357-3. Prepared by LGL Limited, King City, ON for Baffinland Iron Mines Corporation, Oakville, ON. 61 p.

Fewster, R.M., Buckland, S.T., Burnham, K.P., Borchers, D.L., Jupp, P.E., Laake, J.L., and Thomas, L. 2009. Estimating the encounter rate variance in distance sampling. Biometrics 65: 225–236.

Finley, K.J., and Gibb, E.J. 1982. Summer diet of the narwhal (*Monodon monoceros*) in Pond Inlet, northern Baffin Island. Can. J. Zool. 60: 3353–3363.

Heide-Jørgensen, M., Dietz, R., Laidre, K., and Richard, P. 2002. Autumn movements, home ranges, and winter density of narwhals (*Monodon monoceros*) tagged in Tremblay Sound, Baffin Island. Polar Biol. 25: 331–341.

Laake, J.L., and Borchers, D.L. 2004. Methods for incomplete detection at distance zero. *In* Advanced Distance Sampling. Edited by S.T. Buckland, D.R. Anderson, K.P. Burnham, J.L. Laake, D.L. Borchers, and L. Thomas. Oxford University Press, Oxford. pp. 108–189.

Laake J, Borchers, D., Thomas, L., Miller, D., and Bishop, J. 2015. mrds: Mark-Recapture Distance Sampling. R package version 2.1.14.

Marcoux, M., Matthews, C.J.D., Montsion, L.M., and Dunn, J.B. 2019. Estimate of the abundance of the Eclipse Sound narwhal (*Monodon monoceros*) summer stock from the 2016 photographic aerial survey. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/028. iv + 16 p.

Marsh, H., and Sinclair, D.F. 1989. Correcting for Visibility Bias in Strip Transect Aerial Surveys of Aquatic Fauna. J. Wildl. Manag. 53: 1017–1024.

Matthews, C.J.D., Watt, C.A., Asselin, N.C., Dunn, J.B., Young, B.G., Montsion, L.M., Westdal, K.H., Hall, P.A., Orr, J.R., Ferguson, S.H., and Marcoux, M. 2017. Estimated abundance of the Western Hudson Bay beluga stock from the 2015 visual and photographic aerial survey. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/061. v + 20 p.

Miller, D.L., Burt, M. L., Rexstad, E. A. and Thomas, L. 2013a. Spatial models for distance sampling data: recent developments and future directions. Methods Ecol Evol. 4: 1001–1010. doi: 10.1111/2041-210X.12105.

Miller, D.L, Rexstad, E.A, Burt, M.L., Bravington, M.V., and Hedley, S.L. 2013b. dsm: Density surface modelling of distance sampling data.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Richard, P., Weaver, P., Dueck, L., and Barber, D. 1994. Distribution and numbers of Canadian High Arctic narwhals (*Monodon monoceros*) in August 1984. Medd. Grønl., Biosci. 39: 41–50.

Richard, P.R. 2010. Stock definition of belugas and narwhals in Nunavut. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/022. iv + 14 p.

Stenson, G.B., and Hammill, M. 2008. Incorporating the precautionary approach into the provision of advice on marine mammals. DFO Can. Sci. Advis. Sec. Res. Doc. 2008/079. iv + 12 p.

Stenson, G.B., Hammill, M., Ferguson, S., Stewart, R., and Doniol-Valcroze, T. 2012. Applying the Precautionary Approach to Marine Mammal Harvests in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/107. ii + 15 p.

Thomas, L., Buckland, S.T., Rexstad, E.A., Laake, J.L., Strindberg, S., Hedley, S.L., Bishop, J.R.B., Marques, T.A., and Burnham, K.P. 2010. Distance software: design and analysis of distance sampling surveys for estimating population size. J. Appl. Ecol. 47: 5–14. doi: 10.1111/j.1365-2664.2009.01737.x

Thomas, T.A., Raborn, S., Elliott, R.E., and Moulton, V.D. 2015a. Marine mammal aerial surveys in Eclipse Sound, Milne Inlet, Navy Board Inlet, and Pond Inlet, 1 August – 22 October 2014. Final LGL Report No. FA0024-2. Prepared by LGL Limited, King City, ON for Baffinland Iron Mines Corporation, Oakville, ON. 70 p.

Thomas, T.A., Elliott, R.E., and Moulton, V.D. 2015b. Marine mammal aerial surveys in Eclipse Sound, Pond Inlet, and Milne Inlet, 1 August – 17 September 2015: Survey methods and effort. LGL Interim Report No. FA0059-1. Prepared by LGL Limited, King City, ON for Baffinland Iron Mines Corporation, Oakville, ON. 7 p.

Watt, C.A., Orr, J., LeBlanc, B., Richard, P., and Ferguson, S.H. 2012. Satellite tracking of narwhals (*Monodon monoceros*) from Admiralty Inlet (2009) and Eclipse Sound (2010-2011). DFO Can. Sci. Advis. Sec. Res. Doc. 2012/046. iii + 17 p.

Watt, C.A., Marcoux, M., Asselin, N.C., Orr, J.R., and Ferguson, S.H. 2015. Instantaneous availability bias correction for calculating aerial survey abundance estimates for narwhal (*Monodon monoceros*) in the Canadian High Arctic. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/044. iv + 13 p.

Watt, C.A., Witting, L., Marcoux, M., Doniol-Valcroze, T., Guldborg Hansen, R., Hobbs, R., Ferguson, S.H., and Heide-Jørgensen, M.P. 2019. Harvest allocation modelling for narwhal (*Monodon monoceros*) stocks shared between eastern Canada and West Greenland. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/031 vi + 27 p.

Witting, L. 2015. Meta population modelling of narwhals in East Canada and West Greenland. NAMMCO/SC/22 JCNB/SWG/2015-JWG/10. 20 p. doi: http://dx.doi.org/10.1101/059691

TABLES AND FIGURES

Table 1. Summary of aerial visual surveys of narwhals in the Eclipse Sound complex during the summers of 2013, 2014, and 2015. Surveyed strata are indicated by check marks (✓), while those not surveyed are shaded. The proportion of observations missing perpendicular distances are shown for the 2014 and 2015 surveys that were analysed.

Year	Survey	Date	Pond Inlet	Eclipse Sound	Milne Inlet	Koluktoo Bay	Tremblay Sound	Navy Board Inlet	Fiord	Proportion missing distance
2013	1a	Aug. 31		✓*	✓	✓	✓	✓		
	1b	Sept. 01		✓*	✓	✓	✓	✓		
	2a	Sept. 14		✓*	✓	✓	✓	✓		
	2b	Sept. 15		✓*	✓	✓	✓	✓		
	3a	Sept. 29		✓	✓	✓	✓	✓		
	3b	Sept. 30		✓	✓	✓	✓	✓		
	4a	Oct. 14-16	✓	✓	✓	✓	✓	✓		
	4b	Oct. 16-18	✓	✓	✓			✓		
2014	1a	Aug. 01-02	✓	✓	✓	✓	✓	✓	✓	0.06
	1b	Aug. 03-04	✓	✓	✓	✓	✓	✓		0.25
	2a	Aug. 14-15	✓	✓	✓	✓	✓	✓	✓	0.67
	2b	Aug. 16-17	✓	✓	✓	✓	✓	✓		0.31
	3a	Aug. 30-31	✓	✓	✓	✓	✓	✓	✓	0.48
	3b	Sept. 01-02	✓	✓	✓	✓	✓	✓		0.89
	4a	Sept. 14-15	✓	✓	✓	✓	✓	✓	✓	0.03
	4b	Sept. 16-17	✓	✓	✓	✓	✓	✓		0.28
	5a	Sept.. 29-30	✓	✓	✓	✓	✓	✓	✓	0.22
	5b	Oct 01-02	✓	✓	✓	✓	✓	✓		0.00
	6a	Oct. 17-20	✓	✓	✓	✓	✓	✓	✓	0.22
	6b	Oct. 21-22	✓	✓	✓	✓	✓	✓		0.11
2015	1	Aug. 01	✓	✓	✓	✓	✓			0.03

Year	Survey	Date	Pond Inlet	Eclipse Sound	Milne Inlet	Koluktoo Bay	Tremblay Sound	Navy Board Inlet	Fiord	Proportion missing distance
	2	Aug. 16-17	✓	✓	✓	✓	✓			0.78
	3	Aug. 31	✓	✓	✓	✓	✓			0.40
	4	Sept. 15,17	✓	✓	✓	✓	✓			0.94

*only west of Pond Inlet was surveyed.

Table 2. Summary statistics (AIC values and detection probabilities) of CDS and MCDS models with gamma key functions fit to pooled observation data for straight-line transects from Eclipse Sound narwhal surveys in 2014 and 2015. Covariates included observer (six in 2014 and two in 2015), Beaufort sea state (0, 1, 2, and 3+ in both years), sightability (Excellent, Good, Moderate, and Severe in 2014; Excellent, Good, and Moderate in 2015), and glare (None, Moderate, and Severe in 2014 and None and Severe in 2015). Models with the lowest AIC used to estimate probability of detection are bolded.

Year*	Model	AIC	ΔAIC	Average *p*	SE
2014	CDS	6,920.7	157.5	0.443	0.0159
	MCDS (observer)	6,779.9	16.7	0.373	0.0128
	MCDS (Beaufort)	6,908.7	145.5	0.434	0.0164
	MCDS (sightability)	6,921.0	157.8	0.441	0.0157
	MCDS (observer + sightability)	**6,763.2**	**0.0**	**0.362**	**0.0130**
	MCDS (glare)	6,923.1	159.9	0.443	0.0162
	MCDS (Beaufort + glare)	6,911.5	148.3	0.434	0.0164
	MCDS (observer + Beaufort + glare)	6,777.8	14.6	0.367	0.0132
2015	**CDS**	**1,240.9**	**0**	**0.403**	**0.0309**
	MCDS (observer)	1,242.8	1.9	0.403	0.0310
	MCDS (Beaufort)	1,244.2	3.3	0.401	0.0309
	MCDS (sightability)	1,244.8	3.9	0.403	0.0315
	MCDS (observer + sightability)	1,246.5	5.6	0.402	0.0314
	MCDS (glare)	1,242.6	1.7	0.402	0.0308
	MCDS (Beaufort + glare)+	n/a	n/a	n/a	n/a
	MCDS (observer + Beaufort + glare)+	n/a	n/a	n/a	n/a

*A majority of observation data were missing perpendicular distances during all survey years. The number of observations available for detection function fitting (i.e., with perpendicular distances) was 524 in 2014 and 96 in 2015.

+model did not converge.

Table 3. Summary statistics (AIC values and detection probabilities) of CDS and MCDS models with gamma key functions fit to pooled narwhal observation data for transects of fiord strata from 2014 and 2015. Covariates included observer (six in 2014 and two in 2015) and sightability (Excellent, Good, Moderate, and Severe in 2014; Excellent, Good, and Moderate in 2015). Models with the lowest AIC used to estimate probability of detection are bolded.

Year*	Model	AIC	Average p	SE
2014	CDS	693.7	0.655	0.0533
	MCDS (observer)	**679.9**	**0.505**	**0.0559**
	MCDS (sightability)	696.9	0.647	0.0737
	MCDS (observer + sightability)	683.4	0.501	0.0609
2015	CDS	1,764.3	0.437	0.0304
	MCDS (observer)	1,764.7	0.437	0.0302
	MCDS (sightability)	**1,759.6**	**0.422**	**0.0289**
	MCDS (observer + sightability)	1,761.1	0.421	0.0291

*A majority of observation data were missing perpendicular distances during all survey years. The number of observations available for detection function fitting (i.e., with perpendicular distances) was 49 in 2014 and 143 in 2015.

Table 4. Narwhal surface abundance estimates (i.e., not adjusted for availability bias) for each of the strata surveyed in 2014 and 2015. Percent coefficient of variation (% CV) shown in brackets (note: variances for Tremblay Sound and Fiord strata, which were surveyed with just one transect, do not include encounter rate variance). Shaded cells were not surveyed.

Year	Survey	Date	Pond Inlet	Eclipse Sound	Milne Inlet	Koluktoo Bay	Tremblay Sound	Navy Board Inlet	Fiords	TOTAL
2014	1a	Aug. 01-02	741 (58.31)	737 (56.22)	17 (96.73)	0	47 (72.28)	0	0	1,542 (38.90)
	1b	Aug. 03-04	711 (42.74)	2,427 (22.05)	0	629 (40.19)	0	0		3,767 (17.66)
	2a	Aug. 14-15	0	3,433 (25.79)	3,471 (49.34)	2,380 (32.56)	240 (20.87)	10 (67.36)	392 (18.6)	9,926 (20.95)
	2b	Aug. 16-17	0	13 (87.73)	2,198 (83.35)	575 (43.7)	176 (20.09)	0		2,962 (62.44)
	3a	Aug. 30-31	0	0	2,960 (97.08)	1,186 (33.32)	76 (22.54)	0	0	4,222 (68.71)
	3b	Sept. 01-02	0	0	7,367 (86.29)	3,594 (28.84)	1,641 (12.90)	0		12,602 (51.37)
	4a	Sept. 14-15	0	846 (91.20)	92 (102.13)	0	0	0	0	938 (82.86)
	4b	Sept. 16-17	0	2,667 (81.02)	280 (75.21)	0	0	121 (94.04)		3,068 (70.86)
	5a	Sept. 29-30	0	97 (72.29)	8 (96.73)	0	0	278 (115.20)	590 (15.90)	1,064 (32.46)
	5b	Oct. 01-02	0	114 (97.58)	0	0	79 (51.66)	529 (91.82)		722 (69.25)
	6a	Oct. 17-20	3,637 (40.96)	60 (71.71)	0	0	0	0	0	3,697 (40.31)
	6b	Oct. 21-22	960 (11.52)	736 (55.92)	8 (94.88)	0	0	0		1,704 (25.01)
2015	1	Aug. 01	32 (79.64)	33 (127.68)	422 (99.97)	454 (29.90)	192 (21.8)			1,133 (39.53)
	2	Aug. 16-17	0	0	911 (94.04)	172 (90.38)	796 (12.4)			1,879 (46.63)
	3	Aug. 31	0	0	90 (96.97)	727 (65.45)	3,334 (8.7)			4,151 (13.6)
	4	Sept. 15,17	0	3,409 (61.53)	0	6 (147.46)	6 (6.9)			3,421 (61.31)

Table 5. Area, effort, encounter rate, percent coefficient of variation of encounter rate (% CV_{ER}), mean group size, and percent CV of group size (% CV_{GS}) for individual non-fiord strata surveyed in 2014 and 2015.

Year	Survey	Stratum	Area (km^2)	Effort (km)	Encounter Rate (groups/km)	% CV_{ER}	Mean Group Size	% CV_{GS}
2014	1a	Pond Inlet	1,950.3	152.6	0.0852	54.7	3.23	19.9
		Eclipse Sound	2,936.6	302.8	0.0726	54.4	2.50	13.9
		Milne Inlet	751.6	123.8	0.00808	96.7	2.00	n/a
		Koluktoo Bay	236.0	70.7	0	n/a	n/a	n/a
		Navy Board Inlet	1,675.1	241.2	0	n/a	n/a	n/a
	1b	Pond Inlet	1,950.3	151.6	0.145	40.92	1.82	11.8
		Eclipse Sound	2,936.6	320.9	0.209	19.8	2.87	9.0
		Milne Inlet	751.6	126.1	0	n/a	n/a	n/a
		Koluktoo Bay	236.0	100.0	0.620	39.3	3.11	7.4
		Navy Board Inlet	1,675.1	231.8	0	n/a	n/a	n/a
	2a	Pond Inlet	1,950.3	152.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	335.6	0.229	23.5	3.67	9.9
		Milne Inlet	751.6	123.8	0.678	48.4	4.93	9.0
		Koluktoo Bay	236.0	113.8	2.17	31.8	3.36	5.8
		Navy Board Inlet	1,675.1	241.2	0.00415	67.3	1.0	n/a
	2b	Pond Inlet	1,950.3	151.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	320.9	0.00312	87.7	1.0	n/a
		Milne Inlet	751.6	126.1	0.682	82.6	3.10	10.8
		Koluktoo Bay	236.0	120.7	0.464	42.5	3.80	9.5
		Navy Board Inlet	1,675.1	231.8	0	n/a	n/a	n/a
	3a	Pond Inlet	1,950.3	152.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	335.6	0	n/a	n/a	n/a
		Milne Inlet	751.6	123.8	0.678	96.7	4.20	8.3
		Koluktoo Bay	236.0	106.3	0.959	32.2	3.79	7.8
		Navy Board Inlet	1,675.1	241.2	0	n/a	n/a	n/a
	3b	Pond Inlet	1,950.3	151.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	320.9	0	n/a	n/a	n/a
		Milne Inlet	751.6	126.1	1.72	86.5	4.12	4.7
		Koluktoo Bay	236.0	104.3	2.99	28.34	3.68	4.0
		Navy Board Inlet	1,675.1	231.8	0	n/a	n/a	n/a
	4a	Pond Inlet	1,950.3	117.1	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	335.6	0.107	90.4	1.94	11.4
		Milne Inlet	751.6	123.8	0.0242	96.7	3.67	32.8
		Koluktoo Bay	236.0	101.8	0	n/a	n/a	n/a
		Navy Board Inlet	1,675.1	241.2	0	n/a	n/a	n/a
	4b	Pond Inlet	1,950.3	151.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	320.9	0.243	80.3	2.71	9.99
		Milne Inlet	751.6	126.1	0.182	73.9	1.48	13.4

Year	Survey	Stratum	Area (km^2)	Effort (km)	Encounter Rate (groups/km)	% CV_{ER}	Mean Group Size	% CV_{GS}
		Koluktoo Bay	236.0	104.0	0	n/a	n/a	n/a
		Navy Board Inlet	1,675.1	248.0	0.0161	79.0	3.25	50.8
	5a	Pond Inlet	1,950.3	152.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	335.6	0.00596	67.7	4.00	25.0
		Milne Inlet	751.6	123.8	0.00808	96.7	1	n/a
		Koluktoo Bay	236.0	82.2	0	n/a	n/a	n/a
		Navy Board Inlet	1,675.1	241.2	0.0249	112.7	4.83	23.5
	5b	Pond Inlet	1,950.3	151.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	320.9	0.0156	95.3	1.80	20.8
		Milne Inlet	751.6	126.1	0	n/a	n/a	n/a
		Koluktoo Bay	236.0	105.9	0	n/a	n/a	n/a
		Navy Board Inlet	1,675.1	231.8	0.0820	90.3	2.79	16.1
	6a	Pond Inlet	1,950.3	152.6	0.472	39.2	2.86	11.3
		Eclipse Sound	2,936.6	335.6	0.0149	71.6	1.0	0.0
		Milne Inlet	751.6	123.8	0	n/a	n/a	n/a
		Koluktoo Bay	236.0	101.8	0	n/a	n/a	n/a
		Navy Board Inlet	1,675.1	241.2	0	n/a	n/a	n/a
	6b	Pond Inlet	1,950.3	151.6	0.237	7.26	1.50	8.2
		Eclipse Sound	2,936.6	319.5	0.0751	54.0	2.42	14.1
		Milne Inlet	751.6	126.1	0.00793	94.8	1.0	n/a
		Koluktoo Bay	236.0	54.9	0	n/a	n/a	n/a
		Navy Board Inlet	1,675.1	231.8	0	n/a	n/a	n/a
2015	1	Pond Inlet	1,950.3	152.6	0.00655	79.3	2.0	n/a
		Eclipse Sound	2,936.6	335.6	0.00596	123.0	1.50	33.3
		Milne Inlet	751.6	123.8	0.121	96.7	3.73	24.3
		Koluktoo Bay	236.0	148.4	0.438	22.4	3.54	18.2
	2	Pond Inlet	1,950.3	152.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	335.6	0	n/a	n/a	n/a
		Milne Inlet	751.6	123.8	0.517	93.3	1.89	9.1
		Koluktoo Bay	236.0	116.0	0.241	89.3	2.43	11.5
	3	Pond Inlet	1,950.3	152.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	335.6	0	n/a	n/a	n/a
		Milne Inlet	751.6	123.8	0.0969	96.7	1.0	0.0
		Koluktoo Bay	236.0	119.3	1.32	64.8	1.89	5.3
	4	Pond Inlet	1,950.3	152.6	0	n/a	n/a	n/a
		Eclipse Sound	2,936.6	335.6	0.560	60.6	1.67	7.7
		Milne Inlet	751.6	123.8	0	n/a	n/a	n/a
		Koluktoo Bay	236.0	97.5	0.0103	147.3	2.0	n/a

Table 6. Area, effort, mean encounter rate, mean group size, percent coefficient of variation of group size (% CV_{GS}) for Tremblay Sound and individual fiord strata surveyed in 2014 and 2015. Note there is no estimate of encounter rate variance since these strata were surveyed using one transect.

Year	Survey	Stratum	Area (km^2)	Effort (km)	Encounter Rate (groups/km)	Mean Group Size	% CV_{GS}
2014	1a	Tremblay Sound	154.9	45.4	0.0441	7.00	71.4
	2a	Tremblay Sound	154.9	44.7	0.358	4.38	17.7
	2b	Tremblay Sound	154.9	47.1	0.276	4.16	16.8
	3a	Tremblay Sound	154.9	42.5	0.0941	5.25	19.6
	3b	Tremblay Sound	154.9	43.2	2.29	4.67	6.6
	5b	Tremblay Sound	154.9	46.5	0.0859	6.00	50.5
	2a	Fiord (F5)	38.4	14.2	2.61	3.95	15.0
	5a	Fiord (F6)	251.0	77.8	0.373	6.38	11.4
2015	1	Tremblay Sound	154.9	46.8	0.214	3.20	20.7
	2	Tremblay Sound	154.9	43.4	1.41	2.02	10.3
	3	Tremblay Sound	154.9	47.0	4.45	2.70	5.4
	4	Tremblay Sound	154.9	45.3	0.0221	1.0	n/a

Table 7. Narwhal abundance estimates adjusted for availability bias for each of the strata surveyed in 2014 and 2015. Percent coefficient of variation (% CV) shown in brackets. Grey shaded cells represent strata that were not surveyed.

Year	Survey	Date	Pond Inlet	Eclipse Sound	Milne Inlet	Koluktoo Bay	Tremblay Sound	Navy Board Inlet	Fiords	TOTAL	95 % CI
2014	1a	Aug. 01-02	**2,356** (58.41)	**2,344** (56.35)	**54** (96.83)	**0**	**149** (72.36)	**0**	**0**	**4,904** (39.00)	**2,346-10,248**
	1b	Aug. 03-04	**2,261** (42.09)	**7,718** (22.28)	**0**	**2,000** (40.30)	**0**	**0**		**11,979** (17.80)	**8,474-16,934**
	2a	Aug. 14-15	**0**	**10,917** (25.99)	**11,038** (49.47)	**7,568** (32.69)	**763** (21.14)	**32** (67.48)	**1,248** (18.93)	**31,566** (21.03)	**20,996-47,457**
	2b	Aug. 16-17	**0**	**41** (87.84)	**6,990** (83.45)	**1,829** (43.82)	**560** (20.37)	**0**		**9,419** (62.52)	**3,055-29,036**
	3a	Aug. 30-31	**0**	**0**	**9,413** (97.18)	**3,771** (33.48)	**242** (22.79)	**0**	**0**	**13,426** (68.78)	**3,964-45,469**
	3b	Sept. 01-02	**0**	**0**	**23,427** (96.94)	**11,429** (32.82)	**5,218** (13.33)	**0**		**40,074** (57.46)	**14,066-114,173**
	4a	Sept. 14-15	**0**	**2,690** (91.25)	**293** (102.22)	**0**	**0**	**0**	**0**	**2,983** (82.91)	**723-12,312**
	4b	Sept. 16-17	**0**	**8,481** (81.07)	**890** (75.26)	**0**	**0**	**385** (94.07)		**9,756** (70.90)	**2,793-34,081**
	5a	Sept. 29-30	**0**	**308** (72.34)	**25** (96.83)	**0**	**0**	**884** (115.24)	**2,166** (16.26)	**3,384** (32.54)	**1,816-6,301**
	5b	Oct. 01-02	**0**	**363** (97.66)	**0**	**0**	**251** (51.76)	**1,682** (91.86)		**2,296** (69.28)	**673-7,833**
	6a	Oct. 17-20	**11,756** (40.44)	**191** (71.77)	**0**	**0**	**0**	**0**	**0**	**11,756** (40.44)	**5,483-25,208**
	6b	Oct. 21-22	**3,053** (12.00)	**2,340** (56.01)	**25** (94.93)	**0**	**0**	**0**		**5,419** (25.12)	**3,337-8,800**
2015	1	Aug. 01	**102** (79.74)	**105** (127.71)	**1,342** (100.06)	**1,444** (30.07)	**611** (22.09)			**3,603** (39.59)	**1,706-7,611**
	2	Aug. 16-17	**0**	**0**	**2,897** (94.11)	**547** (90.42)	**2,531** (12.82)			**5,975** (46.69)	**2,502-14,268**
	3	Aug. 31	**0**	**0**	**286** (97.06)	**2,312** (65.55)	**10,602** (9.35)			**13,200** (13.88)	**10,070-17,304**
	4	Sept. 15,17	**0**	**10,841** (61.66)	**0**	**19** (147.54)	**19** (7.63)			**10,879** (61.44)	**3,588-32,986**

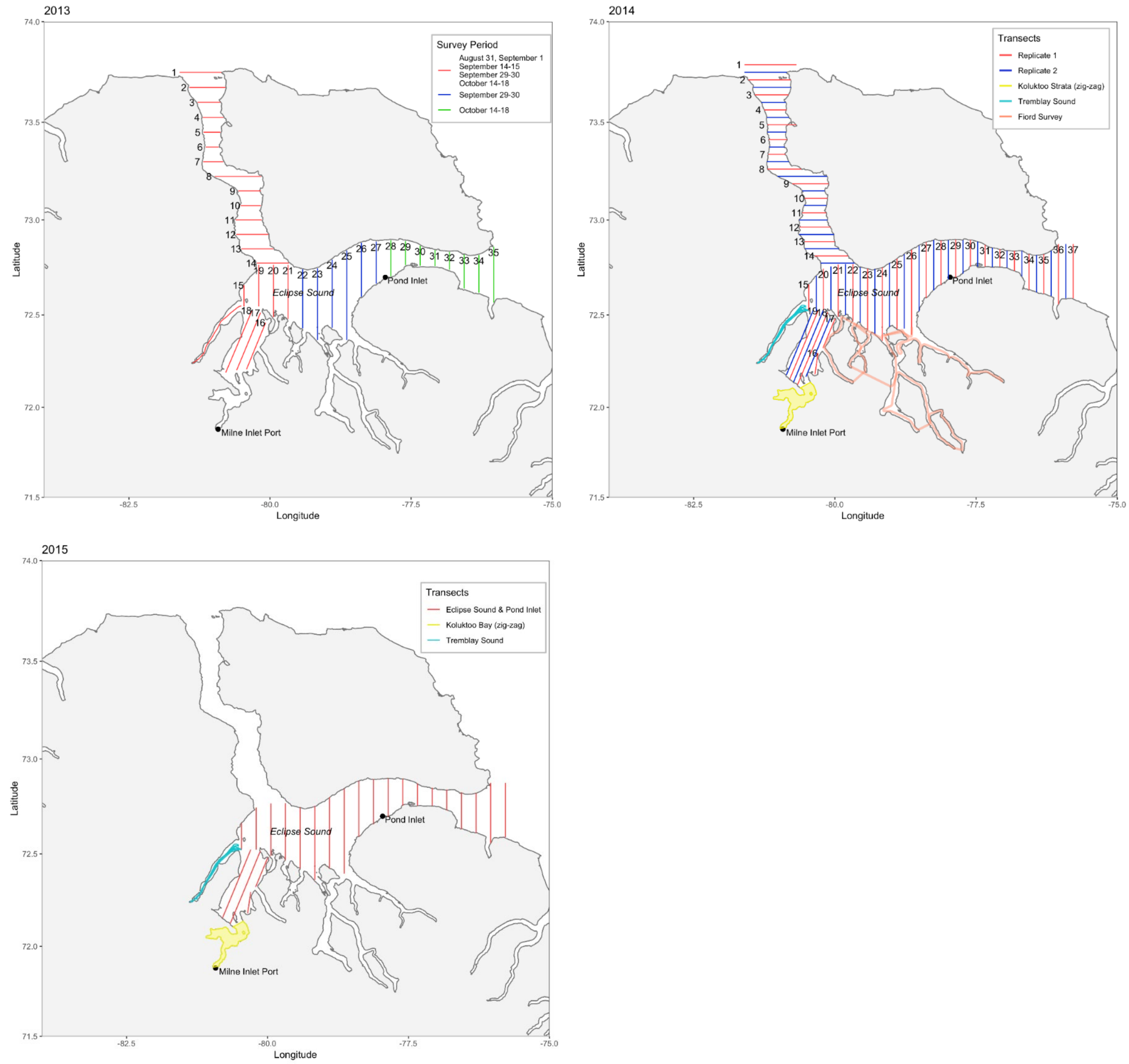

Figure 1. Spatial and temporal coverage of the LGL surveys of Eclipse Sound narwhals in 2013, 2014, and 2015.

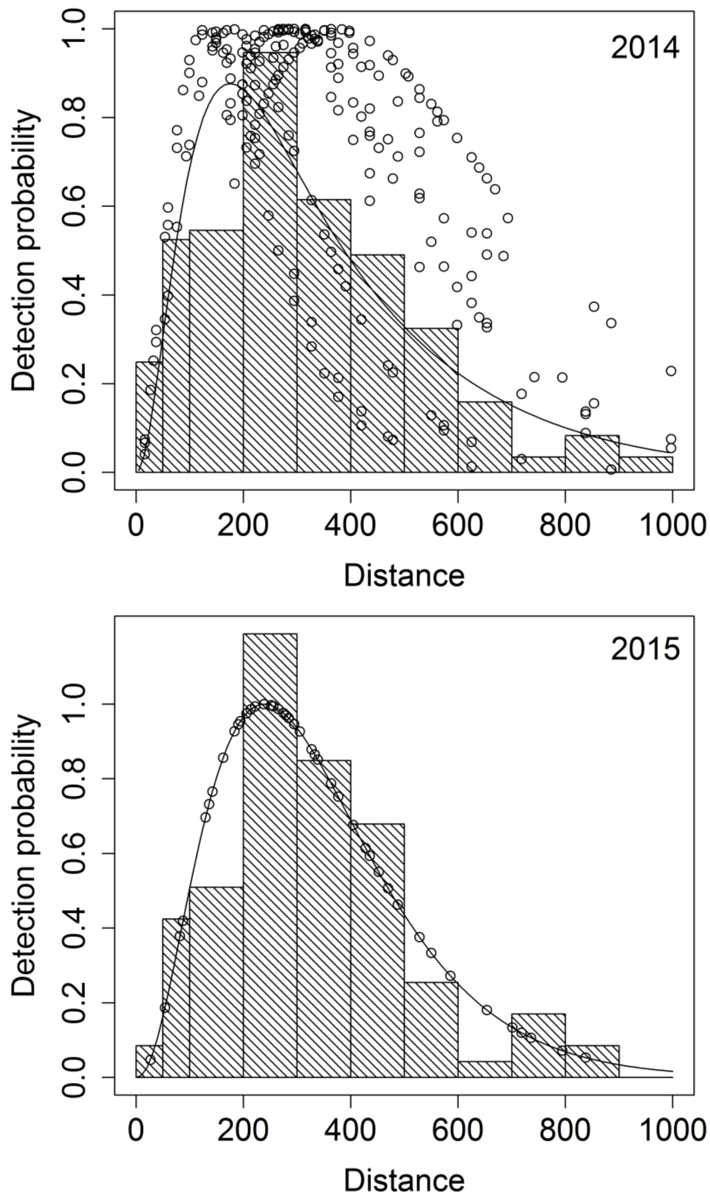

Figure 2. Histogram of perpendicular distances of narwhal groups detected in non-fiord strata in 2014 (top) and 2015 (bottom). A gamma detection function (line) was fitted to pooled data for each year after right-truncation at 1000 m. Circles are the probability of detection of each observation as a function of perpendicular distance and, for the 2014 data, values for the covariates 'Observer' and 'Sightability'.

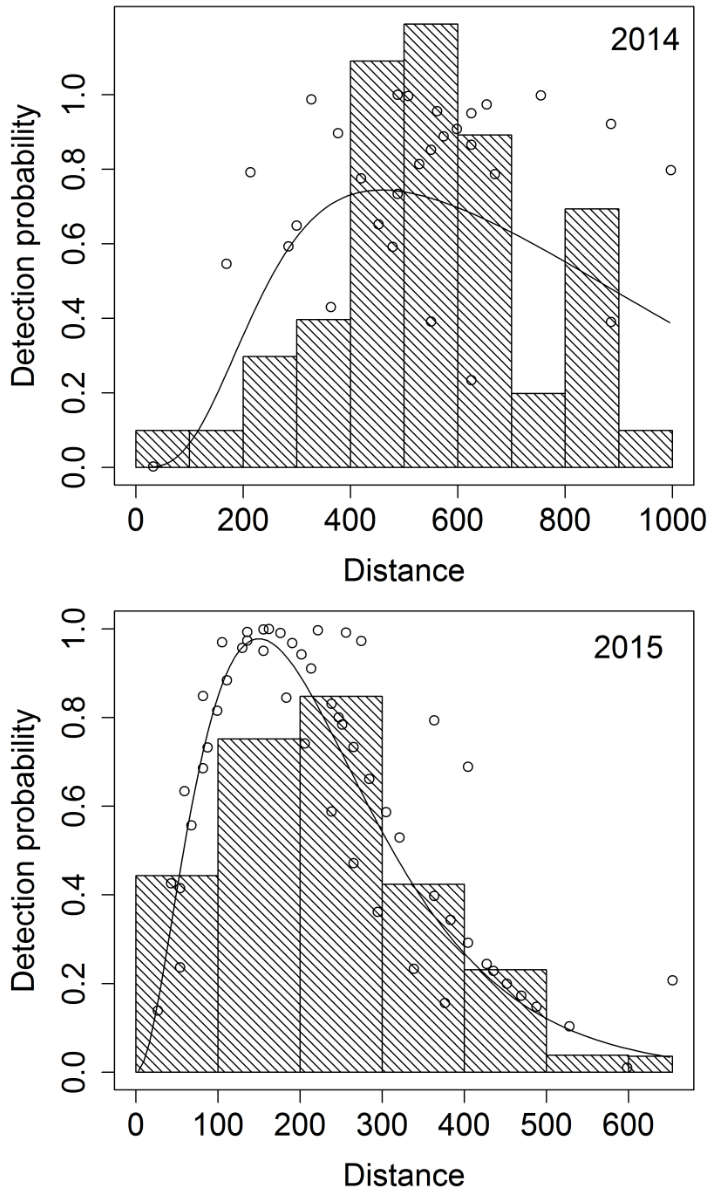

Figure 3. Histogram of perpendicular distances of narwhal groups detected in fiord strata in 2014 (top) and 2015 (bottom). A gamma detection function (line) was fitted to pooled data for each year after right-truncation at 1000 m (2014), or to the maximum detection distance of 654 m (2015). Circles are the probability of detection of each observation as a function of perpendicular distance and covariates 'Observer' (2014) and 'Sightability' (2015).

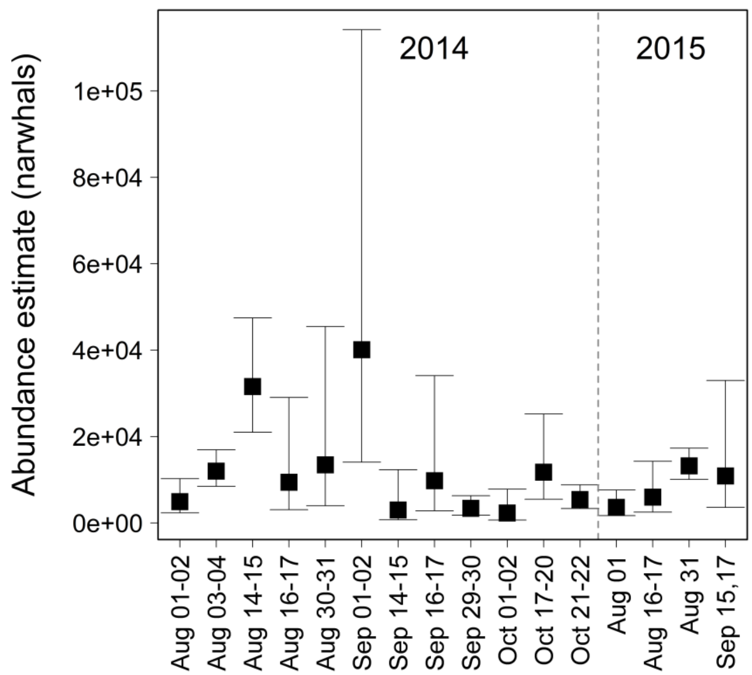

Figure 4. Eclipse Sound narwhal abundance estimates during the open water season in 2014 and 2015. Error bars are 95% Confidence Interval (CI).