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Abundance and Sustainable Harvest Advice from the 2023 High Arctic Cetacean Survey (HACS) for Beluga (*Delphinapterus leucas*) in Cumberland Sound

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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

There are two beluga whale (*Delphinapterus leucas*) populations that summer in Cumberland Sound (CS), but they are indistinguishable during aerial surveys. Therefore, co-management partners manage the beluga whales in CS as a single stock. An aerial survey of beluga whales in CS was conducted from August 23-29, 2023 as part of the High Arctic Cetacean Survey. Three strata were surveyed using systematic photographic survey methods and replicating coverage from the 2017 survey (Clearwater Fiord, Kangilo Fiord, and North CS). In 2023, the fourth stratum in CS (Whole CS) was expanded to survey the entire sound. There were no beluga whales detected outside of Clearwater Fiord. The estimated average abundance from the two surveys was 210 (95% Confidence Interval 90-500 [rounded to the nearest 10]) beluga whales. To estimate current abundance and determine trends in population dynamics, a model was fit to a series of six survey estimates from 1990-2023 and reported annual harvests from 1960-2025. Accounting for recent trends and survey estimates the model estimated a 2026 abundance of 250 (95% Credible Interval 1-900) beluga whales. Using the modelled estimate of abundance and a recovery factor of 0.1, the estimated Potential Biological Removal and Total Allowable Landed Catch (TALC) are 0. The model estimated that a TALC of 0, 0, 1, 2, 2, and 4 beluga per year would result in a 0, 5, 10, 15, 25, and 50% probability of decline, respectively, in beluga whales in CS in ten years. Under the current quota of 41 beluga whales per year the model estimated a 100% probability of decline in abundance in ten years, and the model predicted extirpation in four years. Unfortunately, regardless of which method is used to generate sustainable harvest advice, it is evident that the abundance of beluga whales in CS will not increase or stabilize under the current quota

INTRODUCTION

Beluga whales (*Devinapterus leucas*) that occur in Cumberland Sound (CS) during summer have been genetically assessed as being from two genetically distinct populations with the majority of the whales belonging to the CS beluga population that resides in CS year-round and nurses calves in Clearwater Fiord (Watt et al. 2023). The temporal and spatial overlap of these two distinct populations during the season in which they are hunted is unclear; limited data from samples of only a few harvested whales suggest they occur at the same time and place in CS in the summer (Watt et al. 2023). Unfortunately, the whales from these two distinct populations cannot be distinguished in aerial surveys. As a result, determining how many whales are found in CS in the summer season is the management approach to estimating appropriate subsistence harvest levels by the community of Pangnirtung.

Satellite tagging data from 2006-2008 suggest that beluga whales remain within CS year-round (Richard and Stewart 2009) overwintering in a polynya at the mouth of CS; however, an aerial survey in March 2023 only detected a single beluga whale in CS (DFO unpublished data), suggesting that overwintering grounds may have changed over time. In the open water season, aggregations of beluga whales occur in Clearwater Fiord (Figure 1; Belanger et al. 2024). Cumberland Sound beluga whales have been hunted commercially and for subsistence. Based on hunt records, abundance in 1923 was estimated at over 5,000 beluga whales (Mitchell and Reeves 1981). Commercial whaling, which ended in 1939, depleted the population to less than 1,000 individuals (Brodie et al. 1981, Richard 2013). The subsistence hunt has been regulated since the 1980s and the quota has been 41 beluga per year, since 2002 (Richard and Pike 1993). In 2017, the population was listed as Threatened under the Species at Risk Act (SARA) and as endangered by the Committee on the Status of Wildlife in Canada, in 2020 (COSEWIC 2020).

In 2019, a stochastic stock-production model, assuming density dependence acting on the population growth rate, was fitted by Markov Chain Monte Carlo (MCMC) Bayesian methods to aerial survey and reported harvest data (Watt et al. 2021). The model estimated the population at approximately 1,400 individuals and suggested that with the current quota of 41 animals the probability of population decline in ten years was 96% (DFO 2019). The Pangnirtung Hunters and Trappers Organization (HTO) raised concerns that a lack of survey coverage in the southwestern portion of CS may have negatively biased the 2017 abundance estimate. To address these concerns, a survey with coverage all across CS to the entrance of CS was flown in August 2023, in conjunction with the High Arctic Cetacean Survey (HACS) that also covered eastern Baffin Island, north of CS (see Marcoux et al. In press).

The goal of the present study was to 1) estimate abundance of beluga whales summering in CS based on the 2023 survey, 2) provide advice on a sustainable beluga whale harvest level based on the Potential Biological Removal method, and 3) incorporate the new estimate of abundance into a population model to provide information on the probability that the abundance of beluga whales in CS will decline in 10 years under a range of harvest scenarios (for 0, 5, 10, 15, 25, and 50% probability of decline, and under the existing quota of 41 beluga whales per year).

METHODS

STUDY AREA

Surveys were flown from August 25 to 28, 2023, as recommended by the Pangnirtung HTO at a meeting in March 2023. A later time period was recommended as a result of ice remaining later into the summer in CS in recent years. The study area was divided into four strata, Kangilo

Fiord, North CS, Whole CS, and Clearwater Fiord (Figure 1), and was designed to replicate the coverage of the 2017 aerial survey with modifications recommended by the Pangnirtung HTO. Based on recommendations from the HTO, the West CS strata from the 2017 survey was extended across CS and to the southern opening of CS (referred to as stratum Whole CS). The Kangilo Fiord stratum comprised 13 transect lines spaced 2.5 km apart (Figure 1). The North CS stratum survey consisted of five parallel transects spaced 10 km apart, and the Whole CS stratum survey consisted of 22 parallel transects spaced 10 km apart. The Clearwater Fiord stratum consisted of 24 parallel transects spaced 750 m apart, resulting in complete coverage of the fiord. All transect lines were oriented perpendicular to the long-axis of each stratum.

Photographic surveys were conducted in all strata. The photographic surveys were flown at a target altitude of 610 m (2,000 ft) and speed of 204 km/h (110 knots). A Nikon D850 camera, equipped with a 25 mm lens, mounted at the rear of the aircraft and directed straight down, with the longest side perpendicular to the track-line, was used to photograph continuously along the predefined transect lines. To geo-reference the photographs, the cameras were linked via Bluetooth to a single GPS receiver (Bad Elf GPS Pro+) using a module accessory (Foolography Unleashed D200+ Bluetooth Module). Each camera was also connected to a laptop computer to control exposure settings, the photograph interval, and to save high resolution JPEG and NEF RAW photographs to the computer's hard drive. At the target altitude of 610 m (2,000 ft; as measured by the aircraft system) the ground area covered by each photograph was 875.4 m x 585.2 m. A photographic interval of 6 seconds was used to target ~20% overlap between consecutive photographs along each transect in all strata. In Clearwater Fiord where whales are known to congregate, a full-coverage photographic survey was conducted. In this stratum there was a ~14% overlap between photographs taken on adjacent transects.

ANALYSIS

Photographs were examined for beluga whales using an autodetection algorithm (Mobius) with a human-in-the-loop methodology (Boulent et al. 2023). In addition to this, one reader at DFO (B. Sherbo) manually read 5% of the photographs (1 every 20) in CS from the High Arctic Cetacean Survey 2023 dataset (n = 710 photographs). This allowed us to calculate precision (equation 1), recall (equation 2), and F1 score (equation 3) (Powers 2011, Lawson 2023) for beluga whales for the auto-detector.

$$Precision = \frac{True\ Positives}{True\ Positives + False\ Positives} \quad (1)$$

$$Recall = \frac{True\ Positives}{True\ Positives + False\ Negatives} \quad (2)$$

$$F1\ Score = \frac{2 \times Precision \times Recall}{Precision + Recall} \quad (3)$$

All beluga whale detections from the auto-detector were then validated by C. Watt and B. Sherbo.

There were no new tagging data available to develop a new availability bias adjustment factor. Therefore, the same adjustment factors used in Marcoux and Hammill (2016) and Watt et al. (2021) were used. These factors are based on three female beluga whales tagged in Clearwater Fiord in July of 2006 (n = 1) and August 2007 (n = 2). An availability bias correction factor of 4.46 for the 0–1 m bin was used for instances where only beluga breaking the surface could be seen, while a correction of 2.06 for the 0–2 m bin was used in instances where the whale's

body could be observed at the surface and under the water. Water clarity was evaluated in each photograph by looking at the proportion of the beluga body that could be seen in the photograph by C. Watt. An instantaneous availability bias adjustment factor for the 0–2 m bin was used for photographs where the reader could see the tail and/or the head of the beluga whales beneath the surface of the water and an adjustment for the 0–1 m bin was used if the photograph reader could only see the portion of the beluga body that was breaking the surface of the water (Figure 2). This was done for each beluga identified, and the number of beluga for which the 0-1 m and 0-2 m adjustments were applied is shown in Table 2.

The surface area covered by each photograph was calculated as (equation 4):

$$A_{\text{photograph}} = \text{length} * \text{width} \quad (4)$$

where length = (altitude/ F_s)* L_s and width = (altitude/ F_s)* W_s , and F_s is the focal length of the lens (25 mm), L_s is the length of the camera sensor (35.9 mm) and W_s is the width of the camera sensor (24 mm). Altitude was assumed to remain at 610 m (2000 ft), and pitch and roll were not measured for each photograph. The area covered by land or glare was subtracted from the photograph area. The remaining area covered by water (with no glare) in each photograph was then calculated (A_{noglare}).

The number of beluga whales detected near or at the surface in each photograph was adjusted for the instantaneous availability bias, C_a described above, according to the clarity of the water.

An adjusted abundance estimate was calculated using (equation 5):

$$\hat{N}_{\text{cor}} = C_a \times \hat{N}_{\text{surface}} \quad (5)$$

where $\hat{N}_{\text{surface}}$ is the total number of beluga whales detected at the surface for each photograph.

Beluga whale density was calculated by dividing the summed beluga whale count by the summed area of glare-free water in all the photos. Density was then multiplied by the area covered by the photos to obtain near-surface abundance estimates (equation 6):

$$\hat{N}_{\text{tot}} = A_{\text{stratum}} \times \frac{\sum_{i=1}^I \hat{N}_{\text{cor}_i}}{\sum_{i=1}^I A_{\text{noglare}_i}} \quad (6)$$

where A_{stratum} is the area covered by the survey and I is the number of photographs per survey.

In strata without complete coverage, total variance is calculated by adding the variance of the encounter rate and of the availability bias adjustment factor. Within a single complete coverage photographic survey there is no variance associated with the encounter rate since all observable whales were counted. As a result, the only variance within a single repeat is the variance in the availability bias adjustment factor. Given uncertainty in the depth to which whales can be seen, a 20% coefficient of variation (CV) was used on the availability bias estimate for each repeat (NAMMCO-JCNB Joint Working Group 2021). An average of the two Clearwater Fiord survey estimates, weighted by their respective variance, was calculated. The variance on the average survey estimate was calculated as the standard deviation between the two abundance estimates. Confidence intervals were calculated assuming a log-normal distribution as suggested in Buckland et al. (2001).

MODEL SPECIFICATION

A stochastic stock-production model was fitted to the aerial survey (1990–2023) and reported harvest data (1960–2025) (Table 3 and 4). Observation error (associated with data collection

and abundance estimation) was separated from the process error (arising from natural variability in population dynamics) using a hierarchical state-space model that considers survey data to be the outcome of two distinct stochastic processes: a state process and an observation process (de Valpine and Hastings 2002). The state process describes the underlying population dynamics and the evolution of the true stock size over time, using a discrete formulation of the Pella-Tomlinson model (Pella and Tomlinson 1969, Innes and Stewart 2002), that allows the process error to have either positive or negative impacts on the growth rate, which was used by Watt et al. (2021) (equation 7):

$$N_t = N_{t-1} * \left(1 + (\lambda_{max} - 1) * \left(1 - \left(\frac{N_{t-1}}{K} \right)^\theta \right) \right) * \varepsilon_p - R_t \quad (7)$$

Where: λ_{max} is the maximum growth rate or rate of population increase,

K is the environmental carrying capacity,

θ (Theta) defines the shape of the density-dependent function,

ε_p is a stochastic term for the process error,

R_t are the removals for that year, calculated as reported catches, C_t , that are corrected for the proportion of animals that were struck and lost, $S\&L$ (equation 8):

$$R_t = C_t * (1 + S\&L) \quad (8)$$

The observation process describes the relationship between true population size and observed data. In our model, aerial survey estimates S_t are linked to population size N_t by an error term, ε_{S_t} (equation 9):

$$\ln(S_t) = \ln(N_t) + \varepsilon_{S_t} \quad (9)$$

The final model was run 100,000 times with a 60,000 burn in and 30 thinning. Increased burn in (100,000) and thinning (up to 100) was trialed to reduce autocorrelation, but did not result in an improvement while significantly increasing run time.

PRIORS

Priors were initially based on those used in the previous assessment by Watt et al. (2021). Six different trial models were used to evaluate the chosen population model for the CS beluga population (Table 5). For marine mammals, maximum productivity is thought to occur between 50% and 85% of K (Taylor and DeMaster 1993), but different jurisdictions have used values of θ for whales ranging between 1 and 3, which results in maximum productivity occurring between 50% and 63% (Wade 1998, Hobbs et al. 2015, Jackson et al. 2016, Heide-Jørgensen et al. 2016). Here we examined if θ was fixed at values of 1 or 2, or allowed to vary between 1 and 3 (Table 5), based on previous models that have showed $\theta < 2$ (Marcoux and Hammill 2016). For odontocetes, the maximum rate of population increase (λ_{max}) is thought to lie between 1.02 and 1.06, with most studies using 1.04 (Wade and Angliss 1997, Wade 1998, Lowry et al. 2008, Van de Walle et al. 2025). In all of our models, we allowed the model to estimate λ_{max} using a uniform prior with minimum and maximum values ranging from 1.005–1.05 (Table 5). Reported harvests underestimate the number of beluga whales killed because some animals are wounded or killed but cannot be recovered ($S\&L$). There are no data on $S\&L$ rates for CS, thus, we used the same $S\&L$ factor prior used by Watt et al. (2021), which also includes non-reporting: a Beta (3, 4) distribution, with a median of 0.42 and quartile points at 0.29 and 0.55 (Table 6). Priors for K were explored using both gamma and uniform distributions, as in previous assessments (Marcoux and Hammill 2016, Watt et al. 2021) (Table 5). Priors for

starting population (in 1960) were informed by previous models estimates (Alvarez-Flores unpublished report, Watt et al. 2021). The final model was restricted to only explore possibilities where start population was 20-100% of K.

Based on the previous assessments, the stochastic process error term ε_p was given a log-normal distribution with a zero location parameter. The precision parameter for this log-normal distribution was assigned a moderately informative prior following a Gamma (1.5, 0.0005) distribution. These parameters were chosen so that the resulting error would have a coefficient of variation of 1%, since beluga stock dynamics are not highly variable (Marcoux and Hammill 2016).

Survey variance was incorporated into the fitting process by guiding the formulation of the prior distribution of the survey error. The survey error term ε_{S_t} followed a log-normal distribution with a zero location parameter. Its precision parameter was given a moderately informative prior following a Gamma (2.5, 0.4) distribution. These parameters were chosen so that the resulting CV of the survey estimates would have quartiles Q_1 and Q_3 of 0.35 and 0.55, which were the same used by Marcoux and Hammill (2016) and Watt et al. (2021).

PARAMETER ESTIMATION AND MODEL DIAGNOSTICS

Posterior estimates of all the parameters were obtained using a Gibbs sampler algorithm implemented in JAGS (Plummer et al. 2003). R2jags and coda packages developed in the R programming language were used to examine the results (Plummer et al. 2020, Su et al. 2024). With any Markov Chain Monte Carlo (MCMC) simulation, it is important to check convergence of the sampled values to their stationary distribution (Brooks et al. 2004, King et al. 2010). Initial runs of the code were made to investigate convergence and mixing (i.e., the extent and spread with which the parameter space was explored by the chain), and autocorrelation (Figure A1).

Mixing of the chains was assessed using Geweke's test of similarity between different parts of each chain (Geweke 1996). The Brooks-Gelman-Rubin (BGR) diagnostic compares the width of 80% Credible Interval (CI) of pooled chains with the mean of widths of the 80% CI of individual chains and was used to assess convergence between chains (Brooks and Gelman 1998).

MODEL PROJECTIONS AND MANAGEMENT OBJECTIVES

The population model was used to estimate the probability of beluga whales in CS decreasing in the next 10 years with different harvest scenarios.

Potential Biological Removal (PBR) was calculated following Wade (1998) for the model-based estimate of stock size in 2026 or the abundance estimate from the 2023 survey. PBR was divided by $(1 + S\&L)$ (1.42 [Marcoux and Hammill 2016] or the model output) to calculate a revised Total Allowable Landed Catch (TALC) for different scenarios (equation 10).

$$PBR = (0.5 * R_{Max}) * N_{Min} * F_R \quad (10)$$

Where: $N_{Min} = N / \exp(z \sqrt{\ln(1+CV^2)})$

N = the model estimate for the stock size in 2026 or the abundance estimate from the 2023 survey.

$z = 0.842$ for the 20th percentile of the log-normal distribution of the estimated stock size (Wade 1998).

R_{Max} = maximum rate of increase for the stock. The default for cetaceans when the rate is unknown is 0.04. We also used the rate determined by

the population model. In the PBR equation it is then multiplied by 0.5 to ensure that the stock will continue to grow toward optimum sustainable yield despite the effect of logistic density dependent growth.

F_R = recovery factor set to 0.1 for a threatened declining stock (as recommended by DFO 2025).

The TALC is (equation 11):

$$TALC = PBR / (1 + S\&L) \quad (11)$$

RESULTS

SURVEY

Two aircraft were used to conduct the survey and we strove to survey adjacent strata on the same day to reduce risk of directed whale movement between neighbouring regions. As a result, two surveys occurred for all strata within two 2-day periods, except Whole CS which was covered only once.

Using systematic photographic survey methods, the Clearwater Fiord, Kangilo Fiord, North CS, and Whole CS strata were flown on August 25-26, while a second survey of these strata occurred on August 27-29 (Table 1). Due to weather constraints, the Whole CS stratum was surveyed only once across the two surveys (five transect lines in central CS could not be completed during survey 1 and were instead flown on August 29 (Table 1)). Beaufort Sea State (BSS) was generally good, although deteriorated on a few transect lines mid-flight (Table 1).

PHOTOGRAPHIC ANALYSIS

Every 20th photograph (5%) was manually read in a blind comparison to the Mobius algorithm (Boulent et al. 2023). This resulted in a percent precision of 87.5%, a recall of 100% and a F1 score of 93.3%. Due to a precision of 87.5%, all photographs (and five adjacent images) with identified whales were manually read by C. Watt to confirm presence and species. During this re-assessment, six whales, that were under water or grey calves and in close proximity to confirmed detections (Figure 3) were not detected by Mobius. B. Sherbo confirmed these detections and they were included in the final estimation of abundance.

AVAILABILITY BIAS

In Clearwater Fiord, where animals were in murky water (Figure 2), the 0-1 m adjustment factor was used and applied to 143 beluga whales detected on August 25, and 27 beluga whales detected on August 27 (Table 2). In Clearwater Fiord, where animals were in clear water (Figure 2), the 0-2 m adjustment factor was used and applied to 4 and 117 beluga whales detected on August 25 and 27, respectively (Table 2).

POPULATION ABUNDANCE ESTIMATE

Within Clearwater Fiord a full photographic survey (complete coverage) was conducted on August 25 and 27, where 144 and 147 beluga whales, respectively, were detected at the surface. Applying 0-1 and 0-2 m adjustment factors depending on water clarity, resulted in estimated abundances of 316 and 177 beluga whales (Table 2). There is no variation from total sightings in a single full coverage survey where reviewers come to consensus on detections and so each survey only had variation from the availability bias estimate which was estimated at 20% (NAMMCO-JCNB Joint Working Group 2021). Individual beluga whale sightings in

Clearwater Fiord are presented in Figure 4. There were no beluga whales detected outside of Clearwater Fiord in CS or along northern Baffin Island (Marcoux et al. In press).

The average abundance for the two surveys, weighted by the variance and adjusted for availability bias, was 210 (Table 2). The CV on the survey was calculated using the standard deviation between the two survey estimates and estimated at 46.98%. The 95% confidence interval was 88-504 beluga whales.

MODEL RESULTS AND PROJECTIONS

Six different models were assessed to evaluate the sensitivity of the model to different prior parameters (Table 5; Figure 5). All models showed a population that has declined since 1960, with a 2026 population of approximately 250 animals (Figure 5). All models where theta was allowed to vary updated the prior between one and two.

Priors and posteriors for the selected model (Table 5) are shown in Figure 6. In this model, each chain for the variables K, population size in 2026 (N_{2026}), process error, initial population size (N_{1960}), and S&L rate showed convergence. The overall Gelman and Rubin's potential scale reduction factor for this model were all equal to one, indicating convergence of the chain (Gelman and Rubin 1992) (Table 8), and the Geweke's Convergence Diagnostic Z-scores are all between -1.96 and 1.96 (Geweke 1996).

The model shows the population has been declining since 1960 (Figure 7) and there was some updating of the starting (1960) population prior with an estimated median starting population of 3,702 and a K of 6,841 (Table 7). The prior for λ_{max} was updated to a median of 1.02. The current median population abundance (N_{2026}) is 246 (95% CI 1-905) beluga whales (Table 7).

The model predicts there is a 0, 5, 10, 15, 25, and 50% probability of decline within 10 years with landed catches of 0, 0, 1, 2, 2, and 4 whales, respectively. Under the existing quota of 41 beluga whales per year there is a 100% probability of stock decline and the model predicted extirpation in four years (Table 7 and 8).

PBR

Using the 2023 survey abundance or the model population estimate for 2026, the calculated PBR, using a recovery factor of 0.1 (DFO 2025) and an assumed R_{Max} value of 0.04 (note the model estimate for R_{Max} was 0.02; Table 7) is zero, with an estimated TALC of zero. Using the modelled population estimate for 2026, modelled R_{Max} (0.02), and modelled S&L value (0.45), the PBR and TALC are also zero.

DISCUSSION

The 2023 survey estimate of 210 (CV 0.47; 95% confidence interval 88–504) beluga whales in CS is the sixth of a time series of abundance estimates for this population and allowed us to update the population dynamics model, and use the model to estimate future abundance under different harvest scenarios. The number of beluga whales at the surface was similar for the two survey repeats; however, the CV (0.47) on the average estimate comes entirely from the fact that two different availability biases were used and the majority of whales were detected in murky water on August 25, while on August 27, the majority of whales were detected in clear water. This highlights the impact the availability bias adjustment factor can have on the resulting estimate. Regardless, this estimate is significantly lower than that obtained in 2017 (Watt et al. 2021), and irrespective of availability bias, there were fewer whales detected at the surface in this survey than those previous.

For the survey in 2017, it was argued that surveying during high tide when water clarity conditions were judged to have been better may have positively biased estuary counts in two ways. First the water may have been more clear which would result in them being seen at greater depths; however, there is limited information on how the tides in this region impact turbidity. Secondly, there may have been more whales in the estuary at high tide, since beluga whales have been shown to move into estuaries during high tide and we did not survey adjacent strata at the same time (Ezer et al. 2008, Castellote et al. 2013, Simard et al. 2014). Similarly, general movements between strata could also bias estimates since survey estimates on different days within a season can change significantly (Gosselin et al. 2017). For the 2023 survey, we covered adjacent strata with a second aircraft to eliminate this concern. The August 25 surveys were flown at high tide, but the repeat surveys on August 27 were flown a few hours before high tide (Table 1). Both surveys had effectively the same number of whales seen at the surface ($n=144$ and 147 , respectively) but the proportion of whales for which the larger availability bias adjustment factor was used varied across the repeats, and this may be due to changes in turbidity with the tide. The relationship between tides and turbidity is not straightforward as it can depend on a number of geo- and hydrographical properties of the estuary itself (Wells 1995), but it is evident from Figure 2 that the silty water was more prominent during survey 1 at high tide in Clearwater Fiord. Availability bias has a large influence on abundance estimates and further work should be done to refine this factor in the future if possible.

The Pangnirtung HTO expressed concern that the survey was not flying along the coastline. During the 2023 survey it was also suggested that transect lines south of approximately transect 16 in Whole CS are not necessary and that it was also not necessary to fly all the way across CS. It was suggested that there be more transects and coverage in bays and along shorelines. It was also noted at a CS Beluga Working Group meeting in November 2025 that the “other” population of beluga whales can be found along the shorelines. Shoreline surveys are not systematic in nature and therefore challenging for survey analysis (Buckland et al. 2001); nonetheless, a part of the southwest coastline (from transect 1 at Nettilling Fiord to transect 7 of Whole CS) was surveyed on August 29, and no whales were sighted. However, Nettilling Fiord was surveyed on August 25 and three beluga whales were seen off transect. A single potential beluga whale was also recorded as being visually seen off transect on August 27 in Kangilo Fiord close to the coastline, but at the distance the aircraft was from the coast, accompanied with a BSS of 3-4, it was difficult to be certain (there were also narwhal in this area at the time (see Marcoux et al. In press) so species identification was uncertain). These were the only beluga whales visually seen outside of Clearwater Fiord and they were off transect and therefore not photographed nor included in the overall survey analysis. There should be consideration for adding Nettilling Fiord as its own strata during the next survey.

In the 2017 survey, it was suggested that movement of whales may have occurred during the first survey (in late July) when much lower number of beluga whales were seen in the fiord and this was coupled with higher estimates of beluga whales in strata outside Clearwater Fiord; suggesting beluga whales were still moving into Clearwater Fiord. In 2023, the survey was conducted much later in August to reduce the chances of surveying migrating whales. Another limitation of the 2017 survey was that whales were seen on the west side of CS on the last transect of the survey which suggested the survey may not have been expansive enough to capture all of the beluga whales present in the region. For the 2023 survey, the entirety of CS to the mouth of CS was surveyed, but only once. Outside of CS to the north was surveyed as part of the East Baffin Island survey for narwhal on August 28 and 29. No beluga whales were detected on those transect lines (see Marcoux et al. In press).

We found zero beluga whale detections in strata outside of Clearwater Fiord and we acknowledge there are methods to account for the probability that whales were missed in strata with zero sightings (Doniol-Valcroze and Hammill 2012, NAMMCO 2023). These methods were explored for this assessment; however, it was decided that a full analysis of each survey in the time-series used for the population dynamics model for beluga whales in CS would need to be conducted to account for the chance of missing whales in zero-sightings strata, as there were strata in these surveys where zero whales were detected. This may be something to consider in future assessments, especially if Inuit Qaujimajatuqangit (IQ) supports whales are in the regions during the survey period where zero whales were detected. In strata where there are detections, a much better estimate of abundance comes from the detections and so factoring in a zero-sighting probability would not be relevant.

Genetic evidence (from samples primarily collected in July) and IQ assert there are two populations of beluga whales in CS (Kilabuk 1997, Watt et al. 2023). Visual surveys are not able to separate the two populations, but IQ suggests that the larger CS beluga whales are found in Clearwater Fiord while the morphologically smaller beluga whales are found in the southeast region of CS (Kilabuk 1997). Although genetic assessment supports the presence of beluga whales more similar to Western Hudson Bay (WHB), the sample size was too small to assess if the hunt location and timing of WHB beluga samples varied with the larger Clearwater Fiord whales, and we were unable to assess whether WHB whales were regular migrants, or an ancestral line that now remains in CS (Watt et al. 2023). However, oxygen isotope analysis completed after the genetic assessment suggested that at least some of the WHB whales are migrants as their tooth stable isotope values suggested that they had been in the waters of WHB within their lifetime (Matthews et al. 2024). It is possible that in 2017 the earlier survey dates resulted in surveying some migrant beluga whales from WHB in CS, while in 2023, later survey dates missed these whales, or that these WHB beluga whales are unpredictable in their annual occurrence in CS (they were not found annually in harvest samples analyzed (Watt et al. 2023)). Without more research, we can only speculate on that possibility. The WHB beluga whale population is the largest population of beluga whales in the world (Matthews et al. 2017) and a proportion of the population does not go to WHB estuaries in summer as evidenced by successful hunts in Hudson Bay, Foxe Basin, Hudson Strait, and Frobisher Bay in summer (Parent et al. 2023; Montana et al. 2024). These WHB whales likely move in response to food availability, as other beluga whale populations are known to (Moore et al. 2000; Storrie et al. 2023), and will use areas like CS (Watt et al. 2023). However, during mating, which occurs in late winter, the Clearwater Fiord and WHB beluga populations are geographically separated and likely little genetic mixing occurs (Montana et al. 2024).

Although the 2023 survey estimate is lower than 2017, it is congruent with satellite imagery estimates in Clearwater Fiord from 2020 to 2022 (Belanger et al. 2024). The average corrected abundance estimate for Clearwater Fiord from satellite imagery was 393 (CV 0.036; 95% confidence interval 366-422) beluga whales in 2020, 197 (CV 0.047; 95% confidence interval 180-216) in 2021, and 194 (CV 0.06; 95% confidence interval 172-218) in 2022 (Belanger et al. 2024). Satellite imagery provides a full coverage image in a single snapshot and therefore movement of beluga whales across transect lines is not a concern, but it also provides a much lower resolution image than aerial survey images. In 2019, when the last assessment of beluga whales in CS was conducted, the modelled estimate of abundance had an almost certain chance of decline at a harvest of 41 beluga whales per year (Watt et al. 2021). At that time, the estimate of abundance projected ahead 10 years was estimated at ~750 beluga whales with a lower confidence limit of 65 beluga whales (these numbers themselves were not presented in Watt et al. (2021) but are the forward projections from the model presented there), which overlaps with our current estimate of abundance between 88-504 beluga whales.

The population model presented here only included harvest data back to 1960, similar to the last few assessments that have been conducted on beluga whales in CS (Marcoux and Hammill 2016, Watt et al. 2021). There was a significant effect of autocorrelation and serial correlation in the model, which indicated there was not enough information in the data to properly update the priors for K , $S\&L$, and the starting population. To alleviate some of this autocorrelation, the model was only evaluated back to 1960 (Marcoux and Hammill 1960). In the current assessment we also trialed (although not presented here), running the model back to 1920, and autocorrelation was still an issue in this model with no improvement (no reduction in autocorrelation) observed after increasing the number of runs, burn-in, or thinning. For the purpose of this assessment, the resulting model had a similar 2026 estimate of abundance and therefore effectively the same sustainable harvest recommendations, but this model resulted in a much higher K . Recent environmental changes in CS may also impact K , thereby influencing population dynamics (Biddlecombe and Watt 2022). As a result, future assessments that may want to develop reference points which are based on K (DFO 2025) will need to carefully evaluate the K that should be used, and may want to consider including pre-1960 harvest data, which has been collated by Stewart (2018), or environmental data (Biddlecombe and Watt 2022). We do not recommend utilizing the estimate for K presented in this study outside of this population assessment.

The Pangnirtung HTO has expressed concern about the impacts killer whales (*Orcinus orca*) are having on beluga whales in CS. In 2023, there were sightings of killer whales in CS on July 18 and August 8 (Ferguson et al. 2025). This was prior to the survey period but we cannot rule out that killer whales may have changed the distribution of beluga whales in CS, as they have been known to do in other regions (Westdal et al. 2016). However, in Western Hudson Bay, beluga whales did return to their similar range within a few days after the killer whales were documented (Westdal et al. 2016). There has been no study to evaluate impacts of killer whales on beluga whale abundance or distribution in CS.

Despite a restricted (albeit higher than recommended) harvest in Pangnirtung, beluga whales in CS continue to decline. After the significant commercial harvest of beluga whales in CS from 1860 through 1966 that removed an estimated 14,000 beluga whales (Stewart 2018), the remnant population was small. Small populations of toothed-whales have a difficult time recovering (Wade et al. 2012) as evidenced by the population of beluga whales in Cook Inlet, Alaska that has been under a harvest moratorium for >20 years and yet has still not recovered (Norman et al. 2015). It is believed that the lack of recovery seen in toothed whales could be attributed, in part, to social and behavioural factors (Wade et al. 2012). The removal of key individuals reduces network cohesion and may adversely affect the viability of the population if knowledge and foraging specialization are lost (Williams and Lusseau 2006). There are a number of individual factors, or the cumulative impacts of these factors, that could drive the lack of recovery in CS beluga whales other than harvest, including high stress (Kucheravy et al. 2023), low reproduction rates (Watt et al. 2021), changes in diet (Watt et al. 2016), loss of social structure (Wade et al. 2012), and killer whale predation (Ferguson et al. 2025). In addition to this, it has been shown genetically that CS beluga whales are harvested by hunters in Hudson Strait in spring and fall (see Table 5 in Parent et al. 2023), which would also be contributing to the decline in abundance but is not considered within the assessment model presented here.

Unfortunately, regardless of whether PBR from the survey abundance, PBR from the modelled abundance, or a risk-based assessment to generate sustainable harvest advice is used, it is evident that the CS beluga whale population will not increase nor remain stable under current harvest levels. In fact, the model estimated that a 0, 5, 10, 15, 25, and 50% probability of decline would occur with a TALC of 0, 0, 1, 2, 2, and 4 beluga per year CS in ten years. Under

the current quota of 41 beluga whales per year, the model estimated a 100% probability of decline in abundance in ten years, and the model predicted extirpation in four years.

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REFERENCES CITED

- Belanger, A.M., Sherbo, B.A.H., Roth, J.D., and Watt, C.A. 2024. Use of satellite imagery to estimate distribution and abundance of Cumberland Sound beluga whales reveals frequent use of a glacial river estuary. *Frontiers in Marine Science*. 10: 1305536. doi: 10.3389/fmars.2023.1305536
- Biddlecombe, B.A., and Watt, C.A. 2022. Incorporating environmental covariates into a Bayesian stock production model for the endangered Cumberland Sound beluga population. *Endang. Species Res.* 48: 51-65. doi: 10.3354/esr01186
- Boulent, J., Charry, B., McHugh Kennedy, M., Tissier, E., Fan, R., Marcoux, M., Watt, C. A., and Gagné-Turcotte, A. 2023. Scaling whale monitoring using deep learning: a human-in-the-loop solution for analyzing aerial datasets. *Front. Mar. Sci.* 1: 1099479. doi: 10.3389/fmars.2023.1099479
- Brodie, P.F., Parsons, J.L., and Sergeant, D.E. 1981. Present status of the white whale (*Delphinapterus leucas*) in Cumberland Sound, Baffin Island. *Rep. Int. Whal. Comm.* 31: 579–582.
- Brooks, S.P., and Gelman, A. 1998. General methods for monitoring convergence of iterative simulations. *J. Comp. Graph. Stats.* 7: 434–455. doi: 10.1080/10618600.1998.10474787
- Brooks, S., King, R., and Morgan, B. 2004. A Bayesian approach to combining animal abundance and demographic data. *Anim. Biodiversity Conserv.* 27(1): 515–529. doi: 10.32800/abc.2004.27.0515
- Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L., and Thomas, L. 2001. Introduction to distance sampling: estimating abundance of biological populations. Oxford University Press, Oxford, U.K. 434 p.
- Castellote, M., Leeney, R.H., O’Corry-Crowe, G., Lauhakangas, R., Kovacs, K.M., Lucey, W., Krasnova, V., Lydersen, C., Stafford, K.M., and Belikov, R. 2013. Monitoring white whales (*Delphinapterus leucas*) with echolocation loggers. *Polar Biol.* 36: 493–509. doi: 10.1007/s00300-012-1276-2
- COSEWIC. 2020. COSEWIC assessment and status report on the Beluga Whale *Delphinapterus leucas*, Eastern High Arctic – Baffin Bay population, Cumberland Sound population, Ungava Bay population, Western Hudson Bay population, Eastern Hudson Bay population and James Bay population in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xxxv + 84 pp. (Species at risk public registry).
- De Valpine, P., and Hastings, A. 2002. Fitting Population Models Incorporating Process Noise and Observation Error. *Ecol. Monogr.* 72(1): 57–76. doi:10.2307/3100085.

-
- DFO. 2019. [Sustainable harvest advice for Cumberland Sound beluga based on the 2017 aerial survey and modelled abundance estimates](#). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/024.
- DFO. 2025. [Revised Atlantic Seal Management Strategy](#). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2025/005.
- Doniol-Valcroze, T., and Hammill, M.O. 2012. [Information on abundance and harvest of Ungava Bay beluga](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2011/126. iv + 12 p.
- Ezer, T., R., Hobbs, and Oey, L-Y. 2008. On the movement of beluga whales in Cook Inlet, Alaska: Simulations of tidal and environmental impacts using a hydrodynamic inundation model. *Oceanogr.* 21(4): 186–195. doi: 10.5670/oceanog.2008.17
- Ferguson, S.H., Biddlecombe, B.A., Westdal, K., Petersen, S.D., Watt, C.A., Matthews, C.J.D., and Higdon, J. 2025. Killer whale range expansion and extended seasonal presence in the eastern Canadian Arctic, 2002-2023. *Front. Mar. Sci.* 12: 1595960. doi: 10.3389/fmars.2025.1595960
- Gelman, A., and Rubin, D.B. 1992. Inference from iterative simulation using multiple sequences. *Statist. Sci.* 7(4): 457–511.
- Geweke, J. 1996. Evaluating the accuracy of sampling-based approaches to the calculation of posterior moments. *In* Bayesian Statistics 4. Edited by J.M. Bernardo, J.O. Berger, A.P. Dawid, and A.F.M. Smith. Oxford University Press, Oxford, U.K. pp. 169–193.
- Gosselin, J.-F., Hammill, M.O., and Mosnier, A. 2017. [Indices of abundance of beluga \(*Delphinapterus leucas*\) in James Bay and eastern Hudson Bay in summer 2015](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2017/067. iv + 25 p.
- Heide-Jørgensen, M.P., Hansen, R.G., Fossette, S., Nielsen, N.H., Borchers, D.L., Stern, H., and Witting, L. 2016. Rebuilding beluga stocks in West Greenland. *Anim. Conserv.* 20: 282–293. doi: 10.1111/acv.12315
- Hobbs, R.C., Wade, P.R., and Shelden, K.E.W. 2015. Viability of a small, geographically-isolated population of beluga whales, *Delphinapterus leucas*: effects of hunting, predation, and mortality events in Cook Inlet, Alaska. *Mar. Fish. Rev.* 77: 59-88. doi: 10.7755/MFR.77.2.4
- Innes, S., and Stewart, R.E.A. 2002. Population size and yield of Baffin Bay beluga (*Delphinapterus leucas*) stocks. *NAMMCO Sci. Publ.* 4: 225–238. doi: 10.7557/3.2846.
- Jackson, J.A., Carroll, E.L., Smith, T.D., Zerbini, A.N., Patenaude, N.J., and Baker, C.S. 2016. An integrated approach to historical population assessment of the great whales: case of the New Zealand southern right whale. *R. Soc. Open Sci.* 3(3): 150669. doi: 10.1098/rsos.150669.
- Kilabuk, P. 1998. A study of Inuit knowledge on the Southeast Baffin Beluga. Report prepared for The Southeast Baffin Beluga Management Committee. Nunavut Wildlife Management Board, Iqaluit, Canada. 74 p.
- King, R., Gimenez, O., Morgan, B. and Brooks, S. 2010. Bayesian Analysis For Population Ecology. Chapman & Hall (CRC Press), USA. 442 p.
- Kucheravy, C.E., Trana, M.R., Watt, C.A., Roth, J.D., Tomy, G.T., Anderson, W.G., and Ferguson, S.H. 2022. Blubber cortisol in four Canadian beluga whale populations is unrelated to diet. *Mar. Ecol. Prog. Ser.* 698: 171-189. doi: 10.3354/meps14147

-
- Lawson, J. 2023. [A preliminary review of the efficacy of several acoustic autodetection algorithms to identify North Atlantic right whale calls, and recommendations for next steps to further assess and optimize these algorithms](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2023/050. iv + 17 p.
- Lowry, L.F., Frost, K.J., Zerbini, A., DeMaster, D., and Reeves, R.R. 2008. Trend in aerial counts of beluga or white whales (*Delphinapterus leucas*) in Bristol Bay, Alaska, 1993–2005. J. Cetacean Res. Manage. 10(3): 201–207. doi: 10.47536/jcrm.v10i3.636
- Marcoux, M., and Hammill, M.O. 2016. [Model Estimate of Cumberland Sound beluga \(*Delphinapterus leucas*\) population size and total allowable removals](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2016/077. iv + 35 p.
- Marcoux, M., Sherbo, B., Ghazal, M., Shuert, C., Gillespie, M., Lapierre Poulin, F., Breiter, C.-J., Biddlecombe, B., Stewart, J., Laing, J., Belanger, A.M., O'Doherty, S., Goulet, P., Davies-Marsh, A., and Watt, C.A. In press. Narwhal (*Monodon monoceros*) Stock Abundance from the 2023 High Arctic Cetacean Survey in the Canadian High Arctic. DFO Can. Sci. Advis. Sec. Res. Doc.
- 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.
- Matthews, C.J.D., Longstaffe, F.J., Parent, G.J., Hornby, C.A., and Watt, C.A. 2024. Discriminating Canadian Arctic beluga management stocks using dentine oxygen and carbon isotopes. Endang. Species Res. 54: 93-104. doi: 10.3354/esr01333
- Mitchell, E., and Reeves, R.R. 1981. Catch history and cumulative catch estimates of initial population size of cetaceans in the Eastern Canadian Arctic. Rep. Int. Whal. Comm. 31: 645–682.
- Montana, L., Bringloe, T.T., Bourret, A., Sauvé, C., Mosnier, A., Ferguson, S.H., Postma, L., Lesage, V., Watt, C.A., Hammill, M.O., and Parent, G.J. 2024. Reduced Representation and Whole-Genome Sequencing Approaches Highlight Beluga Whale Populations Associated to Eastern Canada Summer Aggregations. Evolutionary Applications 17: 1–20. doi: 10.1111/eva.70058
- Moore, S.E., Sheldon, K.E., Litzky, L.K., Mahoney, B.A., and Rugh, D.J. 2000. Beluga, *Delphinapterus leucas*, habitat associations in Cook Inlet, Alaska. Mar. Fish. Rev. 62: 60-80.
- NAMMCO-JCNB Joint Working Group. 2021. Report of the Joint Working Group Meeting of the NAMMCO Scientific Committee Working Group on the Population Status of Narwhal and Beluga in the North Atlantic and the Canada/Greenland Joint Commission on Conservation and Management of Narwhal and Beluga Scientific Working Group, December 2021, Winnipeg, Canada. North Atlantic Marine Mammal Commission, Tromsø, Norway. v + 40 p
- NAMMCO-North Atlantic Marine Mammal Commission (2023). Report of the Scientific Committee Ad hoc Working Group on Narwhal in East Greenland, December 2023, Copenhagen, Denmark.
- Norman, S.A., Hobbs, R.C., Goertz, C.E., Burek-Huntington, K.A., Sheldon, K.E., Smith, W.A., and Beckett, L.A. 2015. Potential natural and anthropogenic impediments to the conservation and recovery of Cook Inlet beluga whales, *Delphinapterus leucas*. Mar. Fish. Rev. 77: 89-105. doi: 10.7755/MFR.77.2.5

-
- Parent, G.J, Mosnier, A., Montana, L., Cortial, G., St-Pierre, A.P., Bordeleau, X., Lesage, V., Watt, C., Postma, L., and Hammill, M.O. 2023. [Re-examining populations of beluga in the Hudson Bay-Strait Complex and assessing the impact on harvests in Nunavik and Sanikiluaq management units](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2023/004. iv + 31 p.
- Pella, J.J., and Tomlinson, P.K. 1969. A generalized stock production model. *Inter-Am. Trop. Tuna Comm.* 13(3): 420–496.
- Plummer, M. 2003. JAGS: A program for analysis of Bayesian graphical models using Gibbs sampling. *In* Proceedings of the 3rd International Workshop on Distributed Statistical Computing. Edited by: K. Hornik, F. Leisch, and A. Zeileis. Vienna, Austria. p. 1–8.
- Plummer, M., Best, N., Cowles, K., Vines, K., Sarkar, D., Bates, D., Almond, R., and Magnusson, A. 2020. CODA: Output Analysis and Diagnostics for MCMC. R package version 0.19-4.
- Powers, D.M.W. 2011. Evaluation: from precision, recall and F-measure to ROC, informedness, markedness and correlation. *J. Mach. Learn. Tech.* 2: 37-63.
- Richard, P.R. 2013. [Size and trend of the Cumberland Sound beluga whale population, 1990 to 2009](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2012/159. iii + 28 p.
- Richard, P.R., and Pike, D.G. 1993. Small whale co-management in the Eastern Canadian Arctic: A case history and analysis. *Arctic* 46(2): 138–143.
- Richard, P., and Stewart, D.B. 2009. [Information relevant to the identification of critical habitat for Cumberland Sound belugas \(*Delphinapterus leucas*\)](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2008/085: iv + 24 p.
- Simard, Y., Loseto, L., Gautier, S., Roy, N. 2014. Monitoring beluga habitat use and underwater noise levels in the Mackenzie Estuary: Application of passive acoustics in summers 2011 and 2012. *Can. Tech. Rep. Fish. Aquat. Sci.* 3068: vi + 49 p.
- Stewart, D.B. 2018. Commercial and subsistence catches of beluga whales (*Delphinapterus leucas*) from Cumberland Sound, Nunavut, 1840-2016. *Can. Tech. Rep. Fish. Aquat. Sci.* 3250: viii + 89 p.
- Storrie, L., Loseto, L.L., Sutherland, E.L., MacPhee, S.A., O’Corry-Crowe, G., and Hussey, N.E. 2023. Do beluga whales truly migrate? Testing a key trait of the classical migration syndrome. *Movement Ecol.* 11: 53. doi: 10.1186/s40462-023-00416-y
- Su, Y., Yajima, M., and Baio, G. 2024. [R2jags: Using R to Run ‘JAGS’](#). R package version 0.8-9.
- Taylor, B.L., and DeMaster, D.P. 1993. Implications of non-linear density dependence. *Mar. Mammal Sci.* 9(4): 360–371. doi: 10.1111/j.1748-7692.1993.tb00469.x
- Van de Walle, J., Tinker, M.T., and Sauvé, C. 2025. [Abundance Estimate and Harvest Impacts on Belcher Islands-Eastern Hudson Bay and James Bay Beluga: 2024 Update](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2025/056. v + 66 p.
- Wade, P.R. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Mar. Mammal Sci.* 14(1): 1–37. doi: 10.1111/j.1748-7692.1998.tb00688.x
- Wade, P.R., and Angliss, R.P. 1997. Guidelines for assessing marine mammal stocks: report of the GAMMS workshop April 3-5, 1996, Seattle, Washington. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-OPR-12: 93 p.
-

-
- Wade, P.R., Reeves, R.R., and Mesnick, S.L. 2012. Social and behavioural factors in cetacean responses to overexploitation: are odontocetes less “resilient” than mysticetes? *J. Mar. Sci.* 1: 567276. doi: 10.1155/2012/567276
- Watt, C.A. 2021. Catch statistics for beluga (*Delphinapterus leucas*) harvested from the Eastern High Arctic – Baffin Bay and Cumberland Sound populations from 1977-2020. *Can. Tech. Rep. Fish. Aquat. Sci.* 3444: vii + 18 p.
- Watt, C.A., Orr, J., and Ferguson, S.H. 2016. A shift in foraging behaviour of beluga whales *Delphinapterus leucas* from the threatened Cumberland Sound population may reflect a changing Arctic food web. *Endang Species Res.* 31: 259-270. doi: 10.3354/esr00768
- Watt, C.A., Marcoux, M., Hammill, M.O., Montsion, L., Hornby, C., Charry, B., Dunn, J.B., Ghazal, M., Hobbs, R., Lee, D.S., Mosnier, A., and Matthews, C.J.D. 2021. [Abundance and total allowable landed catch estimates from the 2017 aerial survey of the Cumberland Sound beluga \(*Delphinapterus leucas*\) population](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2021/050. iv + 33 p.
- Watt, C.A., Montana, L., Hudson, J., and Parent, G.J. 2023. [Stock definition and genetic composition of Cumberland Sound beluga whales \(*Delphinapterus leucas*\)](#). DFO Can. Sci. Advis. Sec. Res. Doc. 2023/069. iv + 38 p.
- Wells, J.T. 1995. Chapter 6: Tide-dominated estuaries and tidal rivers. *Develop. Sediment.* 53: 179-205. doi: 10.1016/S0070-4571(05)80026-3
- Westdal, K.H., Davies, J., McPherson, A., Orr, J., and Ferguson, S.H. 2016. Behavioural changes in belugas (*Delphinapterus leucas*) during a killer whale (*Orcinus orca*) attack in southwest Hudson Bay. *Can. Field. Nat.* 130: 315-319. doi: 10.22621/cfn.v130i4.1925
- Williams, R., and Lusseau, D. 2006. A killer whale social network is vulnerable to targeted removals. *Biol. Lett.* 2: 497-500. doi: 10.1098/rsbl.2006.0510

TABLES AND FIGURES

Table 1. Summary of photographic aerial survey of beluga whales conducted in Cumberland Sound in August 2023.

Date	Stratum	Time (UTC)	Times of High Tide (UTC)*	Tide Height (m)	Survey Repeat	Transects	Beaufort sea state
25-Aug	Clearwater Fiord	14:40-16:32	16:27	5.02	1	1-22	0-1
25-Aug	North	16:32-17:40	16:27	5.02	1	1-5	1-3
25-Aug	Whole Cumberland Sound	19:04-20:45	16:27	5.02	1	1-4, 13-16	1
25-Aug	Kangilo Fiord	15:09-17:12	16:27	5.02	1	1-13	1
26-Aug	Whole Cumberland Sound	14:27-16:30 & 19:09-21:25	17:59	4.95	1	10-21	0-4
27-Aug	Kangilo Fiord	15:03-17:09	19:25	5.23	2	1-8	3-4
27-Aug	Clearwater Fiord	15:14-17:09	19:25	5.23	2	1-22	1
28-Aug	Kangilo Fiord	13:59-14:44	20:30	5.70	2	9-13	3
28-Aug	North	15:07-16:44	20:30	5.70	2	1-5	3-4
29-Aug	Whole Cumberland Sound	14:33-16:23	21:21	6.20	1	5-9	1-2

High tide times from (<https://tides.gc.ca/en/stations/04040/2023-08-25?tz=UTC&unit=m>)

Table 2. Abundance estimates of beluga whales from the photographic survey conducted in August 2023. Adjustment factors to account for availability bias (Ca) of 4.46 (coefficient of variation [CV] 0.2) for the 0–1 m bin were used for instances where only beluga breaking the surface could be seen, while an adjustment of 2.06 (CV 0.2) was used for the 0-2 m when the tail and/or the head of the belugas could be seen beneath the surface of the water (see Figure 2).

Strata	Date in August	Photographs (#)	Strata area (km ²)	Photo area (km ²)	Total beluga at surface	Beluga (#) 0-1m Ca 4.46	Beluga (#) 0-2m Ca 2.06	$\hat{N}$ Ca	Adjusted density	$\hat{N}$	CV (%)	95% Conf. Interval
Clearwater Fiord	25	479	102.9	210.1	147	143	4	646	3.07	316	20.0	215-466
Clearwater Fiord	27	553	109.2	223.2	144	27	117	361	1.62	177	20.0	120-261
Weighted Average	-	-	-	-	-	-	-	-	-	210	47.0	-
North	25	818	2689	172.9	0	0	0	0	0	0	-	-
North	28	782	2689	185.0	0	0	0	0	0	0	-	-
Kangilo Fiord	25	811	554	171.4	0	0	0	0	0	0	-	-
Kangilo Fiord	27-28	898	554	208.6	0	0	0	0	0	0	-	-
Whole Cumberland Sound	25-26-29	5290	21593	1153	0	0	0	0	0	0	-	-
Total	-	-	-	-	-	-	-	-	-	210	47.0	88-504

Table 3. Previous and current estimates of Cumberland Sound beluga whale abundance within Clearwater Fiord, the area of main concentration, the estimated number of animals outside the fiord and the total. The availability bias factors used to adjust the counts for animals not at the surface in Clearwater Fiord (Ca_{CF}) and outside (Ca_{OCF}) are provided along with the estimated abundances inside (N_{CF}) and outside (N_{OCF}) Clearwater Fiord for each survey. The total abundance (N_{Total}), coefficient of variation (CV), and % of whales found outside the fiord are also presented. Complete photographic coverage occurred in Clearwater Fiord in 2014, 2017, and 2023, while systematic visual surveys occurred outside of Clearwater Fiord for all years except 2023 when a systematic photographic survey was conducted.

Year	Ca_{CF}	N_{CF}	Ca_{OCF}	N_{OCF}	N_{Total}	CV	% Outside	complete photographic, photographic	Strata	Reference
1990	2.57	1,180	2.54	0	1,180	0.10	0	complete photographic, visual systematic	Clearwater Fiord, North	Richard 2013
1999	2.57	1,924	2.54	347	2,270	0.09	15	complete photographic, visual systematic	Clearwater Fiord, North, and West	Richard 2013
2009	2.57	303	2.54	546	849	0.38	64	complete photographic, visual systematic	Clearwater Fiord, North, and West	Richard 2013
2014	4.46 and 2.06	603	2.54	548	1,151	0.21	48	complete photographic, visual systematic	Clearwater Fiord, North, and West	Marcoux et al. 2016
2017	4.46 and 2.06	301	2.54	1,379	1,749	0.42	31	complete photographic, visual systematic	Clearwater Fiord, Kangilo Fiord, North, and West	Watt et al. 2021
2023	4.46 and 2.06	210	-	-	210	0.47	0	complete photographic, photographic systematic	Clearwater Fiord, Kangilo Fiord, North, and Whole CS	Present Study

Table 4. Reported harvests and quotas of Cumberland Sound beluga whales 1960–2025. Data for 1960 to 1972 are from Stewart (2004 unpubl. rep.); 1973–1976 are from the Planning Committee for the Co-Management of Southeast Baffin Beluga (1994 unpubl. rep.), 1977–2020 from Watt (2021), and 2021–2025 DFO unpublished data. There was no reported harvest for several years since 2004. In those years, it was assumed that the entire quota was taken.

Year	Reported landed	Year	Reported landed	Quota	Year	Quota	Reported landed
1960	155	1989	42	-	2018	41	41
1961	60	1990	36	-	2019	41	41
1962	52	1991	31	35	2020	41	41
1963	167	1992	35	35	2021	41	41
1964	69	1993	15	35	2022	41	41
1965	65	1994	35	35	2023	41	42
1966	80	1995	31	35	2024	41	41
1967	60	1996	41	35	2025	41	41
1968	28	1997	47	35	-	-	-
1969	27	1998	35	35	-	-	-
1970	60	1999	50	35	-	-	-
1971	50	2000	37	35	-	-	-
1972	61	2001	39	35	-	-	-
1973	43	2002	41	41	-	-	-
1974	44	2003	46	41	-	-	-
1975	50	2004	-	41	-	-	-
1976	120	2005	-	41	-	-	-
1977	178	2006	52	41	-	-	-
1978	85	2007	48	41	-	-	-
1979	70	2008	-	41	-	-	-
1980	43	2009	-	41	-	-	-
1981	45	2010	-	41	-	-	-
1982	40	2011	42	41	-	-	-
1983	44	2012	-	41	-	-	-
1984	40	2013	-	41	-	-	-
1985	44	2014	-	41	-	-	-
1986	26	2015	18*	41	-	-	-
1987	40	2016	41	41	-	-	-
1988	46	2017	34	41	-	-	-

*significant ice in 2015 limited harvesting

Table 5. Trial runs of the population model which evaluated changes to the shape parameter of the density-dependent function (theta), the carrying capacity, rate of population increase (λ_{Max}), and the start population of Cumberland Sound beluga whales. All model runs started with catch data from 1960. The function dgamma (8,0.0015) has 0.0275, 0.25, 0.5, 0.75 and 0.975 quantiles at 3,466, 5,973, 7,687, 9,704, and 14,429 respectively. Bold indicates final model presented.

Model	Theta	Carrying capacity (K)	λ_{Max}	Start Population
1	1	Uniform(2,000–15,000)	Uniform(1.01–1.05)	1,000–4,000
2	Uniform(1,3)	Uniform(2,000–15,000)	Uniform(1.01–1.05)	1,000–4,000
3	2	Uniform(2,000–15,000)	Uniform(1.01–1.05)	2,000–5,000
4	Uniform(1,3)	dgamma(8,0.0015)	Uniform(1.01–1.05)	2,000–5,000
5	1	dgamma(8,0.0015)	Uniform(1.005–1.05)	2,000–5,000
6	1	Uniform(2,000–15,000)	Uniform(1.005–1.05)	20-100% K

Table 6. Prior distributions, parameters and hyper-parameters used in the final Cumberland Sound beluga whale population model (model 6 in Table 5). “dist.” denotes a hyper-parameter with its own prior distribution.

Parameters	Notation	Prior distribution	Hyper-parameters	Values
Survey error (t)	ε_{st}	Log-normal	μ_s τ_s	0 <i>dist.</i>
Precision (survey)	τ_s	<i>Gamma</i>	α_s β_s	2.5 0.4
Process error (t)	ε_{pt}	Log-normal	μ_p τ_p	0 <i>dist.</i>
Precision (process)	τ_p	Gamma	α_p β_p	1.5 0.00005
Density dependence shape function (theta)	Θ	Fixed	-	1
Struck-and-lost*	<i>S&L</i>	Beta	α_{sl} β_{sl}	3 4
Initial population	N_{1960}	Uniform	N_{upp} N_{low}	100% K 20% K
Carrying capacity	K	Uniform	N_{upp} N_{low}	2000 15,000
Lambda _{Max}	λ_{max}	Uniform	N_{upp} N_{low}	1.005 1.05

*struck and lost also includes non-reporting.

Table 7. Model outputs for model 6 (see Table 5), for beluga whales in Cumberland Sound. The mean, standard deviation (SD), median (50th Q), 25th and 75th quantiles (25th Q, 75th Q), 95% credibility intervals (2.5%CI, 97.5%CI) are given for the following model parameters and their priors: carrying capacity (K), maximum growth rate (λ_{max}) process error (process), survey precision (surv), starting population (startpop), struck and lost (S&L), and population size in 2018 (N_{2026}). $\hat{R}$ is the Brooks-Gelman-Rubin statistics; values near 1 indicate convergence of chains. N.eff is the number of effective chains after considering autocorrelation.

Parameter	Mean	SD	2.5%CI	25 th Q	50 th Q	75 th Q	97.5%CI	$\hat{R}$	n.eff
K	7612.81	3065.68	3565.14	5082.21	6841.32	9765.68	14261.67	1.00	8400.00
K.prior	8495.26	3755.09	2318.49	5239.61	8506.72	11749.98	14668.38	1.00	5e+05
Theta	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
deviance	92.34	1.95	89.99	91.00	91.89	93.17	97.39	1.00	5e+05
λ_{max}	0.02	0.01	0.01	0.01	0.02	0.03	0.05	1.00	68000.00
λ_{prior}	0.03	0.01	0.01	0.02	0.03	0.04	0.05	1.00	5e+05
prec.process	29994.52	24488.52	2179.19	12120.08	23652.55	41073.96	93792.54	1.00	70000.00
prec.process.prior	30008.62	24477.88	2164.58	12125.25	23667.41	41155.29	93171.17	1.00	5e+05
prec.surv	4.52	2.08	1.43	3.01	4.20	5.69	9.42	1.00	5e+05
prec.surv.prior	6.25	3.95	1.03	3.35	5.45	8.29	16.03	1.00	190000.00
startpop	3717.71	701.85	2426.46	3210.99	3702.17	4201.85	5111.45	1.00	44000.00
startpop.prior	3717.71	701.85	2426.46	3210.99	3702.17	4201.85	5111.45	1.00	44000.00
S&L	0.46	0.17	0.14	0.34	0.46	0.59	0.80	1.00	260000.00
S&L prior	0.43	0.18	0.12	0.30	0.42	0.55	0.78	1.00	5e+05
N_{2026}	295.91	247.36	1.00	128.43	245.50	401.03	904.70	1.00	2e+05

Table 8. Probability (P) that Cumberland Sound beluga whales, subjected to different levels of annual landed catch, will decline from the modelled 2026 population abundance estimate after 10 years of harvest.

P (%)	Landed Catch
0	0
5	0
10	1
15	1
20	1
25	2
30	2
40	3
50	4
60	5
70	6
80	8
90	14
95	35
100	41

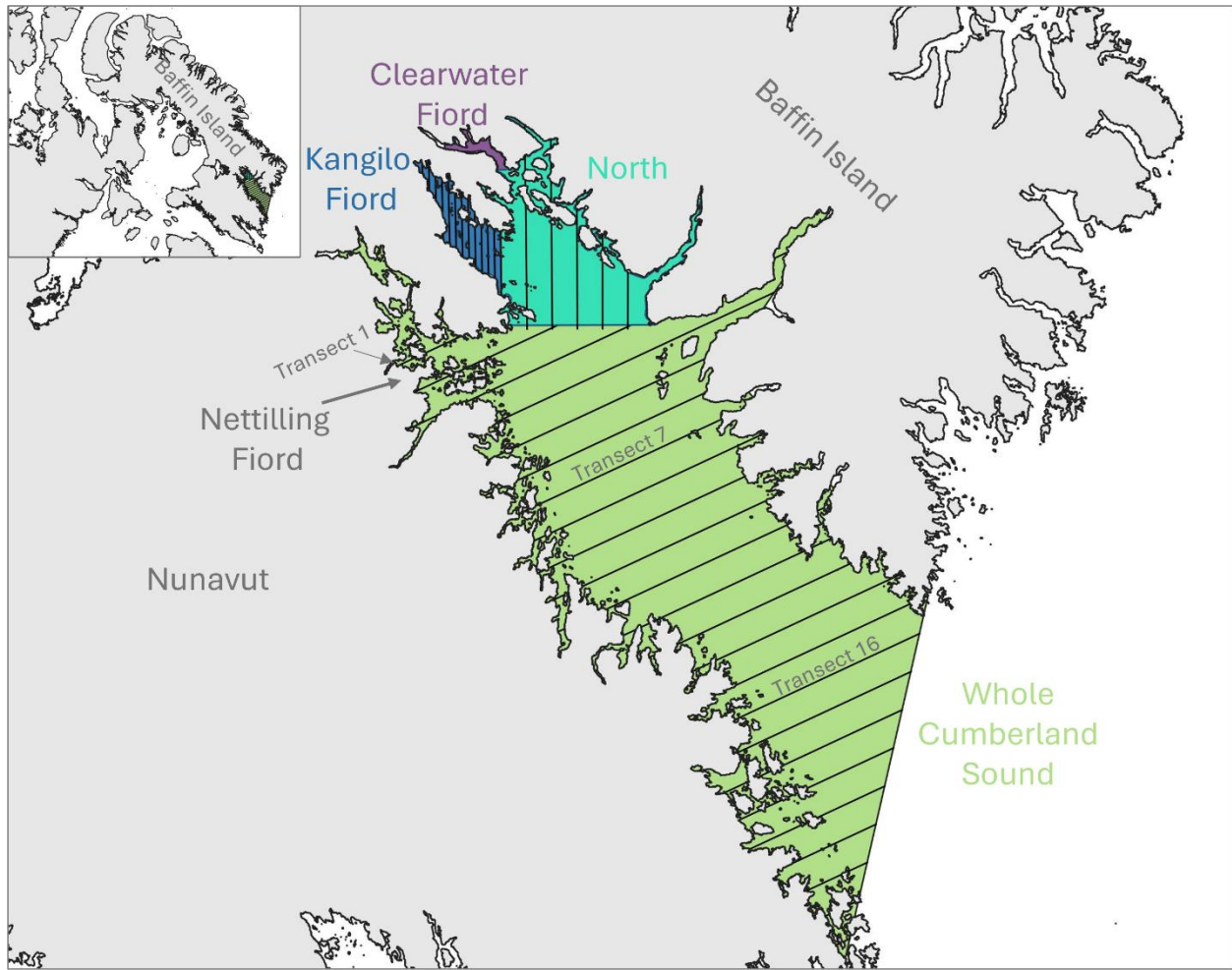
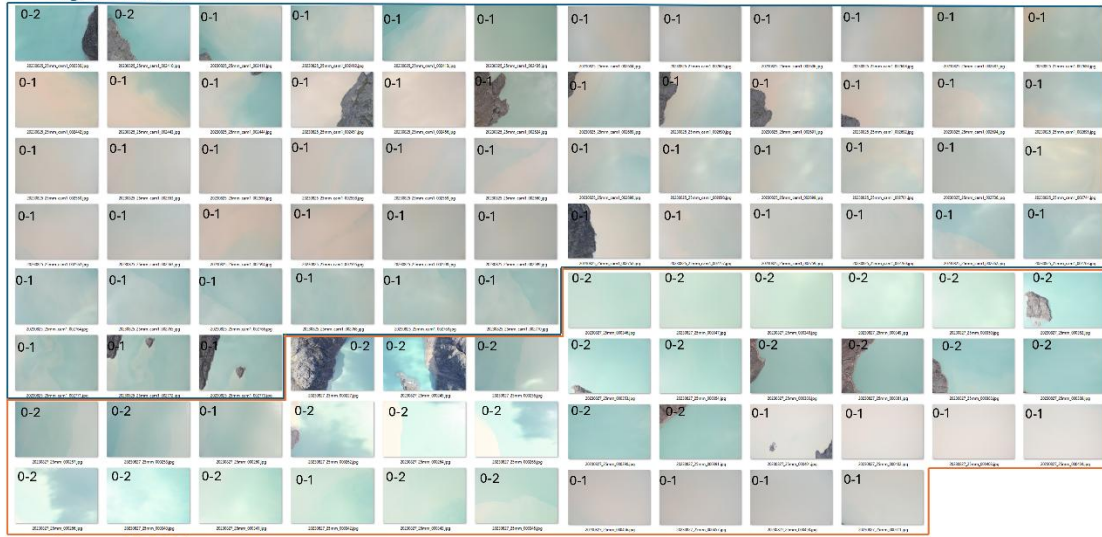


Figure 1. Map indicating four strata and transect lines surveyed in the aerial survey for beluga whales in Cumberland Sound in 2023.

A August 25 2023



August 27 2023

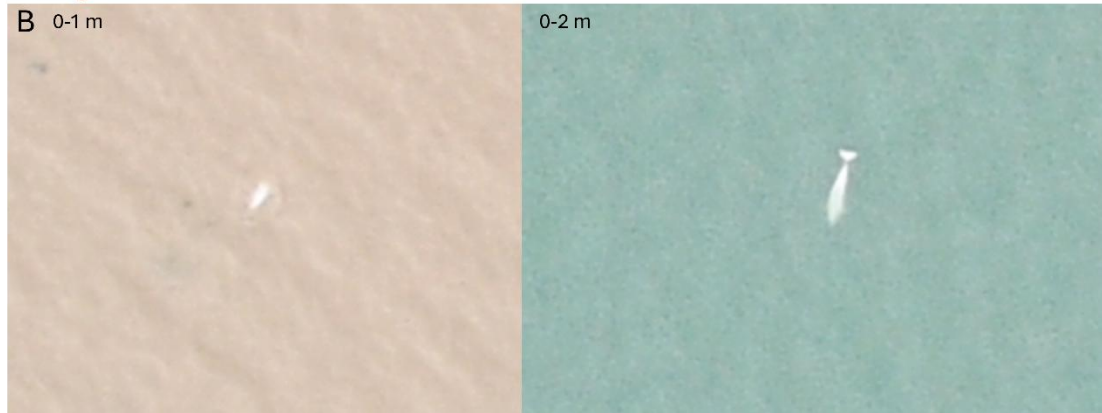


Figure 2. A) Individual photographs with Cumberland Sound beluga whale detections that were assessed as requiring an availability bias adjustment for the 0-1m versus the 0-2m bin on August 25 (blue) and August 27 (orange), 2023, and B) examples of whales, in murky (0-1 m) and clear (0-2 m) water.

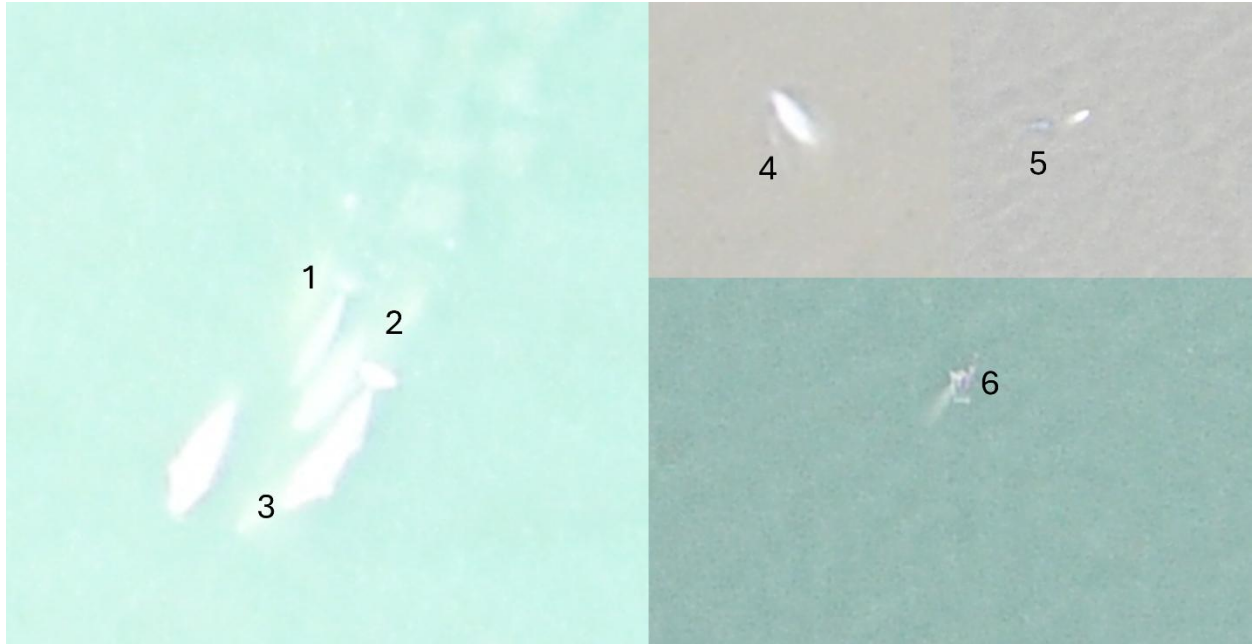


Figure 3. Beluga whales missed by the auto-detector included whales under water (1, 2, and 3) and grey calves with their assumed mothers (4, 5, and 6). These whales were identified in a non-blind post-hoc analysis and were included in analysis.

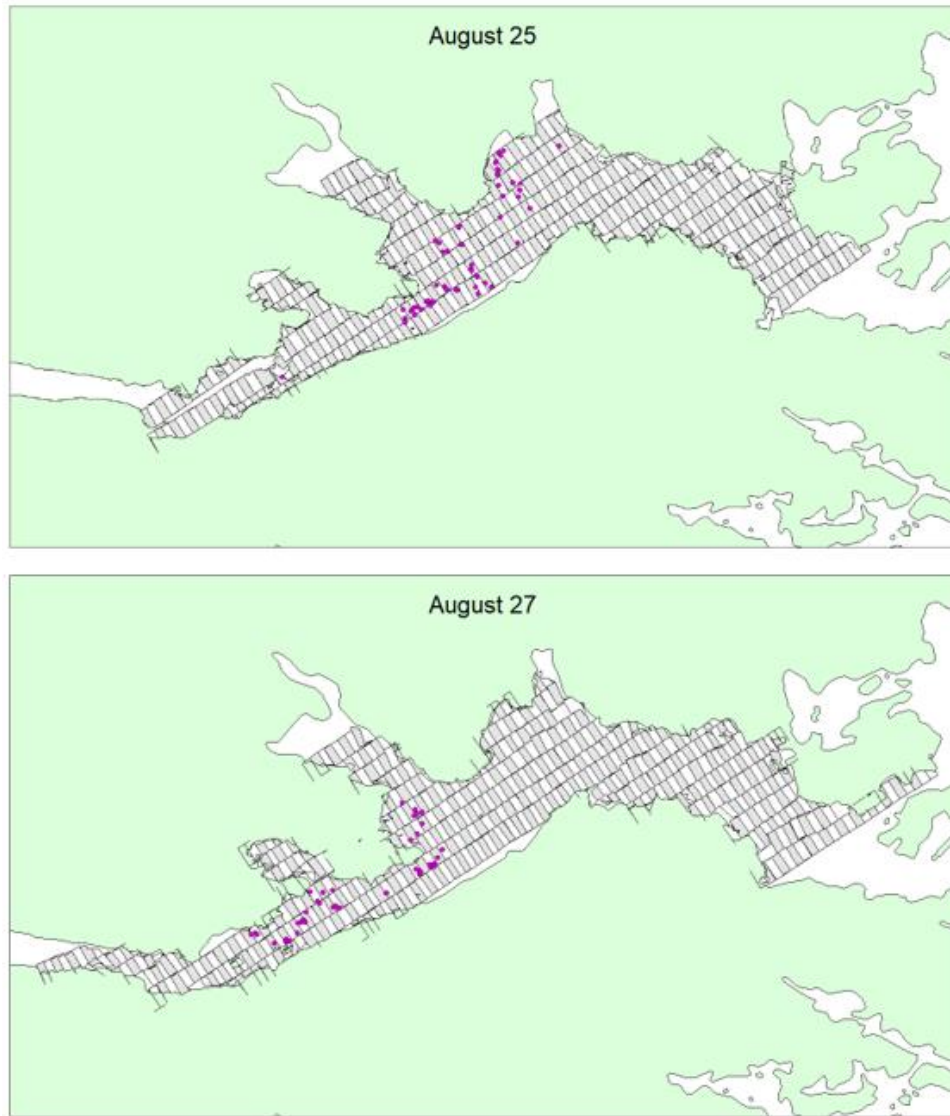


Figure 4. Map of the two photographic surveys of Clearwater Fiord showing individual beluga whale detections and the geographic coverage of each photograph on a) August 25 and b) August 27, 2023.

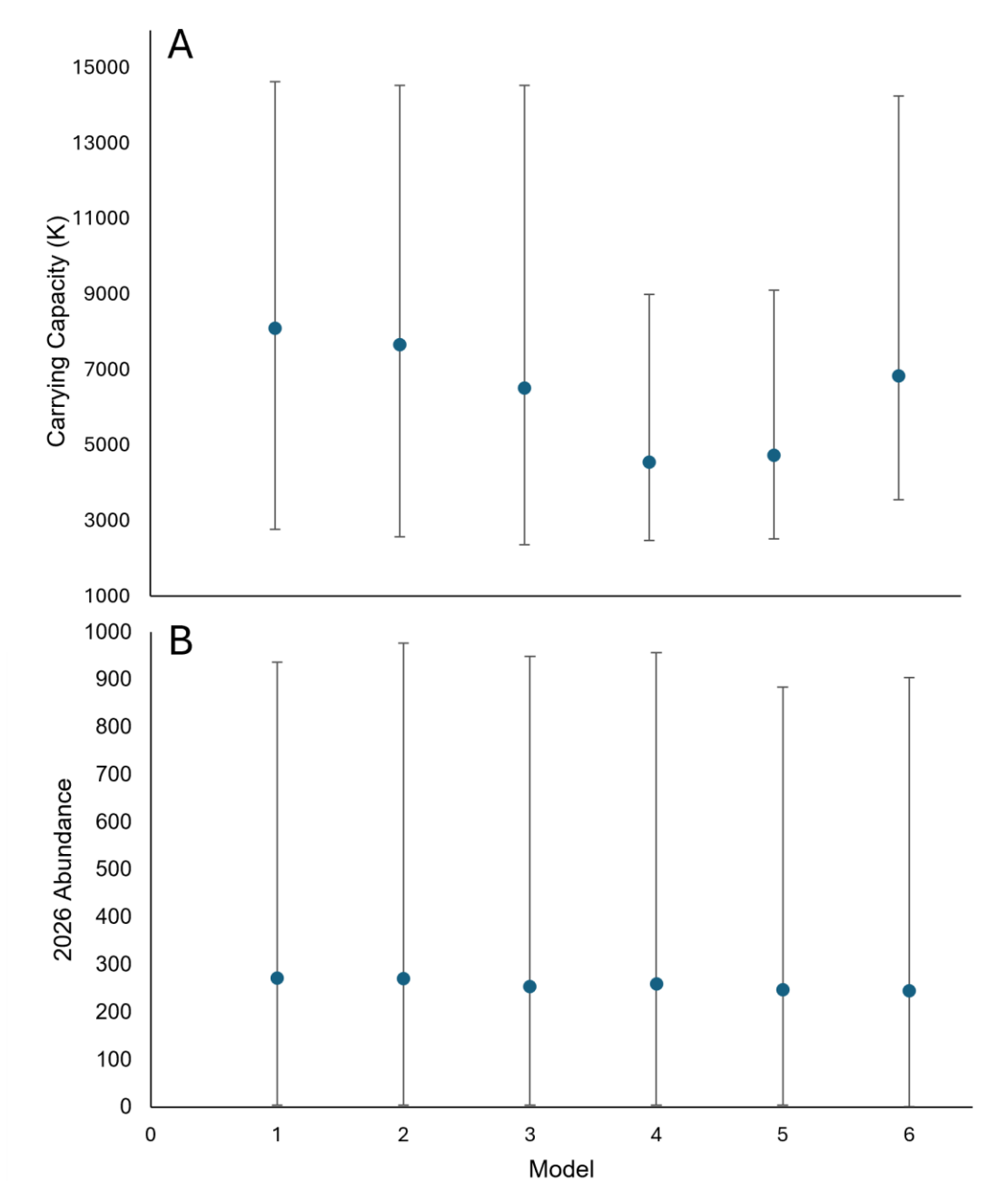


Figure 5. Sensitivity of median A) carrying capacity and B) 2026 abundance ($\pm 95\%$ CI) to the hyper-parameters used in prior distributions for the Cumberland Sound beluga whale population (see Table 5).

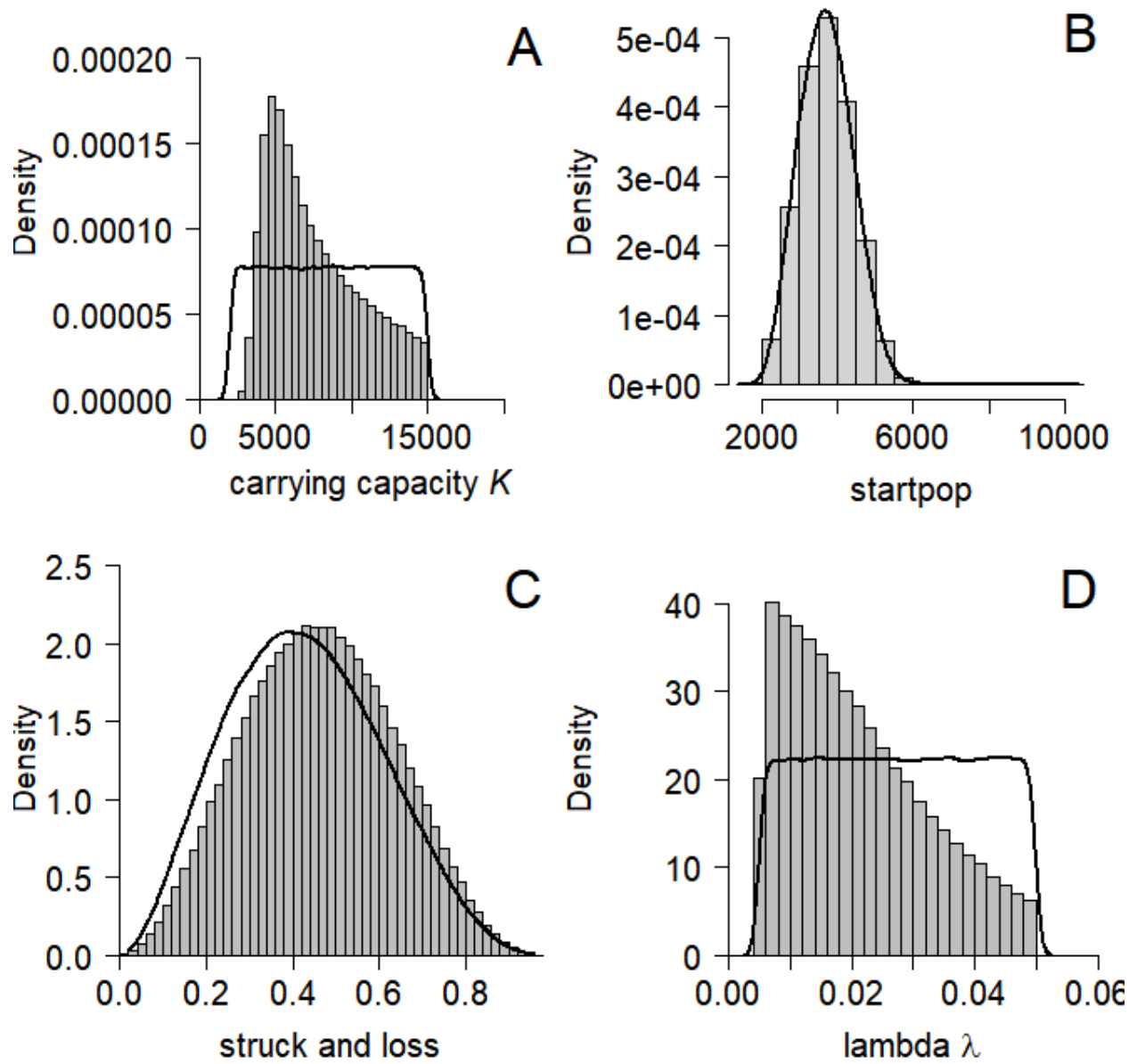


Figure 6. Plots show priors (lines) and posterior (histograms) for (A) carrying capacity (K), (B) initial population, (C) struck and loss (S&L), and (D) lambda (λ_{MAX}) when $\theta = 1$ for the Cumberland Sound beluga whale population (model 6 in Table 5).

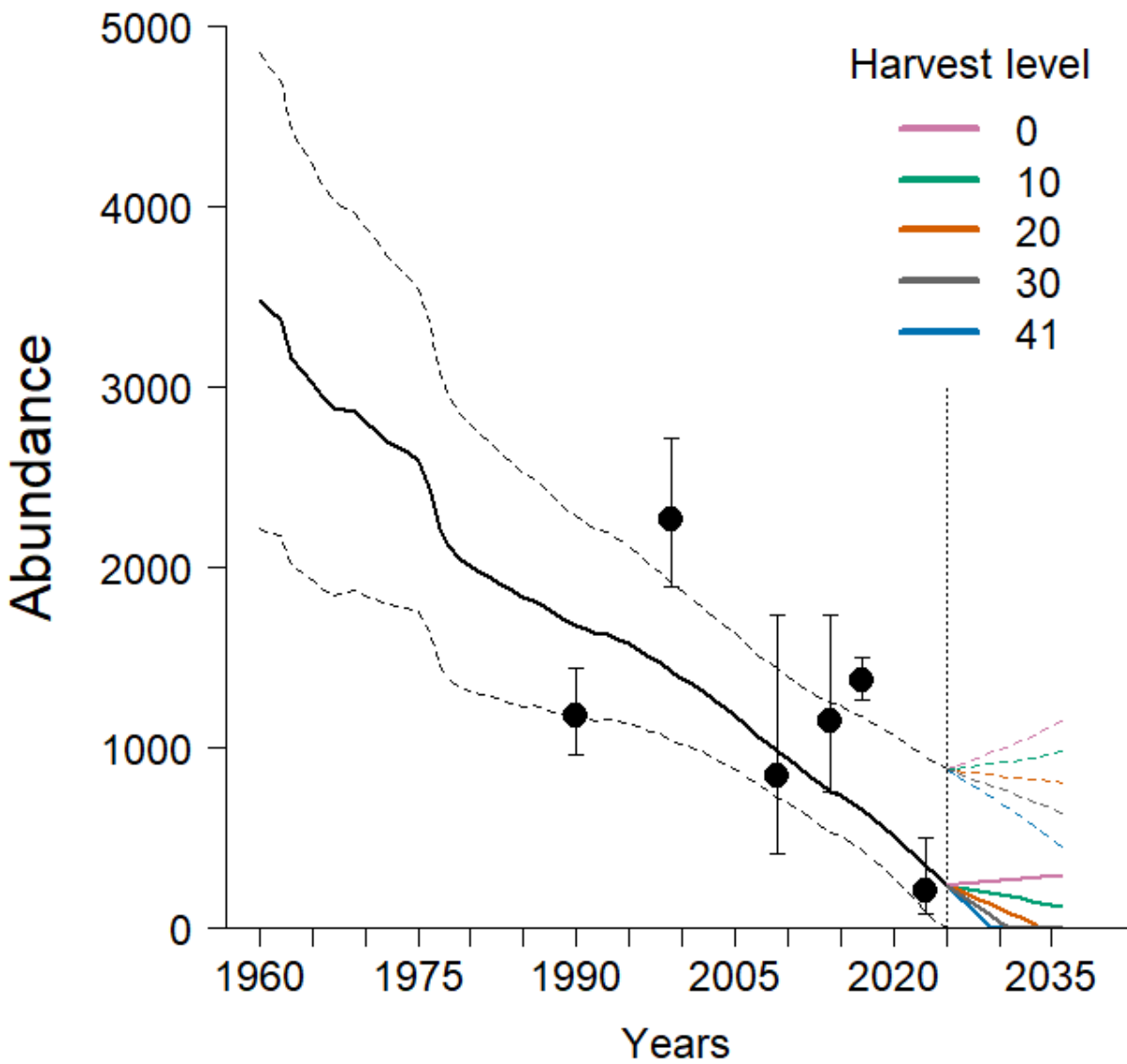


Figure 7. Estimated changes in abundance of beluga whales in CS determined after fitting the population model to abundance estimates from aerial surveys flown between 1990–2023. The solid line indicates the median estimate and dotted lines represent the 95% Credibility Intervals. Beyond 2025 indicates future population projections at harvests of 0–41 beluga whales annually.

APPENDIX

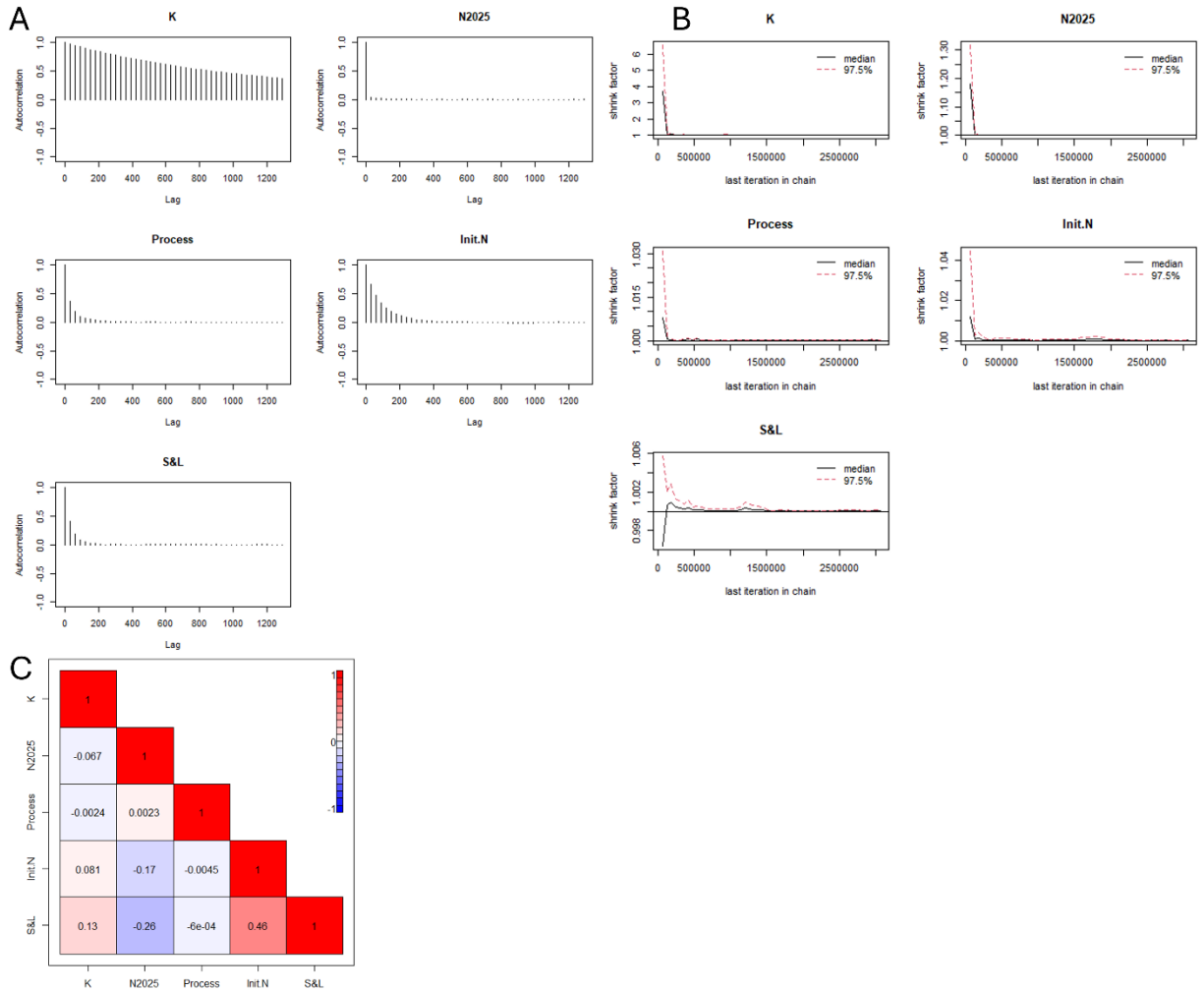


Figure A1. The model was fit to harvest data (1960 – 2024) and adjusted aerial survey data (1990 – 2023). Plots show change in A) autocorrelation, B) BGR test results, and C) cross correlation.