Aquatic Mammals 2024, *50*(4), 342-351, DOI https://doi.org/10.1578/AM.50.4.2024.342

Geographic Distribution of North Atlantic Humpback Whales (*Megaptera novaeangliae*) with Fluke Scars Caused by Killer Whales (*Orcinus orca*)

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Abstract

Although killer whale (*Orcinus orca*) predation on humpback whales (*Megaptera novaeangliae*) is rarely witnessed, resultant scars on humpback flukes provide evidence of non-lethal interactions. Humpback whale photo-identification catalogs from the North Atlantic were used to evaluate humpback flukes (n = 10,957) for the presence and severity of killer whale scarification (e.g., rake marks, teeth indentations, missing tissue). Flukes were coded as none, light, moderate, or severe based on the extent of scarring. Even with increased sample sizes, especially for Norway and Iceland, the distribution of high-latitude humpbacks with killer whale scarring was consistent with prior studies: Atlantic Canada (21.7%), West Greenland (15.5%), Gulf of Maine (13.5%), Iceland (combined with East Greenland, 9.3%), and Norway (7.9%). For the first time, scarring rates are presented based on data from Ireland, Scotland, and England (11.0%) as well. Scarring frequencies generally differed between the eastern and western North Atlantic despite the co-occurrence of all migrating humpbacks in low-latitude breeding grounds, suggesting the occurrence of killer whale interactions in the distinct feeding grounds or along northward migration routes. While it was not possible to determine exactly where these interactions took place, the likelihood of a killer whale encounter and subsequent scar acquisition was greatest for humpbacks that feed in Atlantic Canada.

Key Words: humpback whale, killer whale, rake marks, non-lethal interactions, feeding ground, photo-identification, North Atlantic Ocean

Introduction

Humpback whales (*Megaptera novaeangliae*) migrate seasonally from specific high-latitude summer foraging sites to tropical and subtropical wintering grounds for breeding and calving (Martin et al., 1984; Katona & Beard, 1990; Clapham & Mead, 1999; Clapham, 2001). In the North Atlantic, the low-latitude breeding grounds include the West Indies (Greater and Lesser Antilles) and the Cape Verde Islands (CVI) off northwest Africa (Stevick et al., 2018; Wenzel et al., 2020). During its first year of life, a humpback calf will travel to a particular feeding ground accompanied by its mother, leading to strong maternally influenced site fidelity and a low tendency to move among different feeding grounds (Martin et al., 1984; Katona & Beard, 1990; Larsen et al., 1996; Palsbøll et al., 1997; Barendse et al., 2013). The five primary feeding areas in the North Atlantic are (1) the Gulf of Maine, (2) Atlantic Canada (the Gulf of St. Lawrence, Newfoundland, and Labrador), (3) West Greenland, (4) East Greenland and Iceland, and (5) northern Norway (including the Barents Sea and Svalbard) (Katona & Beard, 1990; Stevick et al., 2003; Hansen et al., 2018). Feeding has also been documented along the northwestern European coast, where increasing numbers of humpbacks have been sighted over the past decade (Berrow & Whooley, 2022).

North Atlantic killer whales (*Orcinus orca*) have a broad distribution with suggested greater abundances at higher latitudes (Forney & Wade, 2006; Ferguson et al., 2012; Reinhart et al., 2013; Lawson & Stevens, 2014; North Atlantic Marine Mammal Commission [NAMMCO], 2018; Jourdain et al., 2019; Lefort et al., 2020; Pike et al., 2020). As group-hunting apex predators, killer whales feed on an assortment of prey that includes fish, seabirds, turtles, cephalopods, pinnipeds, and cetaceans (Matkin & Leatherwood, 1986; Jefferson et al., 1991; de Bruyn et al., 2013; Samarra et al., 2018; Lefort et al., 2020). Killer whale sightings have been reported in the Caribbean (Katona et al., 1988; Kiszka et al., 2021; Bolaños-Jiménez et al., 2023) and the CVI (Berrow et al., 2015; P. López Suárez, pers. comm., 30 June 2023). Only a handful of diet studies on North Atlantic killer whales have been published. Diet estimates revealed prey compositions ranging from primarily odontocete cetaceans in the eastern Caribbean; cetaceans and pinnipeds in the Canadian Arctic and Atlantic Canada; pinnipeds and fish off Greenland; and mostly fish in Iceland, Faroe Islands, and Norway (Reinhart et al., 2013; Samarra et al., 2018; Kiszka et al., 2021; Bolaños-Jiménez et al., 2023; Remili et al., 2023). There is limited evidence from North Atlantic killer whale diet studies of predation on large baleen whales (e.g., Foote et al., 2009, 2010, 2011; Reinhart et al., 2013; Remili et al., 2023), so the extent and significance of humpbacks as prey for North Atlantic killer whales remains a mystery.

Only a few records of killer whale attacks on humpbacks exist worldwide, and the final outcome of most cases is not known (Whitehead & Glass, 1985; Jefferson et al., 1991; Flórez-González et al., 1994; Visser, 1999), with the exception of lethal attacks on humpback calves off east and west Australia (Naessig & Lanyon, 2004; Pitman et al., 2015) and off Baja California, Mexico (Whale Watch Cabo, 2019). To date, there have been no documented, published accounts of lethal predation on North Atlantic humpbacks; however, humpbacks bearing teeth scars from killer whale interactions have been sighted across the entire ocean (Katona et al., 1988; Jefferson et al., 1991; Lawson et al., 2007; Mehta et al., 2007; McCordic et al., 2014). When a whale is bitten during an attack from a killer whale, resulting scars from the inflicted wounds provide documentation of these interactions (Mehta et al., 2007; Steiger et al., 2008; McCordic et al., 2014; Corsi et al., 2021). As killer whales are thought to grasp the flukes of their prey, likely trying to slow them down and/or potentially drown them, and humpbacks thrash their flukes in defense, resultant teeth scars should appear as rake marks or indentations on the flukes (Jefferson et al., 1991; Naessig & Lanyon, 2004; Ford & Reeves, 2008; Corsi et al., 2021). Such scars become stable markers captured through ventral fluke photographs used for individual identification of humpback whales (Katona & Whitehead, 1981; Carlson et al., 1990; Blackmer et al., 2000; Mehta et al., 2007; McCordic et al., 2014). Therefore, photo-identification records can be used as a tool to identify the survivors of past killer whale encounters (Mehta et al., 2007; Steiger et al., 2008; McCordic et al., 2014; Corsi et al., 2021).

This study aimed to review where killer whale interactions with North Atlantic humpback whales may be more likely to occur by investigating regional differences in fluke scarring. Although lethality could not be measured by studying resultant fluke scars on surviving humpback individuals, analyzing the severity of scarring provided an insight into the potential intensity of a non-lethal encounter (Mehta et al., 2007). North Atlantic humpback whale ventral fluke photographs have been used for individual identification of humpback whales for decades (Katona & Whitehead, 1981), and the North Atlantic Humpback Whale Catalog supported similar studies that estimated killer whale rake marks on humpback flukes (e.g., Mehta et al., 2007; McCordic et al., 2014). This study had increased sample sizes for all regions, especially from the eastern North Atlantic, which may be particularly relevant to predation risks on an endangered humpback whale population that breeds in the CVI (Bettridge et al., 2015; Wenzel et al., 2020). The widespread occurrence and long-distance migration of humpback whales can overlap spatially and ecologically with killer whales across the entire North Atlantic. To determine the geographic distribution of non-lethal killer whale interactions, humpback flukes in six North Atlantic high-latitude regions were evaluated to quantify the occurrence and severity of killer whale tooth scarring.

Methods

To analyze fluke scarring, this study used two existing photo-identification sources: (1) North Atlantic Humpback Whale Catalog (NAHWC), 1975-2021, and (2) North Norwegian Humpback Whale Catalog (NNHWC), 2002-2020. Curated by Allied Whale (College of the Atlantic, Bar Harbor, ME, USA), the NAHWC consists of contributions from collaborating groups and individuals across the North Atlantic. An experienced technician evaluated all fluke photographs submitted to the NAHWC for overall photo quality based on contrast, clarity, and angle (Friday et al., 2000). All images that were analyzed met the minimum quality threshold for inclusion in the catalog. Calf flukes were excluded from the study as they are not cataloged by the NAHWC unless the individual is resighted later in life. The NNHWC provided > 400 supplementary fluke-identified individuals for Norway that were not present in the larger NAHWC at the time of the study. Any previous matches of the same individual between catalogs were only counted once in the sample size for the given region. Photographic data, collected between 1975 and 2021, included living or deceased individuals with at least one good quality ventral fluke photograph (Table 1).

For all individual humpbacks (n = 10,957), two reviewers examined available fluke photographs for the presence and severity of healed wounds caused by killer whales. Killer whale scars included rake marks, a set of three or more parallel, equidistant lines; teeth indentation marks; and missing tissue accompanied by rakes or indentations (i.e., mutilation) (Mehta et al., 2007; Steiger et al., 2008; McCordic et al., 2014; Corsi et al., 2021). Injuries, when present, were coded based on a visual estimation of the extent of fluke scarring and mutilation as light (< 10% scar coverage), moderate (10 to 50% scar coverage and/or < 10% mutilation), or severe (> 50% scar coverage and/or > 10% mutilation; Figure 1). When no scars were detected, the individual was coded as none (i.e., non-scarred). Of the humpbacks with no fluke scars, 16 (0.2%) were not agreed upon by the two reviewers for presence or absence of scarring caused by killer whales and, hence, were categorized conservatively as non-scarred.

Humpback whales were assigned to their northernmost high-latitude sighting region under the assumption that this location was their main feeding ground, indicated by migration patterns and site fidelity. Following the divisions used in the NAHWC, the five primary feeding grounds were defined as (1) the Gulf of Maine, including the Scotian Shelf; (2) Atlantic Canada (the Gulf of St. Lawrence, Newfoundland, and Labrador); (3) West Greenland; (4) East Greenland and Iceland; and (5) Norway, including the Barents Sea and Svalbard (Figure 2). After assessing every cataloged individual in the North Atlantic, those exclusively sighted south of these primary areas were excluded from the analysis. However, additional data were analyzed from Ireland, Scotland, and England, a potential feeding ground where humpback whale sightings and resightings have increased recently (Berrow et al., 2021; Berrow & Whooley, 2022; Blázquez et al., 2023).

Scarring rates were calculated for these six high-latitude feeding grounds by dividing the number of humpback whales with tooth-rake scars on the ventral side of their flukes (scarred humpbacks) by the total number of individuals assigned to that specific region. Also, for all six regions, proportions for each category of scarification (none, light, moderate, severe) were determined based on the total number of humpbacks in the given region. Two competing ordinal logistic regression models were compared on the basis of the Akaike information criterion (AIC) to judge the strength of evidence for regional differences among scarring distribution categories. The better-fitting model considered the effect of region as a predictor on the ordinal outcome (severity), with a lower AIC (8,774.6) than the null model which neglected its effect (AIC = 8,948.5), providing strong evidence that the distribution of scarring

Table 1. Details of photo-identification data sources based on the time of study (June 2021). **Note:** Size of collection refers exclusively to the number of fluke-identified individuals (n = 10,957).

Humpback whale catalog	Primary administrator	Sampling period	Geographic range	Size of collection	Number previously matched to NAHWC
North Atlantic	Allied Whale	1975-2021	North Atlantic Ocean	10,557	--
North Norwegian	Fredrik Broms	2002-2020	Northern Norway and Svalbard	1,020	~620

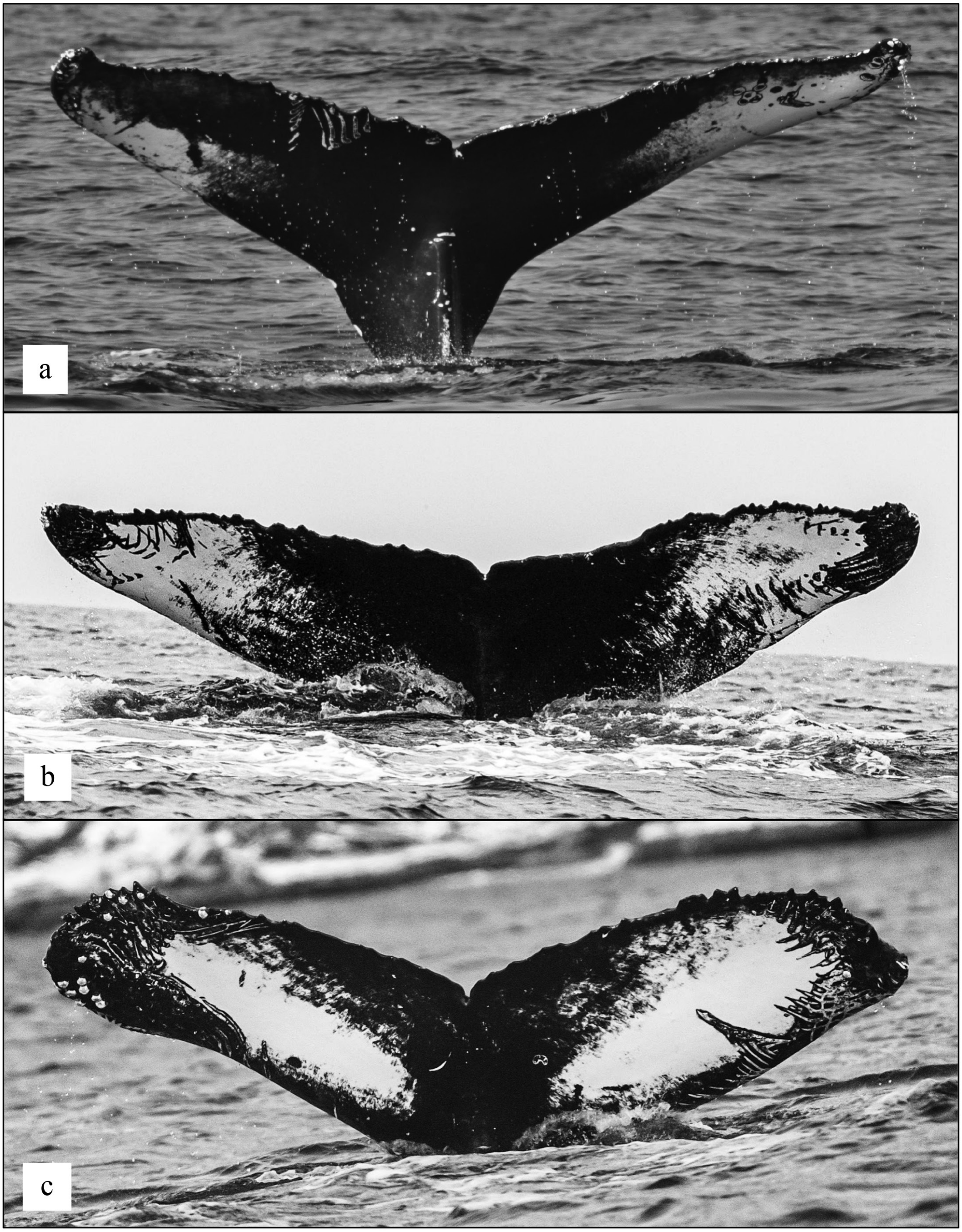

Figure 1. Humpback whale (*Megaptera novaeangliae*) ventral flukes with killer whale (*Orcinus orca*) scars ranging in severity: (a) light, with rakes on the trailing edge; (b) moderate, with indentations and rakes on the trailing and leading edges and fluke tips; and (c) severe, with amputation and mutilation of both fluke tips and extensive rakes. (*Photo credits:* [a] Nick Massett [IWDG] and [b, c] Fredrik Broms [NNHWC])

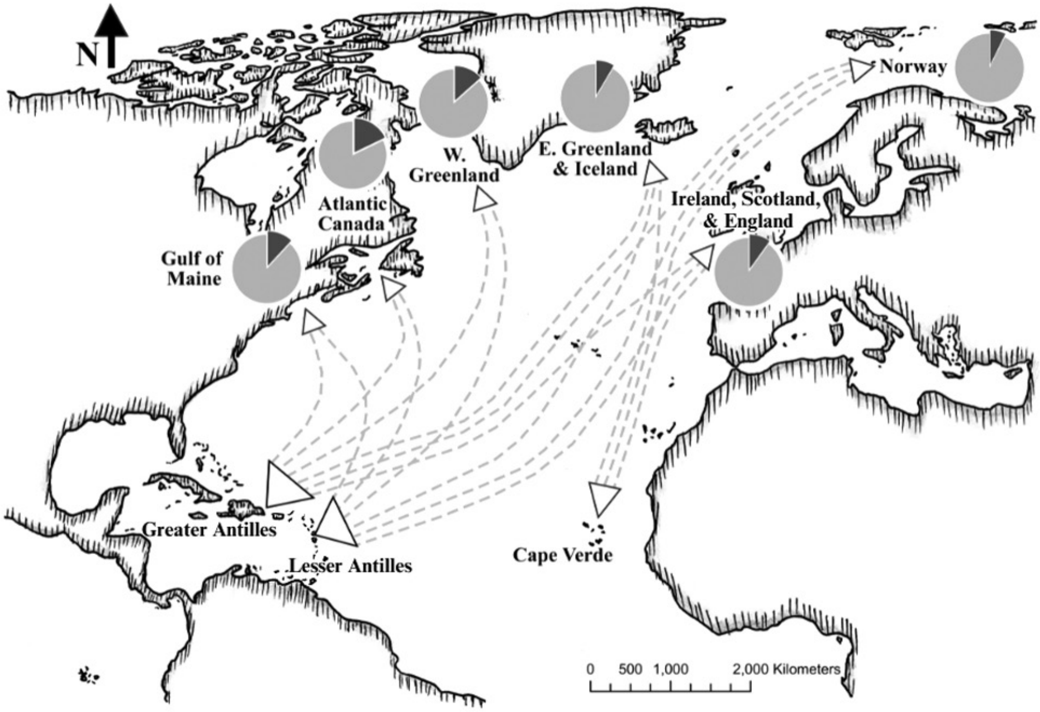

Figure 2. Map displaying the six North Atlantic feeding areas included in the study: (1) Gulf of Maine; (2) Atlantic Canada; (3) West Greenland; (4) East Greenland and Iceland; (5) Norway; and (6) Ireland, Scotland, and England. Dashed lines indicate relative humpback whale migration routes between breeding grounds (Greater and Lesser Antilles and Cape Verde) and high-latitude feeding grounds. Pie charts represent the proportion of fluke-identified humpback whales bearing killer whale fluke scars (dark gray slice) out of the total number of individuals assigned to each feeding area. (Base map created by Kristin Zunino, College of the Atlantic '24).

severity differed among regions. Each region's coefficient, which explains the effect of the predictor on severity, was exponentiated to convert to an odds ratio (OR). *P* values and 95% confidence intervals were computed for the ORs using Wald methods. Predicted probabilities of fluke scarring at each level of severity were estimated and plotted for each region (Agresti, 2002).

Results

Of the total 10,957 photo-identified humpback whales at the time of the study, 2,844 humpbacks were not sighted on a North Atlantic feeding ground and were therefore excluded from the analysis. Overall, 1,291 (15.9%) of 8,113 humpback whales from the feeding grounds bore killer whale tooth scars on their flukes. Total regional scarring rates ranged from 7.9% in Norway to 21.7% in Atlantic Canada (Figure 2; Table 2). In general, scarring rates were higher in the western North Atlantic (Gulf of Maine, Atlantic Canada, West Greenland) compared to the eastern North Atlantic (East Greenland and Iceland; Norway; Ireland, Scotland, and England; Figures 2 & 3). Relative to Norway, the odds of more severe scarring were significantly greater ($p < 0.05$) by 3.3 times in Atlantic Canada (95% CI = [2.6, 4.1]), 2.2 times in West Greenland (95% CI = [1.6, 3.0]), and 1.8 times in the Gulf of Maine (95% CI = [1.4, 2.4]). The predicted probabilities of scarring for Norway were indistinguishable from Ireland, Scotland, and England ($p = 0.22$; OR = 1.5; 95% CI = [0.8, 2.7]) and East Greenland and Iceland ($p = 0.23$; OR = 1.2; 95% CI = [0.9, 1.7]). For all regions, the predicted probabilities of no scarring or light scarring were relatively greater than the odds of moderate or severe scarring (Figure 3).

Table 2. Frequency of humpback (*Megaptera novaeangliae*) flukes with killer whale (*Orcinus orca*) teeth scars (scarring rate) based on the total number of unique individuals (N) within a given feeding ground (n = 8,113)

Region	N	Scarring rate (%)
Gulf of Maine	2,044	13.5
Atlantic Canada	3,473	21.7
West Greenland	574	15.5
East Greenland & Iceland	806	9.3
Norway	1,107	7.9
Ireland, Scotland & England	109	11.0

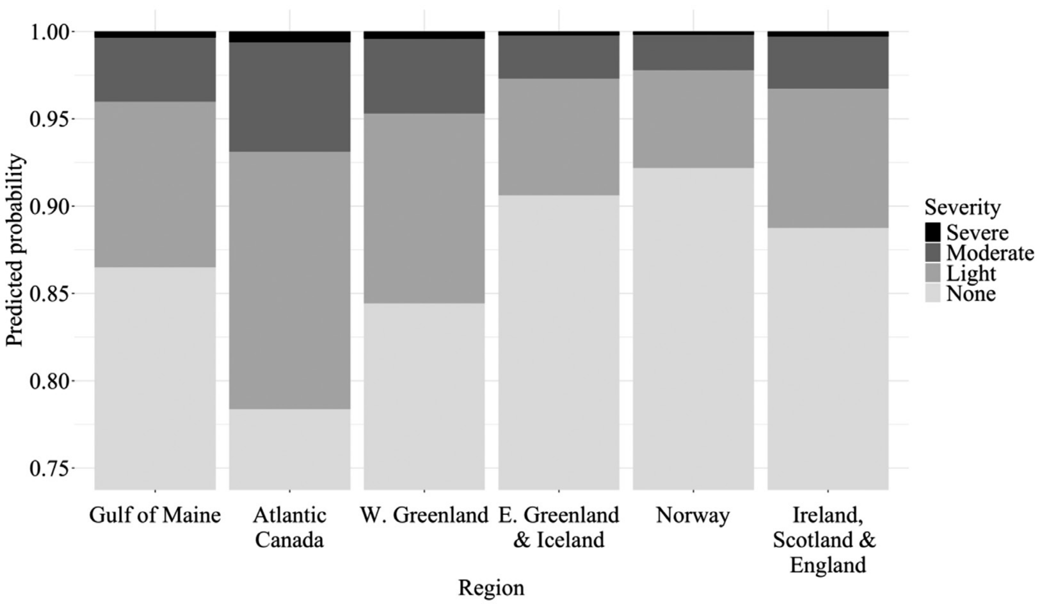

Figure 3. Distribution of scarring severity for killer whale teeth scars on humpback flukes across six North Atlantic feeding areas based on an ordinal logistic regression model

Discussion

These results indicate considerable geographic variation of photo-identified humpback whale flukes bearing scars from killer whale interactions in the North Atlantic. Despite greater sample sizes for every region, the frequency of scarring among humpbacks across primary feeding grounds aligned with trends from previous studies (Mehta et al., 2007; McCordic et al., 2014). More recent photo-identification efforts in the eastern North Atlantic allowed for inclusion of previously underrepresented foraging areas off the east coast of Greenland (here merged with Iceland); Norway; and Ireland, Scotland, and England. The probability of scarring relative to Norway differed significantly in West Greenland but not in East Greenland and Iceland, supporting the distinction of two separate humpback feeding grounds off Greenland. While it was possible that the sample size effect contributed to the lack of difference in predicted probabilities of severity between Norway (n = 1,107) and Ireland, Scotland, and England (n = 109), the East Greenland and Iceland region (n = 806) was also indistinguishable even with a larger sample size.

Since the probability of humpback fluke scarring was highest in Atlantic Canada, the likelihood of encountering a killer whale may be greater for humpbacks that feed in this region. While Atlantic Canada has higher densities of killer whales relative to the low-latitude humpback breeding grounds (Forney & Wade, 2006; Lawson & Stevens, 2014), the question of where these non-lethal interactions occur has been widely debated (e.g., Corkeron & Connor, 1999; Clapham, 2001; Mehta et al., 2007; McCordic et al., 2014). Humpback whale calves, as the main cohort seemingly targeted by killer whales, are thought to face the greatest predation risk on the breeding grounds and/or along their first northward migration route (Corkeron & Connor, 1999; Clapham, 2001; Gabriele et al., 2001; Naessig & Lanyon, 2004; Reeves et al., 2006; Mehta et al., 2007; Steiger et al., 2008; Pitman et al., 2015). This is supported by the fact that the vast majority of identifiable injuries are acquired by the first time that a calf is observed/photo-identified on the feeding grounds (Mehta et al., 2007). However, if most killer whale attacks took place on humpback breeding grounds, humpbacks from these shared breeding areas that diverge to different feeding grounds would be expected to have similar scarring frequencies. The differential distribution of humpbacks with killer whale-related scars across feeding regions therefore suggests that some non-lethal interactions occur in or en route to their separate high-latitude feeding grounds, particularly in Atlantic Canada (Mehta et al., 2007; McCordic et al., 2014).

Fatty-acid based dietary studies of killer whales from Canada to Norway suggest that Atlantic Canada and the Canadian Arctic are the only areas of the North Atlantic where killer whale diet is dominated by cetaceans (Remili et al., 2023). Thus, it is conceivable that humpback calves could be a potential seasonal prey item for killer whales off Atlantic Canada. Even in the central and eastern regions of the North Atlantic where killer whales largely feed on seals and fish, individual variation in prey choice and switching has been observed (Vongraven & Bisther, 2014; Remili et al., 2023). However, in Iceland and Norway, killer whales and humpback whales share an abundant prey source of herring and have been recorded feeding in proximity with no apparent predator/prey interactions (Similä & Ugarte, 1993; Jourdain & Vongraven, 2017; Samarra et al., 2018; Marchon et al., 2024). Although a number of killer whales deviate from the fish-eating majority in these regions to supplement their diet with higher trophic level prey like seals, records of predation on large whales like humpbacks and aggressive interactions between the two cetacean species have not yet been published (Vongraven & Bisther, 2014; Jourdain & Vongraven, 2017; Samarra et al., 2018; Bories et al., 2021; Remili et al., 2023). So, while non-lethal interactions may occur in these high-latitude regions, it is plausible that most killer whale tooth scars on humpback whales were acquired during migration to feeding grounds.

Fatality, or successful predation, could not be assessed in this study; however, varying degrees of severity of killer whale scars demonstrate different types of interactions with ranging intensities. The higher proportions of no or light scarring compared to moderate and severe scarring indicate the possibility that killer whale scars were more commonly the result of non-predatory interactions. Less severe encounters leading to greater rates of minor scarring may have been caused by harassment or an attempt to feed on the skin and blubber without killing their prey, to provide a learning opportunity for juvenile killer whales, to single out calves, or may reflect better defense or outmaneuvering by the humpback (Whitehead & Glass, 1985; Jefferson et al., 1991; Reeves et al., 2006; Mehta et al., 2007; McCordic et al., 2014). Regardless of the nature of the interaction, the prevalence of resultant killer whale tooth scars on humpback flukes offers evidence that contact between humpback and killer whales occurs much more frequently in the North Atlantic than documented by diet studies and observations. With gaps in knowledge concerning killer whale abundance and ecology in the North Atlantic, the predation risk to humpback whale populations can only be inferred from non-lethal interactions captured by fluke scars, and it remains uncertain exactly where and when these events occur.

Acknowledgments

This research was the product of a large international humpback whale photo-identification effort, so we recognize the many contributors to the NAHWC, NNHWC, and Irish Humpback Whale Catalog. Contributing institutions and organizations included Allied Whale, College of the Atlantic, Center for Coastal Studies, Mingan Island Cetacean Study, Sea of Whales Adventures, Greenland Institute of Natural Resources, University of Iceland, Marine and Freshwater Research Institute of Iceland, Atlantic Technological University, Irish Whale and Dolphin Group, and Bios Cabo Verde. We also recognize the photographic contributions from Finn Larsen, formally of the Technical University of Denmark. Special thanks to Richard Pace for his invaluable expertise and guidance with the statistical analysis and figure creation. We also extend appreciation to Jessica McCordic for her original work on the topic. Funding support to the primary author (HAK) was through the NOAA Ernest F. Hollings Undergraduate Scholarship.

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