

**Investigating temporal and spatial patterns in group composition and summer  
habitat use by group type in Baffin Bay narwhal (*Monodon monoceros*)**

By

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# Abstract

Arctic marine mammals are increasingly influenced by climate-driven environmental change and expanding anthropogenic pressures, yet variation in population structure and habitat use remains poorly understood. Narwhals (*Monodon monoceros*), an ice-associated cetacean endemic to the Arctic, occupy a rapidly changing environment characterized by general warming, sea ice changes, increasing vessel activity, and shifting predator dynamics. Despite these pressures, limited information exists on how social structure and spatial ecology vary across the Baffin Bay narwhal population and the stocks within. Using aerial photographic surveys conducted in 2013 and 2023 across the six Canadian summering stocks of the Baffin Bay population, variation in group composition, demographic structure, and habitat use was assessed. Narwhals were identified, classified by age (adult or newborn), and assigned to social groups based on proximity. Groups were then identified as adult only, individual whales, or groups with at least one newborn. These data were used to assess temporal changes in group size and newborn-to-adult ratios, as well as spatial differences in habitat use among group types. A total of 3,633 groups were documented across both years. Mean group size declined from 2013 to 2023, with the most pronounced reductions observed in Eclipse Sound, a region experiencing the most vessel traffic. Groups containing newborns were typically small, mostly consisting of mother–newborn pairs, whereas larger aggregations were dominated by adults. Newborn-to-adult ratios were slightly higher in 2023 than in 2013, although interpretation of this result is limited without additional demographic information such as abundance estimates. Depth, distance to shore, and sea surface temperature were used to assess narwhal summer habitat. Habitat use overlapped broadly among group types, indicating little evidence of strong spatial segregation during summer. However, consistent fine-scale differences were observed.

Groups containing newborns were more frequently associated with shallow, nearshore habitats, adult groups occupied similar but slightly deeper environments, and solitary individuals were more common in deeper offshore areas. Depth and distance to shore were important predictors of group type, whereas sea surface temperature showed no influence, suggesting that thermal conditions are not drivers of differences in summer habitat use based on social groupings. These findings provide new insight into narwhal social and spatial ecology, demonstrating declines in group size alongside relatively stable patterns in group composition and habitat use. Group-level metrics offer a valuable approach for detecting early demographic change at both population and stock levels and improving understanding of population responses to environmental stressors in a rapidly changing Arctic.

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# Table of Contents

Acknowledgments.....	4
List of Tables .....	6
List of Figures.....	7
Contributions of Authors .....	10
Thesis Format.....	10
Chapter 1: General Introduction .....	11
1.1 Aerial Survey .....	16
1.2 Gaps and Project Goals.....	17
1.3 References.....	18
Chapter 2: Assessing Baffin Bay narwhal group composition across temporal and spatial scales .....	27
Abstract.....	27
2.1.0 Introduction.....	28
2.2.0 Methods.....	31
2.2.1 Study Area .....	31
2.2.2 High Arctic Cetacean Aerial Surveys .....	31
2.2.4 Photographic Analysis .....	33
2.2.5 Automated Algorithm Detector Performance .....	34
2.2.6 Age Classification.....	35
2.3.2 Model Choice.....	35
2.2.7 Grouping .....	36
2.2.8 Data Analysis and Modelling.....	37
2.3.0 Results.....	38
2.3.1 Automated Algorithm Detector Performance .....	38
2.3.2 Model Choice.....	39
2.3.3 Descriptive Survey Results .....	40
2.3.4 Group Size .....	41
2.3.5 Newborn to Adult Ratio.....	43
2.4.0 Discussion .....	45
2.5.0 Conclusion .....	53
2.6.0 References.....	55
Chapter 3: Investigating Summer Habitat Use by Group Type in Baffin Bay Narwhals .....	70
Abstract.....	70
3.1.0 Introduction.....	71
3.2.0 Methods.....	77
3.2.1 Study Area .....	77
3.2.2 High Arctic Cetacean Survey (HACS) 2023 .....	78

3.2.3 Automated Algorithm Detector .....	79
3.2.4 Narwhal Identification and Aging .....	80
3.2.5 Group Type .....	80
3.2.6 Habitat Variables .....	80
3.2.5 Statistical Modelling .....	81
3.3.0 Results.....	82
3.3.1 Automated Detector Performance.....	82
3.3.2 Selected Models.....	82
3.3.3 Group Summary Stats .....	83
3.3.4 Bayesian Mixed Effect Models.....	84
3.4.0 Discussion .....	87
3.5.0 Conclusion .....	93
3.6.0 References.....	95
Chapter 4: Conclusion.....	106
4.1.0 General Conclusion.....	106
4.2.0 Summary of Key Findings .....	106
4.2.1 Chapter 2: Baffin Bay narwhal group composition across temporal and spatial scales .....	106
4.2.2 Chapter 3: Investigating summer habitat use by group type in Baffin Bay narwhals	107
4.3.0 Social and spatial segregation in narwhal summering areas.....	108
4.4.0 Limitations .....	108
4.5.0 Directions for future research .....	109
4.6.0 Climate change context.....	110
4.7.0 References.....	112
5.0 Appendix.....	114

## List of Tables

<b>Table 2.1.</b> Candidate models and associated AIC scores for modelling group size.....	39
<b>Table 2.2.</b> Comparison of candidate models explaining variation in newborn ratio based on group size, stock, and year.....	39-40
<b>Table 2.3.</b> Number of narwhal detections from the 2013 and 2023 High Arctic Cetacean Aerial Surveys across all stocks by age class.....	40-41
<b>Table 2.4.</b> Number of narwhal groups for different age group types across all years.....	41
<b>Table 3.1.</b> Number of narwhal groups by group type 2023.....	84

# List of Figures

<b>Figure 2.1.</b> Spatial extent of Baffin Bay narwhal population summering stocks in the eastern Canadian Arctic. Coloured polygons delineate the boundaries of the six summering stocks included in this study: Eclipse Sound, East Baffin Island, Admiralty Inlet, Somerset Island, Smith Sound, and Jones Sound.....	31
<b>Figure 2.2.</b> Transect lines flown from the High Arctic Cetacean Survey in 2023 of the Baffin Bay narwhal population, colour-coded by stock.....	32
<b>Figure 2.3.</b> Detection Certainty Scale used to identify the degree of quality of the image used for narwhal detection for the analysis.....	34
<b>Figure 2.4.</b> Newborn Classification and Identification Flowchart adapted from (Charry et al., 2018).....	36
<b>Figure 2.5.</b> Change in narwhal average group size by stock and year in the Baffin Bay population. Points show mean group size and error bars represent 95% confidence intervals. Lines connect year-specific estimates within each stock to illustrate temporal change. ....	42
<b>Figure 2.6.</b> Distribution of narwhal group sizes by stock and survey year from the 2013 and 2023 High Arctic Cetacean Aerial Surveys of the Baffin Bay population. Violin plots show the density of observed group sizes, with points representing individual group observations. The dashed red line indicates a group size of two, corresponding to mother–newborn pairs.....	43
<b>Figure 2.7.</b> Proportion of narwhal newborns to adults across stocks and years from the 2013 and 2023 High Arctic Cetacean Aerial Surveys of the Baffin Bay population.....	45
<b>Figure 3.1.</b> Narwhal group types observed in the Baffin Bay population during August 2023 and the associated habitat variables used to compare habitat use among group types.....	77
<b>Figure 3.2.</b> Summer habitat range extent for the Baffin Bay narwhal population. Separated by stock, Admiralty Inlet, East Baffin Island, Eclipse Sound, Jones Sound, Smith Sound, and Somerset Island.....	78
<b>Figure 3.3.</b> Distribution of distances to shore for different narwhal group types in the Baffin Bay population across all stocks. Boxplots show the median, interquartile range, and variation in distances, with individual points overlaid. Distances are shown in kilometers.....	85

**Figure 3.4.** Boxplot showing the distribution of summering narwhal group types by depth in the Baffin Bay population across all stocks. Depths are plotted with 0 m at the top of the y-axis to represent the sea surface and increasing depth downward. Blue boxes indicate shore to average depth. Individual group observations are shown as jittered points (black).....86

**Figure 3.5.** Distribution of sea surface temperature (SST, °C) by narwhal group type during summer in the Baffin Bay population across all stocks. Individual group temperatures are demonstrated as jittered points. ....87

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## Thesis Format

Chapter 1 is a general literature review and introduction to research gaps. Chapter 2 is the first data chapter. Chapter 3 is the second data chapter. Chapter 4 is the conclusion, future directions, limitations and significance chapter.

# Chapter 1: General Introduction

## 1.0 General Introduction

Demographic parameters such as population abundance, age structure, recruitment, and sex ratios provide essential baselines for assessing population status and informing species management (Symons et al., 2018; Taylor et al., 2007, 1987). For large marine mammals such as cetaceans, with complex group living, understanding group structure and composition is also critical for interpreting population dynamics (Charry et al., 2018; Kutsukake, 2009), as social organisation influences reproduction, survival, and vulnerability to disturbance (Gowans, 2019). Because these species are long-lived and reproduce slowly (Hay, 1984; Heide-Jørgensen & Garde, 2011), changes in group composition and demographic structure may emerge independently of, or before, shifts in overall abundance, making them valuable indicators of population status. Repeated monitoring using consistent and reliable methods is therefore necessary to track demographic patterns over time and to support effective conservation and management (Booth et al., 2020), particularly as marine mammal habitats and environmental conditions continue to change.

Cetaceans form groups to support key ecological and social functions, including reproduction, calf rearing (Cartwright et al., 2012), foraging, and predator avoidance (Gowans, 2019; Laidre et al., 2006). Group size and composition can be stable over long periods or shift dynamically through fission–fusion processes, with individuals joining or leaving groups in response to changing conditions or needs (Aureli et al., 2008). However, with group living comes the costs of increased risk of detection by predators, competition for resources (Sheppard et al., 2018), and parasite transmission (Alexander, 1974). Assessing group composition, including age and sex, can provide insight into group function and inform baseline aspects of

cetacean ecology (Betty et al., 2023; Charry et al., 2018). Monitoring group composition over time can reveal shifts in behaviour, habitat use, and population dynamics. However, studying group composition in cetaceans is challenging because they are highly mobile and elusive, with most of their time spent submerged. This challenge is even greater for Arctic species, whose ice-covered, remote habitats make access and direct observation in the natural environment difficult.

Narwhals (*Monodon monoceros*) are one of three endemic Arctic whale species. Their range extends from Hudson's Bay across the Atlantic sector of the High Arctic, from eastern Canada to Russia (COSEWIC, 2024). There are two sub-populations of narwhal in Canada: Northern Hudson Bay and Baffin Bay (COSEWIC, 2024). COSEWIC defines Baffin Bay and Hudson Bay narwhals as sub-populations because of strong site fidelity (Heide-Jørgensen et al., 2013), and distinct seasonal movements that limit interchange between regions, even though complete genetic separation is not expected (COSEWIC, 2024). Even further, some studies indicate genetic distinction between narwhals in the Canadian High Arctic (Ajuittuq/Grise Fiord) and those around Baffin Island, even though they are presently considered part of the same sub-population (de Greef et al., 2024; Petersen et al., 2011). The largest number of narwhals is found in the Baffin Bay population in Northern Nunavut, with an estimated 142,000 individuals (Doniol-Valcroze et al., 2020). This population migrates seasonally, following traditional routes along the sea ice edge in spring and autumn (Heide-Jørgensen et al., 2003). Narwhal migrate in the fall following ice freeze-up and spend the winter in ice-dense deep offshore waters of Baffin Bay and Davis Strait, while in summer following ice break-up, they return to fjords, sounds, and bays around Baffin Island (Heide-Jørgensen et al., 2003). They have high site fidelity, meaning they return to the same summering areas each year (Laidre et al., 2004). There are four recognized Canadian stocks, defined for management purposes by

Fisheries and Oceans Canada, for the Baffin Bay population based on summering aggregations: Admiralty Inlet, Eclipse Sound, East Baffin Island, Somerset Island, and two alleged stocks, Jones Sound and Smith Sound (Doniol-Valcroze et al., 2020). The Baffin Bay narwhal population in Canada is co-managed by Inuit organizations and federal agencies, with the Nunavut Wildlife Management Board working alongside local Hunters and Trappers Organizations in communities such as Pond Inlet, Arctic Bay, and Clyde River to allocate quotas and monitor harvests (Richard & Pike, 1993).

Narwhals are medium-sized toothed whales that live in relatively small groups (1-25) of mixed sex and age (Marcoux et al., 2009). Sexual dimorphism between males and females exists, with males generally slightly larger, with a large tooth that erupts as a spiralled tusk from the left side of the jaw (Graham et al., 2020). Although tusks are primarily a male trait, some females also develop tusks (Garde & Heide-Jørgensen, 2022; Hay, 1984). Females give birth after an estimated 11–15-month gestation period, typically between May and July off the coast of Baffin Island, and generally produce one calf every three years (Hay, 1984; Heide-Jørgensen & Garde, 2011). During the first few months of life, newborns remain close to their mothers, and exclusive mother-calf pairs are often observed (Charry et al., 2018).

Current knowledge of narwhal diet in the Canadian high Arctic is largely based on stomach content analyses from hunted individuals and stable isotope data, which identify Greenland halibut (*Reinhardtius hippoglossoides*), Arctic cod (*Arctogadus glacialis*), polar cod (*Boreogadus saida*), squid, and shrimp as prey (Finley & Gibb, 1982; Laidre & Heide-Jørgensen, 2005; Watt et al., 2013; Watt & Ferguson, 2015). Narwhals feed more intensely in the winter season than in the summer (Laidre & Heide-Jørgensen, 2005), as stomach content collected in the summer consisted of Arctic cod, polar cod, and *Gonatus* squid, while the winter diet was

dominated by Greenland halibut (Laidre & Heide-Jørgensen, 2005). Narwhals have historically been considered dietary specialists with limited foraging flexibility (Finley & Gibb, 1982), yet recent evidence suggests they may exhibit greater behavioural flexibility than previously assumed (Watt et al., 2013). This flexibility may be increasingly important as prey availability shifts, with predicted abundance declines for Arctic cod (Geoffroy et al., 2023), and Greenland halibut increasing in Baffin Bay under warming conditions (Czich et al., 2023).

Narwhals hold deep cultural, nutritional, and economic importance for Inuit communities across the Canadian Arctic (Nweeia, 2024). They are a vital source of traditional food, including *maktaaq* (skin and blubber), which is rich in essential nutrients and highly valued in Inuit diets (Government of Nunavut, 2013). From 1999 to 2020, on average 524 narwhals were hunted yearly from the Baffin Bay population during the summer months, which is within the total allowable catch set at 1540 per year (COSEWIC, 2024). The tusk and other parts of the narwhal are used for tools, art, and trade, supporting both subsistence economies and cultural expression (Hoover et al., 2013; Nweeia, 2024). Hunting narwhals is embedded in Inuit Qaujimagatuqangit, and this practice is passed down through generations, strengthening community identity and connections to the land and sea (Hoover et al., 2013; Nweeia, 2024). The sustainable management of narwhal populations is therefore critical not only for ecological conservation but also for maintaining Inuit food security, livelihoods, and cultural continuity.

As the Arctic warms at roughly four times the global average, habitats are being transformed, and wildlife is increasingly exposed to a combination of changing environmental conditions and growing human disturbances (Carvalho & Wang, 2020; Dawson et al., 2018; Lefort et al., 2020; Rantanen et al., 2022). Rising sea temperatures have been linked to declines in narwhal abundance, highlighting sensitivity to persistent warming (Chambault et al., 2020).

Narwhals strongly prefer cold waters year-round, especially in winter when they select cold coastal areas and avoid warmer offshore waters (Heide-Jørgensen et al., 2020). They rely heavily on sea ice for both migration (Laidre et al., 2004), and winter feeding (Laidre & Heide-Jørgensen, 2005), and changes in ice conditions have delayed annual fall migration to wintering areas over time (Shuert et al., 2022).

In Baffin Bay, long-term tracking and sea ice data reveal decreasing open water availability in key wintering areas (Heide-Jørgensen & Laidre, 2004), suggesting increased vulnerability to changing Arctic sea ice conditions and heightened risk of ice entrapments (Laidre & Heide-Jørgensen, 2005). With the changes and loss of sea ice, there has been an increase in both vessel traffic (Hauser et al., 2018), and potential interactions with killer whales (Breed et al., 2017; Lefort et al., 2020). Killer whales may spend extended periods in areas also used by narwhals, increasing the duration and intensity of predation risk where their distributions overlap (Breed et al., 2017). The distance traveled by ships in the Canadian Arctic from 1990 to 2015 has tripled, with cargo vessels and icebreakers dominating the region's traffic (Dawson et al., 2018). A recent study found that narwhals repeatedly encountered icebreakers, with some interactions lasting days and occurring at close range, highlighting concerns about prolonged exposure to ship noise (Mayette et al., 2024). Tallurutiup Imanga National Marine Conservation Area, located in Lancaster Sound within the Eclipse Sound stock bounds, experiences vessel traffic from both the eastern entrance of the Northwest Passage and nearby mineral extracting efforts (Halliday et al., 2022), increasing overall vessel presence for narwhals that summer in Eclipse Sound and Milne Inlet. Narwhals have very high sensitivity to sound disturbances, relying on acoustic cues not only for communication but also for navigation, prey detection, and avoiding predators (Tervo et al., 2021, 2023). Compared to other Arctic marine mammals,

narwhals are considered the most vulnerable to vessel traffic due to their high exposure and sensitivity, particularly in geographic bottlenecks such as the eastern Canadian Arctic (Halliday et al., 2022; Hauser et al., 2018). Narwhals in Baffin Bay have relatively low genetic diversity (de Greef et al., 2024), which may limit their ability to adapt to changes in their environment.

During past warming periods, such as after the Last Glacial Maximum narwhal populations expanded; however, future climate change is expected to reduce habitat and prey availability (Louis et al., 2020). By 2100, suitable narwhal habitat is projected to decline by 25% and shift northward, threatening the long-term survival of the species (Louis et al., 2020).

Narwhals have historically had low effective population sizes and limited genetic diversity; however, recent evidence indicates increases in effective population size, and narwhals do not appear to be at high risk of losing current levels of genetic variation (de Greef et al., 2024). This is likely a consequence of persistently low effective population size and the absence of evidence for recent demographic decline (de Greef et al., 2024). In contrast, other marine mammals with historically low effective population sizes are more vulnerable to climate change (Phillips et al., 2011). Coupled with increasing threats from shipping traffic and changing predator dynamics, this combination of low diversity and environmental instability might place certain narwhal stocks at heightened risk.

## 1.1 Aerial Survey

Aerial surveys are routinely used to assess abundance in remote areas (Doniol-Valcroze et al., 2020; Richard et al., 2010); however, various other aspects of narwhal ecology, including distribution, density, and grouping behaviours, can also be identified. Photographic surveys, which are a more recent alternative to visual identification, are increasingly used in wildlife management to generate abundance estimates for marine mammal populations and stock-based

assessments (Bröker et al., 2019; Ferguson et al., 2018). Aerial surveys are particularly useful for covering large geographic areas in a relatively short amount of time, by flying predetermined transect lines over known habitat ranges. Aerial surveys offer several advantages over vessel-based surveys for estimating marine mammal distribution and abundance, including reduced disturbance and the ability to cover a greater area in less time. Additionally, aerial images can be used to assess group dynamics, including group size, sex composition, and age composition providing more detailed information on population dynamics (Charry et al., 2018, 2020). Effective management and monitoring require integrating knowledge from multiple fields to make well-informed conservation decisions (Lacy, 2019).

## 1.2 Gaps and Project Goals

The Arctic landscape has changed significantly over the last decade, exposing threats to the persistence of the Baffin Bay narwhal population. While the combined effects of climate change and other anthropogenic pressures are difficult to assess directly, examining group composition across time and space provides a useful lens for detecting whether and where narwhals are being affected by environmental change. Variation in age structure and group size can indicate shifts in recruitment, survival, and social behaviour, offering insight into how populations respond to changing conditions (Gowans, 2019; Kutsukake, 2009).

Understanding how different group types use habitat further strengthens this approach by linking social structure to space use, helping establish baseline ecological patterns against which future change can be assessed. Despite its importance, little work has examined whether group composition influences summer habitat selection in narwhals, and over the last decade, information on group structure and sex ratios remains limited. Addressing these gaps provides a foundation for identifying differential responses among summering stocks with varying

intensities of pressure from environmental change, and for assessing whether social, sexual, and age differences might be driving differences in preferred summer habitat use.

### 1.3 References

- Alexander, R. D. (1974). The Evolution of Social Behavior. *Annual Review of Ecology and Systematics*, 5, 325–383.
- Aureli, F., Schaffner, C. M., Boesch, C., Bearder, S. K., Call, J., Chapman, C. A., Connor, R., Fiore, A. D., Dunbar, R. I. M., Henzi, S. P., Holekamp, K., Korstjens, A. H., Layton, R., Lee, P., Lehmann, J., Manson, J. H., Ramos-Fernandez, G., Strier, K. B., & Schaik, C. P. van. (2008). Fission-Fusion Dynamics: New Research Frameworks. *Current Anthropology*, 49(4), 627–654. <https://doi.org/10.1086/586708>
- Betty, E. L., Stockin, K. A., Hinton, B., Bollard, B. A., Orams, M. B., & Murphy, S. (2023). Age- and sex-specific survivorship of the Southern Hemisphere long-finned pilot whale (*Globicephala melas edwardii*). *Journal of Mammalogy*, 104(1), 39–48. <https://doi.org/10.1093/jmammal/gyac085>
- Booth, C. G., Sinclair, R. R., & Harwood, J. (2020). Methods for Monitoring for the Population Consequences of Disturbance in Marine Mammals: A Review. *Frontiers in Marine Science*, 7. <https://doi.org/10.3389/fmars.2020.00115>
- Breed, G. A., Matthews, C. J. D., Marcoux, M., Higdon, J. W., LeBlanc, B., Petersen, S. D., Orr, J., Reinhart, N. R., & Ferguson, S. H. (2017). Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales. *Proceedings of the National Academy of Sciences*, 114(10), 2628–2633. <https://doi.org/10.1073/pnas.1611707114>

- Bröker, K. C. A., Hansen, R. G., Leonard, K. E., Koski, W. R., & Heide-Jørgensen, M. P. (2019). A comparison of image and observer based aerial surveys of narwhal. *Marine Mammal Science*, 35(4), 1253–1279. <https://doi.org/10.1111/mms.12586>
- Cartwright, R., Gillespie, B., LaBonte, K., Mangold, T., Venema, A., Eden, K., & Sullivan, M. (2012). Between a Rock and a Hard Place: Habitat Selection in Female-Calf Humpback Whale (*Megaptera novaeangliae*) Pairs on the Hawaiian Breeding Grounds. *PLOS ONE*, 7(5), e38004. <https://doi.org/10.1371/journal.pone.0038004>
- Carvalho, K. S., & Wang, S. (2020). Sea surface temperature variability in the Arctic Ocean and its marginal seas in a changing climate: Patterns and mechanisms. *Global and Planetary Change*, 193, 103265. <https://doi.org/10.1016/j.gloplacha.2020.103265>
- Chambault, P., Tervo, O. M., Garde, E., Hansen, R. G., Blackwell, S. B., Williams, T. M., Dietz, R., Albertsen, C. M., Laidre, K. L., Nielsen, N. H., Richard, P., Sinding, M. H. S., Schmidt, H. C., & Heide-Jørgensen, M. P. (2020). The impact of rising sea temperatures on an Arctic top predator, the narwhal. *Scientific Reports*, 10(1), 18678. <https://doi.org/10.1038/s41598-020-75658-6>
- Charry, B., Marcoux, M., Cardille, J. A., Giroux-Bougard, X., & Humphries, M. M. (2020). Hierarchical Classification of Narwhal Subpopulations Using Social Distance. *The Journal of Wildlife Management*, 84(2), 311–319. <https://doi.org/10.1002/jwmg.21799>
- Charry, B., Marcoux, M., & Humphries, M. M. (2018). Aerial photographic identification of narwhal (*Monodon monoceros*) newborns and their spatial proximity to the nearest adult female. *Arctic Science*, 4(4), 513–524. <https://doi.org/10.1139/as-2017-0051>

- Czich, A. N., Stanley, R. R. E., Avery, T. S., den Heyer, C. E., & Shackell, N. L. (2023). Recent and projected climate change–induced expansion of Atlantic halibut in the Northwest Atlantic. *FACETS*, 8, 1–14. <https://doi.org/10.1139/facets-2021-0202>
- Dawson, J., Pizzolato, L., Howell, S. E. L., Copland, L., & Johnston, M. E. (2018). Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015. *Arctic*, 71(1), 15–26.
- de Greef, E., Müller, C., Thorstensen, M. J., Ferguson, S. H., Watt, C. A., Marcoux, M., Petersen, S. D., & Garroway, C. J. (2024). Unraveling the Genetic Legacy of Commercial Whaling and Population Dynamics in Arctic Bowhead Whales and Narwhals. *Global Change Biology*, 30(10), e17528. <https://doi.org/10.1111/gcb.17528>
- Doniol-Valcroze, T., Gosselin, J.-F., Pike, D., Lawson, J., Asselin, N., Hedges, K., & Ferguson, S. (2020). Narwhal Abundance in the Eastern Canadian High Arctic in 2013. *NAMMCO Scientific Publications*, 11. <https://doi.org/10.7557/3.5100>
- Ferguson, M. C., Angliss, R. P., Kennedy, A., Lynch, B., Willoughby, A., Helker, V., Brower, A. A., & Clarke, J. T. (2018). Performance of manned and unmanned aerial surveys to collect visual data and imagery for estimating arctic cetacean density and associated uncertainty. *Journal of Unmanned Vehicle Systems*, 6(3), 128–154. <https://doi.org/10.1139/juvs-2018-0002>
- Finley, K. J., & Gibb, E. J. (1982). Summer diet of the narwhal (*Monodon monoceros*) in Pond Inlet, northern Baffin Island. *Canadian Journal of Zoology*, 60(12), 3353–3363. <https://doi.org/10.1139/z82-424>

- Garde, E., & Heide-Jørgensen, M. P. (2022). Tusk anomalies in narwhals (*Monodon monoceros*) from Greenland. *Polar Research*, 41, Article 8343.  
<https://doi.org/10.33265/polar.v41.8343>
- Geoffroy, M., Bouchard, C., Flores, H., Robert, D., Gjørseter, H., Hoover, C., Hop, H., Hussey, N. E., Nahrgang, J., Steiner, N., Bender, M., Berge, J., Castellani, G., Chernova, N., Copeman, L., David, C. L., Deary, A., Divoky, G., Dolgov, A. V., Walkusz, W. (2023). The circumpolar impacts of climate change and anthropogenic stressors on Arctic cod (*Boreogadus saida*) and its ecosystem. *Elementa: Science of the Anthropocene*, 11(1), 00097. <https://doi.org/10.1525/elementa.2022.00097>
- Government of Nunavut. (2013). *Nutrition Fact Sheet Series: Inuit Traditional Foods*.  
Department of Health, Nunavut.  
[https://livehealthy.gov.nu.ca/sites/default/files/resource\\_attachments/EN\\_WEB\\_itf--nutrition-fact-sheet-series.pdf](https://livehealthy.gov.nu.ca/sites/default/files/resource_attachments/EN_WEB_itf--nutrition-fact-sheet-series.pdf)
- Gowans, S. (2019). Grouping Behaviors of Dolphins and Other Toothed Whales. In B. Würsig (Ed.), *Ethology and Behavioral Ecology of Odontocetes* (pp. 3–24). Springer International Publishing. [https://doi.org/10.1007/978-3-030-16663-2\\_1](https://doi.org/10.1007/978-3-030-16663-2_1)
- Graham, Z. A., Garde, E., Heide-Jørgensen, M. P., & Palaoro, A. V. (2020). The longer the better: Evidence that narwhal tusks are sexually selected. *Biology Letters*, 16(3), 20190950. <https://doi.org/10.1098/rsbl.2019.0950>
- Halliday, W. D., Dawson, J., Yurkowski, D. J., Doniol-Valcroze, T., Ferguson, S. H., Gjerdrum, C., Hussey, N. E., Kochanowicz, Z., Mallory, M. L., Marcoux, M., Watt, C. A., & Wong, S. N. P. (2022). Vessel risks to marine wildlife in the Tallurutiup Imanga National Marine Conservation Area and the eastern entrance to the Northwest Passage.

*Environmental Science & Policy*, 127, 181–195.

<https://doi.org/10.1016/j.envsci.2021.10.026>

Hauser, D. D. W., Laidre, K. L., & Stern, H. L. (2018). Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route.

*Proceedings of the National Academy of Sciences*, 115(29), 7617–7622.

<https://doi.org/10.1073/pnas.1803543115>

Hay, K. A. (1984). *The life history of the narwhal, Monodon monoceros l., in the eastern Canadian arctic* /. McGill University.

<https://escholarship.mcgill.ca/concern/theses/v118rf31m>

Heide-Jørgensen, M. P., Blackwell, S. B., Williams, T. M., Sinding, M. H. S., Skovrind, M., Tervo, O. M., Garde, E., Hansen, R. G., Nielsen, N. H., Ngô, M. C., & Ditlevsen, S.

(2020). Some like it cold: Temperature-dependent habitat selection by narwhals. *Ecology and Evolution*, 10(15), 8073–8090. <https://doi.org/10.1002/ece3.6464>

Heide-Jørgensen, M. P., Dietz, R., Laidre, K. L., Richard, P., Orr, J., & Schmidt, H. C. (2003).

The migratory behaviour of narwhals (*Monodon monoceros*). *Canadian Journal of Zoology*, 81(8), 1298–1305. <https://doi.org/10.1139/z03-117>

Heide-Jørgensen, M. P., & Garde, E. (2011). Fetal growth of narwhals (*Monodon monoceros*).

*Marine Mammal Science*, 27(3), 659–664. <https://doi.org/10.1111/j.1748-7692.2010.00423.x>

Heide-Jørgensen, M. P., & Laidre, K. L. (2004). Declining extent of open-water refugia for top predators in Baffin Bay and adjacent waters. *Ambio*, 33(8), 487–494.

<https://doi.org/10.1579/0044-7447-33.8.487>

- Heide-Jørgensen, M. P., Richard, P. R., Dietz, R., & Laidre, K. L. (2013). A metapopulation model for Canadian and West Greenland narwhals. *Animal Conservation*, *16*(3), 331–343. <https://doi.org/10.1111/acv.12000>
- Hoover, C., Bailey, M., Higdon, J., Ferguson, S. H., & Sumaila, R. (2013). Estimating the Economic Value of Narwhal and Beluga Hunts in Hudson Bay, Nunavut. *Arctic*, *66*(1), 1–16.
- Kutsukake, N. (2009). Complexity, dynamics and diversity of sociality in group-living mammals. *Ecological Research*, *24*(3), 521–531. <https://doi.org/10.1007/s11284-008-0563-4>
- Lacy, R. C. (2019). Lessons from 30 years of population viability analysis of wildlife populations. *Zoo Biology*, *38*(1), 67–77. <https://doi.org/10.1002/zoo.21468>
- Laidre, K. L., & Heide-Jørgensen, M. P. (2005). Winter Feeding Intensity of Narwhals (monodon Monoceros). *Marine Mammal Science*, *21*(1), 45–57. <https://doi.org/10.1111/j.1748-7692.2005.tb01207.x>
- Laidre, K. L., Heide-Jørgensen, M. P., Logdson, M. L., Hobbs, R. C., Heagerty, P., Dietz, R., Jørgensen, O. A., & Treble, M. A. (2004). Seasonal narwhal habitat associations in the high Arctic. *Marine Biology*, *145*(4), 821–831. <https://doi.org/10.1007/s00227-004-1371-1>
- Laidre, K. L., Heide-Jørgensen, M. P., & Orr, J. R. (2006). Reactions of Narwhals, Monodon monoceros to Killer Whale, *Orcinus orca* Attacks in the Eastern Canadian Arctic. *The Canadian Field-Naturalist*, *120*(4), 457–465. <https://doi.org/10.22621/cfn.v120i4.355>

- Lefort, K. J., Garroway, C. J., & Ferguson, S. H. (2020). Killer whale abundance and predicted narwhal consumption in the Canadian Arctic. *Global Change Biology*, 26(8), 4276–4283. <https://doi.org/10.1111/gcb.15152>
- Louis, M., Skovrind, M., Samaniego Castruita, J. A., Garilao, C., Kaschner, K., Gopalakrishnan, S., Haile, J. S., Lydersen, C., Kovacs, K. M., Garde, E., Heide-Jørgensen, M. P., Postma, L., Ferguson, S. H., Willerslev, E., & Lorenzen, E. D. (2020). Influence of past climate change on phylogeography and demographic history of narwhals, *Monodon monoceros*. *Proceedings of the Royal Society B: Biological Sciences*, 287(1925), 20192964. <https://doi.org/10.1098/rspb.2019.2964>
- Marcoux, M., Auger-Méthé, M., & Humphries, M. M. (2009). Encounter frequencies and grouping patterns of narwhals in Koluktoo Bay, Baffin Island. *Polar Biology*, 32(12), 1705–1716. <https://doi.org/10.1007/s00300-009-0670-x>
- Mayette, A., Shuert, C. R., Hussey, N. E., & Marcoux, M. (2024). Proximity analysis between icebreakers and narwhals in Tasiujaq, Nunavut, Canada. *The Journal of Wildlife Management*, 88(8), e22655. <https://doi.org/10.1002/jwmg.22655>
- Nweeia, M. T. (2024). Biology and Cultural Importance of the Narwhal. *Annual Review of Animal Biosciences*, 12(Volume 12, 2024), 187–208. <https://doi.org/10.1146/annurev-animal-021122-112307>
- Petersen, S. D., Tencula, D., & Ferguson, S. H. (2011). *Population Genetic Structure of Narwhal (Monodon monoceros)*. DFO Can. Sci. Advis. Sec. Res. Doc.
- Phillips, C. D., Gelatt, T. S., Patton, J. C., & Bickham, J. W. (2011). Phylogeography of Steller sea lions: Relationships among climate change, effective population size, and genetic

- diversity. *Journal of Mammalogy*, 92(5), 1091–1104. <https://doi.org/10.1644/10-MAMM-A-305.1>
- Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruostenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, 3(1), 1–10. <https://doi.org/10.1038/s43247-022-00498-3>
- Richard, P. R., Laake, J. L., Hobbs, R. C., Heide-Jørgensen, M. P., Asselin, N. C., & Cleator, H. (2010). Baffin Bay Narwhal Population Distribution and Numbers: Aerial Surveys in the Canadian High Arctic, 2002-04. *Arctic*, 63(1), 85–99.
- Richard, P. R., & Pike, D. G. (1993). Small Whale Co-Management in the Eastern Canadian Arctic: A Case History and Analysis. *Arctic*, 46(2), 138–143.
- Sheppard, C. E., Inger, R., McDonald, R. A., Barker, S., Jackson, A. L., Thompson, F. J., Vitikainen, E. I. K., Cant, M. A., & Marshall, H. H. (2018). Intragroup competition predicts individual foraging specialisation in a group-living mammal. *Ecology Letters*, 21(5), 665–673. <https://doi.org/10.1111/ele.12933>
- Symons, J., Sprogis, K. R., & Bejder, L. (2018). Implications of survey effort on estimating demographic parameters of a long-lived marine top predator. *Ecology and Evolution*, 8(21), 10470–10481. <https://doi.org/10.1002/ece3.4512>
- Taylor, B. L., Martinez, M., Gerrodette, T., Barlow, J., & Hrovat, Y. N. (2007). Lessons from Monitoring Trends in Abundance of Marine Mammals. *Marine Mammal Science*, 23(1), 157–175. <https://doi.org/10.1111/j.1748-7692.2006.00092.x>

- Taylor, M., Carley, J. S., & Bunnell, F. L. (1987). Correct and Incorrect Use of Recruitment Rates for Marine Mammals. *Marine Mammal Science*, 3(2), 171–178.  
<https://doi.org/10.1111/j.1748-7692.1987.tb00159.x>
- Tervo, O. M., Blackwell, S. B., Ditlevsen, S., Conrad, A. S., Samson, A. L., Garde, E., Hansen, R. G., & Mads Peter, H.-J. (2021). Narwhals react to ship noise and airgun pulses embedded in background noise. *Biology Letters*, 17(11), 20210220.  
<https://doi.org/10.1098/rsbl.2021.0220>
- Tervo, O. M., Blackwell, S. B., Ditlevsen, S., Garde, E., Hansen, R. G., Samson, A. L., Conrad, A. S., & Heide-Jørgensen, M. P. (2023). Stuck in a corner: Anthropogenic noise threatens narwhals in their once pristine Arctic habitat. *Science Advances*, 9(30), eade0440.  
<https://doi.org/10.1126/sciadv.ade0440>
- Watt, C. A., & Ferguson, S. H. (2015). Fatty acids and stable isotopes ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) reveal temporal changes in narwhal (*Monodon monoceros*) diet linked to migration patterns. *Marine Mammal Science*, 31(1), 21–44. <https://doi.org/10.1111/mms.12131>
- Watt, C. A., Heide-Jørgensen, M. P., & Ferguson, S. H. (2013). How adaptable are narwhal? A comparison of foraging patterns among the world's three narwhal populations. *Ecosphere*, 4(6), art71. <https://doi.org/10.1890/ES13-00137.1>

## Chapter 2: Assessing Baffin Bay narwhal group composition across temporal and spatial scales

### Abstract

Monitoring population demography is essential for the conservation of Arctic marine mammals, which are characterized by slow reproductive rates and ecological specialization. Narwhals (*Monodon monoceros*), long-lived, ice-associated cetaceans endemic to the Arctic, face environmental and anthropogenic pressures, including sea ice loss, increased vessel traffic, and potential predation risk from killer whales. Despite these challenges, temporal and spatial variation in narwhal social structure, particularly group composition, remains poorly understood. We analyzed aerial photographic survey data from 2013 and 2023 covering the six Canadian summering stocks of the Baffin Bay population: Eclipse Sound, Admiralty Inlet, Somerset Island, Jones Sound, East Baffin Island, and Smith Sound. Narwhals were aged (adult or newborn) and assigned to groups based on proximity, with group size and newborn-to-adult ratios quantified. Group size was modeled using negative binomial generalized linear models, while newborn-to-adult ratios were analyzed with Bayesian hurdle-gamma models. We identified 8,790 narwhals forming 3,633 groups. Average group size declined from 2013 to 2023 with the most pronounced reductions in Eclipse Sound, an area of high shipping concern. Small groups, typically mother–newborn pairs, dominated newborn-containing groups, and larger groups were adult dominated. Newborn-to-adult ratios were slightly higher in 2023 than in 2013, however further demographic parameters including abundance are needed to further interpret this finding. These results suggest that narwhal group sizes have decreased over the past decade, potentially due to environmental change, predation, and vessel disturbance, while newborn social structures remain stable. Analyses of group composition provide critical insights into population structure and early demographic change, complementing abundance estimates. Continued monitoring of group dynamics across space and time is essential to assess future population structure changes and inform management strategies under rapidly changing Arctic conditions.

## 2.1.0 Introduction

Assessing population demography over time is essential for the long-term conservation of species (Morrison et al., 2022). Reliable demographic information allows researchers to detect changes in population structure, evaluate population health, and identify early warning signs of decline (Taylor et al., 2007, 1987). While abundance estimates provide valuable insight into overall population size and trends (Doniol-Valcroze et al., 2020), analysing group composition and dynamics across temporal and spatial scales offers a more detailed perspective of population structure. This is especially important for Arctic marine mammals with slow reproductive rates and specialized ecologies, as they may be more vulnerable to environmental change (Laidre et al., 2015).

Narwhals (*Monodon monoceros*) are one of three whale species endemic to the region. They are long-lived, ice-associated cetaceans with low reproductive rates and strong summering site fidelity (Hay, 1984; Heide-Jørgensen et al., 2003; Laidre et al., 2004). There are two distinct sub-populations in Canada, the Northern Hudson Bay sub-population and the Baffin Bay sub-population (COSEWIC, 2024). The Baffin Bay population, located in northern Nunavut is the largest, migrating seasonally from the ice-dense deep waters of Baffin Bay and Davis Strait in winter to the shallower bays and fjords off Baffin Island in summer (Heide-Jørgensen et al., 2003). The Baffin Bay narwhal population is managed by Fisheries in Oceans Canada in six stocks based off different summering aggregations; Admiralty Inlet, Eclipse Sound, East Baffin Island, Somerset Island, Jones Sound, and Smith Sound (Doniol-Valcroze et al., 2020).

Narwhals in Baffin Bay are experiencing persistent environmental and anthropogenic pressures that may influence population structure and group dynamics. Narwhals, which show a strong preference for cold coastal waters (Heide-Jørgensen et al., 2020), and occupy a narrow

thermal niche, rely heavily on sea ice for migration and foraging on Greenland halibut in winter (Laidre et al., 2004; Laidre & Heide-Jørgensen, 2005). Arctic warming has reduced sea ice extent since the mid-1980s, altering the timing of autumn freeze-up and delaying migration, while forcing narwhals to adjust to a longer open-water season (Laidre et al., 2012; Shuert et al., 2022). Additionally, changes in sea ice and its loss can increase interactions with predators, such as longer periods of range overlap with killer whales (Breed et al., 2017; Lefort et al., 2020). At the same time, amplified vessel traffic focused in Eclipse Sound and Milne Inlet has introduced additional acoustic and physical disturbances in key summering areas (Dawson et al., 2018; Ewing et al., 2025; Halliday et al., 2022; Hauser et al., 2018; Williams et al., 2022). Most of the increase in vessel traffic in Eclipse Sound (Ewing et al., 2025; Halliday et al., 2022), can be attributed to mineral extraction operations nearby, and cruise ship stops at the town of Pond Inlet (Jones et al., 2023). These pressures may be worsened by historically low genetic diversity (de Greef et al., 2024; Louis et al., 2020), which could limit their ability to adapt to rapid environmental. Together, these factors underscore the importance of monitoring demographic indicators, which may respond to ecological change before shifts in abundance become apparent and can reveal population changes not detectable through abundance alone.

Narwhals are medium-sized toothed whales (*Odontocetes*) that live and travel in social groups (Marcoux et al., 2009). *Odontocetes* form social groups for a range of ecological purposes, including mating, foraging, parental care, and reduced predation risk (Ezenwa et al., 2016; Gowans, 2019). However, living in close association can also intensify competition and disease spread, and may even increase predation risk (Alexander, 1974; Rankins et al., 2024). Because of these trade-offs, changes in grouping behaviour can have important consequences for mating opportunities, calf survival, foraging efficiency, and vulnerability to predators (Gowans,

2019). Groups may persist as long-term stable units or form temporary aggregations, depending on their functional role.

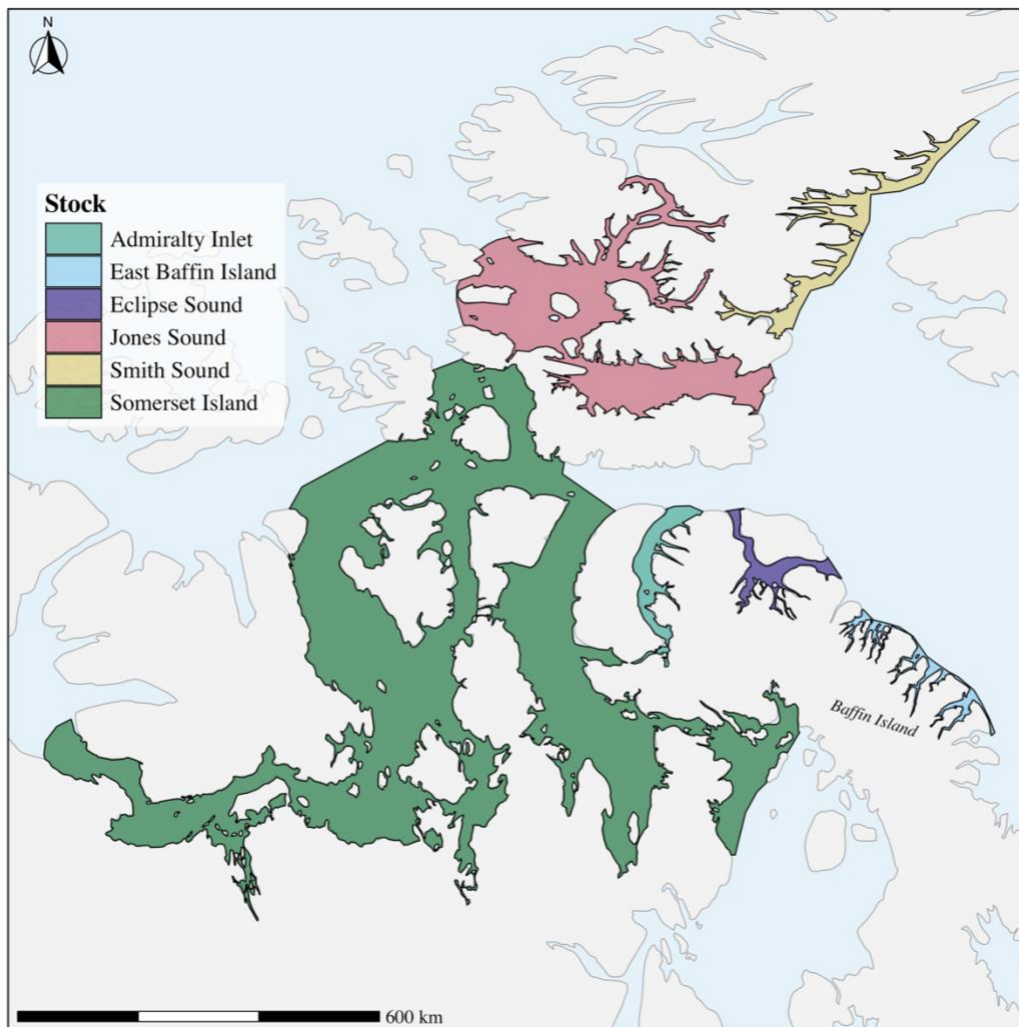
Odontocetes often exhibit a flexible social pattern called fission-fusion grouping, in which group composition and size change depending on the costs and benefits at a particular time (Aureli et al., 2008). Individuals or smaller subgroups might join a group due to cooperative foraging, mating opportunities, social learning, and predator protection, but may leave a group due to foraging competition, sexual or age differences, calf rearing, noisy environments, and predation risk (Gowans, 2019; La Manna et al., 2023). Because social structure, ecological conditions, and mating systems all shape how groups form and change, patterns in group size and calf presence can serve as indicators of potential reproductive changes and shifts in group structure across space and time.

Shipping traffic (Ewing et al., 2025; Halliday et al., 2022), predator exposure (Breed et al., 2017), and ongoing climate warming (Laidre et al., 2010) , have intensified stressors over the last two decades, yet their combined effects on narwhal group structure remain unknown. Consequently, little is known about how group composition, including newborn-to-adult ratios and group size, may have changed over time or how these patterns vary among the Canadian summering stocks of the Baffin Bay population. Evaluating these aspects across both space (stocks) and time (2013–2023) is critical for understanding population dynamics and informing management. We hypothesize that in the Baffin Bay population, potential increased predation (Breed et al., 2017), and ongoing climate warming (Laidre et al., 2010), will reduce both group sizes and newborn-to-adult ratios from 2013 to 2023 and that this decrease will be more pronounced in Eclipse Sound compared to other areas because of higher shipping (Ewing et al., 2025; Halliday et al., 2022; Mayette et al., 2024).

## 2.2.0 Methods

### 2.2.1 Study Area

The six major summering management stocks in the Eastern Canadian High Arctic cover east, west and north of Baffin Island, Nunavut (*Figure 2.1*).



*Figure 2. 1.* Spatial extent of Baffin Bay narwhal population summering stocks in the eastern Canadian Arctic. Coloured polygons delineate the approximate boundaries of the six summering stocks included in this study: Eclipse Sound, East Baffin Island, Admiralty Inlet, Somerset Island, Smith Sound, and Jones Sound.

### 2.2.2 High Arctic Cetacean Aerial Surveys

Fisheries and Oceans Canada conducted aerial photographic surveys of the Baffin Bay narwhal population in August 2013 and August 2023 (*Figure 2.2*) as part of the High Arctic

Cetacean Aerial Survey. Surveys were conducted in August to coincide with reduced ice cover, improved observer conditions, and prior to the onset of narwhal migrating to wintering grounds (Doniol-Valcroze et al., 2020). Survey extent was informed by historical aerial surveys dating back to the 1970s, telemetry data, Inuit Traditional Knowledge, and observations from Inuit hunters.

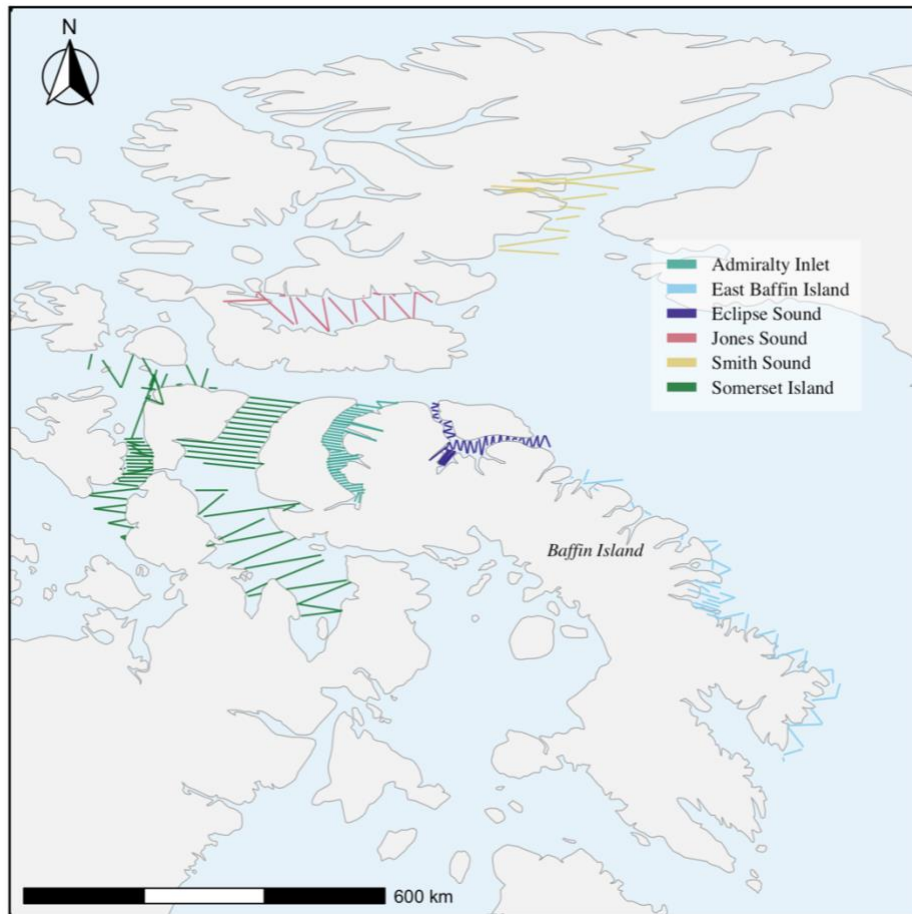


Figure 2. 2. Transect lines flown from the High Arctic Cetacean Survey in 2023 of the Baffin Bay narwhal population, colour-coded by stock.

In 2013, three DeHavilland aircrafts flew transects at an altitude of 305 m and a speed of 100 knots. Each aircraft was equipped with two Nikon D800 cameras fitted with 32 mm lenses, mounted on the ventral side of the plane at a 27° angle. Photographs were captured every three

seconds with approximately 20% overlap between images and were georeferenced using a linked GPS system.

In 2023, surveys were conducted using four DeHavilland aircrafts flying at an altitude of 610 m and a speed of 100 knots. Each aircraft was equipped with a Nikon D850 camera fitted with a 25 mm lens, which captured images every 7 seconds along transects. Images were georeferenced using a linked Garmin GPS.

#### 2.2.4 Photographic Analysis

In 2013, all photographic images containing narwhal were identified manually using ArcGIS (Charry et al., 2018). Identified narwhals were sexed, aged, and assigned to groups by visual observation (Charry et al., 2018). Narwhals within three body lengths were considered in the same group (Charry et al., 2018; Mann, 2000; Marcoux et al., 2009). For this current study, 10% of all detections from the 2013 survey, and all newborn detections, were manually reviewed and verified. Following the 2023 aerial survey, we used an automated algorithm (Mobius) to identify narwhals in the photographs (Boulent et al., 2023). The Mobius system uses a deep learning model to automatically detect whales in aerial images, with human reviewers checking and correcting the results to improve accuracy (Boulent et al., 2023). Narwhal detections were then projected in QGIS and were manually sexed, aged, and assigned to a group (QGIS Development Team, 2024). A detection certainty scale was developed to identify true narwhal sightings and assess whether each detection was of sufficient quality to be included in the analysis with confidence (*Figure 2.3*). All detections from 2013 and 2023 that could not be confidently identified as narwhal or assigned an age class (adult or newborn) were excluded from the analyses. Eleven narwhals missed by the automated algorithm but manually identified were assigned latitude and longitude using shape file tools on QGIS. Duplicate detections were

identified by manually reviewing overlapping photographs, aligning consecutive images, and evaluating spatial distance and group composition. Records were classified as duplicates when consistent overlap and similar group characteristics were observed and were subsequently removed from the dataset.

## Detection Certainty Scale

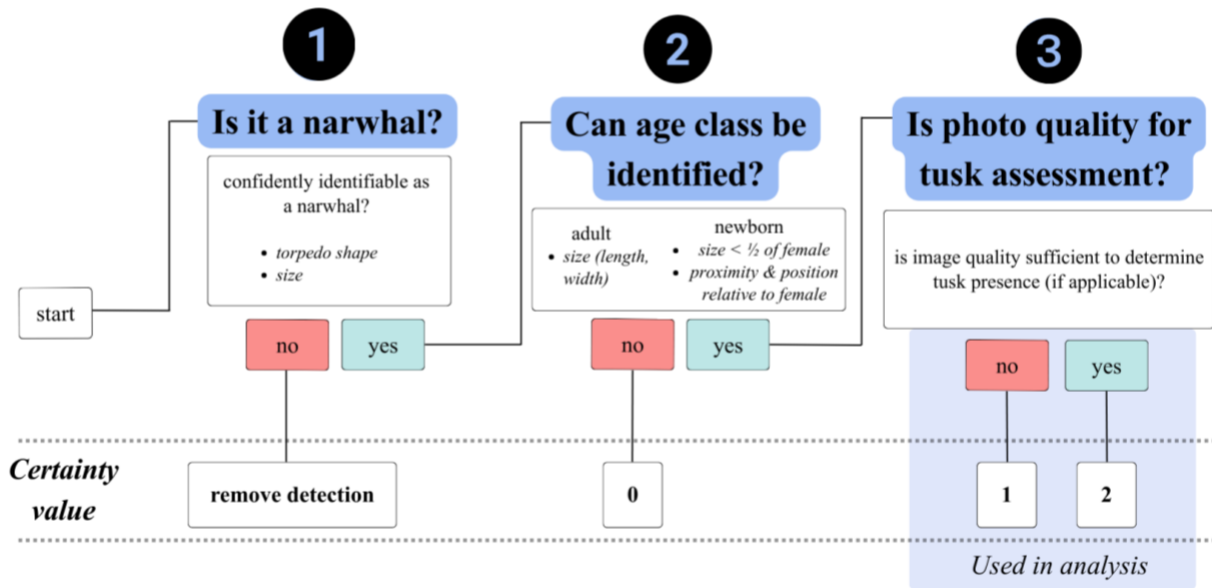


Figure 2. 3. Detection Certainty Scale used to identify the degree of quality of the image used for narwhal detection for the analysis.

### 2.2.5 Automated Algorithm Detector Performance

To evaluate the automated detector reliability and accuracy, a subset of 5% of raw aerial photography images from 2023 was compared against the automated detections (Boulent et al., 2023). Performance for automated detectors is commonly evaluated using metrics such as precision, recall, and the F-score (Christin et al., 2019; Tyshko et al., 2023). Precision represents the proportion of detections classified as a whale that were true whale detections (i.e., how often the model is correct when it predicts a whale) (Boulent et al., 2023). Recall reflects the

proportion of true whales present in the images that the model successfully detected. The F1-score is the harmonic mean of precision and recall and provides a single metric that balances both false positives and false negatives.

### 2.2.6 Age Classification

A validated dichotomous key was used to identify newborn narwhals in both the 2013 and 2023 datasets (*Figure 2.4*) (Charry et al., 2018). Newborn narwhals were born that year in June-August and therefore could be 0-3 months old. Identification was based on the size of the newborn relative to the nearest tuskless adult (presumed mother), the distance from the adult, and the position in relation to the adult. Newborns are defined as measuring 140–170 cm, or up to half the size of the nearest adult female, located within two body lengths (approximately 10 meters) of the adult and positioned at the side, behind, below or above the female (Charry et al., 2018). Narwhals that did not meet these criteria were classified as adults and, when possible, further identified as males (tusked) or females (non-tusked). The measuring tool on QGIS assisted when identifying unsure adult narwhals and newborns. In one case there were 2 newborns with one adult.

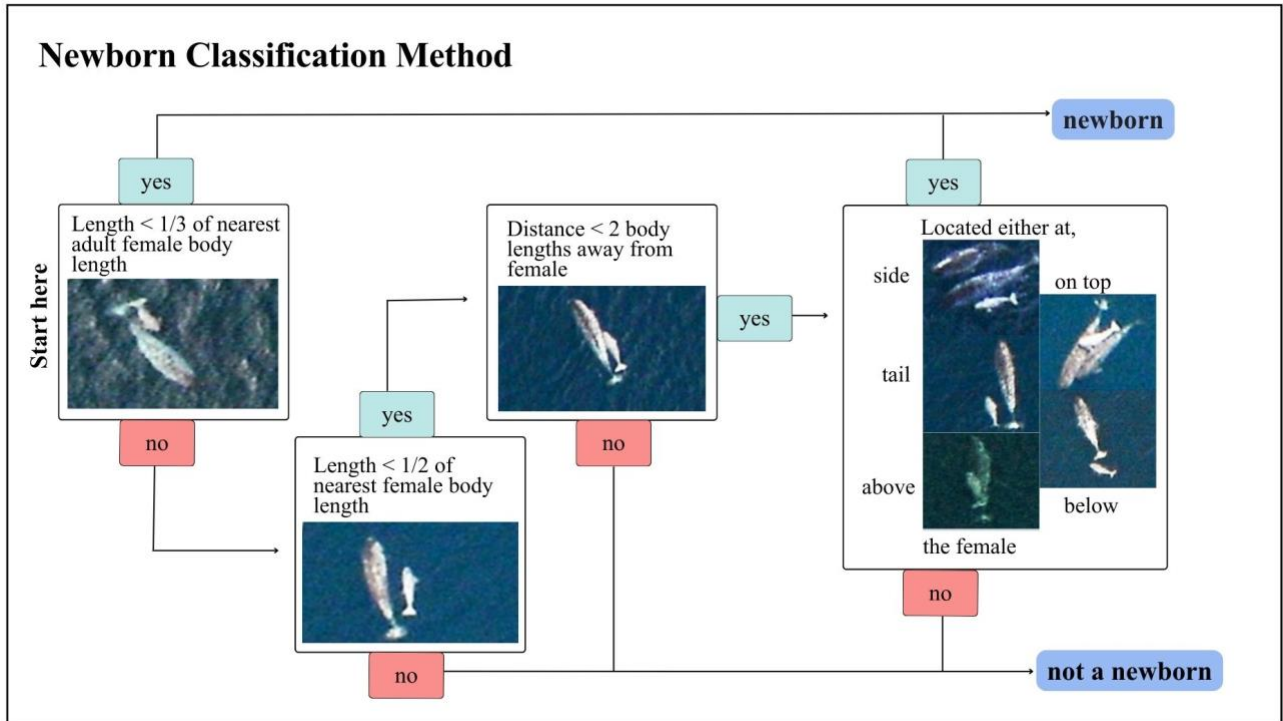


Figure 2. 4. Newborn Classification and Identification Flowchart adapted from (Charry et al., 2018).

## 2.2.7 Grouping

All data cleaning and analysis was completed in Rstudio version 4.4.2 (R Core Team, 2025). To assess group size and newborn-to-adult ratios, narwhals were assigned to groups based on a 10 adult narwhal body widths (3 body lengths) proximity (Charry et al., 2018; Mann, 2000; Marcoux et al., 2009). The latitudes and longitudes of all individuals within a group were averaged to provide a single coordinate per group. Newborn-to-adult ratios were calculated by dividing the number of newborns by the number of adults within each group, and group size was quantified by counting the total number of narwhals per group.

## 2.2.8 Data Analysis and Modelling

### ***Group Size***

To examine how group size varied across summering stocks and between survey years (2013 vs. 2023), we fitted negative binomial generalized linear models to account for overdispersion in group counts using the Modern Applied Statistics with S (*MASS*) package in R (Ripley et al., 2025). Two models were compared: one including an interaction between stock and year and one without the interaction. Model selection followed Akaike information criterion (AIC), which is commonly preferred in ecological studies for its emphasis on predictive performance (Burnham & Anderson, 2004). To assess spatial autocorrelation in group size residuals, we calculated Moran's I for the latitude and longitude (WGS 84/ North Pole LAEA Canada) projected to meters and tested multiple distance thresholds (10, 100, 300 km) with row-standardized weights (Bivand et al., 2025).

### ***Newborn to Adult Group Ratio***

To examine newborn-to-adult group ratio in the different stocks and years, four different zero-inflated gamma models (hurdle gamma), were fitted using the Bayesian Regression Models using 'Stan' (*brms*) package (Bürkner et al., 2025). Group size was included to test whether social structure or aggregation influences the proportion of newborns, while stock was included to account for variation among distinct stocks. Year was included to evaluate temporal differences in newborn ratios that may reflect environmental change or population dynamics.

We considered alternative model structures by systematically varying the inclusion of two-way interactions (group size  $\times$  stock and group size  $\times$  year) to test whether the relationship between group size and newborn ratio differed among stocks or across years. The global model including only additive effects (group size + stock + year) was included as a simpler baseline for

comparison. This approach allowed us to assess whether additional interaction terms improved predictive performance beyond the simpler additive model.

A negative binomial distribution link was used to account for overdispersion and right-skewed data. We used Pareto Smoothed Importance Sampling Leave-One-Out cross-validation to compare four candidate hurdle-gamma models predicting newborn-to-adult ratios. We compared models using the expected log predictive density (ELPD), where higher values indicate better out-of-sample predictive performance. The model with the highest ELPD under PSIS-LOO, accounting for uncertainty in the ELPD differences, was selected as the top-performing model.

## 2.3.0 Results

### 2.3.1 Automated Algorithm Detector Performance

A DFO photographic reader (B. Sherbo) manually examined 5% of the dataset (every 20th photo;  $n = 3,239$ ) to assess the performance of the Mobius auto-detector. Comparison with manual reads identified 2,916 true negatives, 65 true positives, 17 false positives, and 3 false negatives, yielding a precision of 79.3%, recall of 95.6%, and F1 score of 86.7%. Because precision was <100%, all whales identified by the detector were manually verified for presence and species. Discrepancies primarily occurred in images containing multiple narwhals or under challenging environmental conditions, such as whitecaps, where detection errors were more common.

### 2.3.2 Model Choice

#### *Group Size*

AIC strongly supported the interaction model for group size ( $\Delta\text{AIC} = 12.06$ ), so the AIC-selected model was retained (*Table 2.1*). At 10 km, Moran's I was statistically significant ( $I = 0.0296$ ,  $p < 0.001$ ) but very small, suggesting minimal spatial clustering and no biologically meaningful autocorrelation. These results support using the negative binomial GLM without additional spatial correlation structures for modelling group size.

Model Formula	AIC	$\Delta\text{AIC}$
<i>group_size~stock × year</i>	13,599.71	0.00
<i>group_size~stock + year</i>	13,611.77	12.06

*TABLE 2.1.* Candidate models and associated AIC scores for modelling group size. Interaction terms in the models were specified using the \* operator in R, which includes both main effects and their interaction term.

#### *Newborn to Adult Group Ratio*

Multicollinearity among predictor variables (year, stock, and group size) was assessed using variance inflation factors (VIF), with no evidence of problematic collinearity detected. Model 2 and Model 3 did not have statistically significant interactions. Model 4 had the highest expected predictive accuracy based on LOO, but lacked the interaction structure of interest. We therefore selected Model 1, which included group size × stock interaction (*Table 2.2*). Spatial autocorrelation in the model residuals was assessed using Moran's I, and although statistically significant ( $I = 0.03$ ), the effect was essentially zero. As a result, geographic coordinates were excluded from the final model.

Model	Formula	$\Delta\text{ELPD}$	$\text{SE}(\Delta\text{ELPD})$	Comments
Model 1	<i>newborn_ratio~group_size × stock + year</i>	-7.6	4.6	Biologically meaningful interactions chosen for inference

Model 2	$newborn\_ratio \sim group\_size \times year + stock$	-4.8	2.0	Interactions not stat significant
Model 3	$newborn\_ratio \sim group\_size + year \times stock$	-3.8	1.9	Interactions not stat significant
Model 4	$newborn\_ratio \sim group\_size + year + stock$	0.0	0.0	Best predictive performance

TABLE 2.2. Comparison of candidate models explaining variation in newborn ratio based on group size, stock, and year, evaluated using  $\Delta$ ELPD from LOO cross-validation. Interaction terms in the models were specified using the \* operator in R, which includes both main effects and their interaction term.

### 2.3.3 Descriptive Survey Results

When comparing 2013 and 2023, more whales overall were detected in 2013 but more newborns were detected in 2023. After removing duplicates, we identified 8790 unique narwhals, 6166 individuals from 2013 and 2624 from 2023 (Table 2.3). Of the 6166 from 2013, 136 were newborns. Of the 2624 narwhals from 2023, 170 were newborns. A total of 3,633 groups were identified (table 2.4): 2,391 from 2013 and 1,242 from 2023. Of the 2391 from 2013, 1059 were individual narwhal, 1206 were groups of adults, and 126 were groups containing at least one newborn calf across all stocks. Of the 1242 from 2023, 607 were individual whales, 490 were groups of adults, and 145 were groups containing at least one newborn across all stocks. We were unable to determine the sex of a sufficient number of individuals due to a likely overestimation of females (un-tusked) narwhals, and image quality or submerged positions prevented reliable assessment of sex.

Stock	Year	Adults	Newborns	Total
<i>Eclipse Sound</i>	2013	2134	49	2183
	2023	834	54	888
<i>Admiralty Inlet</i>	2013	2278	56	2334
	2023	735	54	789
<i>Somerset Island</i>	2013	544	18	562
	2023	643	42	685
<i>Jones Sound</i>	2013	546	7	553
	2023	180	10	190
<i>East Baffin Island</i>	2013	426	4	430
	2023	42	6	48
<i>Smith Sound</i>	2013	102	2	104
	2023	20	4	24

TABLE 2.3. Number of narwhal detections from the 2013 and 2023 High Arctic Cetacean Aerial Surveys across all stocks by age class in the Baffin Bay population.

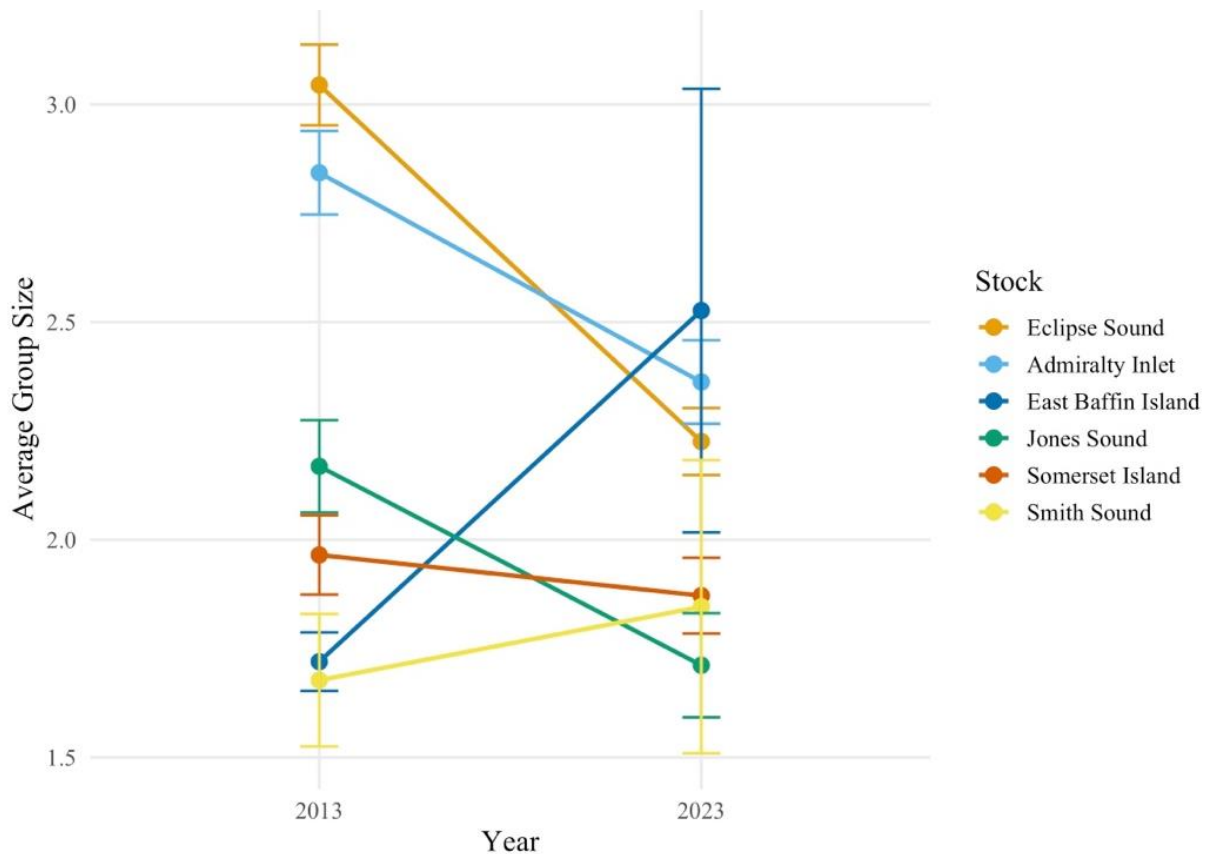
Stock	Year	Total # Groups	Individual	Adult	Newborn	Average Group Size
<i>Eclipse Sound</i>	2013	717	246	427	44	3.04
	2023	399	167	186	46	2.22
<i>Admiralty Inlet</i>	2013	821	340	429	52	2.84
	2023	334	141	146	47	2.36
<i>Somerset Island</i>	2013	286	161	108	17	1.96
	2023	366	221	109	36	1.87
<i>Jones Sound</i>	2013	255	129	119	7	2.16
	2023	111	63	38	10	1.71
<i>East Baffin Island</i>	2013	250	142	104	4	1.72
	2023	19	7	9	3	2.52
<i>Smith Sound</i>	2013	62	41	19	2	1.67
	2023	13	8	2	3	1.84

TABLE 2.4. Number of narwhal groups for different age group types (with one individual only, with adults only, and including at least one newborn) and average group size across stocks and years for the 2013 and 2023 High Arctic Cetacean Surveys of the Baffin Bay population.

### 2.3.4 Group Size

In 2013, groups averaged 2.58 whales (SD = 2.33; median = 2; range = 1–20). In 2023, the mean group size was 2.11 whales (SD = 1.64; median = 2; range = 1–13). Group sizes varied across stocks and between years. In Eclipse Sound, the average group size in 2013 was approximately 3.0 narwhals per group (log-scale intercept = 1.113, SE = 0.026,  $p < 2e-16$ ). Group sizes in Eclipse Sound decreased significantly from 2013 to 2023 (negative binomial GLM, log difference = -0.313, SE = 0.0048,  $p = 4.57e-11$ ), representing a 27% reduction. Groups in East Baffin Island, Jones Sound, Somerset Island, and Smith Sound were smaller than Eclipse Sound in 2013 (negative binomial GLM, log differences = -0.571, -0.339, -0.438, and -0.596, respectively; SEs = 0.061, 0.057, 0.056, and 0.115; all  $p < 0.001$ ).

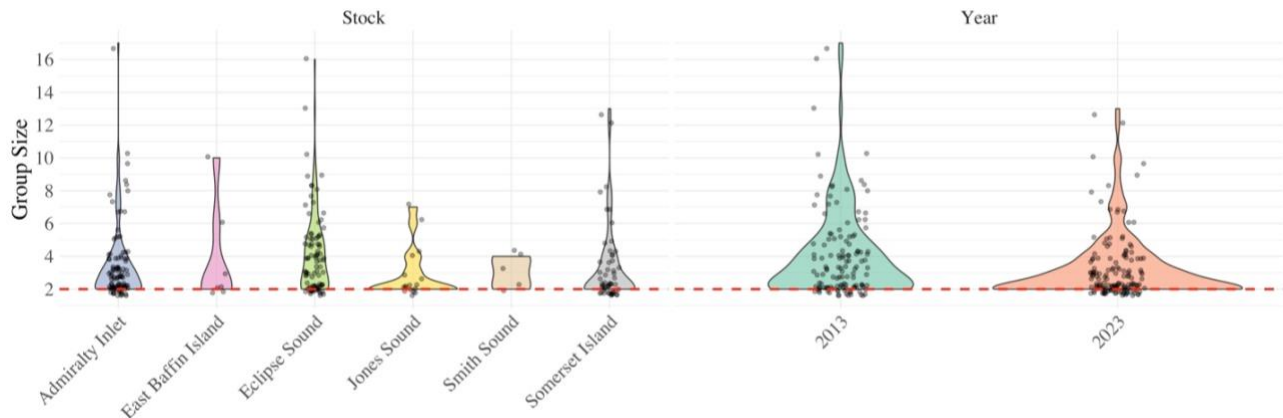
The change in group size from 2013 to 2023 differed among stocks (*Figure 2.5*). East Baffin Island group size increased from 2013 to 2023 (negative binomial GLM, interaction = 0.698, SE = 0.188,  $p = 0.0002$ ), however the sample size in 2023 was small (19 groups). Group size declined from 2013 to 2023 in Somerset Island (interaction = 0.265, SE = 0.081,  $p = 0.0011$ ), although the magnitude of this decrease was smaller than in Eclipse Sound. In Admiralty Inlet group sizes showed a marginal increase over time (interaction = 0.128, SE = 0.069,  $p = 0.061$ ). In contrast, Jones Sound (interaction = 0.077, SE = 0.108,  $p = 0.476$ ), and Smith Sound (interaction = 0.409, SE = 0.264,  $p = 0.121$ ) did not differ significantly in their changes relative to Eclipse Sound.



*Figure 2. 5.* Change in narwhal average group size by stock and year in the Baffin Bay population. Points show mean group size and error bars represent 95% confidence intervals. Lines connect year-specific estimates within each stock to illustrate temporal change.

### 2.3.5 Newborn to Adult Ratio

Mean newborn-to-adult group ratio in 2013 was 0.03 (range = 0–1), increasing to 0.08 in 2023 (range = 0–2). The hurdle gamma model indicated that group size was negatively associated with newborn ratio ( $\beta = -0.20$ , 95% CI = -0.23 to -0.17), suggesting that larger groups contained proportionally fewer newborns. This pattern was consistent across both years. Across groups containing at least one newborn (group size range 2–17), 43% consisted of one adult paired with one newborn, while 19% were groups of three individuals, typically composed of two adults and one newborn (*Figure 2.6*). Larger groups were generally dominated by adults, with newborns more commonly occurring in smaller groups.



*Figure 2.6.* Distribution of narwhal group sizes of groups that included newborns by stock and survey year from the 2013 and 2023 High Arctic Cetacean Aerial Surveys of the Baffin Bay population. Group size starting at smallest group size of 2 on y axis and stock and year on x axis. Violin plots show the density of observed group sizes, with points representing individual group observations. The dashed red line indicates a group size of two, corresponding to mother–newborn pairs.

Stock-level effects were generally weak and uncertain, with credible intervals overlapping zero. Relative to Admiralty Inlet, estimates were: East Baffin Island ( $\beta = 0.12$ , 95% CI = -0.41 to 0.67), Eclipse Sound ( $\beta = -0.06$ , 95% CI = -0.26 to 0.13), Jones Sound ( $\beta = 0.40$ , 95% CI = -0.02 to 0.82), Somerset Island ( $\beta = -0.10$ , 95% CI = -0.33 to 0.12), and Smith Sound

( $\beta = 0.15$ , 95% CI = -1.02 to 1.40), indicating no clear differences in newborn ratio among stocks. Interactions between group size and stock were also generally small and overlapped zero: East Baffin Island ( $\beta = 0.05$ , 95% CI = -0.06 to 0.17), Eclipse Sound ( $\beta = 0.00$ , 95% CI = -0.04 to 0.04), Somerset Island ( $\beta = 0.04$ , 95% CI = -0.01 to 0.09), and Smith Sound ( $\beta = -0.02$ , 95% CI = -0.41 to 0.36). However, in Jones Sound, increasing group size was associated with a stronger decline in newborn ratio ( $\beta = -0.16$ , 95% CI = -0.28 to -0.03), suggesting that groups containing newborns were smaller in this stock relative to Admiralty Inlet.

Year had a modest positive effect ( $\beta = 0.15$ , 95% CI = 0.05 to 0.25), corresponding to a slight increase in newborn-to-adult group ratio in 2023 compared to 2013 (*Figure 2.7*). The hurdle component indicated a high probability (~93%) of groups containing no newborns ( $h_u = 0.93$ , 95% CI = 0.92 to 0.93), consistent with many groups consisting solely of adults. The estimated shape parameter (6.29, 95% CI = 5.28 to 7.40) indicated moderate variability in non-zero newborn ratios.

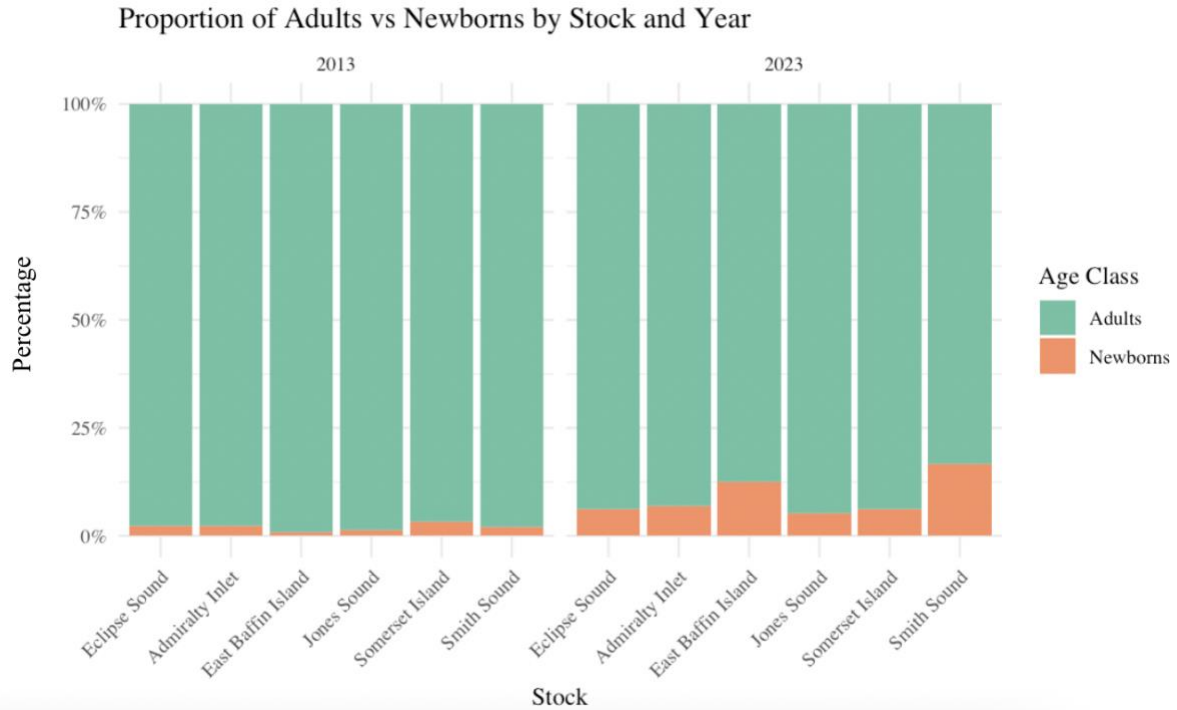


Figure 2. 7. Percentage of narwhal newborns to adults across stocks and years from the 2013 and 2023 High Arctic Cetacean Aerial Surveys of the Baffin Bay population.

## 2.4.0 Discussion

Stock-specific differences in group size observed in this study can be compared with patterns reported in earlier aerial surveys. Largest group sizes were found in Eclipse Sound and Admiralty Inlet stocks compared to Jones Sound, Somerset Island, East Baffin Island, and Smith Sound. However, Somerset Island historically has the largest summering aggregation of narwhals (Doniol-Valcroze et al., 2020; Richard et al., 2010) suggesting that larger group sizes are not necessarily associated with stocks exhibiting the largest aggregations.

Average group size declined between 2013 and 2023 in most stocks, potentially reflecting changes in environmental conditions. Over the past decade, sea surface temperatures (SST) have increased (Singh et al., 2013), and higher SSTs have been associated with smaller group sizes in other odontocetes (La Manna et al., 2023). In that study, the authors hypothesized

that this relationship may be mediated by changes in prey distribution or availability under warmer conditions, although prey data were not directly examined. This pattern may reflect similarities in Baffin Bay narwhal, where Arctic cod, a main prey item, may be less abundant because eggs and larvae are vulnerable to climate-driven temperature fluctuations (Geoffroy et al., 2023). Alternatively, Greenland halibut, another key prey item for narwhals, has been increasing in abundance as warming creates more favourable thermal habitat (Czich et al., 2023). Given that Arctic cod are a primary summer prey for narwhals, declines in cod availability or aggregation may be especially relevant to the observed reductions in summer group size, while increases in Greenland halibut, a prey consumed largely in winter, are unlikely to exert the same seasonal influence (Finley & Gibb, 1982; Laidre & Heide-Jørgensen, 2005). However, since narwhals concentrate their foraging in winter and forage relatively little in summer, warming-related changes in prey availability may have a smaller impact on group size compared to other environmental factors (Chambault et al., 2023).

Ship presence and duration is increasing in the Arctic and may have impacts on group size and cohesion. Narwhals are highly sensitive to ship noise, showing both auditory and physiological responses when vessels are nearby (Tervo et al., 2021; Williams et al., 2022). Narwhals have very high overall and complex vocal activity (Walmsley et al., 2020). They produce paired patterns, likely for close-range or individual communication, and burst-pulse series, which occur during periods of high vocal activity to facilitate group-level coordination. At a distance of 12 kilometers, buzzing rate (a marker for foraging) halved and ceased entirely at 7–8 kilometers from the ship (Tervo et al., 2021). Effects were detectable at distances greater than 40 kilometers, showing long-range sensitivity even when ship sound was below background noise. In Eclipse Sound, narwhal acoustic presence decreased in response to nearby vessel

activity, suggesting behavioural avoidance at greater distances and lower noise levels than previously recognized (Ewing et al., 2025). This sensitivity may reflect changes in group composition or temporary fragmentation when disturbances are present, and communication is impaired.

Ship noise has been found to mask important group-specific communication in other cetacean species (Buckstaff, 2004; Dunlop, 2019). In noisy environments, communication among group members can be further disrupted by the number of individuals present. In one study, mother–calf pairs of bottlenose dolphins (*Tursiops truncatus*), may have mitigated the impact of boat noise by forming smaller groups, so that signal masking from conspecifics was reduced (La Manna et al., 2023). By contrast, increased cohesion and group size were observed in long-finned pilot whales (*Globicephala melas*), in response to ship disturbance (Visser et al., 2016). Although there is limited documentation of decreases in group size in response to vessels, a variety of behavioural changes, including altered grouping, communication, swimming speed, and swimming direction have been observed (Halliday et al., 2019; Martin et al., 2023; Tervo et al., 2021; Williams et al., 2022). These responses indicate disruption of normal behaviour and appear to vary across species and populations, suggesting that disturbance can manifest differently among cetaceans. Given their high auditory sensitivity and the potential for communication masking, narwhals may respond to vessel noise by forming smaller groups to maintain effective social contact. This pattern is most evident in Eclipse Sound, where group sizes declined significantly between 2013 and 2023, coinciding with increased vessel traffic over the last decade (Ewing et al., 2025).

Predation pressure from killer whales can induce lasting behavioural changes in narwhals, as shown by satellite-tracking and observational studies that suggest major shifts in

movement when predators are present (Breed et al., 2017; Laidre et al., 2006). Predation by killer whales may be contributing to declining narwhal group sizes, as rapid sea ice loss increasingly exposes narwhals as prey as killer whales are in overlapping narwhal areas in 2013 and 2023 (Ferguson et al., 2025).

While killer whales were present in Admiralty Inlet, satellite-tracked narwhals responded by moving slowly, staying extremely close to shore, using very shallow water, and forming tight surface groups (Breed et al., 2017). During another attack, they dispersed broadly, group clumping decreased, and their spatial area doubled (Laidre et al., 2006). Even after the killer whales departed from the area, dispersal and offshore space use remained high for several days (Laidre et al., 2006). These observations suggest that increased predator presence can fragment groups and strongly affect movement behaviour (Breed et al., 2017; Laidre et al., 2006). It is plausible that, depending on the frequency and proximity of killer whale attacks in Baffin Bay, narwhals could form smaller groups for extended periods under high predation pressure. We know killer whales are increasingly seen in the area but if they are predated on narwhals and the intensity is widely unknown. Group sizes in the East Baffin Island stock showed an increase from 2013 to 2023 which may reflect different killer whale pressures or stock specific differences in strategies to avoid predation, however the sample size was small. In contrast, beluga whales and humpback whales preyed upon by killer whales rarely display group-dispersal behaviour during predator interactions; instead, tight grouping, reduced foraging, and increased swimming speed is most common (Curé et al., 2015; Westdal et al., 2016). Narwhals have been observed both dispersing and forming tight groups in response to threats (Breed et al., 2017; Laidre et al., 2006), highlighting the variety of anti-predator strategies, including the potential for group fragmentation.

We found that as group size increased, the newborn ratio decreased. Small group sizes were common among groups containing at least one newborn, reflecting the benefits of the mother–newborn pairing. Across both years and all stocks, 43% of newborn groups consisted of a single mother–newborn pair (37% in 2013 and 49% in 2023), followed by 19% of groups consisting of three individuals (either two newborns with one adult or two adults with one newborn). Nursery groups, defined as groups with more than one mother–newborn pair, were rare, representing only 4% overall (2% in 2013, 6% in 2023). For most odontocetes, the mother–newborn bond is critical for survival, especially during the first few months after birth. During the neonatal period (the first few days to weeks), newborns are highly dependent on their mothers for basic survival skills such as swimming, breathing, and following, with minimal independence (Mann, 2019). This period is characterized by high levels of mother–newborn synchrony, including parallel swimming, coordinated breathing, and body-to-body contact such as rubbing and petting (Sakai et al., 2013). These behaviours gradually decline as the calf ages. In narwhals, newborns are typically positioned within one body length of the nearest female, highlighting the importance of proximity during the first months of life (Charry et al., 2018). Our 2023 results are consistent with a previous study based on the 2013 dataset, which reported that mother–newborn pairs were most common, followed by groups of three or four individuals, with nursery groups being rare (Charry et al., 2018). Our study supports the 2013 pattern and demonstrates that similar group composition persists a decade later. The strong mother–newborn bond during the first few months likely explains why we most often observed mother–newborn pairs in our August surveys, when they would be 0–3 months old.

Not all newborn groups consisted solely of mother–newborn pairs, suggesting potential benefits from the presence of additional adults. During summer, narwhal mother–newborn pairs

have been observed forming social units with an extra female, and these units often travel alongside other groups during migration (Charry et al., 2018; Marcoux et al., 2009). Although our study lacked reliable sex data for adult whales in the newborn groups, such associations could suggest allocare. Prolonged nursing, in combination with these triad groups, may reflect this type of care, in which additional adults help protect, supervise, or assist in nursing the calf (Zhao et al., 2021). Although not yet documented in narwhals, allocare can increase calf protection and reduce maternal energy expenditure (Aubin et al., 2023). Similar behaviours have been observed in other odontocetes, including closely related beluga whales (*Delphinapterus leucas*) (Aubin et al., 2023; Hill & Campbell, 2014; Konrad et al., 2019).

Newborn-to-adult group ratios were higher in 2023 compared to 2013. The ratio could increase either because the number of newborns rose, because the number of adults fell, or because both increased. Without abundance estimates and corrections, we cannot determine which is more likely; we can only conclude that the population structure appears to have changed between 2013 and 2023, warranting further assessment. However, we can speculate about the drivers of the ratios if different scenarios were true. If the higher newborn ratio across all stocks in 2023 reflects increased reproduction, warmer summer waters may contribute to supporting newborn rearing. The eastern Canadian Arctic was warmer in 2023 than in 2013, and although this relationship has not been tested in narwhals, such conditions could indirectly benefit calving. While studies focus mostly on southern baleen whales, mothers and calves have been shown to prefer warmer, shallower waters which may indirectly reflect a thermal or energetic benefit for newborns (Corkeron & Connor, 1999; Pack et al., 2017). A similar thermal benefit has been suggested for beluga neonates, although results remain mixed (Westdal et al., 2022). Beluga and narwhal neonates are equally insulated, yet only belugas seasonally occupy warmer waters

(Smith et al., 2016). In contrast, adult narwhals in Greenland have been shown to prefer cold waters, likely due to prey concentrations at these temperatures (Heide-Jørgensen et al., 2020). Another possible explanation for an increased calf ratio is improved winter foraging. A thermal advantage has been observed in Greenland halibut, a primary winter prey item of narwhals, whose abundance has increased in the Arctic (Czich et al., 2023b). If winter food availability is high, adult narwhals may enter the summer with greater energy reserves, potentially supporting higher reproductive output during a period when they feed relatively little. However, no research has documented seasonal warming preferences in adult narwhals, and rather than being driven by summer temperature conditions, the observed increase in newborn ratios in 2023 may more likely reflect improved energy acquisition during the winter that supports reproductive output in the following summer.

It is also important to note that, although apparent reproduction increased from 2013 to 2023, recruitment remains unknown. Recruitment is the survival of newborns to later life stages and is a critical demographic measure for population status (Taylor et al., 1987). Newborn mortality is often higher than post-weaning and adult mortality in long living cetaceans (Betty et al., 2023), meaning not all newborns recorded in 2023 will survive to contribute to the future population. Additionally, the rates and causes of calf mortality are hard to identify and are likely under reported (Mann, 2019).

Narwhals are iteroparous, with extended gestation and parental care that prevent annual reproduction (Heide-Jørgensen, 2009). Calf counts alone do not measure recruitment, as survival to reproductive age varies and annual newborn numbers fluctuate naturally (Taylor et al., 1987). Female narwhals reach sexual maturity around 6-7 years of age (Garde et al., 2007), therefore not all individuals classified as adults in this study are necessarily reproducing, and those that are

may do so at different rates. Without multi-year data on abundance, age structure, and survival, it is impossible to separate true population growth or decline from natural inter-annual variation (Taylor et al., 1987). Given that narwhals typically produce one calf every three years (Hay, 1984; Heide-Jørgensen & Garde, 2011), 2013 may have had fewer reproducing females and 2023 more. This effect of decadal variation in reproduction is observed in other marine (Hastings et al., 2023), and land (Forrester et al., 2024) mammals. Additionally, populations undergo natural cycles of birth, with reproductive output rising and falling across the population in response to environmental conditions, density, and other ecological factors (Myers, 2018). Assessing population growth reliably requires complex inter-year demographic models, which are challenging for deep-diving cetaceans that spend large parts of the year under sea ice. While newborn counts cannot directly indicate reproductive trends, they can reveal insights into group structure, such as the relative frequency of mother–newborn pairs and triads across temporal and spatial scales. Therefore, we can only suggest changes in population structure between 2013 and 2023, while the direction, magnitude, and validity of any change requires a combination of methods.

When considering the other half of the ratio, a higher newborn-to-adult ratio can also be due to fewer adults in the population. Whether there are truly fewer adults or fewer adults are detected in the survey remains unknown without abundance estimates. Narwhals have been observed to increase diving in response to environmental stressors, including ships and entanglements (Tervo et al., 2023; Williams et al., 2017, 2022). As large ships, including icebreakers, become more common in their habitat, diving behaviour might increase. This increase in diving behaviour could reduce detection if it occurs at a large scale during the 2023 aerial survey. This could explain why newborns were detected more often, as beluga and

Commerson's dolphin (*Cephalorhynchus commersonii*) newborns are known to spend more time at the surface and have limited deep-diving capacity compared to adults (Noren & Suydam, 2016; Sakai et al., 2013). Similarly, narwhals were observed to increase swimming speed and distance covered in response to predation, which could reflect quicker transient behaviour between areas, a behavioural change, with fewer adults being detected by the survey (Laidre et al., 2006). Additionally, narwhals rely on sea ice cues for movement, and as sea ice conditions continue to change with warming including interannual variability (Laidre & Heide-Jørgensen, 2005), they may be occupying different areas at different times of the year. This shift could require adjustments to the timing and design of future survey monitoring efforts.

## 2.5.0 Conclusion

Overall, our findings suggest that Baffin Bay narwhal group structure has shifted over the past decade, with generally smaller groups and higher newborn-to-adult ratios observed in 2023 compared to 2013. These patterns may reflect a combination of climate-driven environmental change, increasing vessel traffic (Dawson et al., 2018; Ewing et al., 2025; Halliday et al., 2022; Hauser et al., 2018; Williams et al., 2022), and opportunities for predation pressures (Breed et al., 2017; Laidre et al., 2006), all of which can influence grouping behaviour, communication, and detectability. Newborn groups were consistently small and dominated by mother-calf pairs, underscoring the importance of close maternal care during early development. However, without updated abundance estimates, it remains unclear whether changes in group size and calf ratios reflect true demographic shifts or behavioural responses to disturbance, underscoring the limitations. Continued, standardized monitoring across stocks, incorporating metrics beyond group dynamics, such as abundance, reproductive rates, and sex structure, is needed to determine

how narwhal populations are responding to rapid ecological change in the eastern Canadian Arctic.

## 2.6.0 References

- Alexander, R. D. (1974). The Evolution of Social Behavior. *Annual Review of Ecology and Systematics*, 5, 325–383.
- Aubin, J. A., Michaud, R., & Wal, E. V. (2023). Protection, energetic assistance, or social perks: How do beluga offspring benefit from allocaire? *Marine Mammal Science*, 39(1), 77–97.  
<https://doi.org/10.1111/mms.12957>
- Aureli, F., Schaffner, C. M., Boesch, C., Bearder, S. K., Call, J., Chapman, C. A., Connor, R., Fiore, A. D., Dunbar, R. I. M., Henzi, S. P., Holekamp, K., Korstjens, A. H., Layton, R., Lee, P., Lehmann, J., Manson, J. H., Ramos-Fernandez, G., Strier, K. B., & Schaik, C. P. van. (2008). Fission-Fusion Dynamics: New Research Frameworks. *Current Anthropology*, 49(4), 627–654.  
<https://doi.org/10.1086/586708>
- Betty, E. L., Stockin, K. A., Hinton, B., Bollard, B. A., Orams, M. B., & Murphy, S. (2023). Age- and sex-specific survivorship of the Southern Hemisphere long-finned pilot whale (*Globicephala melas edwardii*). *Journal of Mammalogy*, 104(1), 39–48.  
<https://doi.org/10.1093/jmammal/gyac085>
- Bivand, R., Altman, M., Anselin, L., Assunção, R., Bera, A., Berke, O., Blanchet, F. G., Carvalho, M., Christensen, B., Chun, Y., Dormann, C., Dray, S., Dunnington, D., Gómez-Rubio, V., Koley, M., Kossowski, T., Krainski, E., Legendre, P., Lewin-Koh, N., ... Yu, D. (2025). *spdep: Spatial Dependence: Weighting Schemes, Statistics* (Version 1.4-1) [Computer software]. <https://cran.r-project.org/web/packages/spdep/index.html>
- Booth, C. G., Sinclair, R. R., & Harwood, J. (2020). Methods for Monitoring for the Population Consequences of Disturbance in Marine Mammals: A Review. *Frontiers in Marine Science*, 7.  
<https://doi.org/10.3389/fmars.2020.00115>

- Boulent, J., Charry, B., Kennedy, M. M., Tissier, E., Fan, R., Marcoux, M., Watt, C. A., & Gagné-Turcotte, A. (2023). Scaling whale monitoring using deep learning: A human-in-the-loop solution for analyzing aerial datasets. *Frontiers in Marine Science*, *10*.  
<https://doi.org/10.3389/fmars.2023.1099479>
- Breed, G. A., Matthews, C. J. D., Marcoux, M., Higdon, J. W., LeBlanc, B., Petersen, S. D., Orr, J., Reinhart, N. R., & Ferguson, S. H. (2017). Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales. *Proceedings of the National Academy of Sciences*, *114*(10), 2628–2633. <https://doi.org/10.1073/pnas.1611707114>
- Bröker, K. C. A., Hansen, R. G., Leonard, K. E., Koski, W. R., & Heide-Jørgensen, M. P. (2019). A comparison of image and observer based aerial surveys of narwhal. *Marine Mammal Science*, *35*(4), 1253–1279. <https://doi.org/10.1111/mms.12586>
- Buckstaff, K. C. (2004). Effects of Watercraft Noise on the Acoustic Behavior of Bottlenose Dolphins, *Tursiops Truncatus*, in Sarasota Bay, Florida. *Marine Mammal Science*, *20*(4), 709–725.  
<https://doi.org/10.1111/j.1748-7692.2004.tb01189.x>
- Bürkner, P.-C., Gabry, J., Weber, S., Johnson, A., Modrak, M., Badr, H. S., Weber, F., Vehtari, A., Ben-Shachar, M. S., Rabel, H., Mills, S. C., Wild, S., Popov, V., Kosmidis, I., Schneider, B., Kallioinen, N., Silva, W. J., Carvalho, L., & Pekin, S. (2025). *brms: Bayesian Regression Models using “Stan”* (Version 2.23.0) [Computer software]. <https://cran.r-project.org/web/packages/brms/index.html>
- Burnham, K. P., & Anderson, D. R. (Eds.). (2004). *Model Selection and Multimodel Inference*. Springer.  
<https://doi.org/10.1007/b97636>
- Cartwright, R., Gillespie, B., LaBonte, K., Mangold, T., Venema, A., Eden, K., & Sullivan, M. (2012). Between a Rock and a Hard Place: Habitat Selection in Female-Calf Humpback Whale

- (Megaptera novaeangliae) Pairs on the Hawaiian Breeding Grounds. *PLOS ONE*, 7(5), e38004.  
<https://doi.org/10.1371/journal.pone.0038004>
- Carvalho, K. S., & Wang, S. (2020). Sea surface temperature variability in the Arctic Ocean and its marginal seas in a changing climate: Patterns and mechanisms. *Global and Planetary Change*, 193, 103265. <https://doi.org/10.1016/j.gloplacha.2020.103265>
- Chambault, P., Blackwell, S. B., & Heide-Jørgensen, M. P. (2023). Extremely low seasonal prey capture efficiency in a deep-diving whale, the narwhal. *Biology Letters*, 19(2), 20220423.  
<https://doi.org/10.1098/rsbl.2022.0423>
- Chambault, P., Tervo, O. M., Garde, E., Hansen, R. G., Blackwell, S. B., Williams, T. M., Dietz, R., Albertsen, C. M., Laidre, K. L., Nielsen, N. H., Richard, P., Sinding, M. H. S., Schmidt, H. C., & Heide-Jørgensen, M. P. (2020). The impact of rising sea temperatures on an Arctic top predator, the narwhal. *Scientific Reports*, 10(1), 18678. <https://doi.org/10.1038/s41598-020-75658-6>
- Charry, B., Marcoux, M., Cardille, J. A., Giroux-Bougard, X., & Humphries, M. M. (2020). Hierarchical Classification of Narwhal Subpopulations Using Social Distance. *The Journal of Wildlife Management*, 84(2), 311–319. <https://doi.org/10.1002/jwmg.21799>
- Charry, B., Marcoux, M., & Humphries, M. M. (2018). Aerial photographic identification of narwhal (*Monodon monoceros*) newborns and their spatial proximity to the nearest adult female. *Arctic Science*, 4(4), 513–524. <https://doi.org/10.1139/as-2017-0051>
- Christin, S., Hervet, É., & Lecomte, N. (2019). Applications for deep learning in ecology. *Methods in Ecology and Evolution*, 10(10), 1632–1644. <https://doi.org/10.1111/2041-210X.13256>
- Corkeron, P. J., & Connor, R. C. (1999). Why Do Baleen Whales Migrate? *Marine Mammal Science*, 15(4), 1228–1245. <https://doi.org/10.1111/j.1748-7692.1999.tb00887.x>

- COSEWIC. (2024). *COSEWIC assessment and status report on the narwhal (Monodon monoceros) in Canada* [Status report]. Government of Canada. <https://species-registry.canada.ca>
- Curé, C., Sivle, L. D., Visser, F., Wensveen, P. J., Isojunno, S., Harris, C. M., Kvadsheim, P. H., Lam, F.-P. A., & Miller, P. J. O. (2015). Predator sound playbacks reveal strong avoidance responses in a fight strategist baleen whale. *Marine Ecology Progress Series*, 526, 267–282. <https://doi.org/10.3354/meps11231>
- Czich, A. N., Stanley, R. R. E., Avery, T. S., den Heyer, C. E., & Shackell, N. L. (2023a). Recent and projected climate change–induced expansion of Atlantic halibut in the Northwest Atlantic. *FACETS*, 8, 1–14. <https://doi.org/10.1139/facets-2021-0202>
- Dawson, J., Pizzolato, L., Howell, S. E. L., Copland, L., & Johnston, M. E. (2018). Temporal and Spatial Patterns of Ship Traffic in the Canadian Arctic from 1990 to 2015. *Arctic*, 71(1), 15–26.
- de Greef, E., Müller, C., Thorstensen, M. J., Ferguson, S. H., Watt, C. A., Marcoux, M., Petersen, S. D., & Garroway, C. J. (2024). Unraveling the Genetic Legacy of Commercial Whaling and Population Dynamics in Arctic Bowhead Whales and Narwhals. *Global Change Biology*, 30(10), e17528. <https://doi.org/10.1111/gcb.17528>
- Doniol-Valcroze, T., Gosselin, J.-F., Pike, D., Lawson, J., Asselin, N., Hedges, K., & Ferguson, S. (2020). Narwhal Abundance in the Eastern Canadian High Arctic in 2013. *NAMMCO Scientific Publications*, 11. <https://doi.org/10.7557/3.5100>
- Dunlop, R. A. (2019). The effects of vessel noise on the communication network of humpback whales. *Royal Society Open Science*, 6(11), 190967. <https://doi.org/10.1098/rsos.190967>
- Ewing, J. P., Hidalgo-Pla, E., Solsona-Berga, A., Frasier, K. E., Ootoowak, A. J., Westdal, K. H., Wiggins, S. M., Hildebrand, J. A., & Jones, J. M. (2025). Narwhal acoustic presence in Eclipse

- Sound, Nunavut: Relationships with sea ice and responses to ships. *Scientific Reports*, 15(1), 23126. <https://doi.org/10.1038/s41598-025-04032-1>
- Ezenwa, V. O., Ghai, R. R., McKay, A. F., & Williams, A. E. (2016). Group living and pathogen infection revisited. *Current Opinion in Behavioral Sciences, Behavioral Ecology*, 12, 66–72. <https://doi.org/10.1016/j.cobeha.2016.09.006>
- Ferguson, M. C., Angliss, R. P., Kennedy, A., Lynch, B., Willoughby, A., Helker, V., Brower, A. A., & Clarke, J. T. (2018). Performance of manned and unmanned aerial surveys to collect visual data and imagery for estimating arctic cetacean density and associated uncertainty. *Journal of Unmanned Vehicle Systems*, 6(3), 128–154. <https://doi.org/10.1139/juvs-2018-0002>
- Ferguson, S. H., Biddlecombe, B. A., Westdal, K., Petersen, S. D., Watt, C., Matthews, C. J. D., & Higdon, J. W. (2025). Killer whale range expansion and extended seasonal presence in the eastern Canadian Arctic, 2002-2023. *Frontiers in Marine Science*, 12. <https://doi.org/10.3389/fmars.2025.1595960>
- Finley, K. J., & Gibb, E. J. (1982). Summer diet of the narwhal (*Monodon monoceros*) in Pond Inlet, northern Baffin Island. *Canadian Journal of Zoology*, 60(12), 3353–3363. <https://doi.org/10.1139/z82-424>
- Forrester, K., Larue, B., King, W. J., & Festa-Bianchet, M. (2024). Cumulative and interannual effects of reproduction in eastern grey kangaroos. *Journal of Animal Ecology*, 93(11), 1684–1696. <https://doi.org/10.1111/1365-2656.14179>
- Geoffroy, M., Bouchard, C., Flores, H., Robert, D., Gjørseter, H., Hoover, C., Hop, H., Hussey, N. E., Nahrgang, J., Steiner, N., Bender, M., Berge, J., Castellani, G., Chernova, N., Copeman, L., David, C. L., Deary, A., Divoky, G., Dolgov, A. V., ... Walkusz, W. (2023). The circumpolar impacts of climate change and anthropogenic stressors on Arctic cod (*Boreogadus saida*) and its

ecosystem. *Elementa: Science of the Anthropocene*, 11(1), 00097.

<https://doi.org/10.1525/elementa.2022.00097>

Government of Nunavut. (2013). *Nutrition Fact Sheet Series: Inuit Traditional Foods*. Department of Health, Nunavut.

[https://livehealthy.gov.nu.ca/sites/default/files/resource\\_attachments/EN\\_WEB\\_itf--nutrition-fact-sheet-series.pdf](https://livehealthy.gov.nu.ca/sites/default/files/resource_attachments/EN_WEB_itf--nutrition-fact-sheet-series.pdf)

Gowans, S. (2019). Grouping Behaviors of Dolphins and Other Toothed Whales. In B. Würsig (Ed.), *Ethology and Behavioral Ecology of Odontocetes* (pp. 3–24). Springer International Publishing.

[https://doi.org/10.1007/978-3-030-16663-2\\_1](https://doi.org/10.1007/978-3-030-16663-2_1)

Graham, Z. A., Garde, E., Heide-Jørgensen, M. P., & Palaoro, A. V. (2020). The longer the better: Evidence that narwhal tusks are sexually selected. *Biology Letters*, 16(3), 20190950.

<https://doi.org/10.1098/rsbl.2019.0950>

Halliday, W. D., Dawson, J., Yurkowski, D. J., Doniol-Valcroze, T., Ferguson, S. H., Gjerdrum, C., Hussey, N. E., Kochanowicz, Z., Mallory, M. L., Marcoux, M., Watt, C. A., & Wong, S. N. P. (2022). Vessel risks to marine wildlife in the Tallurutiup Imanga National Marine Conservation Area and the eastern entrance to the Northwest Passage. *Environmental Science & Policy*, 127, 181–195. <https://doi.org/10.1016/j.envsci.2021.10.026>

Halliday, W. D., Scharffenberg, K., MacPhee, S., Hilliard, R. C., Mouy, X., Whalen, D., Loseto, L. L., & Insley, S. J. (2019). Beluga Vocalizations Decrease in Response to Vessel Traffic in the Mackenzie River Estuary. *Arctic*, 72(4), 337–346.

Hastings, K. K., Jemison, L. A., Pendleton, G. W., Johnson, D. S., & Gelatt, T. S. (2023). Age-specific reproduction in female Steller sea lions in Southeast Alaska. *Ecology and Evolution*, 13(9), e10515. <https://doi.org/10.1002/ece3.10515>

Hauser, D. D. W., Laidre, K. L., & Stern, H. L. (2018). Vulnerability of Arctic marine mammals to vessel traffic in the increasingly ice-free Northwest Passage and Northern Sea Route.

*Proceedings of the National Academy of Sciences*, 115(29), 7617–7622.

<https://doi.org/10.1073/pnas.1803543115>

Hay, K. A. (1984). *The life history of the narwhal, Monodon monoceros L., in the eastern Canadian arctic* /. McGill University. <https://escholarship.mcgill.ca/concern/theses/v118rf31m>

Heide-Jørgensen, M. P., Blackwell, S. B., Williams, T. M., Sinding, M. H. S., Skovrind, M., Tervo, O. M., Garde, E., Hansen, R. G., Nielsen, N. H., Ngô, M. C., & Ditlevsen, S. (2020). Some like it cold: Temperature-dependent habitat selection by narwhals. *Ecology and Evolution*, 10(15), 8073–8090. <https://doi.org/10.1002/ece3.6464>

Heide-Jørgensen, M. P., Dietz, R., Laidre, K. L., Richard, P., Orr, J., & Schmidt, H. C. (2003). The migratory behaviour of narwhals (*Monodon monoceros*). *Canadian Journal of Zoology*, 81(8), 1298–1305. <https://doi.org/10.1139/z03-117>

Heide-Jørgensen, M. P., & Garde, E. (2011). Fetal growth of narwhals (*Monodon monoceros*). *Marine Mammal Science*, 27(3), 659–664. <https://doi.org/10.1111/j.1748-7692.2010.00423.x>

Heide-Jørgensen, M. P., & Laidre, K. L. (2004). Declining extent of open-water refugia for top predators in Baffin Bay and adjacent waters. *Ambio*, 33(8), 487–494. <https://doi.org/10.1579/0044-7447-33.8.487>

Hill, H. M., & Campbell, C. (2014). The frequency and nature of allocaire by a group of belugas (*Delphinapterus leucas*) in human care. *International Journal of Comparative Psychology*, 27(4). <https://doi.org/10.46867/ijcp.2014.27.04.08>

Hoover, C., Bailey, M., Higdon, J., Ferguson, S. H., & Sumaila, R. (2013). Estimating the Economic Value of Narwhal and Beluga Hunts in Hudson Bay, Nunavut. *Arctic*, 66(1), 1–16.

- Jones, J. M., Westdal, K. H., Ootoowak, A. J., Wiggins, S. M., & Hildebrand, J. A. (2023). Impact of ship noise on the underwater soundscape of Eclipse Sound in the northeastern Canadian Arctic. *Marine Pollution Bulletin*, 195, 115534. <https://doi.org/10.1016/j.marpolbul.2023.115534>
- Konrad, C. M., Frasier, T. R., Whitehead, H., & Gero, S. (2019). Kin selection and allocare in sperm whales. *Behavioral Ecology*, 30(1), 194–201. <https://doi.org/10.1093/beheco/ary143>
- Kutsukake, N. (2009). Complexity, dynamics and diversity of sociality in group-living mammals. *Ecological Research*, 24(3), 521–531. <https://doi.org/10.1007/s11284-008-0563-4>
- La Manna, G., Ronchetti, F., Perretti, F., & Ceccherelli, G. (2023). Determinants of group size in the common bottlenose dolphins: The role of water temperature and noise. *Behavioral Ecology and Sociobiology*, 77(4), 45. <https://doi.org/10.1007/s00265-023-03322-w>
- Lacy, R. C. (2019). Lessons from 30 years of population viability analysis of wildlife populations. *Zoo Biology*, 38(1), 67–77. <https://doi.org/10.1002/zoo.21468>
- Laidre, K., Heide-Jørgensen, M. P., Stern, H., & Richard, P. (2012). Unusual narwhal sea ice entrapments and delayed autumn freeze-up trends. *Polar Biology*, 35(1), 149–154. <https://doi.org/10.1007/s00300-011-1036-8>
- Laidre, K. L., & Heide-Jørgensen, M. P. (2005). Winter Feeding Intensity of Narwhals (monodon Monoceros). *Marine Mammal Science*, 21(1), 45–57. <https://doi.org/10.1111/j.1748-7692.2005.tb01207.x>
- Laidre, K. L., Heide-Jørgensen, M. P., Ermold, W., & Steele, M. (2010). Narwhals document continued warming of southern Baffin Bay. *Journal of Geophysical Research: Oceans*, 115(C10). <https://doi.org/10.1029/2009JC005820>

- Laidre, K. L., Heide-Jørgensen, M. P., Logdson, M. L., Hobbs, R. C., Heagerty, P., Dietz, R., Jørgensen, O. A., & Treble, M. A. (2004). Seasonal narwhal habitat associations in the high Arctic. *Marine Biology*, 145(4), 821–831. <https://doi.org/10.1007/s00227-004-1371-1>
- Laidre, K. L., Heide-Jørgensen, M. P., & Orr, J. R. (2006). Reactions of Narwhals, to Killer Whale, Attacks in the Eastern Canadian Arctic. *The Canadian Field-Naturalist*, 120(4), 457–465. <https://doi.org/10.22621/cfn.v120i4.355>
- Laidre, K. L., Stern, H., Kovacs, K. M., Lowry, L., Moore, S. E., Regehr, E. V., Ferguson, S. H., Wiig, Ø., Boveng, P., Angliss, R. P., Born, E. W., Litovka, D., Quakenbush, L., Lydersen, C., Vongraven, D., & Ugarte, F. (2015). Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. *Conservation Biology*, 29(3), 724–737. <https://doi.org/10.1111/cobi.12474>
- Lefort, K. J., Garroway, C. J., & Ferguson, S. H. (2020). Killer whale abundance and predicted narwhal consumption in the Canadian Arctic. *Global Change Biology*, 26(8), 4276–4283. <https://doi.org/10.1111/gcb.15152>
- Louis, M., Skovrind, M., Samaniego Castruita, J. A., Garilao, C., Kaschner, K., Gopalakrishnan, S., Haile, J. S., Lydersen, C., Kovacs, K. M., Garde, E., Heide-Jørgensen, M. P., Postma, L., Ferguson, S. H., Willerslev, E., & Lorenzen, E. D. (2020). Influence of past climate change on phylogeography and demographic history of narwhals, *Monodon monoceros*. *Proceedings of the Royal Society B: Biological Sciences*, 287(1925), 20192964. <https://doi.org/10.1098/rspb.2019.2964>
- Mann, J. (2000). *Cetacean Societies: Field Studies of Dolphins and Whales*. University of Chicago Press.

- Mann, J. (2019). Maternal Care and Offspring Development in Odontocetes. In B. Würsig (Ed.), *Ethology and Behavioral Ecology of Odontocetes* (pp. 95–116). Springer International Publishing. [https://doi.org/10.1007/978-3-030-16663-2\\_5](https://doi.org/10.1007/978-3-030-16663-2_5)
- Marcoux, M., Auger-Méthé, M., & Humphries, M. M. (2009). Encounter frequencies and grouping patterns of narwhals in Koluktoo Bay, Baffin Island. *Polar Biology*, 32(12), 1705–1716. <https://doi.org/10.1007/s00300-009-0670-x>
- Martin, M. J., Halliday, W. D., Storrie, L., Citta, J. J., Dawson, J., Hussey, N. E., Juanes, F., Loseto, L. L., MacPhee, S. A., Moore, L., Nicoll, A., O’Corry-Crowe, G., & Insley, S. J. (2023). Exposure and behavioral responses of tagged beluga whales (*Delphinapterus leucas*) to ships in the Pacific Arctic. *Marine Mammal Science*, 39(2), 387–421. <https://doi.org/10.1111/mms.12978>
- Mayette, A., Shuert, C. R., Hussey, N. E., & Marcoux, M. (2024). Proximity analysis between icebreakers and narwhals in Tasiujaq, Nunavut, Canada. *The Journal of Wildlife Management*, 88(8), e22655. <https://doi.org/10.1002/jwmg.22655>
- Morrison, C. A., Butler, S. J., Clark, J. A., Arizaga, J., Baltà, O., Cepák, J., Nebot, A. L., Piha, M., Thorup, K., Wenninger, T., Robinson, R. A., & Gill, J. A. (2022). Demographic variation in space and time: Implications for conservation targeting. *Royal Society Open Science*, 9(3), 211671. <https://doi.org/10.1098/rsos.211671>
- Myers, J. H. (2018). Population cycles: Generalities, exceptions and remaining mysteries. *Proceedings of the Royal Society B: Biological Sciences*, 285(1875), 20172841. <https://doi.org/10.1098/rspb.2017.2841>
- Noren, S. R., & Suydam, R. (2016). Navigating under sea ice promotes rapid maturation of diving physiology and performance in beluga whales. *Journal of Experimental Biology*, 219(18), 2828–2836. <https://doi.org/10.1242/jeb.143644>

- Nweeia, M. T. (2024). Biology and Cultural Importance of the Narwhal. *Annual Review of Animal Biosciences*, 12(Volume 12, 2024), 187–208. <https://doi.org/10.1146/annurev-animal-021122-112307>
- Pack, A. A., Herman, L. M., Craig, A. S., Spitz, S. S., Waterman, J. O., Herman, E. Y. K., Deakos, M. H., Hakala, S., & Lowe, C. (2017). Habitat preferences by individual humpback whale mothers in the Hawaiian breeding grounds vary with the age and size of their calves. *Animal Behaviour*, 133, 131–144. <https://doi.org/10.1016/j.anbehav.2017.09.012>
- Petersen, S. D., Tencula, D., & Ferguson, S. H. (2011). *Population Genetic Structure of Narwhal (Monodon monoceros)*. DFO Can. Sci. Advis. Sec. Res. Doc.
- Phillips, C. D., Gelatt, T. S., Patton, J. C., & Bickham, J. W. (2011). Phylogeography of Steller sea lions: Relationships among climate change, effective population size, and genetic diversity. *Journal of Mammalogy*, 92(5), 1091–1104. <https://doi.org/10.1644/10-MAMM-A-305.1>
- QGIS (software) QGIS. (2024). *QGIS geographic information system (Version 3.40)* [Computer software]. QGIS Association. <https://www.qgis.org>
- Rankins, S. T., Stephenson, T. R., & Monteith, K. L. (2024). Sociality modulates nutritional carrying capacity of an endangered species. *Frontiers in Ecology and Evolution*, 12. <https://doi.org/10.3389/fevo.2024.1417970>
- Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, 3(1), 1–10. <https://doi.org/10.1038/s43247-022-00498-3>
- R Core Team (2025). *\_R: A Language and Environment for Statistical Computing\_*. R Foundation for Statistical Computing,

Vienna, Austria. <<https://www.R-project.org/>>.

Richard, P. R., Laake, J. L., Hobbs, R. C., Heide-Jørgensen, M. P., Asselin, N. C., & Cleator, H. (2010).

Baffin Bay Narwhal Population Distribution and Numbers: Aerial Surveys in the Canadian High Arctic, 2002-04. *Arctic*, 63(1), 85–99.

Richard, P. R., & Pike, D. G. (1993). Small Whale Co-Management in the Eastern Canadian Arctic: A Case History and Analysis. *Arctic*, 46(2), 138–143.

Ripley, B., Venables, B., Bates, D. M., ca 1998), K. H. (partial port, ca 1998), A. G. (partial port, & polr), D. F. (support functions for. (2025). *MASS: Support Functions and Datasets for Venables and Ripley's MASS (Version 7.3-65)* [Computer software]. <https://cran.r-project.org/web/packages/MASS/index.html>

Sakai, M., Morisaka, T., Iwasaki, M., Yoshida, Y., Wakabayashi, I., Seko, A., Kasamatsu, M., & Kohshima, S. (2013). Mother–calf interactions and social behavior development in Commerson's dolphins (*Cephalorhynchus commersonii*). *Journal of Ethology*, 31(3), 305–313. <https://doi.org/10.1007/s10164-013-0380-2>

Singh, R. K., Maheshwari, M., Oza, S. R., & Kumar, R. (2013). Long-term variability in Arctic sea surface temperatures. *Polar Science*, 7(3), 233–240. <https://doi.org/10.1016/j.polar.2013.10.003>

Sheppard, C. E., Inger, R., McDonald, R. A., Barker, S., Jackson, A. L., Thompson, F. J., Vitikainen, E. I. K., Cant, M. A., & Marshall, H. H. (2018). Intragroup competition predicts individual foraging specialisation in a group-living mammal. *Ecology Letters*, 21(5), 665–673. <https://doi.org/10.1111/ele.12933>

Shuert, C. R., Marcoux, M., Hussey, N. E., Heide-Jørgensen, M. P., Dietz, R., & Auger-Méthé, M. (2022). Decadal migration phenology of a long-lived Arctic icon keeps pace with climate

change. *Proceedings of the National Academy of Sciences*, 119(45), e2121092119.

<https://doi.org/10.1073/pnas.2121092119>

Smith, H., Frère, C., Kobryn, H., & Bejder, L. (2016). Dolphin sociality, distribution and calving as important behavioural patterns informing management. *Animal Conservation*, 19(5), 462–471.

<https://doi.org/10.1111/acv.12263>

Symons, J., Sprogis, K. R., & Bejder, L. (2018). Implications of survey effort on estimating demographic parameters of a long-lived marine top predator. *Ecology and Evolution*, 8(21),

10470–10481. <https://doi.org/10.1002/ece3.4512>

Taylor, B. L., Martinez, M., Gerrodette, T., Barlow, J., & Hrovat, Y. N. (2007). Lessons from Monitoring Trends in Abundance of Marine Mammals. *Marine Mammal Science*, 23(1), 157–

175. <https://doi.org/10.1111/j.1748-7692.2006.00092.x>

Taylor, M., Carley, J. S., & Bunnell, F. L. (1987). Correct and Incorrect Use of Recruitment Rates for Marine Mammals. *Marine Mammal Science*, 3(2), 171–178. [https://doi.org/10.1111/j.1748-](https://doi.org/10.1111/j.1748-7692.1987.tb00159.x)

[7692.1987.tb00159.x](https://doi.org/10.1111/j.1748-7692.1987.tb00159.x)

Tervo, O. M., Blackwell, S. B., Ditlevsen, S., Conrad, A. S., Samson, A. L., Garde, E., Hansen, R. G., & Mads Peter, H.-J. (2021). Narwhals react to ship noise and airgun pulses embedded in

background noise. *Biology Letters*, 17(11), 20210220. <https://doi.org/10.1098/rsbl.2021.0220>

Tervo, O. M., Blackwell, S. B., Ditlevsen, S., Garde, E., Hansen, R. G., Samson, A. L., Conrad, A. S., & Heide-Jørgensen, M. P. (2023). Stuck in a corner: Anthropogenic noise threatens narwhals in

their once pristine Arctic habitat. *Science Advances*, 9(30), eade0440.

<https://doi.org/10.1126/sciadv.ade0440>

- Tyshko, A. A., Krinitskiy, M. A., Shatravin, A. V., & Belikov, R. A. (2023). Automatic Detection of Acoustic Signals of Beluga Whales and Bottlenose Dolphins. *Moscow University Physics Bulletin*, 78(1), S217–S225. <https://doi.org/10.3103/S0027134923070305>
- Visser, F., Curé, C., Kvadsheim, P. H., Lam, F.-P. A., Tyack, P. L., & Miller, P. J. O. (2016). Disturbance-specific social responses in long-finned pilot whales, *Globicephala melas*. *Scientific Reports*, 6(1), 28641. <https://doi.org/10.1038/srep28641>
- Walmsley, S. F., Rendell, L., Hussey, N. E., & Marcoux, M. (2020). Vocal sequences in narwhals (*Monodon monoceros*)a). *The Journal of the Acoustical Society of America*, 147(2), 1078–1091. <https://doi.org/10.1121/10.0000671>
- Watt, C. A., & Ferguson, S. H. (2015). Fatty acids and stable isotopes ( $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ ) reveal temporal changes in narwhal (*Monodon monoceros*) diet linked to migration patterns. *Marine Mammal Science*, 31(1), 21–44. <https://doi.org/10.1111/mms.12131>
- Watt, C. A., Heide-Jørgensen, M. P., & Ferguson, S. H. (2013). How adaptable are narwhal? A comparison of foraging patterns among the world's three narwhal populations. *Ecosphere*, 4(6), art71. <https://doi.org/10.1890/ES13-00137.1>
- Westdal, K. H., Davies, J., & Ferguson, S. H. (2022). Assessing seasonal spatial segregation by age class of beluga whales (*Delphinapterus leucas*) in Western Hudson Bay estuaries. *PLOS ONE*, 17(11), e0255756. <https://doi.org/10.1371/journal.pone.0255756>
- Westdal, K. H., Davies, J., McPherson, A., Orr, J., & Ferguson, S. H. (2016). Behavioural Changes in Belugas (*Delphinapterus leucas*) During a Killer Whale (*Orcinus orca*) Attack in Southwest Hudson Bay. *The Canadian Field-Naturalist*, 130(4), 315–319. <https://doi.org/10.22621/cfn.v130i4.1925>

- Williams, T. M., Blackwell, S. B., Richter, B., Sinding, M.-H. S., & Heide-Jørgensen, M. P. (2017). Paradoxical escape responses by narwhals (*Monodon monoceros*). *Science*, 358(6368), 1328–1331. <https://doi.org/10.1126/science.aao2740>
- Williams, T. M., Blackwell, S. B., Tervo, O., Garde, E., Sinding, M.-H. S., Richter, B., & Heide-Jørgensen, M. P. (2022). Physiological responses of narwhals to anthropogenic noise: A case study with seismic airguns and vessel traffic in the Arctic. *Functional Ecology*, 36(9), 2251–2266. <https://doi.org/10.1111/1365-2435.14119>
- Zhao, S.-T., Matthews, C. J. D., Davoren, G. K., Ferguson, S. H., & Watt, C. A. (2021). Ontogenetic profiles of dentine isotopes ( $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ ) reveal variable narwhal *Monodon monoceros* nursing duration. *Marine Ecology Progress Series*, 668, 163–175.

## Chapter 3: Investigating Summer Habitat Use by Group Type in Baffin Bay Narwhals

### Abstract

Understanding how group composition influences habitat use is essential for interpreting the ecological and social dynamics of Arctic marine mammals. Narwhals (*Monodon monoceros*) exhibit complex social structure and strong site fidelity, yet little is known about whether spatial segregation in summer habitat use exists based on group composition. We used aerial survey data collected in 2023 to identify and age narwhals and to delineate social groups across the Baffin Bay narwhal population. Groups were classified as individual adults, adult-only groups, or groups containing at least one newborn. Habitat use was characterized using environmental variables including bathymetry, distance to shore, and sea surface temperature (SST), and differences among group types were evaluated using Bayesian multinomial mixed-effects models. In total, 1,242 groups were analyzed. Group types showed substantial overlap in summer habitat use, with no evidence of strong niche segregation. However, fine-scale differences were evident. Groups containing newborns were most likely to occur in shallow, nearshore habitats, adult groups occupied similar but slightly deeper environments, and individual narwhals were more frequently observed farther offshore and in deeper waters. Distance to shore and depth were significant predictors of group type, whereas SST was not, indicating no thermal advantage for newborn groups during summer. These findings suggest that narwhal summer habitat use is shaped primarily by social behaviour, predation risk, and physiological constraints rather than by distinct environmental niches among group types. Nearshore habitats likely support risk-sensitive behaviour and social cohesion, while solitary individuals may exploit deeper offshore

areas with fewer social constraints. This study highlights the importance of incorporating group composition into habitat-use analyses to better understand narwhal ecology.

### 3.1.0 Introduction

Animals often live in groups to gain a variety of benefits, including vigilance, improved access to resources, enhanced communication, and social interactions such as cooperative care of young (Alexander, 1974; Baird & Dill, 1996; Gowans, 2019; Kutsukake, 2009). However, group living also entails costs, including increased predation risk, parasite and disease transmission, and heightened competition for resources; consequently, the benefits of group living must outweigh these costs (Alexander, 1974; Gowans, 2019). The composition of individuals within groups can influence both group needs and how groups function to meet them. Within a population, the emergence of distinct group types structured by traits such as sex, age, or kinship is referred to as social segregation (Ward & Webster, 2019). Group composition may also drive differences in habitat use due to varying ecological or physiological requirements, a pattern known as spatial (habitat) segregation (Conradt, 2005; Fury et al., 2013).

Habitat use in cetaceans often reflects the differing energetic, social, and predation-related needs of distinct demographic groups. In marine environments, the needs of certain groups may drive them to occupy shallow and protected areas. Mother–calf pairs of southern right whales (*Eubalaena australis*) for instance, are frequently observed in shallow habitats, which may reduce predation risk from killer whales and facilitate calf care (Nielsen et al., 2019; Rayment et al., 2015; Zeh et al., 2022). Pack et al., (2017), found that newborn humpback whale calf size (length) correlated positively with depth, as mothers brought calves into deeper water as they aged.

These patterns can be explained by multiple, overlapping hypotheses. The predation risk hypothesis predicts selection for areas that reduce vulnerability (Lima & Dill, 1990), especially for vulnerable individuals (Fontaine & Martin, 2006). The activity budget hypothesis underlies spatial segregation, proposing that individuals with different demographic classes (e.g. sexes, age classes, mother-calf pairs) differ in energetic demands and thus often habitat (Ruckstuhl & Neuhaus, 2005). For example, shallow, sheltered waters allow mother–calf pairs to engage in low-energy activities such as resting and nursing without the need to travel long distances (Pack et al., 2017). In some cetaceans, such as humpback whales (*Megaptera novaeangliae*), sex-segregated migration patterns suggest that certain individuals may remain on high-latitude feeding grounds while others undertake energetically costly migrations (Brown et al., 1995). Social cohesion may also play a role, as group members often move together and select habitats based on learned associations or leadership within the group (Webber et al., 2024; Wiszniewski et al., 2009). Sexual segregation occurs when males and females use different habitats often linked to, different energetic requirements or foraging strategies (Breed et al., 2006; Salton et al., 2019), and often, sexual dimorphism can lead to niche specialization within a species (Orgeret et al., 2021). Together, these hypotheses illustrate how multiple ecological, social, and physiological factors interact to shape the fine-scale habitat use and spatial segregation in animals.

Habitat use is also shaped by thermal conditions. Differences in sea surface temperature (SST) can favour certain life stages or group types through effects on energetics, thermoregulation, and prey availability. For example, calves and reproductive females may select warmer (Scharffenberg et al., 2019), often shallower waters (Cartwright et al., 2012) to reduce energetic costs, whereas adults may tolerate cooler, deeper habitats (Heide-Jørgensen et al.,

2020) when foraging. SST has been shown to predict large-scale movements in Arctic marine mammals, with shifts in distribution aligned with thermal gradients (Chambault et al., 2018), indicating that temperature can be a strong driver of habitat use. Similarly, humpback whales often select warm waters for calf development, as it may increase adult size and reproductive success (Rasmussen et al., 2007). Evidence from odontocetes further supports this pattern, as immature Dall's porpoises (*Phocoenoides dalli*) occur more frequently in warmer waters, consistent with the use of warm habitats to reduce energetic constraints during early life stages (Kanaji et al., 2024). Observations of young northern fur seals (*Callorhinus ursinus*) also indicate that cooler water increases thermoregulatory costs for pups, reinforcing the link between juvenile habitat use and ambient temperature (Liwanag, 2010). In contrast, cold water and depth has been linked to foraging activity for adult narwhal (Heide-Jørgensen et al., 2020). Thermal constraints also differ by age, as juvenile California sea lions (*Zalophus californianus*) experience higher energetic costs in cold water due to their smaller body size, which can limit their foraging range relative to adults (Liwanag et al., 2009). While juveniles may be found in shallower waters to reduce energetic and thermoregulatory costs, adults may exploit colder, deeper habitats when prey rewards compensate for higher energetic costs.

Narwhals are medium-sized toothed whales that live exclusively in the Arctic. For Inuit communities, narwhals provide food, economic resources, and hold profound cultural significance (Hoover et al., 2013; Lee, 2005). There are two distinct narwhal sub-populations in Canada: including the Northern Hudson Bay population and the Baffin Bay population (COSEWIC, 2024). COSEWIC classifies narwhals in Baffin Bay and Hudson Bay as sub-populations due to strong site fidelity and distinct seasonal movements that limit interchange between regions, despite the absence of complete genetic separation (COSEWIC, 2024).

Narwhals in Baffin Bay migrate seasonally from deep, ice-dense offshore wintering areas in Baffin Bay and Davis Strait to the shallower inlets and fjords of Baffin Island (Heide-Jørgensen et al., 2003). The Baffin Bay population is managed in defined stocks based on distinct summering locations (Doniol-Valcroze et al., 2020), which they return to each year with high site fidelity (COSEWIC, 2024).

Little is known about the extent of spatial or sexual segregation in narwhals, or how habitat use varies with group composition. Groups containing calves are predominantly composed of mother-calf pairs (Charry et al., 2019; *O'Doherty, Chapter 2*) suggesting some degree of social segregation. Group composition often reflects mixed sex and age classes; however, smaller clusters have been observed to be sexually segregated, with adult tusked males often seen together, and females observed with calves and juveniles (Marcoux et al., 2009). Additionally, young and old narwhals have been observed in the same herd but preferentially associate with their own age class, suggesting fine-scale social structure within herds, but not complete segregation (Marcoux et al., 2010). Whether this social, sexual, and age structuring reflects differences in habitat use remains unclear.

Beluga whale ecology can inform predictions about narwhal ecology, as the two species are closely related, are the only members of the Monodontidae family, share similar body sizes, and are Arctic specialists (Skovrind et al., 2019). In closely related beluga whales (*Delphinapterus leucas*), spatial and habitat segregation by sex and age has been documented in Beaufort Sea belugas (Hauser et al., 2017; Loseto et al., 2006). Larger males have been seen to use offshore, ice-covered habitats and females and calves use nearshore open water (Loseto et al., 2006). Alternatively, beluga whales in estuaries did not segregate based on age class or group type (Mayette et al., 2023; Westdal et al., 2022). For more southerly distributed cetaceans, a

thermal advantage hypothesis has been proposed for calf rearing (Rasmussen et al., 2007), whereby warmer waters may reduce energetic costs for calves; however, this pattern may differ for Arctic and sub-Arctic species (Westdal et al., 2022). In the western Canadian Arctic a thermal advantage was found in estuaries for young belugas, indicating there might be geographical dependence (Scharffenberg et al., 2019). Although thermal benefits of estuarine habitats and insulation have been investigated for beluga neonates and calves (Hill & Campbell, 2014; Sergeant, 1973), comparable studies of thermal preference for narwhal calving is lacking in the literature, and needs to be explored separately.

Adult narwhals generally prefer colder waters and occupy a narrow thermal niche across both winter and summer (Heide-Jørgensen et al., 2020). This temperature preference is closely tied to their deep-diving foraging strategy, as narwhals rely on repeated deep dives to access benthic prey (Laidre et al., 2004). Bottom temperature ranges selected by narwhals on wintering grounds facilitate optimal winter foraging on Greenland halibut (*Reinhardtius hippoglossoides*), (Laidre et al., 2004; Laidre & Heide-Jørgensen, 2005), whereas summer habitat use is associated with less intensive feeding on Arctic and polar cod (*Boreogadus saida*) (Finley & Gibb, 1982; Laidre & Heide-Jørgensen, 2005). Recent Arctic sea-ice loss has allowed killer whales to overlap with narwhal summer habitat for longer periods (Lefort et al., 2020). In response to the presence of killer whales, narwhals have been observed to alter their habitat use, often remaining close to shore or fleeing areas of elevated predation risk. (Breed et al., 2017; Laidre et al., 2006), highlighting how predator dynamics are increasingly shaping habitat use; however, the magnitude of this impact is relatively unknown.

While some narwhal calving areas have been identified using Inuit knowledge (Stewart, 2001), the environmental covariates associated with these areas have not been assessed. Here, I

examine whether habitat use differ among age classes and group types (*Figure 3.1*), with a particular focus on identifying habitat/environmental variables that influence the presence of narwhal groups with newborns. I hypothesize that environmental preferences will broadly overlap across group types but will differ in the use of bathymetry, distance to shore, and sea surface temperature. Specifically, I predict that groups composed solely of adults and individual adult whales will occur farther from shore, in deeper waters, and colder waters than groups containing at least one newborn, reflecting the potential greater diving and foraging capacity of adults (Laidre et al., 2004; Laidre & Heide-Jørgensen, 2005) not engaging in social grouping, even if feeding intake is minimal in the summer months (Chambault et al., 2023; Laidre & Heide-Jørgensen, 2005).

In contrast, based on nearshore beluga calf habitat use (Loseto et al., 2006), and limited aerobic dive capacity of beluga newborns (Noren & Suydam, 2016), I predict that groups with newborns will preferentially use shallower, nearshore habitats. In addition, given the narrow cold-water thermal niche of narwhals (Heide-Jørgensen et al., 2020), there is currently no evidence that narwhals exhibit thermal preferences for warmer waters at any life history stage or season, and I therefore do not expect there to be a difference in sea surface temperature used by

group type.

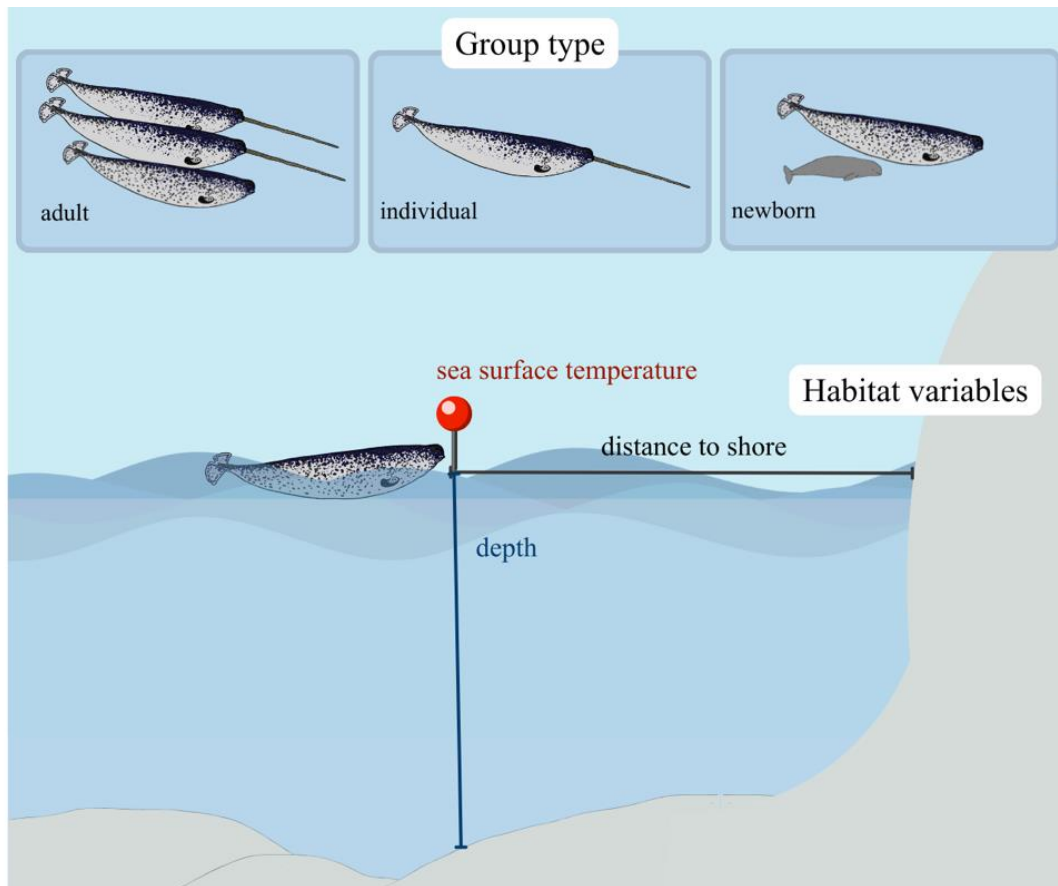


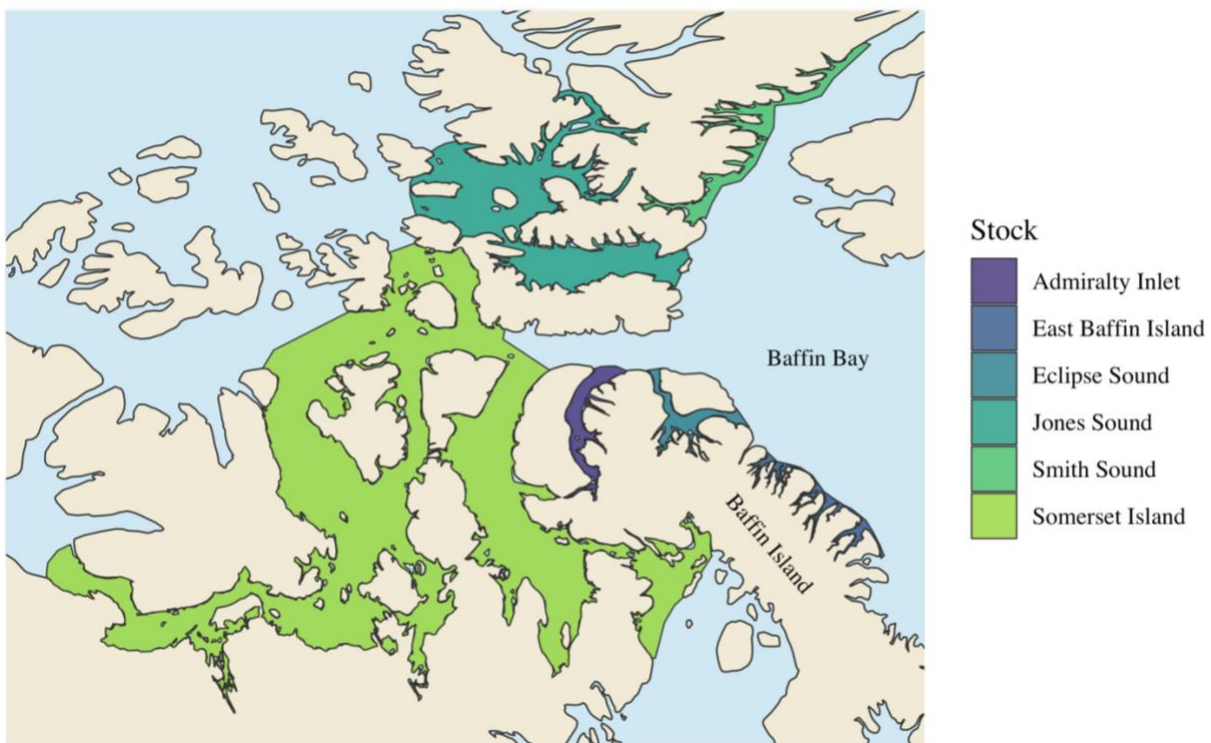
Figure 3. 1. Narwhal group types observed in the Baffin Bay population during August 2023 and the associated habitat variables used to compare habitat use among group types.

## 3.2.0 Methods

### 3.2.1 Study Area

The Baffin Bay narwhal population ranges across Baffin Bay in the northern Atlantic-Arctic transition zone, extending from eastern Canadian Arctic waters to western Greenland (Doniol-Valcroze et al., 2020). This population summers in shallower, coastal waters, fjords, and bays around Baffin Island (Figure 3.2). Marine vessel traffic is relatively high along the

Northwest Passage in the Canadian Arctic due to natural resource exports, resupply, and commercial shipping (Boylan, 2021). Narwhals that summer in the areas of Milne Inlet and Eclipse Sound experience the largest amount of shipping traffic in the whole population (Ewing et al., 2025; Halliday et al., 2022). Mining activity near Milne Inlet in the Qikiqtani region increases shipping activity in the area and remains a concern for nearby communities and narwhal in Eclipse Sound (Halliday et al., 2022).



*Figure 3. 2.* Approximate summer habitat range extent for the Baffin Bay narwhal population. Separated by stock, Admiralty Inlet, East Baffin Island, Eclipse Sound, Jones Sound, Smith Sound, and Somerset Island.

### 3.2.2 High Arctic Cetacean Survey (HACS) 2023

In August of 2023, Fisheries and Oceans Canada conducted an aerial imaging survey across the eastern Canadian Arctic to assess abundance across all 6 stocks of the Baffin Bay narwhal population. The Hunters and Trappers organizations of Mittimatalik (Pond Inlet),

Ikpiarjuk (Arctic Bay), Aujuttuq (Grise Fiord), Kangiqtugaapik (Clyde River), Qikiqtarjuaq, Pangnirtuuq (Pangnirtung), and Iqaluit were involved in the planning and consulting of the aerial survey. Survey extent was based on prior survey coverage (Doniol-Valcroze et al., 2020; Richard et al., 2010), Inuit Qaujimagatuqangit, and existing telemetry data (Dietz et al., 2001, 2008). Surveys were conducted during the summer, when narwhals have not yet migrated to their wintering grounds and sea-ice coverage is minimal, maximizing detectability (Doniol-Valcroze et al., 2020). Four twin otter planes flown at a height of 610 meters and 100 knots were used to cover bays, inlets, fiords, and open water surrounding each stock August 11 – 30. A Nikon D800 camera with 25-mm lens was installed on the ventral side of the aircrafts. Photos were taken consecutively along linear transects every seven seconds. Each photograph was georeferenced using a GPS receiver.

### 3.2.3 Automated Algorithm Detector

Aerial images were analyzed using an automated algorithm (Mobius) developed for detecting narwhals in photographs (Boulent et al., 2023). Using a deep learning approach, Mobius detects whales in aerial imagery, after which human reviewers validate and adjust the outputs to improve reliability (Boulent et al., 2023). A DFO reviewer B. Sherbo, manually reviewed 5% of the total dataset. Performance was quantified using precision, recall, and the F1-score, which are standard metrics for assessing automated cetacean detection in aerial surveys (Christin et al., 2019; Tyshko et al., 2023). Precision measures the proportion of detections identified as narwhals that were in fact narwhals, whereas recall represents the proportion of narwhals present in the imagery that were successfully detected (Boulent et al., 2023). The F1-score, defined as the harmonic mean of precision and recall, provides an integrated measure that balances false positives and false negatives.

### 3.2.4 Narwhal Identification and Aging

Following narwhal detection, a certainty scale (*O’Doherty, Chapter 2*) was used to identify clear, ageable individuals, ensuring that only narwhals for which age could be reliably determined were included in the study. Once narwhals were identified they were aged (adult, newborn) and grouped based on a distance of 3 body lengths (Charry et al., 2018; Mann, 2000; Marcoux et al., 2009) using QGIS software (QGIS Development Team, 2024). Newborn narwhals (0-3 months old) were identified based on a predetermined identification key to identify narwhal newborns (Charry et al., 2018). Newborns were classified as individuals that were less than 50% the size of the nearest adult female, situated within two body lengths, and located above, behind, below, in front of, or alongside the female (Charry et al., 2018).

### 3.2.5 Group Type

Group type was identified similar to (Mayette et al., 2023), where narwhal groups were categorized (*Figure 3.1*) as:

- a. **Individual:** single adult narwhal.
- b. **Adult:** groups of narwhals that consist only of adults.
- c. **Newborn:** groups of narwhals that contained at least one newborn.

### 3.2.6 Habitat Variables

All exploratory statistics and calculations were completed in R, version 4.4.2 (R Core Team, 2025). Bathymetric grid data used for depth were obtained from the General Bathymetric Chart of the Oceans (GEBCO) for 2023, covering the entire survey area (GEBCO, 2023). SST data were accessed from NASA’s OceanColor web using the remote sensor MODIS onboard the Aqua satellite (NASA OB.DAAC, 2024). SST level-3 mapped data were downloaded for a 14

day period during the 2023 aerial survey (August 16- August 29), with 4 km cell resolution ( $0.0417^{\circ} \times 0.0417^{\circ}$ ).

The bathymetric grid (15 arc-second resolution) was resampled to fit the same resolution of the SST data ( $0.0417^{\circ} \times 0.0417^{\circ}$ ). Distance to shore was calculated using `dist2land()` and land polygons from the GEBCO raster with the `ggOceanMaps` package (Vihtakari et al., 2024). Depth at each group location was determined from the GEBCO raster using the group's latitude and longitude. Few detections were recorded as “on land” according to the GEBCO raster, likely due to minor GPS inaccuracies or the coarser resolution of the raster, which may place nearshore points in land cells. For cells located near the shore or on land, depth values were interpolated from the four closest water cells. SST was assigned to each group location and averaged over a 14-day period to ensure that each group location had at least one value. This approach was used to address gaps in SST values. Two groups had missing values for SST and were interpolated from the four nearest cells with available temperature data, within a maximum range of 4km. As a result, each group had a depth, SST, and distance to shore value.

### 3.2.5 Statistical Modelling

To evaluate differences in habitat use among group types, we fitted four Bayesian multinomial mixed-effects models (*Table A. appendix*) using the `brms` package (Bürkner et al., 2025) in R version 4.4.2 (R Core Team, 2025). Group type (individual, adult, or newborn) was modelled as a categorical response variable with logit link function, allowing direct estimation of the probability of observing each group type across environmental gradients. SST was included in all models, while depth and distance to shore were evaluated in separate models due to their strong correlation (*Figure A. Appendix*) and distinct ecological interpretations. Including both variables simultaneously would have introduced multicollinearity. For each predictor

combination, two models were fitted: one including only main effects and a second including the interaction between predictors. All predictors were scaled to improve model convergence and facilitate comparison of effect sizes. Random intercepts for stock were included to account for spatial structuring and repeated sampling within regions. Strong influence of stock is expected due to natural changes in bathymetry in the Arctic Landscape. Model fit was assessed using posterior predictive checks and model comparison based on expected log predictive density (ELPD) derived from leave-one-out cross-validation. Convergence was evaluated using  $\hat{R}$  values and effective sample sizes.

### 3.3.0 Results

#### 3.3.1 Automated Detector Performance

A DFO reviewer (B. Sherbo) manually evaluated 5% of the dataset (every 20th image;  $n = 3,239$ ) to assess Mobius auto-detector performance. Comparison with manual classifications identified 2,916 true negatives, 65 true positives, 17 false positives, and 3 false negatives, resulting in a precision of 79.3%, recall of 95.6%, and an F1 score of 86.7%. Because precision was below 100%, all detections were subsequently manually verified for presence and species.

#### 3.3.2 Selected Models

Bayesian multinomial mixed-effects models were used to estimate the probability of observing different group types (individuals, adults, and newborns) across environmental gradients. Stock was included as a random intercept, allowing baseline probabilities of each group type (relative to a reference category) to vary among stocks. Two models were chosen, one including SST and distance to shore:  $group\ type \sim SST + distance\ to\ shore +$

(1 | *stock*), and a second including SST and depth:  $group\ type \sim SST + depth + (1 | stock)$ . Both models were fit to 1,242 observations and showed good convergence (all  $\hat{R} = 1.00$ ; effective sample sizes  $> 2,000$ ). Model performance was compared using Leave-One-Out Cross-Validation, which indicated no clear difference in predictive fit between the two models ( $\Delta ELPD = -2.7$ ,  $SE = 4.7$ ). In both models, random intercepts for stock captured moderate variation in the baseline probability of observing adult (SDs = 0.24 and 0.46) and newborn (SDs = 0.27 and 0.41) groups, supporting the inclusion of stock as a random effect to account for stock-level differences in group composition independent of environmental covariates. Residual spatial autocorrelation was assessed using Moran's I on posterior predicted probabilities from the multinomial Bayesian models. No evidence of residual spatial autocorrelation was detected for any category or model (e.g., *newborn*, Moran's I  $\approx 0$ ,  $p = 0.5$ ), indicating that spatial terms were not required in the models. Interactions between SST and distance to shore or depth did not improve predictive performance, so models with only main effects were retained.

### 3.3.3 Group Summary Stats

A total of 1,242 groups were recorded, including 607 individual, 490 adult, and 145 newborn groups (*Table 3.1*). Distance to shore ranged from 0.02 to 142.0 km across the dataset, with mean distances of 25.1 km for individual groups, 15.0 km for adult groups, and 14.9 km for newborn groups. Across all observations, depth ranged from 1 to 958 meters. Mean depths were 302 m for individual whales, 232 m for adult groups, and 209 m for newborn groups. Sea surface temperature ranged from 0.01 to 7.71 °C overall, with mean SST values of 3.64 °C for individual groups, 3.98 °C for adult groups, and 3.73 °C for newborn groups.

<b>Stock</b>	<b>Individual groups</b>	<b>Adult groups</b>	<b>Newborn groups</b>	<b>Total number of groups</b>
<i>Admiralty Inlet</i>	141	146	47	334
<i>Eclipse Sound</i>	167	186	46	400
<i>Somerset Island</i>	221	109	36	366
<i>Jones Sound</i>	63	38	10	111
<i>East Baffin Island</i>	7	9	3	19
<i>Smith Sound</i>	8	2	3	13

TABLE 3.1. Number of narwhal groups by group type (individual, adult, and newborn) across summering stocks in the Baffin Bay population. The total number of observed groups is shown for each stock.

### 3.3.4 Bayesian Mixed Effect Models

#### *Distance to shore and Sea surface temperature*

Distance to shore was a significant predictor of group type (*Figure 3.3*). Increasing distance to shore was associated with a lower probability of observing both adult groups ( $\beta = -0.38$ , 95% credible interval [CI]: -0.55, -0.22) and newborn groups ( $\beta = -0.49$ , 95% CI: -0.74, -0.24) relative to individual narwhals. This effect was strongest for newborn groups, which occurred closest to shore, followed by adult groups, with individuals found furthest offshore. Sea surface temperature had weak and uncertain effects, with 95% credible intervals overlapping zero for both adults ( $\beta = 0.11$ , 95% CI: -0.08, 0.30) and newborns ( $\beta = -0.12$ , 95% CI: -0.42, 0.13), indicating that SST was not a significant predictor of group type in this model.

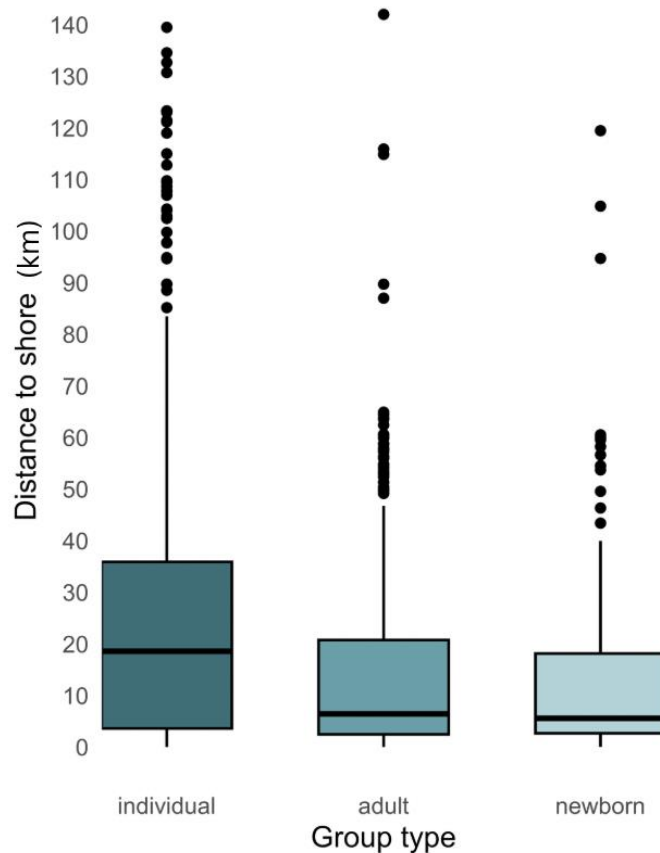
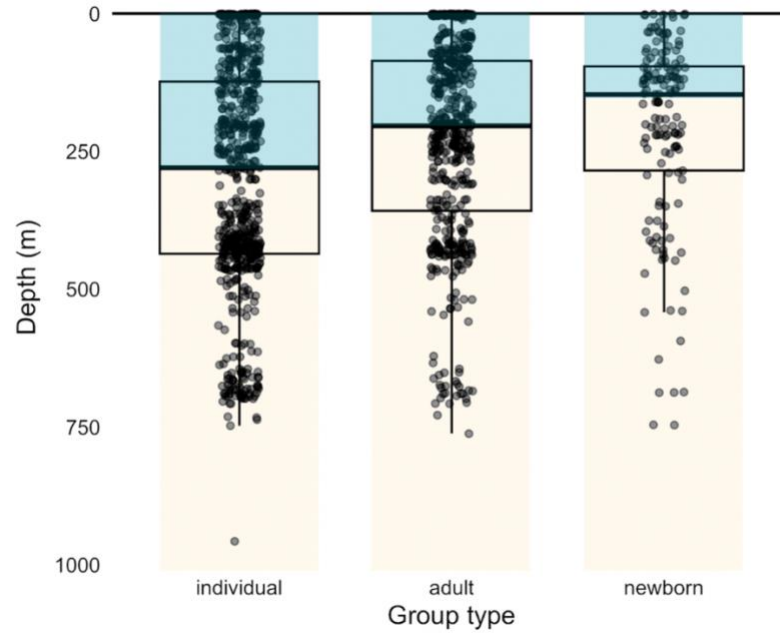


Figure 3. 3. Distribution of distances to shore for different narwhal group types in the Baffin Bay population across all stocks. Boxplots show the median, interquartile range, and variation in distances, with individual points overlaid. Distances are shown in kilometers.

### ***Depth and Sea surface temperature***

Depth was a significant predictor of narwhal group composition (*Figure 3.4*). Shallower waters (lower bathymetry values) were associated with a higher probability of observing adult groups ( $\beta = 0.28$ , 95% credible interval [CI]: 0.16–0.41) and newborn groups ( $\beta = 0.49$ , 95% CI: 0.30–0.69) relative to individual whales, with newborns occurring in the shallowest waters. Sea surface temperature had a small positive effect on the probability of observing groups of adults ( $\beta = 0.22$ , 95% CI: 0.01–0.44) compared to individual whales, whereas its effect on newborn

groups was negligible. Groups of adults are slightly more likely to be found in warmer water than individuals (*Figure 3.5*).



*Figure 3. 4.* Boxplot showing the distribution of summering narwhal group types by depth in the Baffin Bay population across all stocks. Depths are plotted with 0 m at the top of the y-axis to represent the sea surface and increasing depth downward. Blue boxes indicate shore to average depth. Individual group observations are shown as jittered points (black).

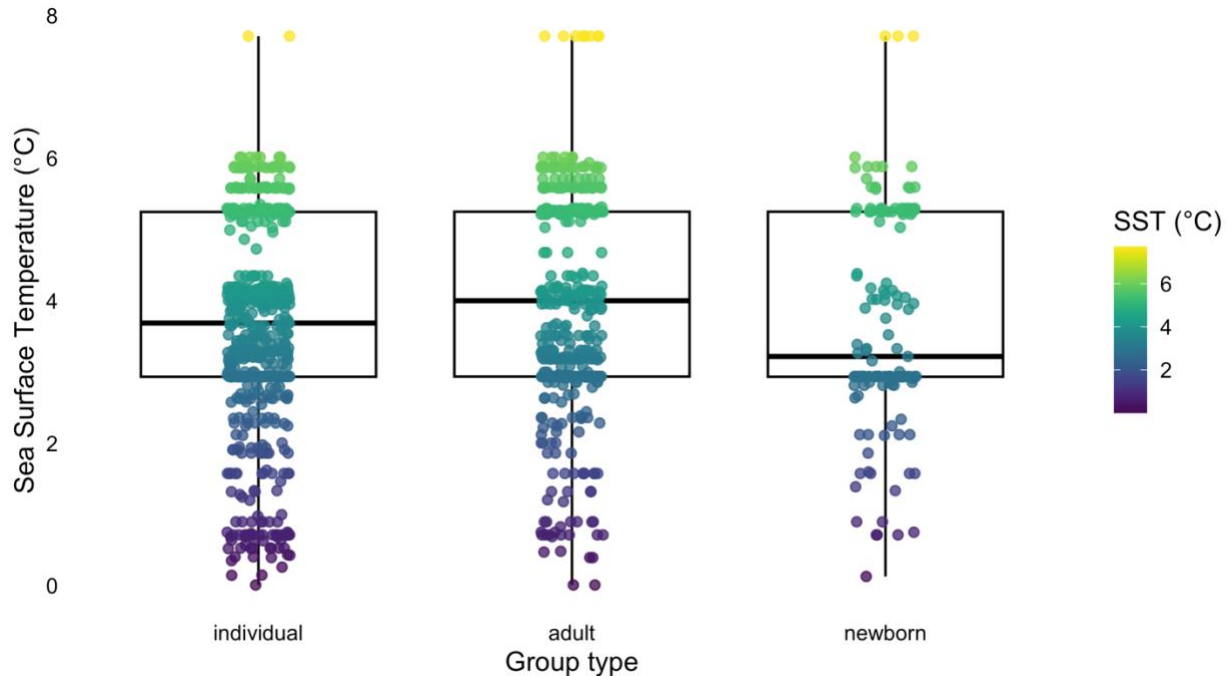


Figure 3. 5. Distribution of sea surface temperature (SST, °C) by narwhal group type during summer in the Baffin Bay population across all stocks. Individual group temperatures are demonstrated as jittered points.

### 3.4.0 Discussion

Despite broad variation in depth, distance to shore, and SSTs, narwhal group types in Baffin Bay showed extensive overlap in summer habitat use, with no evidence of distinct niche separation. All group types occupied similar ranges of depth, proximity to shore, and SST, rather than segregating into exclusive habitats. Similar patterns have been documented in other Arctic marine mammals, where summer aggregations result in substantial spatial overlap and social cohesion (Mayette et al., 2023; Westdal et al., 2022). In Western Hudson Bay estuaries, beluga calves, juveniles, and adults overlap extensively in summer habitat use, with grouping thought to be driven largely by social behaviour and cultural traditions (Westdal et al., 2022). Similarly, beluga whales in the Eastern Beaufort Sea were found not to spatially segregate based on group types of individual, newborn, and adults (Mayette et al., 2023). Habitat overlap among age and sex classes has been documented in species other than marine mammals. For example, mouflon

sheep (*Ovis gmelini*) display social segregation outside the breeding season, but males, females, and juveniles show similar habitat use in winter and summer (Cransac et al., 1998). While we found that group type influenced patterns of habitat use, all groups overlapped extensively in the range of summer habitats they occupied.

Despite fine-scale differences in depth and proximity to shore among group types, summer habitat overlap might be driven by several interacting factors. Narwhal foraging intensity is relatively low during the summer months (Laidre & Heide-Jørgensen, 2005) which may reduce the need for strong spatial segregation for groups with different energetic requirements (Ruckstuhl & Neuhaus, 2005), and may promote more sociality (Galezo et al., 2018). In addition, narwhals exhibit some sexual dimorphism in body size and tusk length, but no sexual body shape dimorphism (Vicari et al., 2022). Strong sexual size dimorphism in other species have been linked to habitat segregation through differences in energy requirements, reproductive costs, and metabolic rate (Breed et al., 2006). However, while strong sexual dimorphism can drive habitat differences, it is not the sole driver of spatial segregation. Studies have shown that modest or context-dependent spatial separation can occur in species with similar body shapes and sizes between sexes (Griffiths et al., 2014), indicating that social behaviour (Galezo et al., 2018) and foraging needs (Breed et al., 2006), may play equally important roles. Although individual narwhals were more likely to occur in deeper and more offshore waters than groups containing newborns, many individuals also used shallow, nearshore environments. Increased killer whale presence (Breed et al., 2017; Lefort et al., 2020), coupled with the tendency of narwhals to group near shore in response to a killer whale threat (Laidre et al., 2006), may promote the use of similar shallow habitats regardless of group type. Together, these factors suggest that group composition modifies some habitat use at fine spatial scales, in

average depth or proximity to shore, rather than driving large-scale division across the summer range.

Groups with newborns were found closest to shore (14.9 km), adult groups occurred at a similar average distance (15.0 km), and individual narwhals were most frequently observed farther offshore (25.1 km). Nearshore, sheltered habitat use by newborn groups is consistent with risk-sensitive habitat selection, whereby vulnerable life stages prioritize reduced predation risk over foraging opportunities. Nearshore activity in narwhals has been observed in contexts where threats are present (Laidre et al., 2006), suggesting that these areas are perceived as safer habitat. The use of sheltered nearshore areas by newborns has also been documented in other marine species, including nursery protection in blacktip reef sharks (*Carcharhinus melanopterus*; Trujillo et al., 2025) and humpback whales (*Megaptera novaeangliae*) (Cartwright et al., 2012). However, newborn groups were not exclusively restricted to nearshore habitats, with some occurring farther offshore. Similar within-species variability in calf habitat use, where some groups occupy nearshore areas while others do not, has been reported in other cetacean species (Cartwright et al., 2012), suggesting that habitat selection may be context dependent and influenced by locally varying pressures.

Adult groups occurring at a similar distance to shore as newborn groups further indicates that nearshore habitat use is not solely calf driven. The contrast between grouped whales and individuals suggests that nearshore environments may facilitate social cohesion and communication. Communication plays a key role in highly social animals, with vocal cues often serving as a means of individual or group recognition (Fernald, 2014; Shapiro, 2006). These social interactions are critical for maintaining group cohesion, facilitating learning, and supporting survival (Stanton & Mann, 2012). In narwhals, for example, mothers and calves are

thought to use distinct contact calls (Ames et al., 2021). Sheltered coastal habitats, perceived “safer” might provide a better opportunity for group sociality in terms of vocal (Ewing et al., 2025b; Marcoux et al., 2012; Zahn et al., 2021) and physical contact (Ghazal et al., 2025), which are increasingly recognized as important components of narwhal social behaviour. If a whale is solitary and offshore, it does not need to (or cannot easily) prioritize social interaction the way grouped whales can. For this whale, habitat use may reflect different behavioural priorities like movement or foraging. Overall, nearshore areas appear linked to group behaviour, but it is not clear how protection and sociality influence habitat choice.

Depth and distance to shore are highly correlated, but each can have distinct ecological implications. Groups with newborns were most likely to inhabit the shallowest waters (-209 m), which may reflect physiological limitations of diving capacity for newborn odontocetes (Noren & Suydam, 2016), and the need for prolonged mother–newborn contact during a critical period of early life (Mann, 2019). During the neonate stage (the first few days to weeks), odontocetes rely heavily on their mothers for essential survival skills, coordinated breathing, and body-to-body contact, showing very little independence (Mann, 2019; Sakai et al., 2013). Additionally, shallower waters have been used for communication crypsis between mother-calf pairs of southern right whales, to avoid detection by predators (Zeh et al., 2022). This suggests that shallower environments might change the effectiveness of communication for mother calf groups compared with deeper waters.

Adult groups were on average found in slightly deeper waters (- 232 m), suggesting that while adult whales can dive more deeply, group-mediated constraints may still limit how far the least capable member can dive. Closely related beluga whale newborns have limited aerobic diving capacity, reaching adult levels by about 14 months (Noren & Suydam, 2016). However,

even two-year-olds, have only 70 – 75% of adult capacity and are still limited by smaller body size (Noren & Suydam, 2016). In our study, any whales that did not meet the criteria for newborns (0-3 months) were classified as adults; however, some of the ‘adult’ whales may still be young individuals with limited diving ability. This is one explanation for why adult groups on average, might occupy depths intermediate between newborn groups and individual adult narwhals.

Individuals, on the other hand, were disproportionately observed in the deepest (- 302 m) offshore waters. This might reflect foraging-directed movement; deeper dives are energetically demanding (Tervo et al., 2021), and often linked to successful foraging for narwhal in the winter season (Laidre & Heide-Jørgensen, 2005). Although narwhal stomach contents indicate minimal feeding in summer (Finley & Gibb, 1982; Laidre & Heide-Jørgensen, 2005), they continue to make presumed foraging dives and buzzes, with only 8–14 % of dives resulting in successful prey capture (Chambault et al., 2023). Overall daily food intake remains very low, suggesting that in the summer, narwhals continue to dive and attempt to forage but with low success (Chambault et al., 2023). Whales that inhabit deeper waters can make deep dives. Solitary whales are not constrained by group members, allowing larger adults to exploit deeper water resources even if the costs involve moving away from protective nearshore areas. Narwhals exhibit some sexual dimorphism (Vicari et al., 2022), and larger animals have greater dive capacity (Noren & Williams, 2000), therefore males might be more capable of feeding on benthic organisms at the sea floor (Watt et al., 2013). In Baffin Bay, males have been observed to feed on more shrimp (*benthic*), and spend more time foraging in benthic food webs, while females feed on cod (*benthic & pelagic*), and use both benthic and pelagic habitats (Watt et al., 2013). This suggests that some of the solitary individuals observed in deeper waters may be

males targeting benthic prey, or adult females exploiting deeper habitats, though sex was not determined in our study. However, deep waters were not exclusive to individuals, both adults and some groups with newborns were found in deep water. While individual whales were more likely to be found in deeper environments, our data is collected at the surface, so we are unable to tell if whales are inhabiting, utilizing (foraging), or transiting through areas where they are found.

Sea surface temperature (SST) was not a strong predictor of group type across the temperature range observed in our survey (0.01 to 7.71 °C). During summer 2023, narwhals in Baffin Bay were observed at SSTs ranging from 0.01 to 7.71 °C, which is warmer than the -2 to 4 °C previously recorded for narwhals in the Canadian Arctic Archipelago (Chambault et al., 2020). Studies of narwhal thermal habitat preferences in Greenland indicate that they select a very narrow temperature range, generally avoiding waters warmer than 2 °C (Heide-Jørgensen et al., 2020). However, the average sea surface temperature for each group type, in terms of habitat use, was above 3 °C in our study (range: 3.64 – 3.98 °C). Consistent warming due to climate change may have reduced the ability to detect temperature-based habitat selection or force narwhals into suboptimal thermal areas. Although thick blubber protects narwhals from hypothermia, it also limits their ability to shed excess heat, making bursts of activity or elevated locomotion a risk for overheating (Chambault et al., 2020). Warmer sea surface temperatures have been linked to lower narwhal abundance (Chambault et al., 2020), raising concern given our findings and the projected warming of Arctic waters (Wijngaard et al., 2025).

We found no thermal advantage in SST use for groups with newborns. Thermal advantages associated with calf rearing in other marine mammals are unlikely to apply to narwhal newborns, as the only temperature selection information available is for adult narwhals,

which consistently prefer cold waters year-round and occupy a strictly Arctic range (Heide-Jørgensen et al., 2020b). No studies have specifically examined temperature preferences of narwhal newborns or calves. Narwhal and beluga calves are similarly and well insulated at birth, yet only belugas are known to live in warmer waters seasonally (Smith & Canada, 1990). This similarity suggests that while narwhal newborns may not select warmer waters they may tolerate warmer conditions, offering some reassurance that their insulation could help them cope as Arctic waters warm in the future.

### 3.5.0 Conclusion

This study demonstrates that narwhal group types in Baffin Bay exhibit extensive overlap in summer habitat use, with no evidence of strong niche partitioning based on depth, distance to shore, or sea surface temperature. While group composition influenced habitat use at fine spatial scales, particularly with newborn groups occurring in shallower, nearshore environments and solitary individuals more frequently observed offshore, these differences did not translate into large-scale spatial segregation across the summer range. Instead, summer habitat use appears shaped by a combination of social behaviour (Stanton & Mann, 2012), predation risk (Laidre et al., 2006), physiological constraints (Noren & Suydam, 2016), and low seasonal foraging intensity (Finley & Gibb, 1982; Laidre & Heide-Jørgensen, 2005), rather than by distinct ecological requirements among group types. Nearshore habitats likely serve multiple functions, supporting risk-sensitive behaviour for vulnerable life stages (Mann, 2019; Sakai et al., 2013), while also facilitating social cohesion and communication for mothers and newborns (Zeh et al., 2022), and in grouped narwhals (Fernald, 2014; Shapiro, 2006). In contrast, solitary individuals may exploit deeper offshore habitats due to fewer social constraints and greater diving capacity (Noren & Williams, 2000), though these areas were not used exclusively by individuals. Sea

surface temperature was not a strong predictor of group type, suggesting limited thermal differentiation due to cold water preference (Heide-Jørgensen et al., 2020). Collectively, these findings indicate that Baffin Bay narwhal summer habitat use is flexible, with some fine scale specialization, and likely mediated by different environmental, biological, and social drivers.

### 3.6.0 References

- Ames, A. E., Blackwell, S. B., Tervo, O. M., & Heide-Jørgensen, M. P. (2021). Evidence of stereotyped contact call use in narwhal (*Monodon monoceros*) mother-calf communication. *PLOS ONE*, *16*(8), e0254393. <https://doi.org/10.1371/journal.pone.0254393>
- Boulent, J., Charry, B., Kennedy, M. M., Tissier, E., Fan, R., Marcoux, M., Watt, C. A., & Gagné-Turcotte, A. (2023). Scaling whale monitoring using deep learning: A human-in-the-loop solution for analyzing aerial datasets. *Frontiers in Marine Science*, *10*. <https://doi.org/10.3389/fmars.2023.1099479>
- Boylan, B. M. (2021). Increased maritime traffic in the Arctic: Implications for governance of Arctic sea routes. *Marine Policy*, *131*, 104566. <https://doi.org/10.1016/j.marpol.2021.104566>
- Breed, G. A., Bowen, W. D., McMillan, J. I., & Leonard, M. L. (2006). Sexual segregation of seasonal foraging habitats in a non-migratory marine mammal. *Proceedings of the Royal Society B: Biological Sciences*, *273*(1599), 2319–2326. <https://doi.org/10.1098/rspb.2006.3581>
- Breed, G. A., Matthews, C. J. D., Marcoux, M., Higdon, J. W., LeBlanc, B., Petersen, S. D., Orr, J., Reinhart, N. R., & Ferguson, S. H. (2017). Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales. *Proceedings of the National Academy of Sciences*, *114*(10), 2628–2633. <https://doi.org/10.1073/pnas.1611707114>
- Cartwright, R., Gillespie, B., LaBonte, K., Mangold, T., Venema, A., Eden, K., & Sullivan, M. (2012). Between a Rock and a Hard Place: Habitat Selection in Female-Calf Humpback Whale (*Megaptera novaeangliae*) Pairs on the Hawaiian Breeding Grounds. *PLOS ONE*, *7*(5), e38004. <https://doi.org/10.1371/journal.pone.0038004>

- Chambault, P., Albertsen, C. M., Patterson, T. A., Hansen, R. G., Tervo, O., Laidre, K. L., & Heide-Jørgensen, M. P. (2018). Sea surface temperature predicts the movements of an Arctic cetacean: The bowhead whale. *Scientific Reports*, *8*(1), 9658. <https://doi.org/10.1038/s41598-018-27966-1>
- Chambault, P., Blackwell, S. B., & Heide-Jørgensen, M. P. (2023). Extremely low seasonal prey capture efficiency in a deep-diving whale, the narwhal. *Biology Letters*, *19*(2), 20220423. <https://doi.org/10.1098/rsbl.2022.0423>
- Chambault, P., Tervo, O. M., Garde, E., Hansen, R. G., Blackwell, S. B., Williams, T. M., Dietz, R., Albertsen, C. M., Laidre, K. L., Nielsen, N. H., Richard, P., Sinding, M. H. S., Schmidt, H. C., & Heide-Jørgensen, M. P. (2020). The impact of rising sea temperatures on an Arctic top predator, the narwhal. *Scientific Reports*, *10*(1), 18678. <https://doi.org/10.1038/s41598-020-75658-6>
- Charry, B., Marcoux, M., & Humphries, M. M. (2018). Aerial photographic identification of narwhal (*Monodon monoceros*) newborns and their spatial proximity to the nearest adult female. *Arctic Science*, *4*(4), 513–524. <https://doi.org/10.1139/as-2017-0051>
- Christin, S., Hervet, É., & Lecomte, N. (2019). Applications for deep learning in ecology. *Methods in Ecology and Evolution*, *10*(10), 1632–1644. <https://doi.org/10.1111/2041-210X.13256>
- COSEWIC. (2024). *COSEWIC assessment and status report on the narwhal (Monodon monoceros) in Canada* [Status report]. Government of Canada. <https://species-registry.canada.ca>
- Cransac, N., Gerard, J.-F., Maublanc, M.-L., & Pépin, D. (1998). An example of segregation between age and sex classes only weakly related to habitat use in mouflon sheep (*Ovis gmelini*). *Journal of Zoology*, *244*(3), 371–378. <https://doi.org/10.1111/j.1469-7998.1998.tb00042.x>
- Dietz, R., Heide-Jørgensen, M. P., Richard, P., Orr, J., Laidre, K., & Schmidt, H. C. (2008). Movements of narwhals (*Monodon monoceros*) from Admiralty Inlet monitored by satellite telemetry. *Polar Biology*, *31*(11), 1295–1306. <https://doi.org/10.1007/s00300-008-0466-4>

- Dietz, R., Heide-Jørgensen, M. P., Richard, P. R., & Acquarone, M. (2001). Summer and Fall Movements of Narwhals (*Monodon monoceros*) from Northeastern Baffin Island Towards Northern Davis Strait. *Arctic*, *54*(3), 244–261.
- Doniol-Valcroze, T., Gosselin, J.-F., Pike, D., Lawson, J., Asselin, N., Hedges, K., & Ferguson, S. (2020). Narwhal Abundance in the Eastern Canadian High Arctic in 2013. *NAMMCO Scientific Publications*, *11*. <https://doi.org/10.7557/3.5100>
- Ewing, J. P., Hidalgo-Pla, E., Solsona-Berga, A., Frasier, K. E., Ootoowak, A. J., Westdal, K. H., Wiggins, S. M., Hildebrand, J. A., & Jones, J. M. (2025b). Narwhal acoustic presence in Eclipse Sound, Nunavut: Relationships with sea ice and responses to ships. *Scientific Reports*, *15*(1), 23126. <https://doi.org/10.1038/s41598-025-04032-1>
- Fernald, R. D. (2014). Communication About Social Status. *Current Opinion in Neurobiology*, *0*, 1–4. <https://doi.org/10.1016/j.conb.2014.04.004>
- Finley, K. J., & Gibb, E. J. (1982). Summer diet of the narwhal (*Monodon monoceros*) in Pond Inlet, northern Baffin Island. *Canadian Journal of Zoology*, *60*(12), 3353–3363. <https://doi.org/10.1139/z82-424>
- Fontaine, J. J., & Martin, T. E. (2006). Habitat selection responses of parents to offspring predation risk: An experimental test. *The American Naturalist*, *168*(6), 811–818. <https://doi.org/10.1086/508297>
- Galezo, A. A., Krzyszczyk, E., & Mann, J. (2018). Sexual segregation in Indo-Pacific bottlenose dolphins is driven by female avoidance of males. *Behavioral Ecology*, *29*(2), 377–386. <https://doi.org/10.1093/beheco/axx177>
- Garde, E., Heide-Jørgensen, M. P., Hansen, S. H., Nachman, G., & Forchhammer, M. C. (2007). Age-Specific Growth and Remarkable Longevity in Narwhals (*Monodon monoceros*) from West

Greenland as Estimated by Aspartic Acid Racemization. *Journal of Mammalogy*, 88(1), 49–58.  
<https://doi.org/10.1644/06-MAMM-A-056R.1>

GEBCO Compilation Group. (2023). *GEBCO 2023 grid* [Bathymetry dataset]. The Nippon Foundation-GEBCO Seabed 2030 Project.

Ghazal, M., Matthews, C. J. D., Hussey, N. E., Guay, J., & Marcoux, M. (2025). Same-sex socio-sexual interactions among male narwhal. *Behavioral Ecology and Sociobiology*, 79(12), 126.  
<https://doi.org/10.1007/s00265-025-03662-9>

Griffiths, S. W., Orpwood, J. E., Ojanguren, A. F., Armstrong, J. D., & Magurran, A. E. (2014). Sexual segregation in monomorphic minnows. *Animal Behaviour*, 88, 7–12.  
<https://doi.org/10.1016/j.anbehav.2013.11.014>

Halliday, W. D., Dawson, J., Yurkowski, D. J., Doniol-Valcroze, T., Ferguson, S. H., Gjerdrum, C., Hussey, N. E., Kochanowicz, Z., Mallory, M. L., Marcoux, M., Watt, C. A., & Wong, S. N. P. (2022). Vessel risks to marine wildlife in the Tallurutiup Imanga National Marine Conservation Area and the eastern entrance to the Northwest Passage. *Environmental Science & Policy*, 127, 181–195. <https://doi.org/10.1016/j.envsci.2021.10.026>

Hauser, D. D. W., Laidre, K. L., Stern, H. L., Moore, S. E., Suydam, R. S., & Richard, P. R. (2017). Habitat selection by two beluga whale populations in the Chukchi and Beaufort seas. *PLoS ONE*, 12(2), e0172755. <https://doi.org/10.1371/journal.pone.0172755>

Heide-Jørgensen, M. P., Blackwell, S. B., Williams, T. M., Sinding, M. H. S., Skovrind, M., Tervo, O. M., Garde, E., Hansen, R. G., Nielsen, N. H., Ngô, M. C., & Ditlevsen, S. (2020). Some like it cold: Temperature-dependent habitat selection by narwhals. *Ecology and Evolution*, 10(15), 8073–8090. <https://doi.org/10.1002/ece3.6464>

- Heide-Jørgensen, M. P., Dietz, R., Laidre, K. L., Richard, P., Orr, J., & Schmidt, H. C. (2003). The migratory behaviour of narwhals (*Monodon monoceros*). *Canadian Journal of Zoology*, *81*(8), 1298–1305. <https://doi.org/10.1139/z03-117>
- Hill, H. M., & Campbell, C. (2014). The frequency and nature of allocare by a group of belugas (*Delphinapterus leucas*) in human care. *International Journal of Comparative Psychology*, *27*(4). <https://doi.org/10.46867/ijcp.2014.27.04.08>
- Hoover, C., Bailey, M., Higdon, J., Ferguson, S. H., & Sumaila, R. (2013). Estimating the Economic Value of Narwhal and Beluga Hunts in Hudson Bay, Nunavut. *Arctic*, *66*(1), 1–16.
- Kanaji, Y., Sasaki, H., Ikuta, S., Azuma, N., & Kobayashi, M. (2024). Temperature-related movement and habitat utilization patterns of Dall’s porpoises, small cetaceans seasonally migrating into the subarctic Pacific. *Frontiers in Marine Science*, *11*. <https://doi.org/10.3389/fmars.2024.1429358>
- Laidre, K. L., & Heide-Jørgensen, M. P. (2005). Winter Feeding Intensity of Narwhals (*monodon Monoceros*). *Marine Mammal Science*, *21*(1), 45–57. <https://doi.org/10.1111/j.1748-7692.2005.tb01207.x>
- Laidre, K. L., Heide-Jørgensen, M. P., Logdson, M. L., Hobbs, R. C., Heagerty, P., Dietz, R., Jørgensen, O. A., & Treble, M. A. (2004). Seasonal narwhal habitat associations in the high Arctic. *Marine Biology*, *145*(4), 821–831. <https://doi.org/10.1007/s00227-004-1371-1>
- Laidre, K. L., Heide-Jørgensen, M. P., & Orr, J. R. (2006). Reactions of Narwhals, *Monodon monoceros*, to Killer Whale, *Orcinus orca*, Attacks in the Eastern Canadian Arctic. *The Canadian Field-Naturalist*, *120*(4), Article 4. <https://doi.org/10.22621/cfn.v120i4.355>
- Lee, D. (2005). *The Ecological and Social Dynamics of Inuit Narwhal Foraging at Pond Inlet, Nunavut* [Doctor of Philosophy]. McGill University.

- Lefort, K. J., Garroway, C. J., & Ferguson, S. H. (2020). Killer whale abundance and predicted narwhal consumption in the Canadian Arctic. *Global Change Biology*, 26(8), 4276–4283.  
<https://doi.org/10.1111/gcb.15152>
- Lima, S. L., & Dill, L. M. (1990). Behavioral decisions made under the risk of predation: A review and prospectus. *Canadian Journal of Zoology*, 68(4), 619–640. <https://doi.org/10.1139/z90-092>
- Liwanag, H. E. M. (2010). Energetic costs and thermoregulation in northern fur seal (*Callorhinus ursinus*) pups: The importance of behavioral strategies for thermal balance in furred marine mammals. *Physiological and Biochemical Zoology: PBZ*, 83(6), 898–910.  
<https://doi.org/10.1086/656426>
- Liwanag, H. E. M., Williams, T. M., Costa, D. P., Kanatous, S. B., Davis, R. W., & Boyd, I. L. (2009). The effects of water temperature on the energetic costs of juvenile and adult California sea lions (*Zalophus californianus*): The importance of skeletal muscle thermogenesis for thermal balance. *Journal of Experimental Biology*, 212(24), 3977–3984. <https://doi.org/10.1242/jeb.033282>
- Loseto, L. L., Richard, P., Stern, G. A., Orr, J., & Ferguson, S. H. (2006). Segregation of Beaufort Sea beluga whales during the open-water season. *Canadian Journal of Zoology*, 84(12), 1743–1751.  
<https://doi.org/10.1139/z06-160>
- Mann, J. (2000). *Cetacean Societies: Field Studies of Dolphins and Whales*. University of Chicago Press.
- Mann, J. (2019). Maternal Care and Offspring Development in Odontocetes. In B. Würsig (Ed.), *Ethology and Behavioral Ecology of Odontocetes* (pp. 95–116). Springer International Publishing. [https://doi.org/10.1007/978-3-030-16663-2\\_5](https://doi.org/10.1007/978-3-030-16663-2_5)

- Marcoux, M., Auger-Méthé, M., & Humphries, M. M. (2009). Encounter frequencies and grouping patterns of narwhals in Koluktoo Bay, Baffin Island. *Polar Biology*, *32*(12), 1705–1716. <https://doi.org/10.1007/s00300-009-0670-x>
- Marcoux, M., Auger-Méthé, M., & Humphries, M. M. (2012). Variability and context specificity of narwhal (*Monodon monoceros*) whistles and pulsed calls. *Marine Mammal Science*, *28*(4), 649–665. <https://doi.org/10.1111/j.1748-7692.2011.00514.x>
- Marcoux, M., Larocque, G., Auger-Méthé, M., Dutilleul, P., & Humphries, M. M. (2010). Statistical analysis of animal observations and associated marks distributed in time using Ripley's functions. *Animal Behaviour*, *80*(2), 329–337. <https://doi.org/10.1016/j.anbehav.2010.04.027>
- Mayette, A., Marcoux, M., Iacozza, J., Ferguson, M., Brower, A., & Loseto, L. (2023). Summer distribution and habitat preference of beluga whale social groups in the Eastern Beaufort Sea. *Arctic Science*. <https://doi.org/10.1139/as-2022-0035>
- NASA Ocean Biology Processing Group. (2020). *MODIS Aqua global Level 3 mapped sea surface temperature (SST) (Version 2019.0)* [Dataset]. PO.DAAC, CA, USA. <https://doi.org/10.5067/MODAM-1D4N9>
- Nielsen, M. L. K., Bejder, L., Videsen, S. K. A., Christiansen, F., & Madsen, P. T. (2019). Acoustic crypsis in southern right whale mother–calf pairs: Infrequent, low-output calls to avoid predation? *Journal of Experimental Biology*, *222*(13), jeb190728. <https://doi.org/10.1242/jeb.190728>
- Noren, S. R., & Suydam, R. (2016). Navigating under sea ice promotes rapid maturation of diving physiology and performance in beluga whales. *Journal of Experimental Biology*, *219*(18), 2828–2836. <https://doi.org/10.1242/jeb.143644>

- Noren, S. R., & Williams, T. M. (2000). Body size and skeletal muscle myoglobin of cetaceans: Adaptations for maximizing dive duration. *Comparative Biochemistry and Physiology. Part A, Molecular & Integrative Physiology*, 126(2), 181–191. [https://doi.org/10.1016/s1095-6433\(00\)00182-3](https://doi.org/10.1016/s1095-6433(00)00182-3)
- Orgeret, F., Reisinger, R. R., Carpenter-Kling, T., Keys, D. Z., Corbeau, A., Bost, C.-A., Weimerskirch, H., & Pistorius, P. A. (2021). Spatial segregation in a sexually dimorphic central place forager: Competitive exclusion or niche divergence? *Journal of Animal Ecology*, 90(10), 2404–2420. <https://doi.org/10.1111/1365-2656.13552>
- Pack, A. A., Herman, L. M., Craig, A. S., Spitz, S. S., Waterman, J. O., Herman, E. Y. K., Deakos, M. H., Hakala, S., & Lowe, C. (2017). Habitat preferences by individual humpback whale mothers in the Hawaiian breeding grounds vary with the age and size of their calves. *Animal Behaviour*, 133, 131–144. <https://doi.org/10.1016/j.anbehav.2017.09.012>
- QGIS (software)QGIS. (2024). *QGIS geographic information system* (Version 3.40) [Computer software]. QGIS Association. <https://www.qgis.org>
- Rasmussen, K., Palacios, D. M., Calambokidis, J., Saborío, M. T., Dalla Rosa, L., Secchi, E. R., Steiger, G. H., Allen, J. M., & Stone, G. S. (2007). Southern Hemisphere humpback whales wintering off Central America: Insights from water temperature into the longest mammalian migration. *Biology Letters*, 3(3), 302–305. <https://doi.org/10.1098/rsbl.2007.0067>
- Rayment, W., Dawson, S., & Webster, T. (2015). Breeding status affects fine-scale habitat selection of southern right whales on their wintering grounds. *Journal of Biogeography*, 42(3), 463–474. <https://doi.org/10.1111/jbi.12443>
- R Core Team (2025). *\_R: A Language and Environment for Statistical Computing\_*. R Foundation for Statistical Computing,

Vienna, Austria. <<https://www.R-project.org/>>.

Richard, P. R., Laake, J. L., Hobbs, R. C., Heide-Jørgensen, M. P., Asselin, N. C., & Cleator, H. (2010).

Baffin Bay Narwhal Population Distribution and Numbers: Aerial Surveys in the Canadian High Arctic, 2002-04. *Arctic*, 63(1), 85–99.

Ruckstuhl, K., & Neuhaus, P. (2005). *Sexual Segregation in Vertebrates*. Cambridge University Press.

Sakai, M., Morisaka, T., Iwasaki, M., Yoshida, Y., Wakabayashi, I., Seko, A., Kasamatsu, M., &

Kohshima, S. (2013). Mother–calf interactions and social behavior development in

Commerson’s dolphins (*Cephalorhynchus commersonii*). *Journal of Ethology*, 31(3), 305–313.

<https://doi.org/10.1007/s10164-013-0380-2>

Salton, M., Kirkwood, R., Slip, D., & Harcourt, R. (2019). Mechanisms for sex-based segregation in

foraging behaviour by a polygynous marine carnivore. *Marine Ecology Progress Series*, 624,

213–226. <https://doi.org/10.3354/meps13036>

Scharffenberg, K., Whalen, D., Marcoux, M., Iacozza, J., Davoren, G., & Loseto, L. (2019).

Environmental drivers of beluga whale *Delphinapterus leucas* habitat use in the Mackenzie

Estuary, Northwest Territories, Canada. *Marine Ecology Progress Series*, 626, 209–226.

<https://doi.org/10.3354/meps13011>

Sergeant, D. E. (1973). Biology of White Whales (*Delphinapterus leucas*) in Western Hudson Bay.

*Journal of the Fisheries Research Board of Canada*, 30(8), 1065–1090.

<https://doi.org/10.1139/f73-178>

Shapiro, A. D. (2006). Preliminary evidence for signature vocalizations among free-ranging narwhals

(*Monodon monoceros*)a). *The Journal of the Acoustical Society of America*, 120(3), 1695–1705.

<https://doi.org/10.1121/1.2226586>

- Skovrind, M., Castruita, J. A. S., Haile, J., Treadaway, E. C., Gopalakrishnan, S., Westbury, M. V., Heide-Jørgensen, M. P., Szpak, P., & Lorenzen, E. D. (2019). Hybridization between two high Arctic cetaceans confirmed by genomic analysis. *Scientific Reports*, *9*(1), 7729. <https://doi.org/10.1038/s41598-019-44038-0>
- Stanton, M. A., & Mann, J. (2012). Early social networks predict survival in wild bottlenose dolphins. *PloS One*, *7*(10), e47508. <https://doi.org/10.1371/journal.pone.0047508>
- Tervo, O. M., Ditlevsen, S., Ngô, M. C., Nielsen, N. H., Blackwell, S. B., Williams, T. M., & Heide-Jørgensen, M. P. (2021). Hunting by the Stroke: How Foraging Drives Diving Behavior and Locomotion of East-Greenland Narwhals (*Monodon monoceros*). *Frontiers in Marine Science*, *7*. <https://doi.org/10.3389/fmars.2020.596469>
- Tyshko, A. A., Krinitskiy, M. A., Shatravin, A. V., & Belikov, R. A. (2023). Automatic Detection of Acoustic Signals of Beluga Whales and Bottlenose Dolphins. *Moscow University Physics Bulletin*, *78*(1), S217–S225. <https://doi.org/10.3103/S0027134923070305>
- Vicari, D., Lorenzen, E. D., Skovrind, M., Szpak, P., Louis, M., Olsen, M. T., Brown, R. P., Lambert, O., Bianucci, G., Sabin, R. C., & Meloro, C. (2022). Skull ecomorphological variation of narwhals (*Monodon monoceros*, Linnaeus 1758) and belugas (*Delphinapterus leucas*, Pallas 1776) reveals phenotype of their hybrids. *PLoS ONE*, *17*(8), e0273122. <https://doi.org/10.1371/journal.pone.0273122>
- Vihtakari, M. (affiliation: I. of M., Bivand, R., & Wickham, H. (2024). *ggOceanMaps: Plot Data on Oceanographic Maps using “ggplot2”* (Version 2.2.0) [Computer software]. <https://cran.r-project.org/web/packages/ggOceanMaps/index.html>

- Watt, C. A., Heide-Jørgensen, M. P., & Ferguson, S. H. (2013). How adaptable are narwhal? A comparison of foraging patterns among the world's three narwhal populations. *Ecosphere*, 4(6), art71. <https://doi.org/10.1890/ES13-00137.1>
- Webber, Q., Prokopenko, C., Kingdon, K., Turner, J., & Vander Wal, E. (2024). Effects of the social environment on movement-integrated habitat selection. *Movement Ecology*, 12(1), 61. <https://doi.org/10.1186/s40462-024-00502-9>
- Westdal, K. H., Davies, J., & Ferguson, S. H. (2022). Assessing seasonal spatial segregation by age class of beluga whales (*Delphinapterus leucas*) in Western Hudson Bay estuaries. *PLOS ONE*, 17(11), e0255756. <https://doi.org/10.1371/journal.pone.0255756>
- Wiszniewski, J., Allen, S. J., & Möller, L. M. (2009). Social cohesion in a hierarchically structured embayment population of Indo-Pacific bottlenose dolphins. *Animal Behaviour*, 77(6), 1449–1457. <https://doi.org/10.1016/j.anbehav.2009.02.025>
- Zahn, M. J., Rankin, S., McCullough, J. L. K., Koblitz, J. C., Archer, F., Rasmussen, M. H., & Laidre, K. L. (2021). Acoustic differentiation and classification of wild belugas and narwhals using echolocation clicks. *Scientific Reports*, 11(1), 22141. <https://doi.org/10.1038/s41598-021-01441-w>
- Zeh, J. M., Dombroski, J. R. G., & Parks, S. E. (2022). Preferred shallow-water nursery sites provide acoustic crypsis to southern right whale mother–calf pairs. *Royal Society Open Science*, 9(5), 220241. <https://doi.org/10.1098/rsos.220241>

## Chapter 4: Conclusion

### 4.1.0 General Conclusion

This is the first study to assess changes in group composition on a large temporal scale, and summer habitat use by group type for any narwhal population. This thesis examined patterns of social organization and habitat use in the Baffin Bay narwhal population during the summer period, with a focus on how group composition varies across space and environmental gradients. Using aerial survey data collected in 2013 and 2023, this research integrated group size, newborn-to-adult ratios, and group-type-specific habitat associations to evaluate whether narwhals exhibit social or spatial segregation during summer, a period traditionally considered one of aggregation and reduced foraging intensity. Together, the findings provide new insight into how life-history stage and social context influence habitat use in a highly social Arctic cetacean. These findings are particularly relevant given ongoing climate-driven changes to narwhal environments, including warming waters, declining sea ice, and increasing anthropogenic activity.

### 4.2.0 Summary of Key Findings

#### ***4.2.1 Chapter 2: Baffin Bay narwhal group composition across temporal and spatial scales***

Chapter 2 quantified variation in group size and newborn-to-adult ratios across management stocks and between survey years (2013 and 2023). Group sizes varied significantly among summering stocks, reflecting potential regional differences in geography, habitat structure, or environmental stressors. Group sizes decreased on average from 2013 to 2023, with a pronounced effect in Eclipse Sound, an area with high vessel traffic and noise (Ewing et al.,

2025; Jones et al., 2023). Newborn-to-adult ratios were strongly influenced by group size, with smaller groups more likely to contain newborns, suggesting that small group structure benefits calf care. In fact, many newborn groups consisted solely of mother calf pairs, highlighting some social segregation for narwhal based on life history stage, consistent between both years 2013(Cherry et al., 2018), and 2023. Newborn to adult ratio increased from 2013 to 2023, however, without additional demographic structures including abundance, sex-ratio, and recruitment (Taylor et al., 1987), these findings can only serve as a warning for potential future changes in population structure.

#### ***4.2.2 Chapter 3: Investigating summer habitat use by group type in Baffin Bay narwhals***

Chapter 3 focused on group-type-specific habitat use in Baffin Bay during summer 2023. Despite substantial overlap in depth, distance to shore, and sea surface temperature among individuals, adult groups, and groups with newborns, clear patterns of partial spatial segregation emerged. Groups with newborns were most frequently observed in shallower waters and closest to shore, adult groups occupied slightly deeper but still nearshore habitats, and solitary individuals were more often found farther offshore and in deeper waters. Sea surface temperature had no strong impact on group-type. These patterns suggest that narwhals do not segregate into discrete or exclusive summer habitats based on group composition, yet group composition can influence habitat use at fine spatial scales.

Importantly, the observed spatial patterns align with life-history constraints of newborn narwhals and potential social behaviour drivers rather than strict niche partitioning. Nearshore habitat use by groups containing newborns, likely reflects a trade-off between reduced predation risk, calmer waters, and the limited aerobic diving capacity of newborns. Adult groups occurring at similar distances to shore further indicate that nearshore habitat use is not solely driven by

newborns, but may also facilitate social cohesion, communication, and group stability for both adults and mother-calf pairs. In contrast, solitary individuals were more likely to occur in deeper, offshore waters, potentially reflecting greater freedom to exploit deeper habitats for foraging attempts without being constrained by the least capable group member.

Across both chapters, the findings indicate that narwhal summer habitat use is shaped by a combination of social structure, life-history stage, and environmental context. Rather than complete spatial segregation, narwhals are flexible in summer habitat use, but how they use the environment might be slightly mediated by group-type differences.

#### 4.3.0 Social and spatial segregation in narwhal summering areas

This thesis contributes to a largely underexplored area by providing evidence of social and spatial structuring in a population where detailed knowledge of how group composition might relate to habitat use is minimal. Social segregation seems important based on newborn life history stages where we saw many mother-calf pairs and smaller newborn group units. Spatial segregation, while incomplete, was partially evident in depth and proximity to shore among group types. These patterns support the idea that summer aggregation does not imply ecological homogeneity, and that fine-scale habitat selection reflects differing behavioural priorities among individuals, adult groups, and newborn groups, that are often mother-calf pairs.

#### 4.4.0 Limitations

Several limitations should be considered when interpreting these results. Comparisons between 2013 and 2023 were not corrected for survey effort. Although surveys covered the same general areas and followed standardized protocols, differences in aircraft altitude, camera configuration, distance, flying time, and area covered were not fully accounted for.

Habitat use was inferred from surface observations only. While group locations provide valuable information about where narwhals are encountered, they do not directly indicate how whales use the water column beneath them. We can suggest that deeper waters provide the opportunity for deeper dives and benthic foraging, but it is speculative. As such, it was not possible to distinguish true behavioural states such as foraging, transit, or social behaviour.

Sex could not be reliably determined for a sufficient proportion of individuals, limiting the ability to assess sexual segregation. The overrepresentation of presumed females due to tusk absence, combined with image quality limitations and submerged individuals, prevented robust sex-based findings. Additionally, individuals in this study were only classified into two age classes; adults and newborns. Narwhals that are one or two years old, or juveniles not yet sexually mature and still dependent on their mothers, given the variation in nursing duration observed in narwhals (Zhao et al., 2021), represent an important additional age class to consider when assessing recruitment and potential effects on future population dynamics.

Group definitions were based on spatial proximity at the surface which are unlikely to fully capture dynamic fission–fusion processes or longer-term social associations outside of mother-calf pairs. Groups identified in aerial imagery represent snapshots in time and likely underestimate the complexity of narwhal social structure, habitat use, and segregation patterns. Additionally, group sizes may actually be higher overall as individuals may be submerged below those on the surface.

#### 4.5.0 Directions for future research

If additional data were available, several extensions of this work would substantially improve understanding of narwhal social, spatial, and population-based ecology. Future studies should prioritize the assessment of sexual segregation by retrieving more specific sex and age

information through drone footage. Improved image resolution or integration with tagging and biopsy data could enable more reliable sex determination and allow evaluation of whether males and females differ in summer or winter habitat use. Additionally, better quality imagery could accurately determine juveniles from adults and be considered a separate age class.

Since Baffin Bay narwhal migrate from Baffin Island fiords and bays to Baffin Bay and Davis Strait (Heide-Jørgensen et al., 2003), it would be beneficial to assess the winter environment and group composition. Such an assessment could test variation in fine-scale winter habitat use, due to limited dive capacity of juveniles, the influence of body size on individual energy requirements, and the increased intensity of winter feeding. However, given the difficulty of winter based remote research this task is less feasible than summer assessments.

Applying standardized effort corrections, integrating density surface modelling, abundance, and other demographic parameters would improve the ability to detect real shifts in group size, newborn ratios, or habitat use over time, particularly in the context of rapid environmental change.

#### 4.6.0 Climate change context

The results of this study highlight the potential influence of ongoing environmental change on the Baffin Bay narwhal population. Observed summer distributions occurred in sea surface temperatures warmer than those traditionally associated with narwhal habitat (Chambault et al., 2020), suggesting that individuals are experiencing or tolerating sub-optimal thermal conditions. In addition, overall group sizes were notably smaller, which is concerning given the prolonged presence of killer whales in overlapping summer habitats (Breed et al., 2017), as narwhals are known to disperse in response to predation risk (Breed et al., 2017; Laidre et al., 2006). Notably, the most pronounced decrease in group size occurred in the area of intense

shipping and noise, Eclipse Sound and Milne Inlet. Together, these patterns serve as markers of how climate change and increased human activity are affecting Baffin Bay narwhal group composition, habitat use, and population or stock level effects, with consequences for future resilience. Changes in surveying methodology might be warranted if narwhal ecology is changing rapidly. The results of this study in a climate change context can inform steps to mitigate activities in areas where vulnerable individuals such as newborn-mother pairs are more present such as shallow, near shore areas. Similarly, these results provide reasoning for vessel mitigation in Eclipse Sound. Recognizing these shifts can inform management strategies, guiding risk assessments, projections of future population changes, and evaluations of the current status of Baffin Bay narwhals as the climate continues to warm.

## 4.7.0 References

- Breed, G. A., Matthews, C. J. D., Marcoux, M., Higdon, J. W., LeBlanc, B., Petersen, S. D., Orr, J., Reinhart, N. R., & Ferguson, S. H. (2017). Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales. *Proceedings of the National Academy of Sciences*, *114*(10), 2628–2633. <https://doi.org/10.1073/pnas.1611707114>
- Chambault, P., Tervo, O. M., Garde, E., Hansen, R. G., Blackwell, S. B., Williams, T. M., Dietz, R., Albertsen, C. M., Laidre, K. L., Nielsen, N. H., Richard, P., Sinding, M. H. S., Schmidt, H. C., & Heide-Jørgensen, M. P. (2020). The impact of rising sea temperatures on an Arctic top predator, the narwhal. *Scientific Reports*, *10*(1), 18678. <https://doi.org/10.1038/s41598-020-75658-6>
- Charry, B., Marcoux, M., & Humphries, M. M. (2018). Aerial photographic identification of narwhal (*Monodon monoceros*) newborns and their spatial proximity to the nearest adult female. *Arctic Science*, *4*(4), 513–524. <https://doi.org/10.1139/as-2017-0051>
- Ewing, J. P., Hidalgo-Pla, E., Solsona-Berga, A., Frasier, K. E., Ootoowak, A. J., Westdal, K. H., Wiggins, S. M., Hildebrand, J. A., & Jones, J. M. (2025). Narwhal acoustic presence in Eclipse Sound, Nunavut: Relationships with sea ice and responses to ships. *Scientific Reports*, *15*(1), 23126. <https://doi.org/10.1038/s41598-025-04032-1>
- Heide-Jørgensen, M. P., Dietz, R., Laidre, K. L., Richard, P., Orr, J., & Schmidt, H. C. (2003). The migratory behaviour of narwhals (*Monodon monoceros*). *Canadian Journal of Zoology*, *81*(8), 1298–1305. <https://doi.org/10.1139/z03-117>
- Jones, J. M., Westdal, K. H., Ootoowak, A. J., Wiggins, S. M., & Hildebrand, J. A. (2023). Impact of ship noise on the underwater soundscape of Eclipse Sound in the northeastern

Canadian Arctic. *Marine Pollution Bulletin*, 195, 115534.

<https://doi.org/10.1016/j.marpolbul.2023.115534>

Laidre, K. L., Heide-Jørgensen, M. P., & Orr, J. R. (2006). Reactions of Narwhals, *Monodon monoceros*, to Killer Whale, *Orcinus orca*, Attacks in the Eastern Canadian Arctic. *The Canadian Field-Naturalist*, 120(4), Article 4. <https://doi.org/10.22621/cfn.v120i4.355>

Taylor, M., Carley, J. S., & Bunnell, F. L. (1987). Correct and Incorrect Use of Recruitment Rates for Marine Mammals. *Marine Mammal Science*, 3(2), 171–178.

<https://doi.org/10.1111/j.1748-7692.1987.tb00159.x>

Zhao, S.-T., Matthews, C. J. D., Davoren, G. K., Ferguson, S. H., & Watt, C. A. (2021).

Ontogenetic profiles of dentine isotopes ( $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$ ) reveal variable narwhal

*Monodon monoceros* nursing duration. *Marine Ecology Progress Series*, 668, 163–175.

## 5.0 Appendix

Table A. Model comparison table (candidate models) for Chapter 3.

<i>Model Formula</i>	<i>Interaction term / main effect</i>
<b><i>group type ~ SST + distance to shore + (1  stock)</i></b>	No interaction term
<b><i>group type ~ SST + depth + (1  stock)</i></b>	No interaction term
<b><i>group type ~ SST × distance to shore + (1  stock)</i></b>	Interaction term
<b><i>group type ~ SST × depth + (1  stock)</i></b>	Interaction term

Figure A. Correlation Matrix (SST, Distance to shore, bathymetry/depth)

