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Estimate of the abundance of the Eclipse Sound narwhal (*Monodon Monoceros*) summer stock from the 2016 photographic aerial survey

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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

In August 2016, an aerial survey was completed to estimate the size of the summer stock of narwhal in Eclipse Sound. The survey was entirely based on aerial photography. Strip transect analyses were performed for the Eclipse Sound, Pond Inlet, Navy Board Inlet, and Milne Inlet strata. A density surface modelling approach estimated the abundance in the Tremblay Sound and Koluktoo Bay strata to accommodate the irregular survey track lines. Although other surveys of strata occurred, the stock abundance estimate was obtained by adding the stratum estimates from August 7-10, a relatively short period when all strata were covered. The abundance estimate, corrected for narwhals that could not be detected because they were underwater (correction factor of 3.18), was 12,039 (coefficient of variation = 0.23, 95% confidence interval = 7,768-18,660). A Total Allowable Landed Catch of 117 narwhals was estimated using the Potential Biological Removal (PBR) method.

INTRODUCTION

The Eclipse Sound narwhal summer stock has been most recently surveyed by Fisheries and Oceans Canada in 2013, producing an estimated stock size of 10,500 (Doniol-Valcroze et al. 2015a, 2015b). This estimate was much lower than the previous estimate of 20,200 narwhals from the 2004 survey (Richard et al. 2010). A photographic aerial survey was flown in August 2016 to update the estimate of this summer stock.

METHODS

STUDY AREA AND DESIGN

The aerial survey was designed to cover the range of the Eclipse Sound narwhal summer stock. Slight changes to previous survey coverage and strata (Richard et al. 2010, Doniol-Valcroze et al. 2015a) included increasing the number of transect lines in most strata and dividing the Navy Board Inlet/Milne Inlet stratum into three strata according to narwhal density recorded in previous surveys. The survey area was divided into six strata: Pond Inlet, Eclipse Sound, Navy Board Inlet, Milne Inlet, Koluktoo Bay, and Tremblay Sound (figure 1). The Pond Inlet, Eclipse Sound, Navy Board Inlet, and Milne Inlet strata were surveyed with evenly spaced parallel transect lines (each 10 km for Navy Board, 4.4 km for Eclipse Sound and Pond Inlet, 3.6 km for Milne Inlet). Survey effort in the Tremblay Sound and Koluktoo Bay strata was designed for density surface modelling methods because their narrow, complex shapes with high-elevation relief on their sides prevented the use of systematic lines. Thus, assumptions of traditional distance sampling methods were violated because of the non-random starting point of transects and unequal coverage probability.

PHOTOGRAPHIC SURVEY METHODS

The entire survey was designed as a photographic survey. The survey was flown in a de Havilland Twin Otter 300 at a target altitude of 610 m (2,000 ft) and a target speed of 185 km/h (100 knots). The rear of the aircraft was equipped with a ventral camera port where a Nikon D800 camera equipped with a 25 mm lens was mounted directed straight down with the longest side perpendicular to the track line. The camera was connected to a GPS unit to geo-reference photographs and to a laptop computer to control exposure settings and photo interval and to save photos to the computer's hard drive. At the target altitude of 610 m, the ground area covered by each photograph was 875.4 m x 585.2 m. At the target speed and altitude, an interval of 9 seconds resulted in 20% overlap between consecutive photos along each transect. However, variations in speed, altitude, and pitch of the aircraft resulted in the need to use a shorter photographic interval of 7 or 8 seconds to ensure photographic coverage of each transect was continuous.

PHOTO ANALYSIS

Photographs were examined for narwhals on a high resolution monitor (24 inch screen) by a photo reader experienced in analysing aerial photos from three previous DFO monodontid surveys. Photographs were georeferenced and examined in ArcMap 10.1 (Esri). Issues with low visibility in images due to darkness were resolved using Adobe PhotoShop (Adobe Systems) by adjusting photograph brightness, contrast, levels, curves, exposure, vibrance, saturation, and hue. Once a first reading of all the photos from the survey was achieved, the photo reader re-analysed 50 photos from the first survey day that was analysed to evaluate repeatability.

Random selection produced a sample with too many photos without narwhals, so the 50 photos were instead selected to provide variation in the number of narwhals detected in each photo.

Water clarity was subjectively evaluated in each photo and classified as either ‘murky’ (water in which narwhals could only be observed at the surface) or ‘clear’ (water in which narwhals could be observed down to 2 m). On some photos, a proportion of the photo was masked by sun glare which made it impossible for the reader to evaluate narwhal presence. For those photos, the reader created a shapefile to cover the glare and did not search for narwhals within the glare area. The area covered by the glare was then calculated and subtracted from the photo area. The overlapping section between subsequent photos was cropped from the first photo. For the Tremblay Sound and Koluktoo Bay strata, there was also an overlap between adjacent line transects which was cropped from the area of the second line. Lastly, land area was cropped from the photos by overlapping a shapefile of land with the photos. The remaining area covered by water (with no glare) in each photo was then calculated.

STRIP TRANSECT ANALYSIS

A strip transect analysis of the individual narwhal detections from the photos for the strata of Eclipse Sound, Pond Inlet, Navy Board Inlet and Milne Inlet was performed. The density of narwhals was calculated by dividing narwhal counts by the total area of glare-free water. Density was then multiplied by the stratum area to obtain near-surface abundance estimates $\hat{N}_{sur}$ for each stratum.

Near-surface abundance estimates were then adjusted to account for diving narwhals which were not available to be observed (see AVAILABILITY BIAS CALCULATION section).

$$\hat{N} = \hat{N}_{sur} \times C_a$$

where C_a is the availability bias correction factor and $\hat{N}$ is the adjusted abundance estimate.

The total variance for each strata was calculated by adding the variance of the encounter rate $var(E(n))$ and of the availability bias correction factor $var(C_a)$ following the delta method (Buckland et al. 2001):

$$var(\hat{N}) = \hat{N}^2 \times \left\{\frac{var(E(n))}{(E(n))^2} + \frac{var(C_a)}{{C_a}^2}\right\}$$

The variance of the encounter rate was calculated following equation 3 in Fewster et al. (2009):

$$var\left(\frac{n}{L}\right) = \frac{k}{L^2(k-1)}\sum_{i=1}^{k} l_i^2\left(\frac{n_i}{l_i} - \frac{n}{L}\right)^2$$

Where $\frac{n}{L}$ is the encounter rate, $n = \sum_{i=1}^{k} n_i$ is the total number of narwhals detected near or at the surface for each transect line, $L = \sum_{i=1}^{k} l_i$ is the total survey effort for that stratum calculated as the sum of the length of each transect line l_i and k is the number of transect lines.

The coefficient of variation, $cv(\hat{N})$, was calculated by dividing the square root of the variance (standard error) by the estimated abundance, $\hat{N}$.

DENSITY SURFACE MODELLING

We used a density surface modelling framework to model spatially-referenced count data. A generalised additive model (GAM) (Wood 2006) was constructed with the counts of narwhals per photo as the response variable. The location of the midpoint of each photo was recorded using a GPS linked to the camera in the aircraft. Latitude and longitude coordinates were projected in meters so that distances were uniform in all directions (see table A1 in Appendix for map projection specification). For each photo, we extracted two spatial covariates: distance from the center of the photo to the nearest shore and to the mouth of the fjord (into the adjacent open-water stratum). These variables were evaluated because narwhals may select shoreline habitat to avoid killer whale predation (Breed et al. 2017). It is also possible that narwhals would move away from the mouth of the fjord for the same reason.

The survey area was divided into grid cells of resolution of 250 m x 250 m (following Doniol-Valcroze et al. 2015b) that was used to predict the abundance of narwhals. Values for the explanatory variables (latitude, longitude, distances to shore, and to mouth) were calculated using the value at the midpoint of each grid cell.

Counts per photo were modelled as a sum of smooth functions of covariates (e.g., location, distances to shore, and to mouth) measured at the photo level using a GAM. Smooth functions were modelled as splines. In addition, for the location data, we also fitted a “soap film” smoother (Wood et al. 2008) which allows for complex strata outline with peninsula or Duchon splines alleviating the problem of inflated prediction away from the observed data (Miller and Wood 2014).

Similar to Doniol-Valcroze et al. (2015b), we decided against using a Poisson distribution (where the variance of each observation is assumed to be equal to its mean). We modelled counts as a negative binomial distribution or as a Tweedie distribution. The Tweedie distribution offers a flexible alternative for count data with high proportion of zeros (Miller et al. 2013).

Model fits were investigated using standard model diagnostic plots. The fitted smooth functions and predicted smooth surfaces were also examined for evidence of edge effects and were discounted accordingly.

The 24 fitted models were ranked based on Akaike Information Criterion (AIC). Top models within < 7 ΔAIC were further considered for the best models (choice of family distribution, smoother and covariates; see Table A.2 in Appendix for list of top models). The best model was the model with the smallest ΔAIC. Selected models were inspected for residuals to ensure normality and homogeneity.

A “naïve” abundance estimate was calculated for each repeat of the survey, similar to a strip transect analysis, to compare with the predictions of the best spatial model.

AVAILABILITY CORRECTION FACTOR

All photos were assessed to have clear water in which narwhals can be viewed from aircraft down to 2 m depths (Richard et al. 1994). Near surface abundance estimates were adjusted to account for narwhals that were diving beyond 2 m depths and were therefore unavailable for detection by observers (availability bias). Watt et al. (2015) calculated correction factors based on dive data from 24 narwhals in Eclipse Sound and Admiralty Inlet in 2009-2012. The availability bias correction factor, C_a, was calculated by:

$$C_a = 1/proportion\ spent\ within\ 2\ m\ of\ surface$$

ABUNDANCE ESTIMATE

The stock abundance estimate was obtained by adding individual stratum estimates obtained over a period of four days (Aug 7-10). The Tremblay Sound stratum was surveyed twice within the survey period; the average abundance estimate of these repeats was used. The total variance for the survey was the sum of the variance of each stratum and the final variance for the average estimate was calculated as (equation 8.8 in Buckland et al. 2001):

$$var(\widehat{N}^*) = \frac{E_1^2 \times var(\widehat{N}_1) + E_2^2 \times var(\widehat{N}_2)}{(E_1 + E_2)^2}$$

where E_1s the effort estimated by the number of photos for the first survey and E_2 is the effort for the second survey, and $\widehat{N}_1$ and $\widehat{N}_2$ are the adjusted abundance estimates for each survey.

Confidence intervals were calculated assuming a log-normal distribution as suggested in Buckland (2001).

RECOMMENDED TOTAL ALLOWABLE LANDED CATCH (TALC)

We used the Potential Biological Removal (PBR) method (Wade 1998), corrected to include hunting losses (i.e., animals that are struck and lost), to calculate the recommended Total Allowable Landed Catch (TALC):

$$TALC = \frac{PRB}{LRC}$$

where:

$$PBR = 0.5 * R_{max} * N_{min} * F_r$$

LRC is the hunting loss rate correction and is equal to 1.28 (SE 0.15; Richard 2008), R_{max} is the maximum rate of increase for the stock (which is unknown, so the default for cetaceans of 0.04 was used; Wade 1998), N_{min} is the 20th percentile of the log-normal distribution of N. F_r is the recovery factor which is set between 0.1 and 1 (Wade 1998). Here, $F_r = 0.75$ was used because the stock is abundant but there is limited data and population trend is unknown (Hammill et al. 2017).

RESULTS

SURVEY DAYS

Surveys were conducted from August 07-21 (Table 1). Because of constraints related to time and resources, it was not possible to analyse the photos from all of the survey days. Instead, a subset of the days was analyzed that would provide the most complete coverage (the most strata covered) within the shortest duration. The following strata were analysed: Navy Board Inlet (August 7), Tremblay Sound (August 7, 9, and 21), Eclipse Sound (August 9 and 21), Pond Inlet (August 9), Koluktoo Bay (August 10 and 21), and Milne Inlet (August 10 and 21).

AVAILABILITY BIAS CORRECTION

The correction factor based on weighted averages of the time 24 narwhals spent within the top 2 meters of water in 2009-2012 was equal to 3.18 (Coefficient of Variation [CV] = 0.107).

PHOTO ANALYSIS

Repeat counts of 50 photos were highly correlated (simple linear regression; adj $r^2 = 0.997$, $F_{1,48} = 1.863 \times 10^4$, $p < 0.001$). Counts for the first and repeat reads were the same for 42 of the 50 photos, differed by 1 for 7 photos, and by 2 for one photo, resulting in a mean absolute difference of 0.18 narwhals per photo. The original counts were kept for the abundance analysis.

LINE TRANSECT ANALYSIS

No narwhals were observed in the Navy Board Inlet or the Pond Inlet strata (Table 2). The near-surface estimate for the Eclipse Sound stratum on August 9 was 1,924 (CV = 0.39) and 85 (CV = 0.53) on August 21 (Figure 2). The surface estimate for the Milne Inlet stratum was of 853 (CV = 0.39) narwhals on August 10 and 1,257 (CV = 0.43) narwhals on August 21 (Figure 3).

DENSITY SURFACE MODELLING

The near-surface estimates for Tremblay Sound were 452 (CV = 0.18) on August 7, 361 (CV = 0.19) on August 9, and 525 on August 21 (CV = 0.19; Figure 4; Table 3). Koluktoo Bay near-surface estimates were 602 (CV = 0.11) on August 10 and 884 (CV = 0.12) on August 21 (Figure 5; Table 3).

STOCK ABUNDANCE AND TOTAL AVAILABLE LANDED CATCH (TALC)

All strata were surveyed over four days (August 7-10), providing a combined, complete coverage stock abundance estimate of 12,039 (CV = 0.23, 95% confidence interval of 7,768-18,660; Table 4). The PBR was calculated to be 150 and the TALC was estimated to be 117 narwhals.

DISCUSSION

A total stock estimate was calculated by adding the stratum counts surveyed on August 7-10. This combination of days provided the only complete coverage of the range of the Eclipse Sound narwhal summer stock within relatively short time periods (four days).

Aerial surveys were corrected for whales that cannot be seen by observers because they are too deep underwater (availability bias). Ideally, data from whales equipped with satellite transmitters during the survey period should be used to calculate the availability correction factor. While there was a field program to tag narwhals in Eclipse Sound in 2016, none were tagged during the survey period. We therefore used dive data collected from narwhals tagged in Eclipse Sound and Admiralty Inlet in 2009-2012 to calculate the availability factor correction for this study (Watt et al. 2015). Implicit in this approach is our assumption that narwhals tagged in 2010-2012 behaved similarly to narwhals in 2016.

This was the first entirely photographic survey DFO has conducted on narwhals. While photographic surveys require fewer personnel in the field, it took 1.5 years for our specialist analyst to manually read all the photos for narwhal detection. However, there are numerous advantages to having a permanent photographic survey record including the ability to revisit photographs to acquire data from target (and non-target) species. We therefore suggest continuing photographic surveys. Refinement of semi-automated detection methods currently in development would help to decrease the photo-reading time requirement and allow for inclusion of additional data in final abundance estimates.

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TABLES AND FIGURES

Table 1. Summary of survey completion the Eclipse Sound narwhal summer stock. Check marks (✓) indicate days when a strata was complete flown. Cells in grey indicate strata and days for which the photos were analysed and included in this study. Numbers parenthesis indicates sea state conditions estimated on the Beaufort scale.

	Pond Inlet	Eclipse Sound	Navy Board Inlet	Milne Inlet	Koluktoo Bay	Tremblay Sound
07-Aug.-2016			✓ (2-4)			✓ (2-4)
09-Aug.-2016	✓ (1-2)	✓ (1-2)				✓ (1-3)
10-Aug.-2016			✓	✓ (0)	✓ (0-1)	✓
11-Aug.-2016				✓	✓	
14-Aug.-2016						✓
15-Aug.-2016*		✓		✓	✓	✓
20-Aug.-2016						✓
21-Aug.-2016		✓ (0-1)		✓ (0-1)	✓ (0-1)	✓ (0-1)

**The photos from August 15 were not used in the analysis because of problems with the quality of the images.*

Table 2. Narwhal abundance per strata estimated by strip transect analysis. CV is the coefficient of variation of the surface estimate based on the variance of the encounter rate.

Data	Strata	Strata Area (km^2)	# photos	% glare in photos	% covered by photos	# unique narwhal sightings	Surface estimate	CV
07-Aug.-2016	Navy Board Inlet	1,675	409	3.79	8.94	0	0	-
09-Aug.-2016	Eclipse Sound	2,937	1,646	0.61	18.61	358	1,924	0.39
09-Aug.-2016	Pond Inlet	1,950	977	2.15	15.78	0	0	-
10-Aug.-2016	Milne Inlet	752	416	0.08	18.40	157	853	0.39
21-Aug.-2016	Eclipse Sound	2,937	1,641	0.01	18.88	16	85	0.53
21-Aug.-2016	Milne Inlet	752	416	0.47	18.62	234	1,257	0.43

Table 3. Spatial density models selected for Tremblay Sound and Koluktoo Bay. $N_{naïve}$: naïve abundance estimate (strip transect analysis); (x,y) smoother: best selected smoother among thin plate regression splines, Duchon splines and soap film (with effective degrees of freedom [edf]); covariates: distance to mouth (mouth) and distance to shore (shore); N_{dsm}: surface abundance estimate from spatial density model. S.E.: standard error and CV: coefficient of variation of the surface estimates.

Date	Stratum area (km^2)	# of photos	Area covered by photos (km^2)	Number of unique sightings	$N_{naïve}$	Distribution family	(x,y) smoother (edf)	Covariates	Deviance explained (%)	N_{dsm}	S.E. (CV)
Tremblay Sound											
07-Aug.-2016	154.89	190	68.43	281	636	Negative binomial	Soap (2.86)	mouth	93.7	453	79.90 (0.18)
09-Aug.-2016	154.89	249	70.56	298	654	Negative binomial	Duchon (0.47)	mouth	74.4	361	67.73 (0.19)
21-Aug.-2016	154.89	340	93.15	462	768	Negative binomial	Soap (5.66)	shore mouth	94.9	525	97.6 (0.19)
Koluktoo Bay											
10-Aug.-2016	235.97	331	98.12	323	777	Negative binomial	Soap (14.71)	mouth	80.3	602	67.96 (0.11)
21-Aug.-2016	235.97	337	110.97	447	951	Negative binomial	Duchon (14.87)	mouth	90.84	884	102.75 (0.12)

Table 4. Abundance estimate for the 2016 aerial survey of the Eclipse Sound narwhal adjusted for availability bias (correction factor = 3.18 [CV=0.107]).

Strata	Date	Area (km^2)	Area covered by photos (%)	Surface estimates	Abundance (corrected)	Coefficient of variation
Tremblay Sound	Aug. 7	155	44.18	453	1,437	0.21
Tremblay Sound	Aug. 9	155	45.55	361	1,148	0.22
Average				**407**	**1,294**	**0.14**
Eclipse Sound	Aug. 9	2,937	18.61	1,924	6,118	0.40
Koluktoo Bay	Aug. 10	236	41.16	602	1,914	0.15
Milne Inlet	Aug. 10	752	18.40	853	2,713	0.40
TOTAL				**3,786**	**12,039**	**0.23**

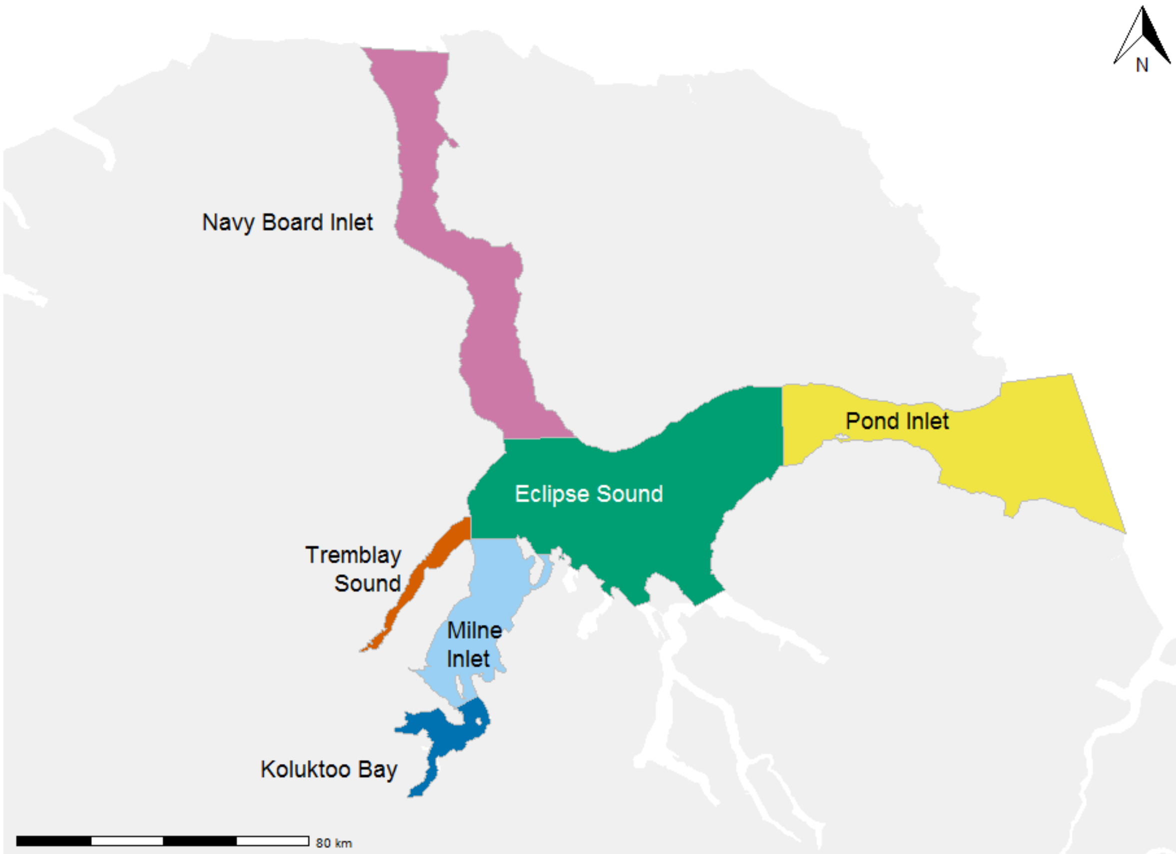

Figure 1. Map of study area of the 2016 aerial survey of the Eclipse Sound narwhal summer stock showing the six strata.

Figure 2. Map of the two repeats of the Eclipse Sound strata showing narwhal sightings (blue dots) and the footprint of each photograph.

Figure 3. Map of the two repeats of the Milne Inlet strata showing narwhal sightings (blue dots) and the footprint of each photograph.

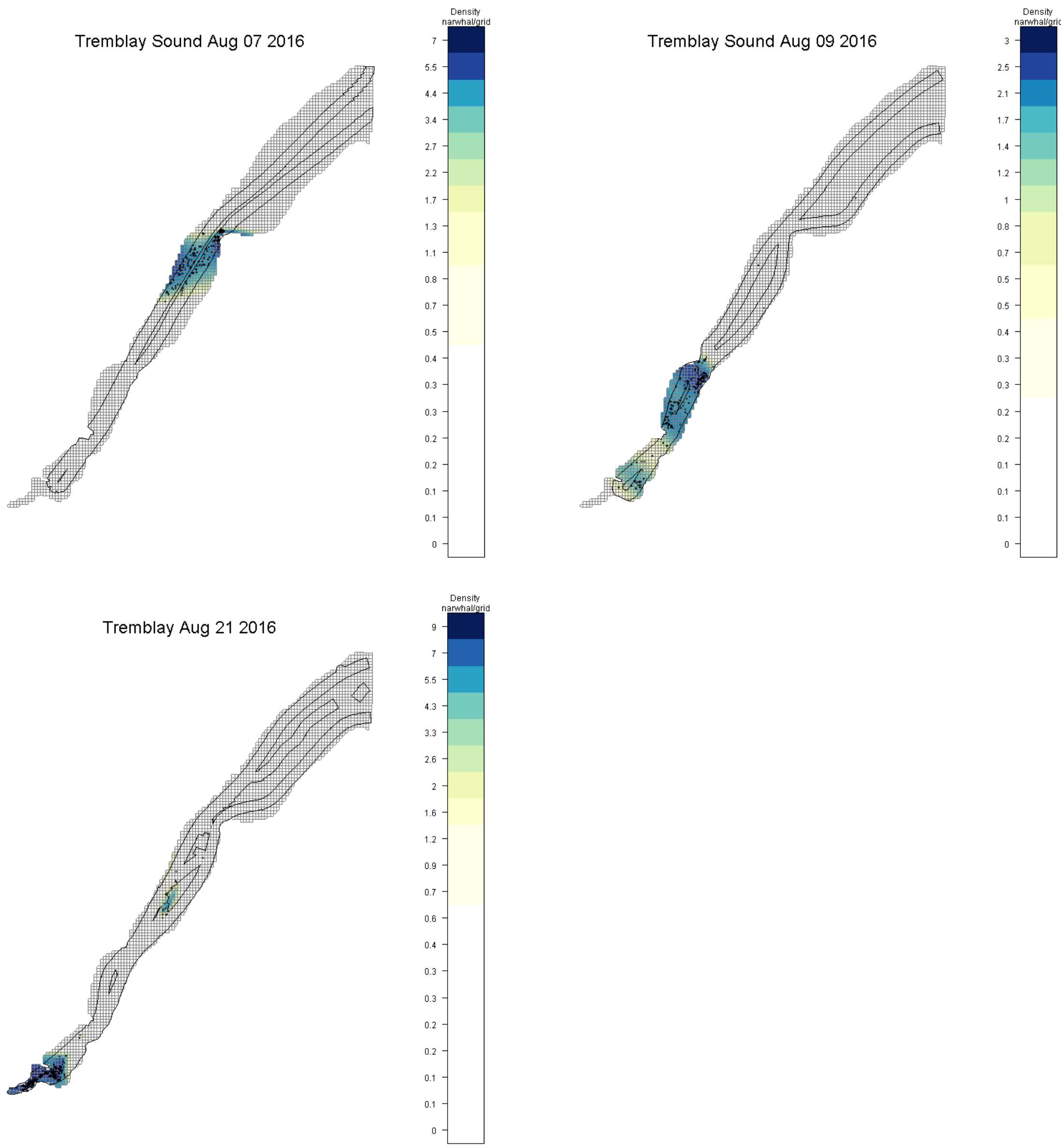

Figure 4. Map of the three repeats of the Tremblay Sound stratum showing the prediction grid from the best density surface model (see colour ramp), the narwhal sightings (black dots), and the outline of the photo coverage (black outline).

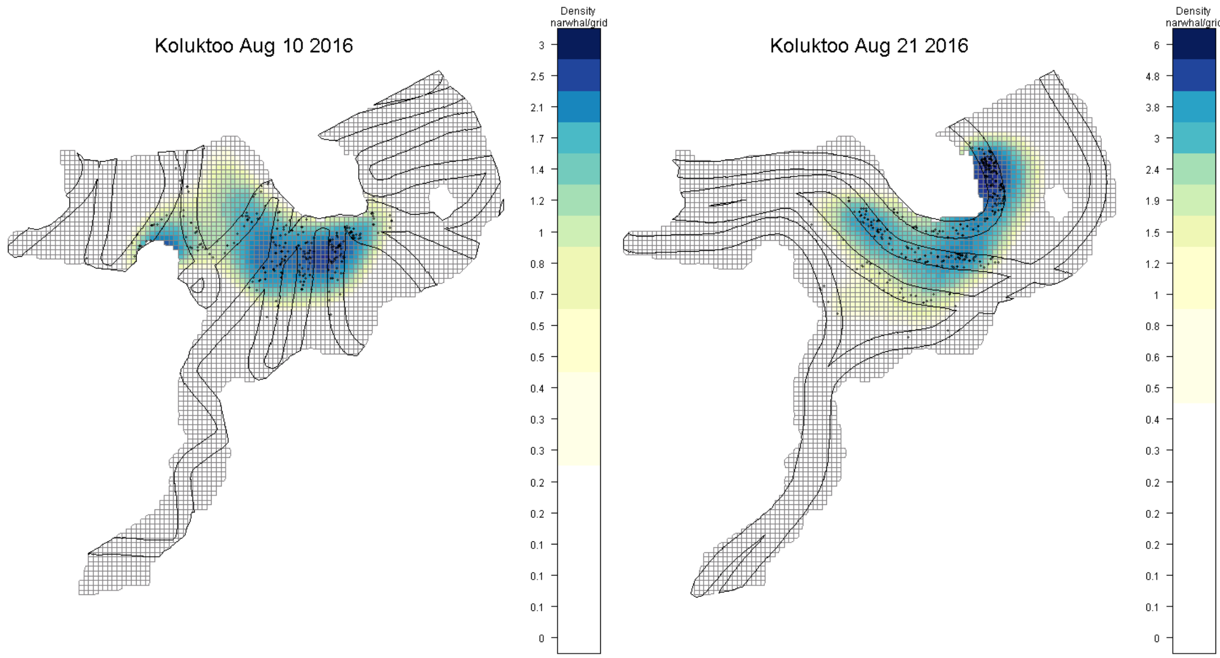

Figure 5. Map of the two repeats of the Koluktoo Bay stratum showing the prediction grid from the best density surface model (see colour ramp), the narwhal sightings (black dots), and the outline of the photo coverage (black outline).

APPENDIX

Table A.1 Map projection use for the calculation of distances and areas in the analysis of the 2016 aerial survey of the Eclipse Sound narwhal summer stock.

Projection	**Lambert Conformal Conic**
Latitude of origin	72.6
Latitude of first standard parallel	73.8
Latitude of second standard parallel	71.9
Central meridian	-79.5
Datum	NAD38
Ellipsoids	GRS80
Datum transformation to WGS84 (towgs84)	0, 0, 0

Table A2. Spatial density models for Tremblay Sound and Koluktoo Bay ranked by AIC with a ΔAIC < 7. Distribution family: nb is negative binomial. Smoother: soap is soap film smoother (Wood et al 2008), Duchon is Duchon slines (Miller and Wood 2014). Covariates: Mouth is distance to mouth of the fjord and shore is distance to shore. N is the abundance estimate from the predictions of the special model. S.E. is the standard error and C.V. is the coefficient of variation of the abundance estimate

Distribution family	Smoother	Covariates	Deviance explained (%)	AIC	ΔAIC	N	S.E.	C.V.
Tremblay Sound Strata								
August 7, 2016								
nb	soap	Mouth	93.66	211.08	0	453	79.90	0.18
nb	soap	-	93.23	211.37	0.29	551	135.06	0.25
August 9, 2016								
nb	Duchon	Mouth	74.39	400.62	0	361	67.73	0.19
nb	Duchon	Mouth Shore	74.94	402.62	2	404	93.81	0.23
nb	Duchon	Shore	74.74	402.7	2.08	400	92.55	0.23
nb	Duchon	-	73.84	403.91	3.29	349	64.93	0.19
nb	Soap	-	74.66	406.99	6.37	420	86.36	0.21
August 21, 2016								
nb	soap	Mouth Shore	94.89	287.05	0	525	97.61	0.19
nb	soap	Mouth	94.27	288.73	1.68	506	92.65	0.18
Koluktoo Bay Strata								
August 10, 2016								
nb	soap	Mouth	80.35	501.08	0	602	67.96	0.11
nb	soap	Mouth shore	80.58	502.18	1.1	601	68.07	0.11
nb	Duchon	Mouth Shore	79.80	503.17	2.09	560	58.70	0.10
nb	Duchon	Shore	79.39	504.99	3.91	557	58.67	0.11
nb	Duchon	Mouth	79.19	505.11	4.03	573	61.11	0.11
nb	Duchon	-	78.84	506.39	5.31	568	60.33	0.11
August 21, 2016								
nb	Duchon	Mouth	90.84	441.69	0	884	102.75	0.12
nb	Duchon	Mouth Shore	90.88	443.01	1.32	1,076	283.38	0.26
nb	Duchon	-	90.32	446.95	5.26	803	82.185	0.10
nb	Duchon	Shore	90.33	448.01	6.32	917	172.38	0.19
nb	soap	Mouth	90.77	448.06	6.37	1,087	316.57	0.29