2018

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Recommended Citation

Helm, Jennifer E., "Confronting the challenges of whale avoidance by large vessels to reduce collision risk: A quantitative approach" (2018). *Graduate Student Theses, Dissertations, & Professional Papers*. 11163.
https://scholarworks.umt.edu/etd/11163

CONFRONTING THE CHALLENGES OF WHALE AVOIDANCE BY LARGE VESSELS TO REDUCE COLLISION RISK: A QUANTITATIVE APPROACH

By

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Thesis

presented in partial fulfillment of the requirements
for the degree of

Master of Science
in Wildlife Biology

The University of Montana
Missoula, MT

May 2018

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Confronting the Challenges of Whale Detection from Large Vessels to Reduce Collision Risk: A Quantitative Approach

Chairperson: Dr. Paul M. Lukacs

ABSTRACT

Disturbance of wildlife by human transportation infrastructure is ubiquitous. This type of human-wildlife conflict has the potential to negatively impact wildlife population growth rates, especially for at-risk species like large whales. While many whale populations are rebounding as a result of a moratorium on commercial whaling, increasing ship traffic constitutes a significant threat to whale conservation efforts in the form of ship-whale collisions ("ship strikes"). Ship strike avoidance is difficult because vessel operators can only see whales when they are breaking the surface of the water, or "available for detection," and even then, they will only see them a fraction of the time (the "perception process"). We investigated the ability of ship operators to detect and actively avoid whales by quantifying two processes: the ability of vessel operators to ascertain the direction of travel of whales (Chapter 2), and the varying detection challenges faced by vessel operators as whales move through the "strike zone" (Chapter 3). In Chapter 2, we modeled the ability of vessel operators to congruously determine whale direction of travel as a function of ship-to-whale distance and the number of surfacings in a bout. We found that the probability of making a congruous DT assignment increased as surfacing bout length increased and as ship-to-whale distance decreased. We also modeled the time it took vessel operators to make a DT assignment after the first sighting of a whale, and found that the probability of making a DT assignment was around 0.5 after three minutes had passed. In Chapter 3, we modeled the probabilities of whales entering and exiting the upper portion of the water column where they are at risk of ship strike (the "strike zone"), as well as the availability probability. We found that whales are present and undetected in the strike zone far more frequently than they are available for detection, which has important consequences for ship strike avoidance protocols and regulations.

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ACKNOWLEDGMENTS

First, I would like to thank the National Park Service (NPS) and Glacier Bay National Park (GLBA) for funding this research. The Park’s commitment to supporting scientific research is unique and inspiring, and I am grateful to be a part of this legacy.

I don’t even know how to begin thanking my advisor, Dr. Paul M. Lukacs, for his absolutely invaluable contributions to this work. Paul, without your input on content and modeling, the outcomes of this project would have looked substantially different. Aside from that, I am so grateful for your mentorship and friendship. I deeply respect your work and the way you operate professionally. I also really appreciated the way I could go into a meeting with you as stressed as I had ever been in my life, and come out the other side feeling like you had solved every single one of my problems. I am honored to have been a part of your lab, and I’m so glad to call you a friend.

I also want to sincerely thank my funder and NPS advisor, Dr. Scott Gende. Scott, your guidance and vision in designing this study and your incredible support of my two demanding seasons of fieldwork were key to my ability to collect this strong dataset. Between days on the bow in the pouring rain and a painful long run in Missoula, we have shared some great – if brutal – experiences together, and I value all of them! Your clarity around expectations and goals for the project, your respect for hard work, your commitment to excellent communication with stakeholders, and of course your infamous and exceptionally useful editing and revising skills with the bigger picture in mind are all traits that I aspire to emulate in the future.

Thanks also to my two other committee members, Dr. Lisa Eby and Dr. Winsor Lowe, for their very helpful input during both my proposal process and my thesis preparation. Your insightful questions and suggestions really helped me to narrow my focus and clarify my ideas. Each of you found the edges of my knowledge and comfort zone in your own way, and you made me a better thinker and scientist in the process. Thank you.

I owe a debt of gratitude to both current and former members of the Lukacs Incubator. Each of these brilliant humans offered wonderful support at different times when I needed it most. Dr. Sara Williams’ previous dissertation research provided a foundation for this work and her willingness to be available for questions and feedback was incredible. Dr. Josh Nowak’s deep knowledge of R programming and his suggestions for R best practices strongly influence the way I understand and write code and will continue to do so for the rest of my life. Anna Moeller’s ability to answer complicated code questions on the spot with kindness and love was uncanny and inspiring. Late-night conversations in the lab with Charlie Henderson really grounded me and were a perfect example of the importance of community and friendship in graduate student success; I valued those fleeting moments so much. Kelsey Wellington’s hilarious storytelling could make the lab fill with laughter on even the grayest days. Molly McDevitt’s innate sense of when I needed to be dragged away from my computer screen for a run up Mt. Sentinel to clear my head was only one of the millions of ways her friendship and support boosted me up through this process.

Thanks to the current and former employees of Glacier Bay National Park and Preserve for their assistance and support during the six months I spent in Bartlett Cove. I would especially like to thank Christine Gabriele, Janet Neilson, and Lou Taylor-Thomas for their expertise. It was amazing to be able to turn to these three women anytime I had questions about anything related to whales or regulations, and I was so grateful to be included on the whale necropsy team and to serve as a volunteer on the Humpback Whale Monitoring Program. I’d like to thank Dr.

Lisa Etherington for taking on supervisory roles with so much expertise and kindness; thanks to Lisa, I truly felt like I was a part of the NPS and like my work was really valued when I was in Bartlett Cove. A deep thanks goes to Craig Murdoch, Hank Lentfer, Elisa Weiss, Javan Bailey, adnd Jen Haas for reminding me of the bigger picture when I was stressed, exhausted, and focused exclusively on my data.

I'd like to thank the faculty and staff in the Wildlife Biology Program at the University of Montana for all of the ways – both seen and unseen – that you made my work possible. Thanks to the Wildlife Biology Program for supporting my professional development in the form of a travel grant to attend the 2018 RStudio Conference, which enabled me to develop skills and make connections that I will continue to draw on for the rest of my career. Dr. Gretchen McCaffrey at the Writing and Public Speaking Center played an instrumental role in helping me to clearly communicate my ideas, and Dr. Tom Martin's Strong Inference Science class was especially useful in the final stages of my thesis preparation.

Both inside and outside the program, there were many key players who helped keep my perspective in check on epic runs, skis, mountain adventures, and countless tea- and coffee-dates. This incredible community includes Jessie Golding, Leah Swartz, Sarah Bassing, William Blake, Danielle Fagre, Greg Kolwicz, Nate Bender, Katie Racette, Lisa Dworak, Chuck Casper, Dara McDevitt, Dallas Clark, Thomas Clark, Jez Cox, Koby Keene, Sam Pannoni, Alice Lubeck, Heidi Blair, Kellie Carim, Hannah Specht, and Ryan Hegstad. Additionally, I am so grateful to my parents, Dot LeBaron and Pete Helm, for supporting my decision to pursue education on the other side of the country. I don't know where I would be without the hilarious and brilliant texts from my brother Ben Helm, whose success as a software engineer in San Francisco constantly reminds that no matter how well I code, he will always win that game.

I am grateful to Princess Cruises and Holland America Line for making it possible for me to collect data. Without their participation, support, and expertise, this project would have been impossible. I'd especially like to thank the captains, pilots, and officers working in the navigational bridge who were so kind and who made me feel so welcome aboard their ships.

A note on authorship

Throughout this document, I use the pronoun "we" in recognition and appreciation of the contributions and guidance of my collaborators and coauthors.

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CHAPTER 1. A GENERAL INTRODUCTION TO THE PROBLEM OF SHIP STRIKES

Human-wildlife conflict occurs when the interests of humans and wildlife do not align (Madden 2004). More specifically, there are two general situations that can lead to a human-wildlife conflict (Madden 2004). The first type occurs when the needs and behavior of wildlife negatively impact the goals of humans, while the second type occurs when the goals of humans negatively impact the needs of wildlife. Examples of the first type include livestock depredation from large felids in Asia (Sangay and Vernes 2008), crop damage by elephants in Africa (Dickman 2010), and perceived competition between wolves and hunters for ungulates in the western United States (Boyd et al. 2008). Examples of the second type occur across taxa, in nearly any system where humans and wildlife interact, and can have important population-level consequences, especially for species at risk (e.g. Lamberson et al. 1992). This second type of human-wildlife conflict is of particular interest to wildlife managers and conservation practitioners, and it is the focus of this work.

Disturbance by human transportation systems is one way that the goals of humans can negatively impact the needs of wildlife. The effects of transportation are many, varied, and can be lethal or sub-lethal. The field of road ecology studies the ecological impacts of linear, terrestrial infrastructure like roads, highways and rail transit (Coffin 2007). Lethal effects, in the form of roadkill, are often the most obvious impact, while sub-lethal impacts include increased noise, habitat loss, habitat degradation, barriers to movement, and either wildlife attraction to or avoidance of particular areas (Coffin 2007). These sub-lethal effects can have population-level consequences by altering vital rates such as fecundity, survival and recruitment, which drive population dynamics. While a great deal of work has been done to understand lethal and sub-lethal effects of terrestrial transportation infrastructure (Lesbarrères and Fahrig 2012, Rytwinski et al. 2015), there is less understanding of the effects of marine transportation infrastructure on wildlife populations, presumably at least in part because ship traffic is often less linear and its effects on marine wildlife are difficult to measure. While the field of marine spatial planning has begun to address these concerns, there are still very few comprehensive spatial plans for marine systems that take in to account all of the activities co-occurring in these areas (Douvere 2008). It is critical that we understand the effects of marine transportation systems on wildlife populations so that we can effectively mitigate wildlife population effects by both planning for future infrastructure and creating regulations that govern existing infrastructure.

Modern society depends on both terrestrial transport and marine shipping for transferring goods, movement, and natural resource extraction as well as military operations and fishing. The human population is continuing to rise, and increasingly connected commercial networks support economies around the world (Hummels 2007). Shipping and marine tourism are both increasing, as evidenced by the rapid growth of the cruise industry (Dowling 2006) and the swift expansion of whale watching worldwide (Hoyt 1995). This will undoubtedly lead to increased vessel traffic in areas that are ecologically sensitive or biologically important. Whales are uniquely positioned as apex consumers that are dependent on areas of high primary productivity which may intersect busy shipping routes. As such, studies of interactions between whales and humans provide important information about how to address conservation challenges and improve human-wildlife coexistence in an increasingly busy ocean.

The global abundance of whales plummeted as a result of both legal and illegal commercial whaling in the 19th and 20th centuries (Ivashchenko et al. 2013). Population declines are estimated to be between 66% and 90% in total, with more extreme decimation of certain species (Roman et al. 2014). Since whales are long-lived with low fecundity, their populations are especially vulnerable to changes in adult survival probability. In 1966, humpback whales (*Megaptera novaeangliae*) were protected from whaling by the International Whaling Commission, and in 1970 they were listed as endangered under the Endangered Species Conservation Act (NOAA 2018a), which was replaced by the Endangered Species Act in 1973 (U.S. Fish and Wildlife Service 1973, 2013). In 1978, humpback whales were also protected under the Marine Mammal Protection Act, which was implemented to achieve optimum sustainable populations of marine mammals (National Marine Fisheries Service 1978). While these efforts have enabled many whale populations to rebound, whales in different species, populations, and regions have responded at different rates (Tulloch et al. 2018). Additionally, while they are protected from intentional disturbance and whaling by this legislation, whales are still susceptible to direct injury from large ships (Douglas et al. 2008). Regardless, global recovery enabled the delisting of nine of fourteen distinct population segments (DPS) of humpback whales in September 2016, while one DPS was listed as threatened and four were listed as endangered (NOAA 2016). The increase of whale populations generally bodes well for both humpback whale population persistence and ecosystem health, but simultaneous increases in whale density and ship traffic is concerning from a collision avoidance perspective.

Collisions and close encounters between vessels and whales can occur across any vessel size, ranging from kayaks and small boats to very large ships. Although collisions between whales and ships (hereafter referred to as “ship strikes”) have been documented since the late 18th century, fatal collisions were rare before 1800 and remained scarcely reported until 1950 when both average ship velocity and the number of ships in operation began to increase (Laist et al. 2001). However, records of ship strikes underestimate the true number of mortalities that result from collisions due to several types of bias (Douglas et al. 2008). Whales struck in remote locations are unlikely to be recovered, and differential decomposition rates and trauma in dead whales can all affect the assessment of cause of death; additionally, certain species are more likely to become wedged on a ship’s bow during collisions, and thus be recovered. (Douglas et al. 2008). Finally, mariners may not report collisions due to a fear of repercussions. These sources of bias lead to uncertain estimates of the true number of whales injured and killed due to ship strikes, as cetacean carcasses may only be recovered in 2% of deaths (Williams et al. 2011). For this reason, it is necessary to improve the capacity of vessel operators to avoid ship strikes in the first place by better understanding whale movement and detectability in the vicinity of ships.

A great deal of work has been done to passively reduce the risk of collisions between ships and whales. Shipping lanes have been moved in the Bay of Fundy, New Brunswick (Vanderlaan et al. 2008), in Boston, Massachusetts, and in San Francisco Bay, California, which enables mariners to “passively” avoid whales by utilizing the new shipping lane designations. Seasonal management areas have been created, where ship speed is regulated, to protect northern right whales on the United States east coast (van der Hoop et al. 2014), which enables “passive” reduction of lethal ship strike risk since vessels that travel more slowly are less likely to kill whales below a certain threshold. Acoustic arrays have been deployed around Stellwagen Bank to alert mariners that northern right whales have been detected nearby. Finally, mobile applications, such as Whale Alert, have been developed to advise mariners of whales in the area. However, while this work has been critical to reducing the probability of spatiotemporal overlap between whales and ships, it has all occurred at a much bigger spatial scale than the very small area in which individual encounters between ships and whales occur. Even if these types of landscape-scale or region-based tools to passively reduce ship strike risk have been implemented and ship strike risk has thus already been mitigated, in the event that a whale still surfaces in the path of a ship, collision avoidance ultimately requires vessel operators to respond quickly and appropriately, and it is this process that merits future study. Understanding the whale behavior and the associated detection process by vessel operators that drives each individual encounter between a ship and a whale is necessary in order to quantify strike risk and make management recommendations that are appropriate on the scale of a single vessel, whose operators can engage in active whale avoidance.

Active whale avoidance refers to the process of mariners intentionally changing course and/or speed in response to a sighted whale. Active whale avoidance is common – and often required – for smaller vessels, and it is also used on many larger ships such as cruise vessels. On cruise ship, active whale avoidance is conducted by personnel on the navigational bridge. The "bridge" is typically one or more decks above the forward-most bow with a view of the entirety of the water from 180 degrees abeam of the port side to 180 degrees abeam of starboard. It is the responsibility of the captain, pilot, and officers who are "on watch" to scan for whales. When a whale is sighted near the ship's path, its location and bearing are called out. Cruise ships may employ an extra person "on watch" in areas of high whale densities. The decision to initiate a turn depends on how far ahead the whale is sighted, how close to the ship's intended path the whale surfaced, and if discernible, whether the whale is traveling into the ship's path or away from it. In most cases, ships will only slow down or initiate a turn if warranted, at least in part because it costs time and money to alter course and speed. In contrast, some types of large cargo and container ships have a very limited view of the water in front of the bow, and thus may not be able to initiate active whale avoidance at all.

If a whale is sighted in the path of a ship, vessel operators can then make a decision regarding whether or not to change course or speed to reduce the chance of collision. They will likely make this decision based on a several variables, including ship speed, weather conditions, water currents, and the locations and headings of other vessels. In southeast Alaskan waters, sea pilots licensed by the state and the United States Coast Guard are required to be aboard large cruise ships (“http://www.seapa.com/” n.d.). These pilots are extremely experienced at maneuvering large crafts in these particular narrow waterways, and they work with the ship captain and officers to make decisions regarding active whale avoidance that are specific to conditions faced during the particular ship-whale encounter.

While application of active whale avoidance efforts to large ships has the potential to reduce collision risk within a maritime sector that is very likely to be involved in lethal collisions due to the size and momentum of this type of vessel, implementation faces significant constraints. Unlike small vessels that can rapidly turn and change speed, large ships are not designed for quick maneuvers. Abrupt changes in heading, such as a sudden turn of 10 degrees, can have severe negative implications for large vessels; cruise would ships run the risk of compromising passenger safety and even draining swim pools. Thus, marine pilots often build up turns over time to achieve a change of heading.

Ascertaining a whale’s direction of travel is thus fundamentally important in the context of active whale avoidance, since determining whether or not a whale sighting merits an avoidance maneuver is highly contingent on its movement behavior. Whales are almost always moving forward in the water when they surface to breathe, and vessels must respond differently to whales that are traveling into the path of the ship than they would to whales traveling away from the path of ship, when they may not need to make an avoidance maneuver to reduce the chance of a collision. This leads into our research objectives for Chapter 2, in which we sought to quantify the probability of vessel operators being able to assign a direction of travel (DT) other than “unknown” to a whale in the vicinity of the ship, and to quantify the probability of vessel operators being able to make congruous DT assignments.

However, implicit in active whale avoidance is the successful detection of whales. Despite decades of work on ship strike risk reduction, the challenge of detecting whales from ships continues to impair the ability of vessel operators to actively avoid them. The detection process can be divided into two main parts: the availability process and the perception process (McLaren 1961, Marsh and Sinclair 1989). The availability process is concerned with animals being visible to observers within the survey range. Whales are typically only available for detection when they are breaking the surface of the water.

The perception process refers to the probability of detecting an animal that is available to be detected. Variation in the probability of perception is a function of a multitude of factors, including the distance between the observer and the animal and visibility conditions (Barlow 2015, Williams et al. 2016). Perception probability decreases as distance increases and as visibility decreases. Visibility is affected by many factors, including precipitation, fog, sun glare, and wind. Additionally, whale surfacing behaviors are differentially detectable (Williams et al. 2016), and large groups of whale whales surfacing together are more perceptible than singletons. While the detection process has been studied and modified to apply to both abundance estimation and collision avoidance, the behavior of the whales that go undetected has not specifically been considered in the context of ship strike risk. This leads to our research objectives for Chapter 3, in which we aimed to quantify two major pieces of the whale detection process that are important for active whale avoidance. We sought an unbiased estimate of humpback whale availability to be detected around large ships, and we sought an unbiased estimate of humpback whale presence in areas where they were at risk of being struck by ships. Understanding the ways that whales surface around ships and how they relate to the probability of vessel operators detecting them and thereby having the opportunity to avoid them is very important for development of best practices in ship strike avoidance for large vessels.

Humpback whale respiration patterns may vary according to movement mode, behavior, presence on feeding or breeding ground, and level of disturbance, among other factors. The number of breaths per surfacing bout for long follows of two tagged humpback whales on their feeding ground ranged from 3 to 18 breaths, while dive durations for the same two whales ranged from approximately 2 to approximately 10 minutes (Goldbogen et al. 2008). Previous work found that the average length of a humpback whale surfacing bout on the feeding ground was 1.1 minutes +- 2.3, while the average number of blows during the surfacing bout was 6.5 +- 8.3 and the mean blow interval was 0.3 mins, or 18 seconds (Dolphin 1987a).

Typically, humpback whales do not dive deeper than 120 meters (W.F. Dolphin, 1987). Additionally, the dive depth is positively correlated with both the number of spouts per surfacing bout, and with the duration of dives and surfacing bouts (W.F. Dolphin, 1987). More recent work at a finer resolution found that the number of feeding lunges initiated within a single foraging dive increases, the duration of the following surfacing bout increased, as did the number of breaths during that interval (Goldbogen et al. 2008), which may show that whales that engage in more feeding lunges while at depth need more time to recover at the surface before resuming foraging. Humpback whale feeding strategy and location in the water column may be associated with the diel movement patterns of their prey (Friedlaender et al. 2009). On the feeding ground, maximum dive durations (10 minutes, (Goldbogen et al. 2008)) are approximately half of the maximum dive durations recorded for singing humpback whales (20 minutes, (Chu 1988)), indicating that feeding may be more energetically demanding than singing. Thus, respiration rates and patterns vary according to the ecological context in which the whales are located.

Background on study system

Glacier Bay National Park and Preserve (GLBA) in Southeast Alaska (Figure 1-1) offers an excellent place to study the factors affecting ship strike risk because it is a popular cruise ship destination, and it also serves as the summer feeding ground for a portion of the Central North Pacific stock of humpback whales (Neilson and Gabriele 2007). The number of whales feeding in Glacier Bay has increased by 4.4% per year for the last 25 years (Saracco et al. 2013). Ships that enter GLBA average 270m in length (Webb and Gende 2015), and along with other vessels, they are required to adhere to variable 20-knot and 13-knot speed limits in different areas, which vary according to season and whale density. A maximum of two ships is allowed to enter GLBA each day, yielding a maximum of four total daily transits between the mouth of the bay and the head of the fjord. There is a 153-use-day quota for a 92-day prime use season covering June through August (Glacier Bay National Park & Preserve 2018), which coincides with the peak use of GLBA by humpback whales. The National Park Service (NPS) is mandated to both protect its resources for future generations and to enable the public to use and enjoy the park, which happens primarily through cruise ship entries in Glacier Bay.

Shipboard humpback whale surveys have been conducted in GLBA for over a decade in order to study the interface between ships and whales (Figure 1-2). Survey protocols remained constant from 2008 – 2015, and in 2016 they changed slightly to enable more detailed data collection on durations of behaviors. While observers are stationed a few decks below the navigational bridge and further forward, we assumed that observation from the bow can be used as a proxy for observation from the bridge (Williams et al. 2016). Many personnel may be present on the bridge at any given time, but often only a single person is designated as the primary lookout.

Past work in this study system has suggested that vessel speed regulation is an effective measure to mitigate the severity of encounters between ships and whales (Gende et al. 2011, Harris et al. 2012), quantified the detection probability of the initial sightings of humpback whales (Williams et al. 2016), and showed that the probability of whales switching movement type in the presence of ships is low (Williams 2017). These studies lend insight into some of the ways that ships and whales use coexist in Glacier Bay, and we aim to add to this body of work by specifically studying two components of ship strike risk. Here, we quantify the probability that a humpback whale is in the “strike zone” (Rockwood et al. 2017), or portion of the water column where it’s at risk of being struck, and the ability of a humpback whale’s direction of travel to be determined by a ship operator. This study will contribute important data to this comprehensive, long-term study of ship strike risk to humpback whales in Glacier Bay National Park (Table 1-1). Throughout this document, the term “whales” refers specifically to humpback whales.

TABLES

Table 1-1. Outcomes of previous work describing and quantifying variables related to ship-whale collisions in Glacier Bay National Park and Preserve.

Variable	**Outcome**	**Authors**
Whale density around ships	Higher in certain areas of GLBA	(Williams 2017)
Whale movement around ships	Whales rarely switch movement types around ships	(Williams 2017)
Whale detection probability at first sighting	Depends on visibility conditions and ship-to-whale distance	(Williams et al. 2016)
Ship speed	Ships encounter whales on average 114m closer when speed is greater than 11.8 knots	(Gende et al. 2011, Harris et al. 2012)
Ship activity	Ability to shift transit route away from whales is limited	(Webb and Gende 2015)
Ability of pilot to determine whale direction of travel	**Refer to Chapter 2**	
Whale presence in strike zone	**Refer to Chapter 3**	

FIGURES

Figure 1-1. A map of the study area (Glacier Bay is the fork-shaped bay in the circular inset map) with superimposed ship tracks recorded using a handheld GPS during shipboard surveys conducted in Glacier Bay National Park and Preserve in 2016 and 2017. Glacier Bay is in southeast Alaska.

Figure 1-2. Photographs of an observer conducting shipboard humpback whale surveys in Glacier Bay. This equipment setup is typical of most surveys, although ship bow shape varies slightly among vessels, and thus the observer may be positioned at varying distances from the rail.

CHAPTER 2: CHALLENGES FACED BY LARGE VESSEL OPERATORS SEEKING TO AVOID SHIP-WHALE COLLISIONS WHEN A WHALE’S COURSE IS UNKNOWN

ABSTRACT

Collisions between ships and whales (“ship strikes”) have the potential to influence the population persistence of many species of large whales across the globe. Substantial research on broad-scale efforts to reduce ship strikes, which we term “passive collision avoidance,” has led to advances including mobile application development, establishment of “areas to be avoided,” passive acoustic monitoring, and the readjustment of shipping lanes in response to high-density aggregations of whales. In contrast, the processes driving “active whale avoidance,” which refers to evasive maneuvers by vessels, are markedly less-studied. One important and heretofore unstudied component of active whale avoidance from large ships is the ability of ship operators to determine a whale’s direction of travel (DT, or “heading”) if it surfaces in the ship’s path. Determining a whale’s DT enables a ship operator to initiate an appropriate avoidance maneuver, which may include turning or slowing down. We investigated DT assignment from two perspectives: first, the elapsed time required to determine a whale’s DT after the initial whale sighting, and second, the probability of making a “congruous” (consecutively identical) DT assignment. First, our model indicated that the probability of DT assignment is primarily a function of time since first sighting, and that the probability of DT assignment decreases very slightly with increasing distance. We found that the probability of DT assignment is approximately 75% one minute after the first sighting. Second, we determined that congruous DT assignment is a function of ship-to-whale distance, cue number, and visibility conditions. We found that even very close to ships (i.e. less than 1000m), less than 50% of DT assignments are congruous at the first sighting when there are 2 or fewer whale cues. Our results highlight the

difficulty of determining a whale's heading from large ships, particularly if the whale has only surfaced a small number of times. We recommend that ship operators focus attention on detecting whales in the ship's path as far ahead as possible so that they may initiate small turns early and avoid coming into close enough proximity to whales that determining DT is necessary to make the correct avoidance maneuver.

INTRODUCTION

The greatest anthropogenic threat facing many species of great whales is lethal collisions with vessels. This is true of North Atlantic Right Whales (*Eubalaena glacialis*) (Nowacek et al. 2001), blue whales (*Balaenoptera musculus*) (Monnahan et al. 2015), fin whales (*Balaenoptera physalus*) (Rockwood et al. 2017), and humpback whales (*Megaptera novaeangliae*), among others. While many whale populations are increasing, ship-whale collisions ("ship strikes") are still a concern because they affect the adult survival probability of species which are otherwise typically long-lived with low fecundity. Thus, an increase in incidence of ship strikes could decrease whale survival rates and thereby drastically impact the reproductive potential of many species. For example, the age of first parturition for humpback whales is five years, with a mean estimated birth interval of 2.38 years (Barlow and Clapham 1997) for a single calf. This slow life history strategy could be strongly affected by changes in adult survival rate.

Given the ubiquity of ship strikes around the world and the concern that this creates for whale population persistence, estimates of the Potential Biological Removal for United States waters (PBR; the maximum number of individuals, not including natural mortalities, that can be removed from a marine mammal stock before affecting the stock's ability to reach its optimum sustainable population; (NOAA 2018b)) have been forecast for several species. In the United

States alone, current whale mortality from ship strikes is estimated to be 2.0 times higher than PBR for humpback whales, 2.7 times higher than PBR for fin whales, and 7.8 times higher for blue whales (Rockwood et al. 2017).

Collisions are continuing to occur despite a great deal of important work that has been done on a broad scale to reduce the probability of spatiotemporal overlap between ships and whales (Vanderlaan and Taggart 2007, Vanderlaan et al. 2008, Redfern et al. 2013, Dransfield et al. 2014). We refer to these broad-scale efforts to reduce ship strikes as “passive ship strike avoidance.” However, it is important to work at the vessel level to elucidate the factors that affect “active ship strike avoidance,” or intentional evasive maneuvering, since this is where any last-minute avoidance decisions will be made. These vessel-level factors may relate to any of three processes: first, how the whale is moving in relation to the vessel; second, how the vessel is moving in relation to the whale; and third, how the vessel operator detects and responds to a whale in the ship’s path. Here, we will focus on humpback whales, which are behaviorally similar to other baleen whales, but whose larger population size leads to the potential for a greater number of ship strikes.

To address the first factor, substantial work has been done to understand the ways that humpback whales move in relation to vessels, although both metrics and results are variable and have primarily been viewed through the lens of human effects on whales rather than the ways that whale behavior drives vessel strike risk. Research has been conducted on both their low-latitude breeding and high-latitude feeding grounds, primarily around small and mid-sized vessels. On the breeding grounds, presence of mid-sized vessels (12-16m in length, (Stamation et al. 2010)) did not affect blow rates (Corkeron 1995) or dive rate (Stamation et al. 2010), but mean dive time was greater in the presence of vessels (Stamation et al. 2010). On the feeding grounds, the presence of vessels did not affect blow rates (Baker and Herman 1989), but whales increased dive time and moved away from vessels when they were within 4000m (Baker and Herman 1989). Other ways that whales have the potential to shift behavior around ships include changing the relative proportions of time they spend transiting, feeding, sleeping, and breeding, and their propensity to switch between movement modes. Thus, study of perceived whale attention and sensory engagement during different behavior modes has the potential to inform collision risk. However, across the spectrum of whale behavior, studies of whale responses to large vessels such as container ships, tankers, and passenger cruise ships are underrepresented in the literature. It is critical to address this gap because large ships are louder, less maneuverable, and have more momentum than smaller vessels. This means that collision avoidance is more challenging, and in the event of a ship strike, it is more likely to be lethal.

The second factor driving vessel strike risk is the variable way that vessels move in relation to whales. Vessel movement depends on the type of craft, which in turn dictates its maneuverability, operational speeds, and routes. Vessel types are highly variable, and include small skiffs, yachts, fishing boats (with associated gear), research crafts, military vessels, and container ships. Vessel movement may be driven by the passengers' intentions (pleasure vs. profit), schedule flexibility (i.e. when the vessel is due at the next port and how much leeway is available), and fuel cost concerns. Here, we aim to study large vessels on tight schedules with the preference of minimizing fuel costs because their movement patterns offer insight into ship strike avoidance in a setting where the initiation of fewer turns is desirable.

The third factor driving ship strike risk is how the vessel operator detects and responds to whales in the ship's path. The detection process is typically described as a combination of two components: the availability process and the perception process (McLaren 1961, Marsh and

Sinclair 1989). The availability process drives whether whales are visible to an observer, which requires breaking the surface of the water when whales are being detected from large ships. The perception process involves an observer detecting a whale that is available, which is affected by visibility conditions and ship-to-whale distance (Barlow 2015, Williams et al. 2016). However, for ship strike avoidance, pilots are not only concerned with detecting whether a whale is present and at risk of collision; they must also determine the direction of travel (DT or “heading”) of any whale that is sighted. This is a key component of active ship strike avoidance, and it is an important knowledge gap in the ship strike literature.

It is important to consider the context in which large vessel operators must assign whale DT because it is quite different from whale observation from many other survey platforms. The field of view that must be monitored by bridge personnel on large ships is disconcertingly enormous. Since the navigational bridge is typically between the sixth and eleventh story, or “deck,” the field of view is drastically larger than one might experience on a smaller vessel. Passengers who are unfamiliar with the scale of the landscape routinely mistake large seabirds on the water’s surface for insects, and the walls of Glacier Bay’s fjords are so tall that they appear to be at arm’s length when they are in fact several kilometers away. In a landscape this size, humpback whales that are farther than two or three kilometers appear as small black dots. At distances around five or six kilometers, most whales are only visible in binoculars, but in good conditions, whales may be detected up to approximately twelve kilometers away. This context is intended to describe the circumstances faced by vessel operators attempting to assign whale DT when the animals may be at a great distance and when they are only available for detection for a few moments at a time.

Here, we examine whale DT assignment from two perspectives. First, we estimate the probability of making a DT assignment other than "unknown" as a function of the elapsed time after the first sighting occurs and ship-to-whale distance. Second, we estimate the probability of making a congruous (consecutively identical) DT assignment as a function of ship-to-whale distance, visibility, and cue number. In combination, these analyses elucidate the primary challenges faced by large vessel operators when making decisions about appropriate active ship strike avoidance maneuvers.

METHODS

Field Methods

Humpback whale surveys were conducted on 79 days in Glacier Bay from late May through mid-August in 2016 (n = 41 days) and 2017 (n = 38 days), using large passenger cruise ships as platforms of opportunity (Table 2-1). Survey effort totaled 464.8 hours of observation over the two summer seasons. Each of the 79 survey days ("cruises") was divided into two survey periods of approximately equal length: a northbound transit (morning) and southbound transit (afternoon). Cruises were divided into two transits to accommodate a multi-hour break in survey effort while the ships remained at the head of the fjord for glacier viewing where whales are very rarely seen. The first 3 cruises of 2016 were excluded from the data set due to observer training, and 11 other cruises were excluded due to data transcription difficulty. Two southbound surveys in 2017 were excluded due to gear malfunctions. Ultimately, this yielded data from a total of 65 cruises over two years used for this analysis.

On each survey day, a single observer boarded a designated cruise ship just inside the mouth of Glacier Bay via a transfer vessel which departed from the NPS headquarters in Bartlett Cove. Beginning shortly after boarding, surveys were conducted continuously throughout each morning as the ship transited northbound from the Lower Bay to the glaciated ends of the West Arm. Surveys did not extend to the northern part of Tarr Inlet and the western part of Johns Hopkins inlet due to a known absence of whales. Surveys were then reinstated as each ship retraced its path south through the bay. Southbound surveys continued until the southern portion of Sitakaday Narrows near Bartlett Cove, yielding a mean of 5.9 hours on effort during each cruise (sd = 0.6 hours). As a result of navigational constraints and speed regulations within the National Park, all ship transits traced similar tracks through the bay (Figure 2-1) at comparable speeds.

Once positioned on the forward-most bow of the ship, scans were conducted using a combination of the naked eye, Swarovski 10 x 42 binoculars, and tripod-mounted (Manfrotto Distribution Inc.; 055 Series; Upper Saddle River, NJ, USA) laser rangefinder binoculars (Leica Viper II; accuracy +1 m at 1km; Leica, Charlottesville, VA, USA) to search for whales. Scans completely covered the 180-degree range from abeam of the port side of the navigational bridge (the “bridge”) to abeam of the starboard bridge. Scans alternated between naked-eye and optics-assisted scans to cover the water’s full extent from near the ship to the limit of the optics (approximately 12 kilometers in excellent visibility conditions). When a whale was detected, the ship’s location was geospatially referenced using a handheld Global Positioning System, or GPS (Garmin 76Cx, Olathe, Kansas, USA), and the distance between the observer and the whale was measured using the rangefinder binoculars. If a surfacing was too brief or too far away to make contact between the laser range-finder and the whale, the ship-to-whale distance was estimated. Intermittently throughout each transit, the accuracy of the observer’s distance estimation was checked by recording estimated distances to locations throughout the bay and checking the estimate using the rangefinder binoculars. Accuracy of distance estimation decreased slightly as distance increased but exhibited no bias, and a linear regression of estimated distance on measured distance yielded a slope of 0.966 and a multiple R-squared value of 0.946 (Figure 2-2). Accuracy of distance estimation to objects that were similar in size and location to whales (e.g. rocks and icebergs) appeared to be estimated relatively accurately. Observer accuracy was not tested past the limits of the laser rangefinder (approximately 5500 meters).

The observer recorded 22 variables describing whale behavior, ship location, and environmental conditions (Table 2-2). Observations were recorded using a digital voice recorder (Olympus Imaging America Inc.; VN-702PC; Center Valley, PA, USA) and a Rite-in-the-Rain notebook (J.L. Darling LLC; Tacoma, WA, USA). This survey protocol used a modified individual-follow approach (Mann 1999). After the observer detected an initial cue, they focused on the area where the whale was detected. They continued to record data until a terminal dive was observed, the ship passed abeam of the whale, or the whale did not resurface. The voice-recorded data collected from each transit was saved as an .mp4 file. The observer then personally transcribed the data from each of the files using version 2.1.2 of Audacity ® recording and editing software (Audacity Team 2018).

While conducting surveys, any whale sightings within 10 degrees of the ship's heading were communicated to the personnel on the navigational bridge, including the captain, pilot, and officers, using a marine VHF radio. On some ships, the bridge personnel also periodically communicated humpback whale sightings to the observer. Additionally, a separate NPS radio was carried aboard during surveys to periodically communicate with the NPS whale biologists on their research vessel on the rare occasions that they were working in the same region of the bay. In these cases, whale sightings were reciprocally shared between the two research groups. Harbor seal (*Phoca vitulina*) and sea ice levels in the heads of the fjords were recorded and communicated to NPS Resource Management employees on a weekly basis, and orca (*Orcinus orca*) sightings were reported to the orca biologist as soon as possible without interfering with humpback whale data collection. Finally, close encounters between ships and whales were reported to the Chief of Resource Management as soon as possible. Close encounters were defined as any encounter when a ship came within 200m of a whale. All research was conducted under observational permits from the University of Montana Institutional Animal Care and Use Committee ("Confronting the challenges of whale detection: Implications for ship strike avoidance," 021-16PLWBP-041216 and 010-17PLWB-022317), as well as under research permits from Glacier Bay National Park and Preserve (GLBA-2013-SCI-0014 and GLBA-2017-SCI-0005).

Each whale's direction of travel in relation to the ship's heading was recorded at each sighting. Nine factor levels were used to describe DT, including the eight major axes of the compass plus "unknown" (Figure 2-3). A whale's DT was recorded as "unknown" unless it was determined to be traveling in a particular direction with at least some degree of belief. The option of "unknown" was included to reduce the chance that a DT would be assigned by "best guess."

Statistical Methods

Time to First Direction Assignment

We implemented a Cox proportional hazard regression analysis (Cox 1972) to estimate the time duration between the first sighting of a whale and the first DT assignment that was not "unknown." We were interested in estimating the time to first DT assignment because we suspected that the timing of the transition from unknown to known DT was important for clarifying active ship strike avoidance recommendations, especially if the amount of time required to make a DT assignment was greater than or similar to the length of the period within which an evasive turn must be made in order to avoid a collision.

We considered testing the effects of three different covariates on time to DT assignment. For our first two covariates, we selected distance and visibility because they are both known to affect detection probability of whales in general (Williams et al. 2016), and DT assignment is simply a different type of detection process. We hypothesized that increasing distance and decreasing visibility would each decrease the probability of making a correct DT assignment. Distance was recorded as a continuous variable and was truncated at 10000m due to a small sample size at farther distances. Visibility was recorded as a categorical variable with four levels: "excellent," "good," "poor," and "poor-fog" (Williams et al. 2016).

For our third covariate, we selected the "cue number" in the surfacing bout at which point the DT was assigned. For example, consider a surfacing bout consisting of three surfacings separated by 20 seconds, where each surfacing consists of two cues (a spout and a back), yielding a total of six cues in the bout. We hypothesized that having more opportunities to see a whale would improve the accuracy of the DT assignment. In our example, this would mean that the DT assignment at cue five (seen approximately 40 seconds after the first sighting) would be more accurate than the DT assignment at cue one (seen at zero seconds after the first sighting).

We conducted all analyses in R 3.4.3 (R Core Team 2017) using packages 'survival' (Therneau 2015) and 'survminer' (Kassambara and Kosinski 2018). Before proceeding, we tested model assumptions. The assumption of non-informative censoring was met because the probability of a DT assignment was not related to the censoring of individual subjects. However, a Schoenfield Individual test, which assesses the independence of residuals and time, revealed that cue number violated the proportional hazards assumption. This is logical, since cue number is functionally an alternative measure of the passage of time. As such, we did not include this covariate in our model set. We tested the assumption of linearity for the single continuous covariate, distance, since this assumption does not apply to the categorical visibility covariate. We plotted the Martingale residuals against distance and found that the relationship was linear enough to satisfy this assumption. We visualized influential observations for both the distance and visibility covariates by plotting the estimated changes in the coefficients as a result of removing each observation, divided by their standard errors. While this produced some large dfbeta residuals, especially for visibility, the majority were clustered relatively close to zero and we felt the assumption was not violated. As such, we fit three candidate Cox proportional hazard regression models (Table 2-3). Since this model type is nonparametric, we could not directly compare the non-nested models containing distance and visibility. However, since visibility was not significant in the univariate ($p = 0.29$), bivariate ($p = 0.39$), or interaction ($p = 0.17$) models while ship-to-whale distance was significant in the univariate model ($p = 0.0016$), we decided to move forward using the most parsimonious, univariate model containing only distance.

Probability of Congruous Direction Assignment

A binary variable indicating whether or not an observer congruously determined DT was constructed by comparing consecutive DT assignments within each surfacing bout. For example, if the observer estimated DT as “away” at both the first and second surfacing, then this was recorded as a “1”, or congruous, in the new variable corresponding to the first surfacing. The “1” was recorded for the first surfacing (and not the second surfacing) because the second surfacing was functionally used to check the DT estimation at the first surfacing. If either of the two consecutive DT assignments did not match, or two consecutive DT assignments were recorded as "unknown," then the corresponding element of the new variable was coded as a "0", or incongruous, at the first surfacing.

We compared consecutive whale DT assignments and estimated the probability of a congruous assignment because our survey design did not enable us to measure a whale's true direction of travel and compare our shipboard observations to that truth. Instead, we needed to develop the closest possible approximation to a "correct" whale DT assignment. Defining a congruous DT assignment as the second of two consecutive, identical DT assignments serves this purpose. However, it is not the same as a correct DT assignment because it encompasses multiple mechanisms. A congruous DT assignment may indicate that either the whale is consistently moving in a single direction, or that the observer misidentified the whale's DT twice in a row. Conversely, an incongruous assignment may result from a whale changing directions during a surfacing bout, or the observer misidentifying the whale's direction at one of the two surfacings. While it would be ideal to estimate the probability of a correct DT assignment, it is still useful to estimate the probability of a congruous DT assignment because in the context of active ship strike avoidance, it is important to understand the probability of a vessel operator assigning a DT that remains consistent within a surfacing bout. Since pilots do not know a whale's true direction of travel in real time, their perception of the whale's direction of travel – which is captured in our definition of a congruous DT assignment – informs whether the whale's trajectory merits the initiation of an evasive turn.

We tested the effects of three covariates – whale-to-ship distance, visibility, and cue number – on the probability of making a congruous DT assignment for the reasons described in the previous sub-section. We used logistic regression to estimate the probability of congruously assigning DT in order to accommodate the binary response variable (congruous/incongruous).

Our data met all of the assumptions and conditions of the model: there was no multicollinearity between the predictor variables, there was linearity between the predictors and the log odds, and we had an appropriately large sample size. Although our data were drawn from consecutive related observations, they met the assumption of independent observations because we incorporated the dependent observation pairs into each element of the response variable (congruous or incongruous). Thus, after constructing the response variable, the elements were independent.

While the analysis was conducted on the full range of cue numbers (range: 1 – 39), for visualization purposes in the results plot, the cue number covariate was binned into five categories. The bin boundaries were constructed in advance in order to approximate equal sample sizes across bins. All surfacing bouts were used, and those whales for which a DT was never assigned before the whale either passed abeam or initiated a terminal fluke-up dive were assigned an event of “0” (i.e. the event of interest, or DT assignment, did not occur).

As for the previous analysis, we used R 3.4.3 (R Core Team 2017). We fit nine candidate logistic regression models (Table 2-4) consisting of additive and interactive effects from the three covariates using the ‘glm’ function in the package ‘stats’ (R Core Team 2017). To assess model fit, we visually inspected residual plots, plots of residuals vs. leverage, and quantile-quantile plots, and all were acceptable. Less than 1% of observations were extreme outliers. The top model was selected using Akaike’s Information Criterion (AIC).

RESULTS

In this analysis, we used 4448 observations of 869 surfacing bouts produced by single whales. The number of observations per surfacing bout ranged from 1 to 39.

Time to First Direction Assignment

Overall, our univariate model estimating the effect of ship-to-whale distance on DT assignment shows that the probability of a pilot being able to make a DT assignment increases with time since the first sighting. The extremely small, negative coefficient on distance (coefficient = -0.0001, SE < 0.000, Table 2-3) indicates that the probability of making a DT assignment decreases only very slightly as distance increases (Likelihood Ratio Test = 19.11, p = 0.000; Wald Test = 18.22, p = 0.000).

Our results suggest that at the first sighting (time = 0 mins), the probability of assigning DT is around 0.5 (Figure 2-4) averaged across whales sighted at all distances. DT assignment probability increases quickly for the first minute after sighting, after which time the rate of increase of the slope decreases until the probability of DT assignment is near 1.00 around 8 minutes after the first sighting. Our results indicate that DT will be assigned for approximately 90% of whales by five minutes after the first sighting.

Probability of Congruous Direction Assignment

The top model predicting the probability of a congruous DT assignment incorporated two covariates: ship-to-whale distance and cue number. Overall, the model showed that accuracy of DT assignment decreases as ship-to-whale distance increases and as the cue number decreases. The model showed marked differences in the probability of making a congruous DT assignment among binned values of the cue number covariate, especially at closer distances (Figure 2-5).

For single or first surfacings that occur very close to the ship, observers can only expect their observations to be congruous approximately 30% of the time. This probability decreases (only slightly) to approximately 20% of the time as ship-to-whale distance increases to 10000m. In contrast, observers can expect to congruously assign DT for whales that surface eight or more times around 85% of the time if they're within 2000m, and this drops off at a higher rate as distance increases. Variability in the congruousness of DT assignment increased as ship-to-whale distance increased.

DISCUSSION

Time to First Direction Assignment

We used a Cox proportional hazards regression model to examine the impacts of ship-to-whale distance and time since first sighting on the probability of DT assignment in order to develop recommendations for active ship strike avoidance.

It is well-documented under distance sampling theory that increasing the distance between an observer and an animal usually decreases the detection probability (Buckland et al. 2001). Since the DT assignment process could be considered a different type of detection process (i.e. detection of a direction of travel), we hypothesized that an increase in ship-to-whale distance would lead to a decrease in the probability of DT assignment, and that it would therefore take more time for ship operators to assign DT at farther distances. While our model suggests that this is indeed the case, the effect size is extremely close to zero. This indicates that in practice, when designing recommendations for active ship strike avoidance procedures, considering the length of time after first detection on the ability of ship operators to assign DT may be more important than incorporating ship-to-whale distance.

It is somewhat surprising that the probability of assigning DT at the first sighting (i.e. time = 0) was only 50% over all distances. Initially, reason might lead one to believe that first sightings within close range of a ship would yield substantially higher proportions of DT assignments than first sightings at far distances, which would therefore increase the impact of the distance covariate, and which would make the probability of assigning DT higher at the first sighting at close distances. However, many first sightings of whales are spouts (Figure 2-6). This is probably the case because spouts are light-colored, extend several meters into the air, and remain there for a few seconds before dissipating. The bodies of whales, which are necessary to determine DT, tend to blend into the water and may not be seen on the initial detection. It is near-impossible to assign a direction of travel to a whale whose presence is only indicated by a single spout in the absence of other cues, which may explain why time since first sighting is an important predictor of DT assignment probability.

The influence of time since first sighting on whale DT assignment highlights the importance of ship operators making every effort to maximize their individual perception probability. Our results show that each time a surfacing is not perceived – and by definition, more time passes – the DT assignment process is delayed. This is especially important in southeast Alaskan waters, where the large passenger cruise ships (averaging 270m in length, (Webb and Gende 2015), must initiate whale avoidance maneuvers at whale-to-ship distances of no less than 500m in order to be successful (Williams et al. 2016). Since whales are only available for detection intermittently when they respire, missing a surfacing could equate to delaying the DT assignment process by seconds or even minutes, during which time the ship can travel a substantial distance.

It is worth noting that whales will inevitably surface for the first time directly in the path of a ship just beyond the 500m required to initiate a turn, but close enough that a turn must be initiated nearly immediately in order to successfully avoid a collision. Actively avoiding a whale in this context will likely come down to the pilot’s reaction time and the whale’s behavior, including whether the whale actively moves out of the path of the ship. However, this same whale would have engaged in a surfacing bout previously, albeit far ahead of the ship's path. If the ship operator was able to detect the whale during its previous surfacing bout, even if it was not possible to assign DT, it could adjust the route well in advance so the whale would never enter the conceptual "cone of concern," or the three-dimensional, relatively cone-shaped area in front of the ship where a whale is at risk of ship strike (Figure 2-6).

Our finding that the elapsed time since the first sighting is more important than ship-to-whale distance on the probability of DT assignment has important ramifications for best practices for ship operators, because it indicates that the fastest way to make a DT assignment is simply to detect the whale as early as possible. While ship operators are excellent at detecting whales due to a great deal of practice and experience, they have the opportunity to focus on different parts of the water around the ship to search for whales, which may vary according to direction they receive from different captains or pilots. Our work suggests that assigning a watch specifically to areas of the water that are very far ahead from the ship may enable earlier detection of whales that can lead to earlier assignment of DT.

Probability of Congruous Direction Assignment

We used logistic regression to examine the impacts of ship-to-whale distance and cue number on the probability of congruous DT assignment in order to develop recommendations for active ship strike avoidance.

On the scale of individual vessels, collision avoidance requires pilots to obtain two pieces of information. First, they must detect if a whale is present within the cone of concern. Second, if a whale is present in the cone of concern, then they must determine the whale's direction of travel. This enables pilots to initiate an appropriate turn in response to the whale's location and heading relative to the location and heading of the ship.

Determining a whale’s direction of travel is especially critical when the whale’s bearing is within a few degrees of either side of the ship’s heading. Humpback whales can swim up to 4.1 m/s (Straley et al. 2017). If a whale is first sighted at fifteen degrees to either starboard or port and the ship-to-whale distance is 1500m, it will initially appear that the ship will pass clear without altering its course (albeit passing relatively close to the whale). However, using simple trigonometry, we find that even if the whale traveled directly into the ship’s path at a more moderate 3 m/s, it would cover those 388m ($1500 * \sin(15^\circ)$) in 2.2 minutes. In that time, a ship whose course remained true and whose speed was a typical 18 knots would reach the place where the whale’s path intersected the ship’s path in 2.7 minutes. Assuming that neither the ship nor the whale changed course in response to each other, if either the whale or the ship’s speed varied slightly, there is substantial risk of ship strike.

Now, given this general scenario, we consider how our model informs the probability of a pilot ascertaining the whale’s direction of travel to avoid a potential collision. At a first sighting at a distance of 1500m, a pilot will make a congruous DT assignment 38% of the time. Assuming a median inter-cue interval of 20s (during which time the ship has traveled forward 184m and the whale has traveled 60m perpendicularly toward the ship’s path), the second sighting of the whale will occur at a distance of 1307m. According to our model, a pilot would make a congruous DT assignment 44% of the time under these conditions. If the whale then entered another 20s dive, at the third surfacing, the ship-to-whale distance would be 1113m and the pilot would make a congruous DT assignment 51% of the time. This bodes well for whales that remain available for detection by repeatedly breaking the surface of the water and affording pilots the opportunity to detect more surfacings as distance decreases, which taken in tandem, increases the probability of congruously assigning DT. But for the whales that have longer-than-average inter-cue intervals, the strong probability that a whale could surface three times at relatively close range and still have an unknown direction of travel is highly concerning.

Our model suggests that the probability of making a congruous DT assignment is highest when more than eight surfacings are seen at very close range. This is challenging from a ship strike avoidance perspective, because when whales are at close range, they are at a greater risk of ship strike, regardless of whether or not their DT is assigned congruously. This highlights the balance that vessel operators face: by the time a whale is close enough and has surfaced enough times to assign DT, it may be too late to initiate an avoidance maneuver. For this reason, we reiterate our recommendation from the previous subsection that vessel operators on watch focus their energy on simply detecting whales as far ahead as possible, even if it is not possible to ascertain DT, so that they can initiate small turns early and keep whales from entering the cone of concern in the first place.

This work led us to consider new questions that could be addressed by future research on the topic of whale DT assignment from large ships. Our primary recommendation for future research is to employ at least two independent observers who simultaneously assign DT at each whale surfacing. This would enable a more accurate understanding of when DT assignments are correct than we were able to capture in our measurement of congruousness (an approximation for correctness), which was necessary due to our single observer survey. Comparing data collected by multiple observers would also enable deeper insight into determining whether consecutive surfacings with different DT assignments are due to whales making many directional changes within a surfacing bout, rather than the observer incorrectly assigning DT on one or more of the sighting occasions.

We also suggest that future work investigates the impact of cue type on DT assignment and the consequences for active ship strike avoidance. For example, it is likely that DT is more easily assigned for a fluke-up dive than it is for a spout with no back or fluke visible. However, our work also indicates that the median fluke-up dive is far shorter (median = 1 second, sd = 5.576 seconds) than the other most commonly observed cues. This means that the chance to detect this cue is shorter than average, and at the same time, it is less important to detect DT on a fluke-up dive than it is on other types of surfacings because the flukes typically indicate that the whale is about to descend out of the strike zone. Quantifying the role of this particular cue type on both DT assignment and its relevance to active ship strike avoidance could yield new insights about best practices for maneuvering ships around whales that are likely descending to depth and out of the path of the ship.

CONCLUSION

Based on both our Cox proportional hazards model of the time required to make a DT assignment and our logistic regression model of the effects of distance and cue number on making a congruous DT assignment, we advise that ship operators put extra effort into detecting whales as far ahead as possible. We suggest this for two reasons. First, if a whale is detected far enough ahead that a ship can make a minor course adjustment to avoid coming into close proximity, then DT may not matter since the ability to assign it is most critical for whales that are very close to vessels and thus at greatest short-term risk of ship strike. Our Cox proportional hazards regression model supports this recommendation because it indicates that the effect of distance on the ability to make a DT assignment is very small, so vessel operators are not much more likely to assign DT at close distances than they are at far distances. Second, if a whale is first detected at a farther distance, it has more opportunities to surface as the ship draws nearer, each of which will increase the probability DT will be determined congruously. We recommend that ship companies invest in high-quality optics like binoculars and spotting scopes for pilots and officers on watch so that they can more easily detect whales farther ahead and avoid close-range encounters where the difficult-to-obtain congruous DT assignment is essential for successful active whale avoidance.

TABLES

Table 2-1. Number of humpback whale cruises conducted aboard large passenger cruise ships in Glacier Bay National Park and Preserve in 2016 and 2017.

Ship	**2016**	**2017**
Coral Princess	3	4
Grand Princess	1	0
Island Princess	5	8
Noordam	7	9
Star Princess	2	0
Volendam	12	10
Westerdam	4	0
Zaandam	7	7
Total Cruises	**41**	**38**

Table 2-2. Whale behavior and environmental variables recorded during shipboard humpback whale surveys in Glacier Bay in 2016 and 2017.

Variable	**Description**
GPS waypoint	Geospatially-referenced location of observer
Cue	A specific whale behavior used to detect presence
Group size	The number of whales in a group
Time that whale surfaced	Elapsed time since commencing survey
Time that whale dove	Elapsed time since commencing survey
Scan type at first sighting	Rangefinder, binoculars, or naked-eye scan
Whale direction of travel	Whale's estimated heading
Ship-to-whale bearing	Bearing of whale in relation to the ship's heading
Ship-to-whale distance	Distance between the observer and the whale
Presence of other vessels	Whether one or more vessels were within 5000m
Observation truncation type	Fluke-up (deep) dive, no resight, passed abeam
Relative ambient light conditions	Relative colors of sea, sky and land
Observer location (starboard/port)	Location of observer station on the bow of the ship
Percent cloud cover	Estimated over whole sky
Rain presence	Raining/not raining during observation
Sea state	In feet (i.e. 1 foot, 2 feet, etc.)
Visibility	Poor/fog, poor, fair, good, or excellent
Sun glare	Whether there was sun glare during observation
Wind level	Absent, light, medium, or strong at observation station
Date of survey	Calendar date when survey was conducted
Northbound or southbound transit	Morning (northbound) or afternoon (southbound) trip
Ship name	Name of vessel from which the survey was conducted

Table 2-3. The candidate model set for estimation of the probability of first assigning whale direction of travel (DT) as a function of time since the first detection using a Cox proportional hazards model. We moved forward with the model containing only distance.

Predictors	**Coefficient**	**SE**	**p-value**
Distance	-0.0001	<0.0000	<0.000 ***
Visibility	-0.0085	0.0415	0.837
Distance +	-0.0001	0.0000	<0.000 ***
Visibility	-0.0215	0.0419	0.609
Distance +	0.0002	0.0001	0.037 *
Visibility +	0.178	0.0873	0.256
Dist * Vis	-0.0000	0.0000	0.320

Significance levels: 0 ***; 0.001 **; 0.01 *

Table 2-4. The nine models in the candidate model set for estimation of the probability of making a congruous assignment of whale direction of travel (DT), which is defined as the second of two consecutive, consistent DT assignments. We selected the top model using AIC. We moved forward with the model containing distance and cue number.

Predictors	Coefficients	Confidence Interval	Deviance	Parameters	AIC	ΔAIC
Intercept +	-0.5125	-0.6798, -0.3462				
Distance +	-0.0002	-0.0002, -0.0001				
Cue Number	0.2466	0.2223, 0.2715	4546	2	4552	0
Intercept +	-0.0159	-0.6306, 0.6093				
Distance +	-0.0003	-0.0004, -0.0001				
Cue Number +	0.2462	0.2219, 0.2711				
Visibility +	-0.1383	-0.3061, 0.0266				
Dist * Vis	0.3005	-0.0000, -0.0000	4543	4	4554	2
Intercept +	-0.4347	-0.7539, -0.1168				
Distance +	-0.0002	-0.0002, -0.0001				
Cue Number +	0.2470	0.2227, 0.2720				
Visibility	-0.0221	-0.0990, 0.0551	4546	3	4554	2
Intercept +	-0.5435	-0.7853, -0.3033				
Distance +	-0.0002	-0.0002, -0.0000				
Cue Number +	0.2544	0.2046, 0.3056				
Dist * CueNum	-0.0000	-0.0000, 0.0000	4546	3	4554	3
Intercept +	-0.0946	-1.2139, -0.9771				
Cue Number	0.2475	0.2235, 0.2723	4636	1	4640	88
Intercept +	1.0530	0.4814, 1.6385				
Distance +	-0.0003	-0.0005, -0.0002				
Visibility +	-0.1389	-0.2975, 0.0167				
Dist * Vis	0.0000	0.0000, 0.0000	5097	3	5105	553
Intercept +	0.5580	0.4284, 0.6885				
Distance	-0.0002	-0.0002, -0.0001	5210	2	5108	556
Intercept +	0.4407	0.1498, 0.7319				
Distance +	-0.0002	-0.0002, -0.0001				
Visibility	0.0326	-0.0397, 0.1052	5103	3	5109	557
Intercept +	-0.1751	-0.4374, 0.0862				
Visibility	0.0413	-0.0299, 0.1127	5209	2	5213	661

FIGURES

Figure 2-1. A map of the study area (Glacier Bay is the fork-shaped bay in the circular inset map) with superimposed ship tracks recorded using a handheld GPS during shipboard surveys conducted in Glacier Bay National Park and Preserve in 2016 and 2017. Glacier Bay is in southeast Alaska.

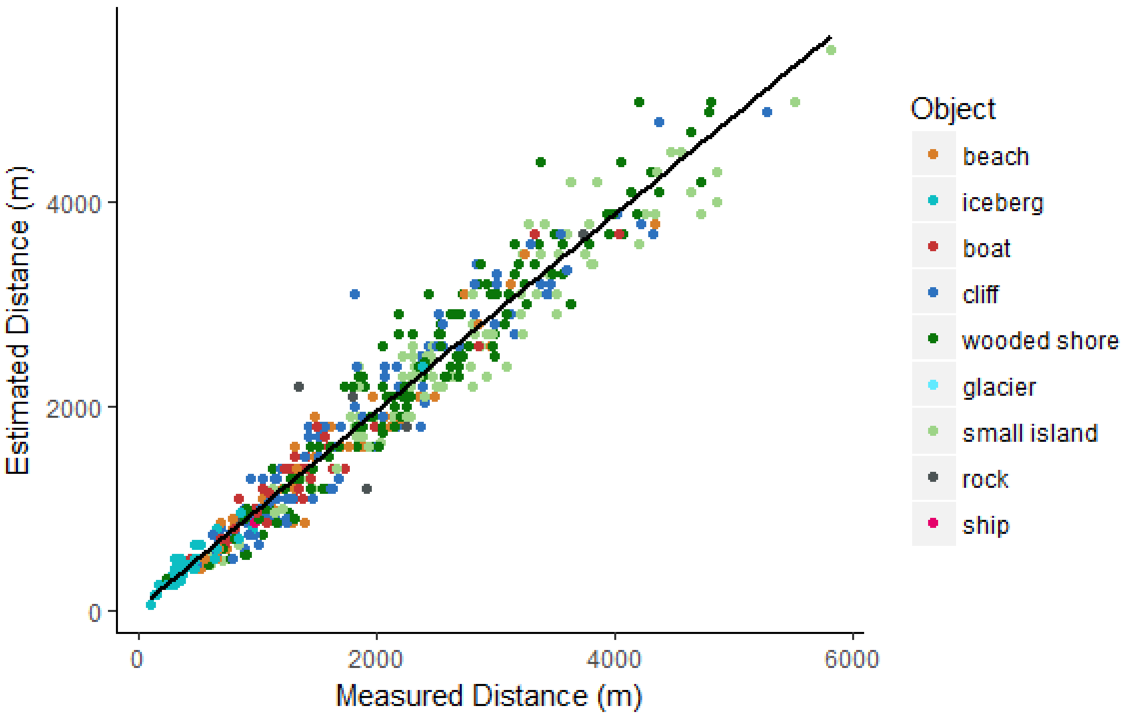

Figure 2-2. Observer error during distance estimation to objects and locations throughout Glacier Bay during shipboard surveys. The solid black line has slope = 1, and a linear regression of estimated distance on measured distance yielded a slope of 0.966.

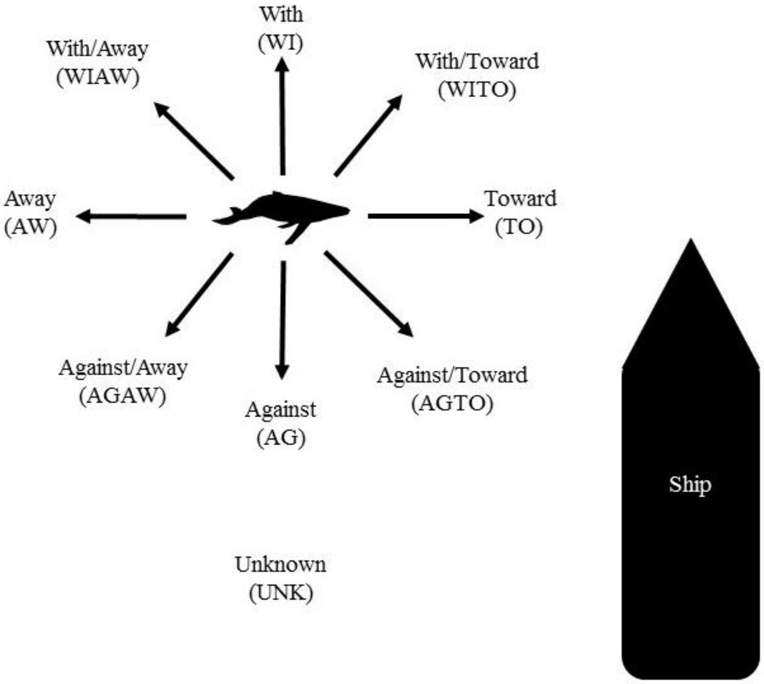

Figure 2-3. Nine assignments of whale direction of travel (DT) that were used to describe the headings of surfacing whales detected by observers during shipboard surveys. Assignments are representative for a whale surfacing on the port side of the ship.

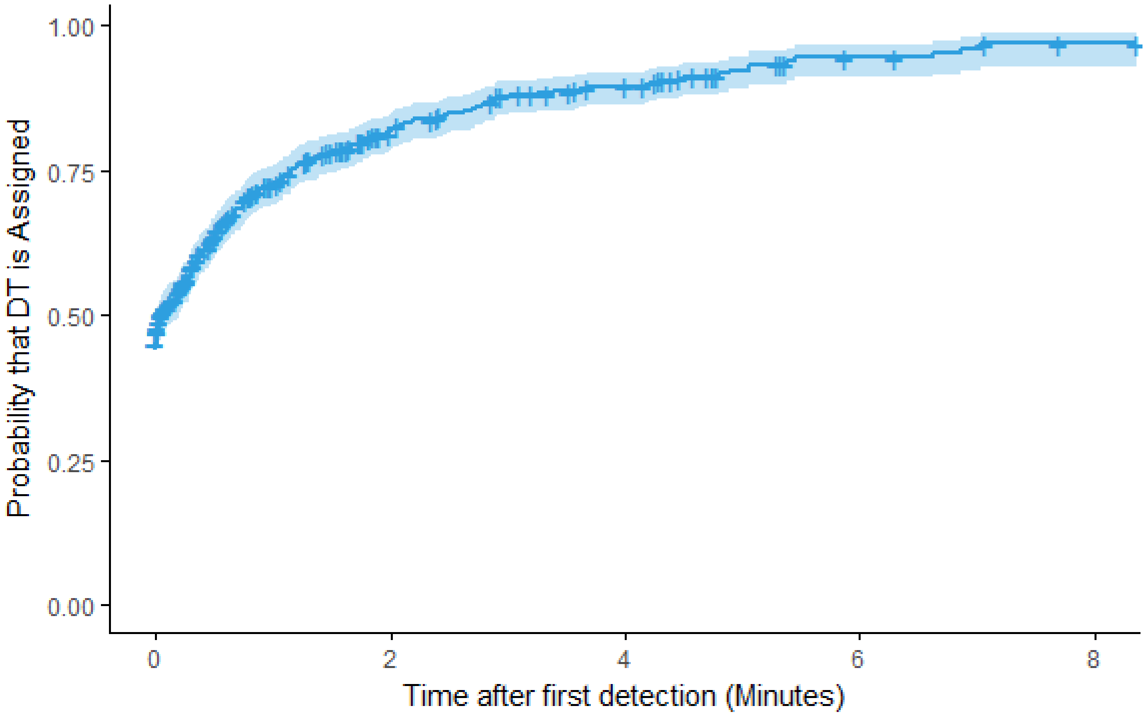

Figure 2-4. The cumulative probability of a vessel operator's ability to first ascertain a whale's direction of travel (i.e. first assign it as anything other than "unknown") as a function of ship-to-whale distance and time since first detection.

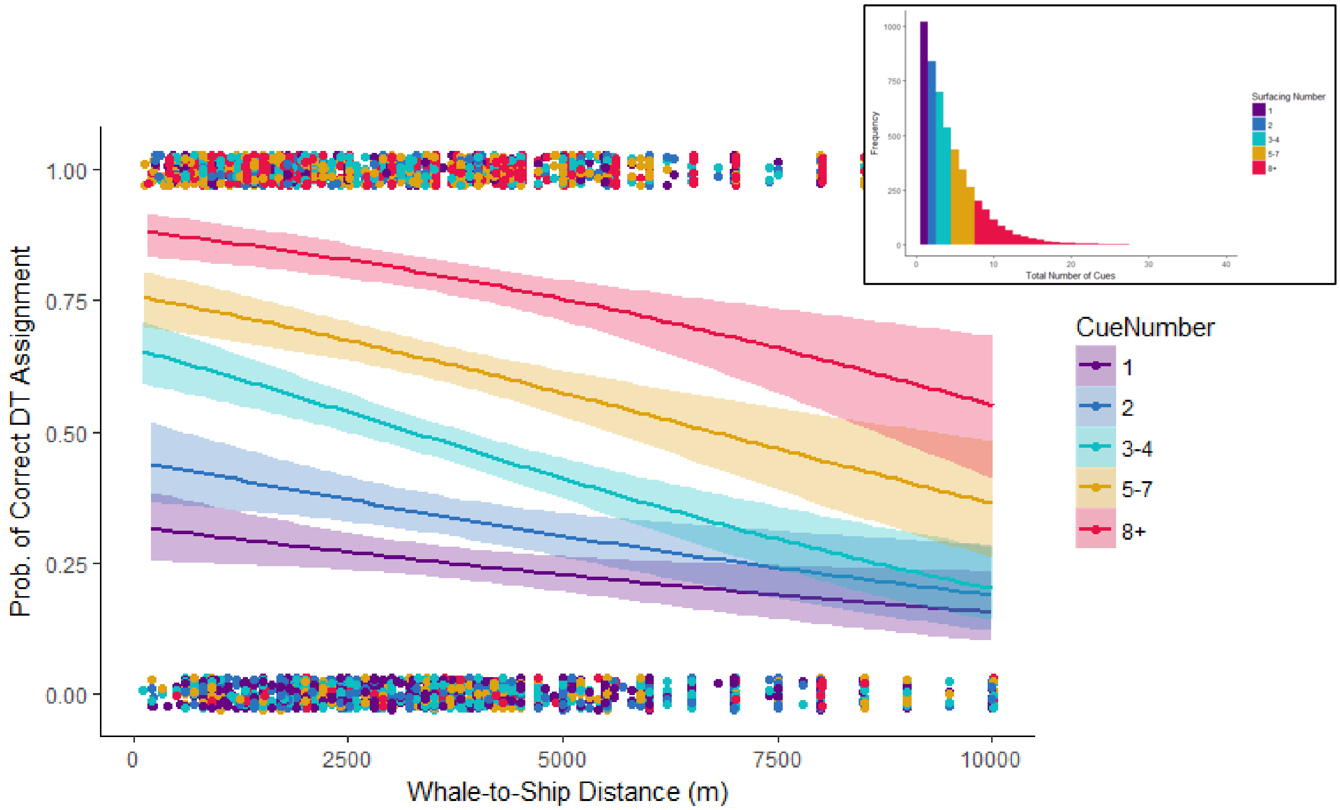

Figure 2-5. The top model selected to estimate of the probability of making a congruous assignment of whale direction of travel (DT), which is defined as the second of two consecutive, consistent DT assignments. This model contains two covariates: whale-to-ship distance and the number of the cue in the surfacing bout. For visualization purposes, cue number (range: 1 – 38) was divided into bins of similar sample size (see inset for divisions), each of which is represented by a colored line.

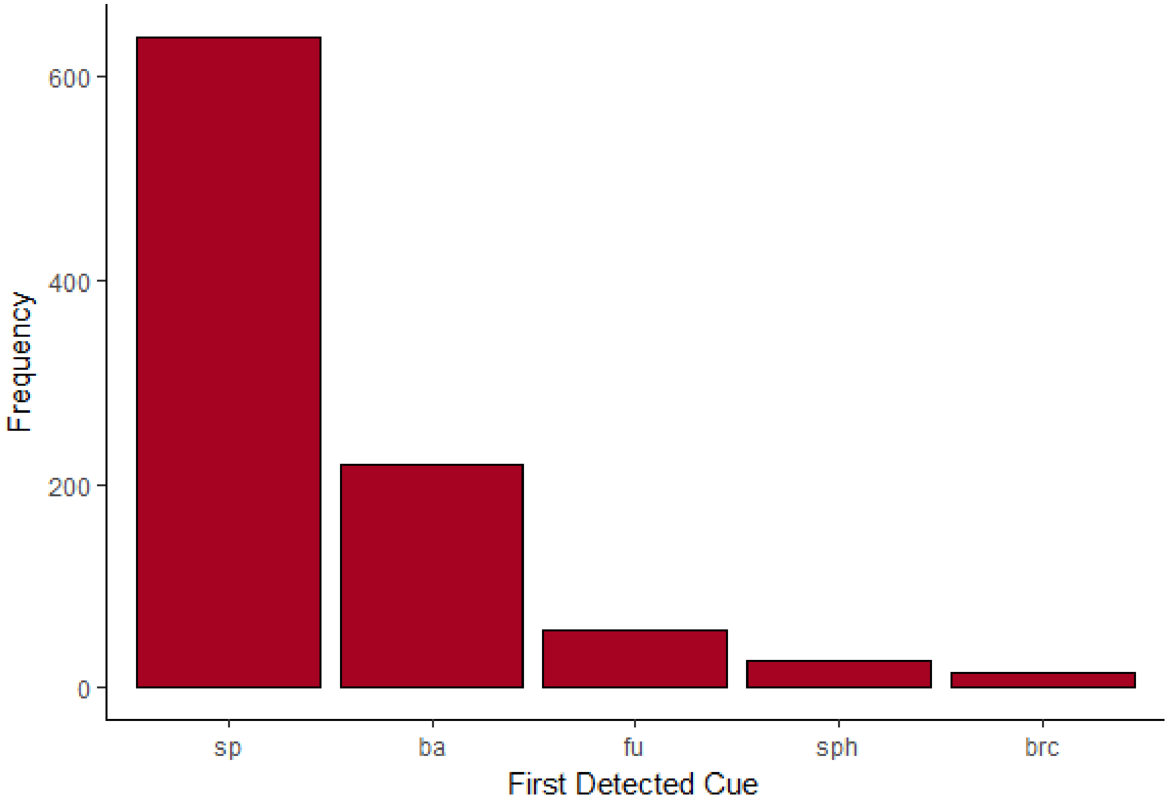

Figure 2-6. The relative frequencies of the first cue detected in each surfacing bout, ranging from spouts (“sp”) at the highest frequency, through backs (“ba”), fluke-up dives (“fu”), splashes (“sph”), and breaches (“brc”).

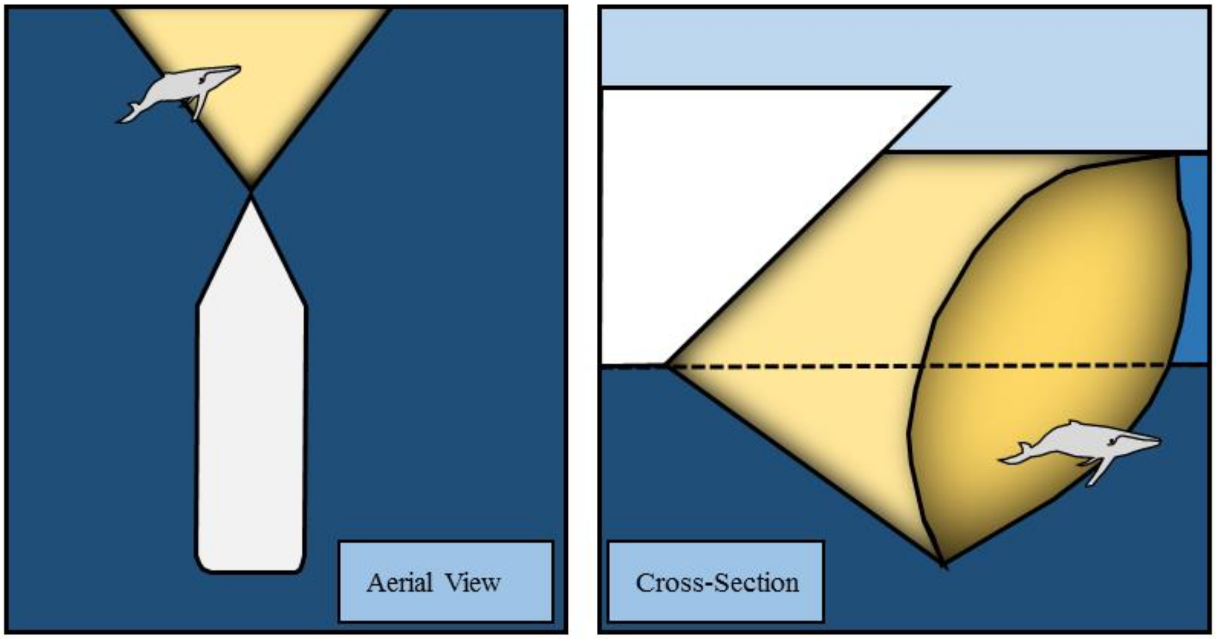

Figure 2-7. The conceptual "cone of concern" (in gold) in which a whale is close enough to a ship that it may be at risk of a collision with the bow. The exact dimensions of the cone of concern depend on ship speed, draft, and maneuverability parameters.

CHAPTER 3. MODELING HOW SHIP-WHALE COLLISION RISK IS DRIVEN BY BOTH DETECTED AND UNDETECTED WHALES PASSING THROUGH THE “STRIKE ZONE”

ABSTRACT

The risk of collisions between large vessels and whales (“ship strikes”) is expected to increase across the globe as shipping traffic intensifies and whale populations rebound from historical depletion, leading to increased spatiotemporal overlap. Research on passive collision avoidance has resulted in various risk reduction initiatives such as the readjustment of shipping lanes and new modes of relaying sightings, such as mobile applications and passive acoustic arrays. However, even when passive collision avoidance is implemented proactively, active collision avoidance is still required by vessel operators for the instances when a whale surfaces and is detected ahead of the ship, and they must adjust course or speed. Here, we extend the theory of the detection process in open populations through the novel application of a mark-recapture model. While the majority of studies involving detection probability describe undetected individuals as either unavailable for detection or unperceived, we study this process in an open population in order to estimate the probability of individuals entering the strike zone as part of the detection process. First, we found that 32% of detected whales will surface in a given 20 second period. Second, we found that 47% of whales are present in the strike zone for 20 seconds prior to their initial detection. These findings highlight the importance of vigilance by vessel operators who are on watch because the opportunities to detect whales are limited in relation to the proportion of time that whales are present in the strike zone and unable to be detected.

INTRODUCTION

Background

Quantifying the effect of the detection process on parameter estimation is a critical statistical underpinning of sound ecological research. When samples are drawn to make inference about a population, there is often some probability that an individual is present but not detected. Estimation of detection probability, in addition to the parameter of interest, can reduce the resulting bias (Royle et al. 2005). Estimation of detection probability is especially important in studies of occupancy and distribution (Chen et al. 2009), abundance (Dénes et al. 2015), population trends (Kéry et al. 2009) and density (Kissling et al. 2006) of organisms. These types of studies typically involve repeated count data of either marked or unmarked individuals, with each data point corresponding to an individual and a period or point in time. However, detection probability is not necessarily an adequate descriptor of the detection process in systems where detection can be divided into its smallest components, availability and perceptibility. Separate estimation of these components may often enable us to address more complex and nuanced ecological questions.

To break down the detection process into its components, we first consider the availability process. For an individual to be available for detection, it must be present in the study area and possible to be detected by an observer, while a lack of availability for detection involves individuals that are present in the study area, but are concealed from observers and impossible to detect. For example, during passerine bird surveys, detection is often contingent upon an observer hearing a song or call (Alldredge et al. 2007), in which case birds that are present but not singing are unavailable for detection. Availability probability depends upon the survey platform (e.g. line-transect or point count), the study system (e.g. the type of cue being detected), and the question of interest (e.g. abundance estimation).

The second component of the detection process is the perception process. Perceptibility results from an individual being potentially visible to an observer (i.e. available for detection), but not detected for some other reason (McLaren 1961, Marsh and Sinclair 1989). An individual's availability probability and perceptibility probability combine to form its detection probability. Conditional on the assumptions of a closed population, where no individuals enter or leave during the observation period, and an individual being present in the study area, detection probability of that individual can be described as:

$$p_{i,j} = a_{i,j} * (r_{i,j} | a_{i,j})$$ **Equation 3-1**

Where p = the probability of detection for individual i at time j, a = the probability of the individual being available for detection, and r = the probability of the individual being perceived given that it's available for detection.

It is clear that estimating detection probability is important for bias reduction, and as such, in some cases, it is important to take a next step and consider what could cause the complement: non-detection probability, or (1 – p). Conditional on an individual's presence in the study area and the assumption of a closed population, an individual may go undetected either because it is unavailable (and thus not perceptible), or because it is available but not perceived due to some environmental or physical circumstances of the study area:

$$1 - p_i = (1 - a_i) + (a_i * (1 - r_i | a_i))$$ **Equation 3-2**

This equation can easily be derived from Equation 3-1 in a closed population. However, substantial complexity is added by relaxing the closure assumption to enable parameter estimation in an open population, where individuals can enter and exit the study area during the observation period. In an open population, non-detection probability involves all of the ways that an individual can go undetected, including not being present at the time of the observation. Therefore, we advocate that it is important to model the non-detection process in open populations where there are high stakes for individuals that go undetected, because modeling this process enables us to quantify differences in risks resulting from an individual being present but undetected (i.e. a false negative) as opposed to absent. For example, a patient who receives a test for a dangerous virus that has a known nonzero false negative rate may be treated differently than they would if the test has perfect sensitivity (i.e. no false negatives are produced) and they were certain that they did not carry the dangerous virus.

Modeling the non-detection process in open populations enables us to quantify: **1.** the probability of individuals being absent (vs. present, which is an assumption in closed populations); **2.** The probability of individuals being present but unavailable for detection (vs. present and available for detection); and **3.** The probability of individuals being present, available, and yet not perceived (vs. present, available, and perceived). Thus, in open populations, the equation for non-detection probability described by Equation 3-2 requires addition of a term that accounts for individuals that are not present in the study area:

$$1 - p_i = (1 - \psi_i) + (1 - a_i) + (a_i * (1 - r_i | a_i)) \qquad \textbf{Equation 3-3}$$

Where ψ = the probability that an individual is present at the time of the survey. In order, the three terms on the right side of Equation 3-3 explain the relationship between absence, lack of availability, and lack of perception, and how these can lead to a non-detection. This re-framing of the way that ecologists currently think about and model the detection process will enable more creative insights into a multitude of ecological questions, especially those with repercussions from non-detections of present individuals such as in the fields of human-wildlife conflict and disease ecology.

Study System

We quantify the non-detection process in a study system with critical management relevance within the broader field of human-wildlife conflict. The interface between wildlife and human transportation infrastructure is one example of a system in which the non-detection process has greater biological implications than the detection process, because if an animal is present but undetected, there is a risk that it will be injured or killed. Encounters between animals and vehicles occur across taxa, on every continent, and in both terrestrial and marine systems. Animal-vehicle collisions can be lethal for animals, and infrastructure may result in sub-lethal effects like habitat degradation and increased noise (Guinard et al. 2012). These encounters have the potential to impact the persistence of rare and endangered species, such as many types of marine mammals.

Collisions between vessels and whales, hereafter referred to as “ship strikes,” are a serious problem facing many whale species worldwide. Past work to report whale sightings and move shipping lanes has been critical in reducing the probability that close encounters will occur (Vanderlaan et al. 2008), especially for the types of collisions involving whales that surface for the first time immediately in front of a vessel with no time for the operator to react, since this is more probable in areas of high whale density. However, ships continue to hit whales in large part because pilots can only avoid whales if they see them, and whales are only available for detection when they’re breaking the surface of the water.

Ship operators rely on detecting whales based on visual observations from their position above the surface of the water for the purpose of collision avoidance. For air-breathing marine mammals, respiration rates and dive duration govern the availability process from large vessels (Sucunza et al. 2018). Humpback whales on their high-latitude feeding grounds spend extended periods deep underwater where they feed on krill and small forage fish (Clapham et al. 1999). While the majority of their time is spent feeding at depth, whales must repeatedly return to the surface to breathe, which means that respiration likely affects their behavior substantially more than it affects terrestrial mammals (Würsig et al. 1984).

When whales breathe, they usually create highly visible spouts during each exhalation, which can reach several meters in height. When a whale returns to the surface from depth, it returns straight to the surface from the prey patch at a uniform speed (Dolphin 1987a). It will then create a series of spouts during its “surfacing bout,” or the series of breaths it takes before returning to depth to feed. Its return to depth is typically indicated by a “fluke-up dive,” when the whale arches its back and raises its tail out of the water in order to propel it back to depth (Zerbini et al. 2006). Each time the whale breathes, it may create between one and four separate but related behaviors that occur above the water, which serve as visual cues for vessel operators that a whale is in the vicinity (Table 3-1). Each time the whale breaks the surface of the water in some fashion is considered a “surfacing,” and each surfacing may consist of multiple cues (Figure 3-1).

A major knowledge gap that we sought to address with this work was obtaining an unbiased estimate of whale respiration behavior, which serves as the availability process for ship operators, since it is the only indicator that they can use to infer when whales are present in the strike zone. In general, it is challenging to separately estimate the availability and perceptibility processes because it is often impossible to determine if an undetected whale was not available to be detected or was available but not detected for another reason. Previous studies have adjusted for availability in several ways. Most commonly, a proportional correction for line-transect surveys will be added (e.g. (Heide-Jorgensen and Laidre 2013, Sucunza et al. 2018), which accounts for the individuals that were present but unavailable. However, the assumption of an instantaneous sample, which is required to use this method, is often very difficult to meet (Borchers et al. 2013). Adjusting for availability can also be done by developing hidden Markov models (Borchers et al. 2013), and while this method is flexible, it requires independent data on availability which are not possible to acquire in many marine studies where access to the study species is difficult to obtain and limited. In this work, we directly estimated the availability probability by making a reasonable assumption about the perception process, which is further described in the methods section.

Whales are mainly at risk of ship strikes when they are between the surface of the water and the “draft” of the ship, or the deepest part of the hull. We refer to the space between the surface and the ship draft as the “strike zone” (Rockwood et al. 2017). Whales in this zone will be variably available for detection, as they spend a fraction of time breaking the surface (the availability process) while they pass through the zone where they could be struck, and they will not necessarily be detected when they are available (the perception process). The depth to which whales dive to forage is correlated with the location of dense prey patches (Dolphin 1987b, Hazen et al. 2009), and the depth to which whales descend on foraging dives can vary up to approximately 120m (Dolphin 1987b) with most dives occurring between 92m and 120m (Witteveen et al. 2008). As such, when they are feeding, whales are usually substantially deeper in the water column than the average ship draft in southeast Alaskan waters (mean = 8m, (Gende et al. 2011)).

However, when whales return to the surface to breathe, they are present in the strike zone for the duration of each surfacing bout. This length is highly variable according to the particular ecological context, but has been estimated to be 1.1 mins +/- 2.3 minutes on the feeding ground (Dolphin 1987a). For the purpose of this study, we define our population of interest as humpback whales present in the 8m-deep strike zone, which is analogous to the period that whales are within a surfacing bout. While there is some evidence that a suction effect can draw whales into a ship's propellers from a greater depth (Silber et al. 2010), we are primarily concerned with ship strikes involving the bulbous bow, and defining the strike zone according to the average ship draft is both conservative and in line with other recent research (Rockwood et al. 2017).

Whales routinely enter and leave the strike zone as they cyclically shift between feeding and breathing, leading us to define the population of whales present in the strike zone as an open population. As such, when ship operators scan for whales, the question of whether or not they detect a whale is driven by the three processes that describe the non-detection process in open populations in Equation 3-3: whale presence/absence (ψ or 1-ψ), availability/unavailability (a or $1 - a$), and perceptibility/imperceptibility ($r|a$ or (a * 1-$r|a$)). The probability of a whale being present is known to be 1 when a whale is available for detection, and it is also known to be 1 between two consecutive surfacings when the whale was observed. However, the probability of a whale being present is unknown at the beginning and end of each surfacing bout, just before the first observed surfacing and just after the last observed surfacing. Understanding whale behavior during these portions of the surfacing bout is key to collision avoidance for two reasons. First, it is probable that a whale will not be detected by a vessel operator until it has surfaced multiple times, which means it is at risk of ship strike before it is even known to be present. Second, being able to predict how long a whale will remain in the strike zone after it is first detected can help inform best practices in active collision avoidance maneuvers for vessel operators.

Since whale presence in the strike zone is known during the observed portion of the surfacing bout, we were interested in estimating the probability of presence before the first detection. We were also interested in estimating the probability of remaining in the strike zone after the first detection. As such, we divided the presence probability (ψ) from Equation 3-3 into two separately-estimated parameters, which are functionally the probabilities of individuals entering and leaving the population. In a study of population dynamics, these parameters could be described as recruitment probability and survival probability. Since our population of inference is whales in the strike zone, the system-specific analogs that we selected are the probability that a whale was previously present in the strike zone but undetected ("undetected-and-strikeable probability," or $1 - \gamma$, the analog to recruitment), and the probability that a whale remained in the strike zone after the first detection ("detected-and-strikeable probability, φ, the analog to survival probability). This enables us to address two critical gaps in knowledge regarding the predictability of whale behavior in the context of ship strike risk. Quantifying the ship strike risk for whales that have not yet been detected could help to estimate rates of undetected ship strikes and collision risk in particular areas where whale densities are known, and quantifying probability of remaining in the strike zone after detection for the whales that have not yet been detected can inform vessel operator response.

Ultimately, to put our work in the context of Equation 3-3, we address the components of the non-detection process in open populations as follows: We directly estimate the probability of an individual being available for detection (a), and we address the perception probability (r) by making a reasonable assumption. We do not directly estimate the presence probability (ψ), but rather, we divide into two components which are each estimated simultaneously: the undetected-and-strikeable probability (γ) and the detected-and-strikeable probability (φ) (Figure 3-2). To do this, we develop a novel application of the "Pradel Method" (Tenan et al. 2014), otherwise known as the "temporal symmetry model" (TSM) (Pradel 1996) for this system.

Model Context

We extended the TSM (Pradel 1996) and applied it to estimation of the parameters governing the behavior patterns of undetected whales in order to better describe ship strike risk at the level of an individual ship-whale encounter. To date, the TSM has been used to estimate survival, recruitment, population growth rate, and detection probability in open populations using capture-recapture data from marked animals (Pradel 1996, Dreitz et al. 2002, Tenan et al. 2014). We apply this model to a novel system where instead of estimating demographic parameters of a biological population, we redefine the parameters to estimate unobserved behavior of a subset of a population of whales that is relevant to management: whales that are present in the strike zone.

The TSM can be parameterized in several ways, each of which enables estimation of three out of four related parameters. In our system, we utilize it to estimate the three related parameters of detected-and-strikeable probability, φ (typically survival probability), the undetected-and-strikeable probability, γ, (typically seniority probability, which is the proportion of individuals that are in the population at the previous encounter period (Tenan et al. 2014)), and detection probability (p). The TSM draws on the fact that encounter histories of observed individuals that are read forwards in time (Equation 3-4) can be used to estimate survival, while they can be used to estimate recruitment when read backwards in time (Equation 3-5). Implemented together (not shown), these equations enable simultaneous estimation of the parameters of interest:

$$\Pr(h) = \left(\prod_{i=e+1}^{l} \varphi \right) \left(\prod_{i=e}^{l-1} p_i^{\epsilon_i} \, (1 - p_i)^{1-\epsilon_i} \right) \xi_e$$

Equation 3-4 (From Pradel 1996)

$$\Pr(h) = \left(\prod_{i=e+1}^{l} \gamma_i \right) \left(\prod_{i=e}^{l-1} p_i^{\epsilon_i} \, (1 - p_i)^{1-\epsilon_i} \right) \chi_l$$

Equation 3-5 (Slightly simplified from Pradel 1996)

Where *h* = the encounter history, *e* = the index of the earliest observation in *h*, *l* = the index of the last observation in *h*, ϵ_i = the event at time *i* (seen/not seen), ξ_i = the probability of not being seen before time *i* for an individual present just after time *i*, χ = the probability of not being seen after time *i* for an individual present just after time *i*, and φ, γ, and *p* are defined as above (Pradel 1996).

Upon referring back to Equation 3-3, it is possible to see how the description of non-detection probability in an open population relates to the temporal symmetry model. As previously described, the presence parameter (*ψ*) is divided into the undetected-and-strikeable probability (*γ*) and detected-and-strikeable probability (*φ*), which are presented in Equations 3-4 and 3-5. Detection probability is described as "*p*" in all three equations. Our technique for separately addressing the perception probability (*r*) and the availability probability (*a*), which comprise detection probability (*p*), is described in the Methods section.

The TSM has almost exclusively been implemented in a frequentist framework using Program MARK. Despite more recent implementation in a Bayesian framework (Tenan et al. 2014), that formulation has seen little use. This is unfortunate, because a Bayesian implementation offers increased flexibility (such as the ability to extend to a random time effects structure), and it enables hierarchical modeling of the state and observation processes (Tenan et al. 2014).

We apply this model to the problem of collision avoidance by defining our population of interest as whales present in the strike zone, and then estimating the probabilities with which animals arrive into and leave that surface population (Figure 3-3), which has direct implications for the non-detection process, since animals are routinely moving through the population and are only detected for a small proportion of the time that they're in the strike zone. Conceptualizing the study system this way is critical – and quite different than building a pure detection function – because it enables us to simultaneously model more specific components of the detection process that are each highly relevant to ship strike avoidance. The ability to model more specific components of detected and undetected whale behavior has important implications for management of vessel speed limits, whale approach regulations, and recommended best practices for large vessel operators.

METHODS

Field Methods

Humpback whale surveys were conducted on 79 days in Glacier Bay from late May through mid-August in 2016 (n = 41 days) and 2017 (n = 38 days), using large passenger cruise ships as platforms of opportunity (Table 2-1). Survey effort totaled 464.8 hours of observation over the two summer seasons. Each of the 79 survey days ("cruises") was divided into two survey periods of approximately equal length: a northbound transit (morning) and southbound transit (afternoon). Cruises were divided into two transits to accommodate a multi-hour break in survey effort while the ships remained at the head of the fjord for glacier viewing where whales are very rarely seen. The first 3 cruises of 2016 were excluded from the data set due to observer training, and 11 other cruises were excluded due to data transcription difficulty. Two southbound surveys in 2017 were excluded due to gear malfunctions. Ultimately, this yielded data from a total of 65 cruises over two years used for this analysis.

On each survey day, a single observer boarded a designated cruise ship just inside the mouth of Glacier Bay via a transfer vessel which departed from the NPS headquarters in Bartlett Cove. Beginning shortly after boarding, surveys were conducted continuously throughout each morning as the ship transited northbound from the Lower Bay to the glaciated ends of the West Arm. Surveys did not extend to the northern part of Tarr Inlet and the western part of Johns Hopkins inlet due to a known absence of whales. Surveys were then reinstated as each ship retraced its path south through the bay. Southbound surveys continued until the southern portion of Sitakaday Narrows near Bartlett Cove, yielding a mean of 5.9 hours on effort during each cruise (sd = 0.6 hours). As a result of navigational constraints and speed regulations within the National Park, all ship transits traced similar tracks through the bay (Figure 2-1) at comparable speeds.

Once positioned on the forward-most bow of the ship, scans were conducted using a combination of the naked eye, Swarovski 10 x 42 binoculars, and tripod-mounted (Manfrotto Distribution Inc.; 055 Series; Upper Saddle River, NJ, USA) laser rangefinder binoculars (Leica Viper II; accuracy +1 m at 1km; Leica, Charlottesville, VA, USA) to search for whales. Scans completely covered the 180-degree range from abeam of the port side of the navigational bridge (the “bridge”) to abeam of the starboard bridge. Scans alternated between naked-eye and optics-assisted scans to cover the water’s full extent from near the ship to the limit of the optics (approximately 12 kilometers in excellent visibility conditions). When a whale was detected, the ship’s location was geospatially referenced using a handheld Global Positioning System, or GPS (Garmin 76Cx, Olathe, Kansas, USA), and the distance between the observer and the whale was measured using the rangefinder binoculars. If a surfacing was too brief or too far away to make contact between the laser range-finder and the whale, the ship-to-whale distance was estimated. Intermittently throughout each transit, the accuracy of the observer’s distance estimation was checked by recording estimated distances to locations throughout the bay and checking the estimate using the rangefinder binoculars. Accuracy of distance estimation decreased slightly as distance increased but exhibited no bias, and a linear regression of estimated distance on measured distance yielded a slope of 0.966 and a multiple R-squared value of 0.946 (Figure 2-2). Accuracy of distance estimation to objects that were similar in size and location to whales (e.g. rocks and icebergs) appeared to be estimated relatively accurately. Observer accuracy was not tested past the limits of the laser rangefinder (approximately 5500 meters).

The observer recorded 22 variables describing whale behavior, ship location, and environmental conditions (Table 2-2). Observations were recorded using a digital voice recorder (Olympus Imaging America Inc.; VN-702PC; Center Valley, PA, USA) and a Rite-in-the-Rain notebook (J.L. Darling LLC; Tacoma, WA, USA). This survey protocol used a modified individual-follow approach (Mann 1999). After the observer detected an initial cue, they focused on the area where the whale was detected. They continued to record data until a terminal dive was observed, the ship passed abeam of the whale, or the whale did not resurface. The voice-recorded data collected from each transit was saved as an .mp4 file. The observer then personally transcribed the data from each of the files using version 2.1.2 of Audacity ® recording and editing software (Audacity Team 2018).

While conducting surveys, any whale sightings within 10 degrees of the ship's heading were communicated to the personnel on the navigational bridge, including the captain, pilot, and officers, using a marine VHF radio. On some ships, the bridge personnel also periodically communicated humpback whale sightings to the observer. Additionally, a separate NPS radio was carried aboard during surveys to periodically communicate with the NPS whale biologists on their research vessel on the rare occasions that they were working in the same region of the bay. In these cases, whale sightings were reciprocally shared between the two research groups. Harbor seal (*Phoca vitulina*) and sea ice levels in the heads of the fjords were recorded and communicated to NPS Resource Management employees on a weekly basis, and orca (*Orcinus orca*) sightings were reported to the orca biologist as soon as possible without interfering with humpback whale data collection. Finally, close encounters between ships and whales were reported to the Chief of Resource Management as soon as possible. Close encounters were defined as any encounter when a ship came within 200m of a whale. All research was conducted under observational permits from the University of Montana Institutional Animal Care and Use Committee ("Confronting the challenges of whale detection: Implications for ship strike avoidance," 021-16PLWBP-041216 and 010-17PLWB-022317), as well as under research permits from Glacier Bay National Park and Preserve (GLBA-2013-SCI-0014 and GLBA-2017-SCI-0005).

Statistical Methods

Data setup

We collected data on all group sizes (range: 1 – 13 whales), which were defined as two or more individuals within two body lengths of each other that coordinated movements for at least one surfacing event (Ramp et al. 2010, Williams et al. 2016). However, since we collected data from the first observed sighting until the end of a surfacing bout (range: 1 – 33 surfacings), it was necessary to utilize only data from single whales to ensure that consecutive observations were from the same individual. This is reasonable because the majority of whales sighted in GLBA constituted group sizes of 1 (90.48% in 2016 & 2017, Table 3-4).

Since the TSM is a mark-recapture model, it is designed to run across encounter periods spaced out across a particular time frame, when individual animals have the opportunity to be captured at sampling occasions at the beginning and end of each encounter period. While we did not physically mark individuals as part of this study, the consecutive sighting of whales that were known to be the same individuals enabled us to apply a mark-recapture model in a highly condensed time frame after making some reasonable assumptions, which are described in detail below. Since observations were conducted continuously in time, the maximum duration of a one-way transit through Glacier Bay (3:55:51) was divided into equal-sized encounter periods of 20 seconds, which is a round approximation of the 21-second (sd = 43.2) median within-bout inter-cue-interval calculated from our data. We also tested encounter period sizes of 10 seconds and 30 seconds to assess the effects of encounter period size on detection probability and other parameters.

Since the encounter periods occurred consecutively across the 96km one-way transit of GLBA, it was not possible to detect the same whale across that entire duration due to the relative speed at which ships and whales travel. As such, it was important to truncate the functional observation period (and thus, the estimation window) for each whale to a biologically-relevant duration. Therefore, the length of each individual's encounter history was reduced to the maximum observed surfacing bout (10.75 minutes). The encounter histories corresponding to individuals that were observed initiating fluke-up dives (n = 370) were truncated at the terminal encounter period, assuming that a fluke-up dive indicated that the whale was descending to depth. For all whales where a terminal dive was not observed and observation of the individual ended for another reason, primarily due to the ship passing abeam (n = 396), the encounter period corresponding with the midpoint of the individual's observed encounter history was centered on the midpoint of the maximum observed surfacing bout and an equal number of leading and trailing encounter periods were made available for estimation. This enabled us to maintain estimation windows of equal length for each whale, while accounting for the fact that if whale was observed diving to depth, the entirety of its estimation window should occur prior to the terminal dive, while if a whale was not observed diving to depth, it may have been present in the strike zone both before and after the observed portion of the surfacing bout.

Initially, we analyzed data from northbound transits and southbound transits separately and compared parameter estimates to control for the possibility that there was a difference in observation conditions between the northbound transits, which always occurred in the morning, and the southbound transits, which occurred from early afternoon to evening. After confirming that there were no biologically-relevant differences among parameter estimates, we pooled the data from northbound and southbound transits for subsequent analyses.

All of the data setup described above was conducted using R 3.4.3 (R Core Team 2017).

Model extension and application

We implemented the temporal symmetry model in a hierarchical Bayesian framework similar to a particular hierarchical implementation of the Cormack-Jolly-Seber (CJS) model (Kery and Schaub 2012) using R 3.4.3 (R Core Team 2017) and package 'R2jags' (Su and Yajima 2015) to run Program JAGS (Plummer 2003). We first ran our implementation of the model on a modified version of the publicly available capsid dataset from Program MARK. We then tested it against the frequentist implementation of the survival/seniority parameterization of the TSM available in Program MARK using the R interface ‘RMark’ (Laake 2013) to compare them. The results were very similar, verifying that this implementation of the model was coded correctly.

We made two major decisions while designing our model extension. First, we included a different detection probability for the initial sighting. We did this by adding an informative prior distribution on the initial detection probability because initial detection probability is lower than all other detection probabilities in the same surfacing bout, and we know that it depends on distance and visibility (Williams et al. 2016). We selected a hazard rate function with a visibility covariate incorporated via a scale parameter. This detection function was developed in the same study system using whale sighting data from previous years (Williams et al. 2016).

Our second major decision was made in order to isolate our detection parameter of interest, the availability probability, which is typically difficult to separate from the perception probability (refer to Equation 3-1). To address this issue, we took advantage of the separate initial detection probability specified by the prior distribution described above. Since the initial detection probability accounts for the difficulties that vessel operators face in detecting a whale when they have not seen it yet, we were able to reasonably assume that once a whale has been detected once, the perception probability (r) is equal to one. This is an acceptable assumption because if a whale is detected within ten degrees of the ships heading, and thus potentially at risk of ship strike, vessel operators will focus their attention and search image on that area in order to be certain of detecting the next surfacing. Referring back to Equation 3-1, when perception probability (r) is equal to 1, then the detection (p) is equal to the availability probability (a), which is our detection parameter of interest since it is the indicator used to estimate the presence of whales in the strike zone.

Additional statistical assumptions of the TSM include that data must be successive independent binomial trials, animals are individually marked & immediately released/removed, no mark is lost or misread, there is no temporary emigration (except possibly random), animals are identical and uniquely identifiable, and animals have independent fates. Each of these assumptions is met in this system.

RESULTS

In 2016 and 2017, we collected data on a total of 79 cruises, each of which incorporated a northbound (morning) transit and a southbound (afternoon) transit. We detected a mean of 17.0 whales per cruise (sd = 11.01). We documented 6804 individual whale cues, whose durations varied according to cue type (Figure 3-4). Each surfacing was comprised of 1 to 4 cues, and durations of surfacings varied according to whether or not they involved a fluke-up dive (Figure 3-5). Each surfacing bout contained 1 to 33 surfacings (mean = 2.9 surfacings, sd = 2.7). The mean observed inter-cue interval was 21s (sd = 43.2 seconds) when measured from the beginning of a surfacing to the beginning of the next surfacing, and the mean inter-availability-interval (i.e. when a whale is unavailable for detection during a surfacing bout) was 15 seconds (sd = 40.1 seconds) when measured from the end of a surfacing to the beginning of the next surfacing (Figure 3-6).

This series of surfacing bouts was used to estimate and compare the undetected-and-strikeable probability, the detected-and-strikeable probability, and the availability probability of humpback whales in Glacier Bay. First, we compared parameter estimates for northbound and southbound transits (Table 3-5). For the northbound transits (n = 468 whales), the undetected-and-strikeable probability was high (mean = 0.616; 95% CI = 0.579, 0.653), as was the detected-and-strikeable probability (mean = 0.874; 95% CI = 0.0.857, 0.889). The availability probability, in contrast, was low (mean = 0.321; 95% CI = 0.298, 0.344). For the southbound transits (n = 561 whales), the undetected-and-strikeable probability was high (mean = 0.606, 95% CI = 0.570, 0.641), as was the detected-and-strikeable probability (mean = 0.888, 95% CI = 0.874, 0.902). Again, the availability probability was low (mean = 0.277; 95% CI = 0.257, 0.298).

Each of the three parameter estimates from the northbound transit data was compared to the corresponding parameter from the southbound transit data. There was a 78.4% posterior overlap between the two estimates of undetected-and-strikeable probability, a 33.9% posterior overlap between the two estimates of detected-and-strikeable probability, and a 5.3% posterior overlap between the two estimates of availability probability (Figure 3-7).

Next, we pooled the survey data from both northbound and southbound transits and estimated the effect of ship-to-whale distance on parameter estimates for four distance bins (Table 3-6). For whales whose initial sighting distance was between 0 and 1000 meters away from the ship (n = 71), the undetected-and-strikeable probability was moderately high (mean = 0.790; 95% CI = 0.713, 0.857), and the detected-and-strikeable probability was high (mean = 0.748; 95% CI = 0.686, 0.807). The availability probability was moderately low (mean = 0.452; 95% CI = 0.361, 0.544).

For whales whose initial sighting distance was between 1001 and 3000 meters away from the ship (n = 287), the undetected-and-strikeable probability was moderately high (mean = 0.672; 95% CI = 0.629, 0.715), and the detected-and-strikeable probability was high (mean = 0.833;

95% CI = 0.809, 0.856). The availability probability was low (mean = 0.366; 95% CI = 0.333, 0.401).

For whales whose initial sighting distance was between 3001 and 4500 meters away from the ship (n = 212), the undetected-and-strikeable probability was moderately high (mean = 0.713; 95% CI = 0.663, 0.759), and the detected-and-strikeable probability was high (mean = 0.878; 95% CI = 0.857, 0.898). The availability probability was low (mean = 0.311; 95% CI = 0.281, 0.342).

For whales whose initial sighting distance was between 4501 and 6000 meters away from the ship (n = 152), the undetected-and-strikeable probability was moderately high (mean = 0.761; 95% CI = 0.705, 0.814), and the detected-and-strikeable probability was high (mean = 0.902; 95% CI = 0.882, 0.921). The availability probability was low (mean = 0.289; 95% CI = 0.258, 0.321). While whales were observed greater than 6000 meters from the ship (n = 133), we did not include them in this portion of the analysis because we did not feel confident that they would meet the assumption of a perception probability of 1, which could influence interpretation of the availability parameter.

Finally, we investigated the effects of changes in encounter period length on parameter estimates (Figure 3-8). For all comparisons, data from the northbound and southbound transits were pooled and analyzed together. For a ten second encounter period (n = 808 whales), the undetected-and-strikeable probability was moderate (mean = 0.546; 95% CI = 0.519, 0.573), and the detected-and-strikeable probability was high (mean = 0.929; 95% CI = 0.921, 0.937). The availability probability was low (mean = 0.229; 95% CI = 0.217, 0.241).

For a 20s encounter period (n = 855 whales), the undetected-and-strikeable probability was essentially identical to the 10s encounter period (mean = 0.540; 95% CI = 0.515, 0.566). The detected-and-strikeable probability was slightly lower (mean = 0.865; 95% CI = 0.854, 0.877), and the availability probability was slightly higher (mean = 0.319; 95% CI = 0.303, 0.336).

For a 30s encounter period (n = 856 whales), the undetected-and-strikeable probability was again nearly identical to that of both the 10s and 20s encounter periods (mean = 0.541; 95% CI = 0.515, 0.566), and the detected-and-strikeable probability was higher (mean = 0.796; 95% CI = 0.781, 0.811). The availability probability was higher as well (mean = 0.414; 95% CI = 0.392, 0.437).

DISCUSSION

Overall, our results demonstrate that whales are present in the strike zone far more frequently than they are available to be detected by vessel operators, and far earlier than one might surmise based exclusively on observed surfacings.

Our first objective was to obtain an unbiased estimate of the availability portion of the detection process faced by vessel operators, which is functionally the same as humpback whale respiration rates since the whales are only available for detection when either part of their body or their spout is breaking the surface of the water. This is highly important to active collision avoidance because it represents how often vessel operators have an opportunity to detect a whale relative to the duration that it is present in the strike zone. Thus, we can use this estimate to parameterize a training simulator with whale cue intervals, as well as to test the effects of ship speed on detection and associated collision risk.

We found that overall, a mean of 32% of whales that are present in the strike zone will surface in a given twenty-second period. This estimate is unbiased relative to a detection probability estimate derived from observations made by a single observer during a typical line-transect survey because our implementation of the TSM (Pradel 1996) with an informative prior on the first detection probability enabled us to account for perception challenges and thereby estimate availability directly. Accounting for perception probability in this way enabled us to compare availability across different distances from the ship in a way that is generally not possible for observation data collected from single-observer surveys.

When compared across binned ship-to-whale distances (Figure 3-9), we found that availability showed a slightly decreasing pattern when moving from the closest distance bin (0m to 1000m from the ship at first sighting) to the farthest distance bin (3001m to 4501m from the ship at first sighting). First, it is important to note that the differences in the availability probability (range 0.452 to 0.289) may not be substantial enough to make a difference to vessel operators. Second, we suggest that the result from the smallest distance bin is not emphasized because the sample size for the first distance bin was much smaller than that of each of the other bins, and also because when an initial sighting distance is close to the ship, the time that it is observed is much smaller before it passes abeam. With that said, there is still a slightly decreasing pattern in availability as ship-to-whale distance increases, which has the potential to be biologically driven. One of the only published studies involving experimental manipulation of vessel approach behavior around humpback whales (Baker and Herman 1989) found that there was a significant difference in “respiratory interval” (i.e. the interval between “spout” cues) among whales that were approached by vessels compared to those that were not approached. They found that the median respiratory interval was 22 seconds for whales that were approached by vessels (vessel approaches included “obtrusive,” “unobtrusive,” or “pass-by” types), while the median spout rate was 51 seconds for whales that were not approached by vessels. It is possible that the slight changes in availability probability across ship-to-whale distance that were estimated by our model describe whale responses to the ship that lead to a higher rate of surfacing at closer range. While it is possible that this slight pattern in availability probability over distance could suggest that the observer's perception probability was less than 1 after the initial sighting, which would violate that assumption, we feel confident that it is a reasonable assumption over the distances compared, and we specifically excluded whales detected at greater than 6000m from this analysis to address that concern.

Our second objective after obtaining an unbiased estimate of the availability process was to obtain an unbiased estimate of the probability that whales are present in the strike zone but undetected, and thus at risk of ship strike. We found that across the whole bay, 54% of detected whales were present in the strike zone prior to their detection. Extending backwards in time, we found that 47% of whales were present in the strike zone twenty seconds before they were detected, 22% of whales were in the strike zone for forty seconds before they were detected, and 10% were in the strike zone for a minute before they were detected. No pattern in undetected-and-strikeable probability was detected across binned ship-to-whale distance (Table 3-6).

To put this in context, a ship traveling at a typical speed of 18 knots will travel 370 meters over the course of forty seconds, and 556 meters over the course of a minute. To comply with federal regulations within GLBA, vessels must not approach whales within 463m, or 0.25 nautical miles (NPS 2003). Elsewhere in Alaskan waters, vessels are prohibited from approaching humpback whales within 91 meters, or 100 yards (NOAA 2001). Throughout Alaska, including GLBA, vessels must not disrupt the normal behavior or prior activity of a whale, and that they operate using a “slow, safe speed” when they are knowingly in the presence of whales (NOAA 2001). These regulations apply to all humpback whale populations, including those that are not endangered (NOAA 2001) such as the majority of the whales that use southeast Alaska as their seasonal feeding ground.

For large ships with lots of momentum at higher speeds, the distance at which a pilot must detect a whale is far greater in order to ensure that they can initiate a turn that occurs in time to avoid the whale. This distance is suggested to be 500m in southeast Alaskan waters (Williams et al. 2016), based on average ship length (270m, (Webb and Gende 2015)) and maneuverability. However, making the reasonable assumption that all whales are equally detectable and that the whales that we detected on our survey were a random sample of whales, our model suggests that there is substantial risk of ship strike to whales that happen to be in the ship's path. It is encouraging that only 10% were estimated to be present in the strike zone for a full minute before their first detection, but the fact that nearly half of surfacing whales are present in the strike zone for 20 seconds prior to their detection is still concerning to ship strike avoidance.

This portion of the non-detection process – presence in the strike zone and simultaneous unavailability for detection – is impossible for ship operators to address from an active avoidance perspective, because they can't steer the ship clear of a whale that they are unable to detect. This highlights that larger-scale efforts to shift shipping lanes and reduce spatiotemporal overlap between whales and ships are even more important than previously suggested, because if whales are not detectable by operators, then the only way to avoid them is to not encounter them at close range in the first place.

However, while ship operators can't directly address a whale's undetected-and-strikeable probability, they can address the opposite – the detected-and-strikeable probability, which refers to a whale's continued presence in the strike zone after the first detection. We found that 87% of detected whales will remain in the strike zone for the next 20 seconds after a surfacing, while 66% of detected whales will remain for a full minute and 50% will remain for a minute and forty seconds after the first detection. We observed a slightly increasing pattern in detected-and-strikeable probability over increasing ship-to-whale distance, which suggests that whales that are farther away from ships remain in the strike zone after their first detection for longer periods of time than those close to ships.

This yields another important contribution of this work: a deeper understanding of how the detection and non-detection processes vary with time. While the ramifications of correcting for availability during instantaneous or non-instantaneous surveys have been thoroughly explored (Borchers et al. 2013), considering how detection probability and availability probability can change with even miniscule differences in the time spent observing has not. It is logical that the probability of detecting a whale increases the longer one spends observing, but quantifying these differences is critical for the problem of ship strike avoidance because it lends insight into how easy it is to miss a chance to detect an animal if a vessel operator pauses scanning for even a moment. Our work demonstrates that a whale’s availability for detection nearly doubles (from 0.229 to 0.414) if an observer scans for thirty seconds instead of ten seconds (Table 3-7). Since initially perceiving whales has a lower detection probability than the surfacings after the first sighting, it is important that observers scan as much as possible to avoid missing a first detection. This is very important, because we determined that the median first surfacing duration is only 4 seconds (sd = 6.4 seconds), while the inter-availability interval (Figure 3-6), or the time it is not available for detection between surfacings, is highly right-skewed with a median of 15 seconds (sd = 40.1 seconds). Our results show that a vessel operator could easily miss detecting the comparatively short first sighting of a whale by looking away from the water for only five seconds. If that whale has an above-median inter-availability interval, then it may not be detected for a very long time, which would put it at risk since the probability that it remains in the strike zone and undetected for the next twenty seconds is 47%.

This study was conducted within some logistical constraints. First, it is highly likely that we recorded repeated observations of individual whales day after day as well as on both the northbound and southbound transits of Glacier Bay on the same day. While individual humpback whales can be identified by reviewing photographs of the tail flukes and comparing with a catalogue of known whales (Saracco et al. 2013), whales observed from large ships are usually too distant to individually identify without specialized equipment, and the field methods and effort required to identify individuals were beyond the scope of this study. Nevertheless, treating each sighting as independent is not problematic in this setting because we are concerned with estimating parameters at the intersection of a biological process and a human process. This means that since ship operators in Glacier Bay are concerned with avoiding the whales that are present in Glacier Bay, even if these whales behave slightly differently than whales in other areas due to the particular circumstances of prey depth, bathymetry, or other region-specific variables, ship operators still need to know how to best avoid them.

A second constraining factor is that this study was conducted across an area where there are variable vessel speed limits set to protect humpback whales. While it is likely that whales behave differently in some regions of the bay than others, we were not able to compare among regions because some of those regions carried speed restrictions, which had the potential to impact our parameter estimation. While this constraint prevented the addition of region as a covariate, it did not impact our inference in the current analysis because the speed limits equally affected all distances from the ship, and are therefore included equally across all sightings and parameter estimates. Since speed limits are a part of typical ship operation in Glacier Bay, they affect the whale avoidance process and thus it is not problematic that they are incorporated in our parameter estimates.

This research has led to several new questions that we recommend for future study of best practices in active whale avoidance. First, we suggest that future study incorporates group sizes of greater than one into analysis. It will require some creativity, and multiple observers, to conduct focal follows of multiple whales simultaneously while remaining certain that individual whales are followed separately. While this is not an important variable in Glacier Bay where group sizes of greater than one are rare, in other regions including migration zones and breeding grounds, larger groups of whales are much more frequently observed. We also suggest that future research explores the influence of light conditions on marine mammal detection probability. Glacier Bay experiences substantial overcast weather, and we hypothesize that the relative amount of reflected light on the water, which has not yet been quantified, could affect detection probability in this study system.

CONCLUSION

This work has important management implications for ship strike avoidance protocols. The implication that whales are at risk of ship strike well before they are even possible to be detected reflects perhaps the greatest difficulty faced by vessel operators concerning whale avoidance. Given this challenging situation, we recommend that vessel operators employ multiple people on watch so that at least one person can watch the far horizon for distant whale cues. In this way, they can detect whales far enough ahead that even if they enter a deep dive between surfacing bouts, the vessel operators know that a whale is in the general vicinity and they can select a course that is clear of that area.

While estimation of the undetected-and-strikeable probability may not have direct implications for whale avoidance by pilots since they cannot react to a whale that they do not know is present, it may be useful in the future as a way to correct estimates of undetected ship strikes, which has long been very difficult to quantify as a result of multiple types of bias, and which could be used to better understand the occurrence and population-level impacts of large vessel strikes.

In addition to quantifying some parts of whale behavior and detection around ships that are important for development of ship strike avoidance protocols, this work expands the theory of detection probability in open populations by considering it from the non-detection side, which is substantially more complex. It also considers detection probability in relation to time spent observing in the setting of a management concern.

Finally, this work applies the TSM (Pradel 1996) in a novel way, because it is used to estimate parameters on the scale of seconds instead of days or years, and it is applied to a study system where the population of interest is truly not a population at all and thus the parameters must be redefined. Additionally, the individuals are not technically marked, which has previously been a requirement for implementation of this model, and instead they are individually identifiable for the duration of the observation window. Finally, we believe that our hierarchical Bayesian implementation of the model will be more accessible to future users than an existing Bayesian option, which will enable more widespread future use of a promising model that has been historically underutilized.

TABLES

Table 3-1. Specific whale-produced behaviors, or "cues," that ship operators use to detect whales. Groups of cues may form a single surfacing (e.g. a spout and a back are a typical cue combination for a single surfacing within a surfacing bout).

Cue Type	**Description**
Spout	Whale produces a tall column of vapor during exhalation
Back	Whale raises a portion of the top of its back above the water during a surfacing
Arch	Whale raises its back high during a surfacing, typically just prior to a deep dive
Fluke-Up Dive	Whale lifts its tail high out of the water as it descends, typically indicating a deep dive
Low Fluke	Whale lifts its tail low out of the water as it descends, typically just skimming the surface
Fluke Slap	Whale slaps its tail on the surface of the water, typically producing a large splash
Pec Slap	Whale slaps its pectoral fin on the surface of the water, typically producing a large splash
Surface-Active	Whale is engaged in activity at or just below the surface, which may be difficult to distinguish beyond splashing and occasional parts of the whale breaking the surface
Head Lunge	Whale visibly lunges forward at the surface, typically a sign of active feeding
Breach	Whale forcibly leaps out of the water, producing a large splash
Splash	Specific activity was not detected, but a large splash that only a whale could make was detected, either from a tail slap, a pec slap, a breach, or unspecified surface activity

Note: More specific cues are recorded in other systems, but these are the only ones typically visible from the height and distance that observers and vessel operators experience on large ships

Table 3-2. Number of humpback whale cruises conducted aboard large passenger cruise ships in Glacier Bay National Park and Preserve in 2016 and 2017.

Ship	**2016**	**2017**
Coral Princess	3	4
Grand Princess	1	0
Island Princess	5	8
Noordam	7	9
Star Princess	2	0
Volendam	12	10
Westerdam	4	0
Zaandam	7	7
Total Cruises	**41**	**38**

Table 3-3. Whale behavior and environmental variables recorded during shipboard humpback whale surveys in Glacier Bay in 2016 and 2017.

Variable	Description
GPS waypoint	Geospatially-referenced location of observer
Cue	A specific whale behavior used to detect presence
Group size	The number of whales in a group
Time that whale surfaced	Elapsed time since commencing survey
Time that whale dove	Elapsed time since commencing survey
Scan type at first sighting	Rangefinder, binoculars, or naked-eye scan
Whale direction of travel	Whale’s estimated heading
Ship-to-whale bearing	Bearing of whale in relation to the ship’s heading
Ship-to-whale distance	Distance between the observer and the whale
Presence of other vessels	Whether one or more vessels were within 5000m
Observation truncation type	Fluke-up (deep) dive, no resight, passed abeam
Relative ambient light conditions	Relative colors of sea, sky and land
Observer location (starboard/port)	Location of observer station on the bow of the ship
Percent cloud cover	Estimated over whole sky
Rain presence	Raining/not raining during observation
Sea state	In feet (i.e. 1 foot, 2 feet, etc.)
Visibility	Poor/fog, poor, fair, good, or excellent
Sun glare	Whether there was sun glare during observation
Wind level	Absent, light, medium, or strong at observation station
Date of survey	Calendar date when survey was conducted
Northbound or southbound transit	Morning (northbound) or afternoon (southbound) trip
Ship name	Name of vessel from which the survey was conducted

Table 3-4. Whale group size displayed as the proportion of total whale sightings in Glacier Bay in 2016 and 2017. Group sizes of 8 and 13 each contained only a single sighting.

Group Size	**Proportion of total sightings**
1	0.905
2	0.062
3	0.020
4	0.008
5	0.003
8	0.001
13	0.001

Table 3-5. Comparison of parameter estimates for availability probability, undetected-and-strikeable (UAS) probability, and detected-and-strikeable (DAS) probability from northbound (morning) and southbound (afternoon) transits during whale surveys in Glacier Bay.

Parameter	Transit	Estimate	95% CI	Rhat
Availability	Northbound	0.321	(0.298, 0.344)	1.001
Availability	Southbound	0.277	(0.257, 0.298)	1.003
UAS	Northbound	0.616	(0.579, 0.653)	1.001
UAS	Southbound	0.606	(0.570, 0.641)	1.001
DAS	Northbound	0.874	(0.857, 0.889)	1.002
DAS	Southbound	0.888	(0.874, 0.902)	1.003

Table 3-6. Comparison of parameter estimates for availability probability, undetected-and-strikeable (UAS) probability, and detected-and-strikeable (DAS) probability from three different encounter period lengths (10 seconds, 20 seconds, and 30 seconds) during whale surveys in Glacier Bay. We selected a biologically-based 20-second encounter period (in bold) that aligned with the median observed whale inter-cue interval, and compared two other encounter period lengths to assess the effect of period length on parameter estimation.

Parameter	**EP Length**	**Estimate**	**95% CI**	**Rhat**
Availability	10s	0.229	(0.217, 0.241)	1.003
Availability	**20s**	**0.319**	**(0.303, 0.336)**	**1.001**
Availability	30s	0.414	(0.392, 0.437)	1.002
UAS	10s	0.546	(0.519, 0.573)	1.002
UAS	**20s**	**0.540**	**(0.515, 0.566)**	**1.001**
UAS	30s	0.541	(0.515, 0.566)	1.005
DAS	10s	0.929	(0.921, 0.937)	1.004
DAS	**20s**	**0.865**	**(0.854, 0.877)**	**1.001**
DAS	30s	0.796	(0.781, 0.811)	1.001

Table 3-7. Comparison of parameter estimates for availability probability, undetected-and-strikeable (UAS) probability, and detected-and-strikeable (DAS) probability from four different ship-to-whale distance bins during whale surveys in Glacier Bay.

Parameter	**Distance**	**Estimate**	**95% CI**	**Rhat**
Availability	0 – 1000m	0.452	(0.361, 0.544)	1.001
Availability	1001 – 3000m	0.366	(0.333, 0.401)	1.001
Availability	3001 – 4500m	0.311	(0.281, 0.342)	1.001
Availability	4501 – 6000m	0.289	(0.258, 0.321)	1.001
UAS	0 – 1000m	0.790	(0.713, 0.857)	1.003
UAS	1001 – 3000m	0.672	(0.629, 0.715)	1.001
UAS	3001 – 4500m	0.713	(0.663, 0.759)	1.001
UAS	4501 – 6000m	0.761	(0.705, 0.814)	1.007
DAS	0 – 1000m	0.748	(0.686, 0.807)	1.001
DAS	1001 – 3000m	0.833	(0.809, 0.856)	1.001
DAS	3001 – 4500m	0.878	(0.857, 0.898)	1.001
DAS	4501 – 6000m	0.902	(0.882, 0.921)	1.001

FIGURES

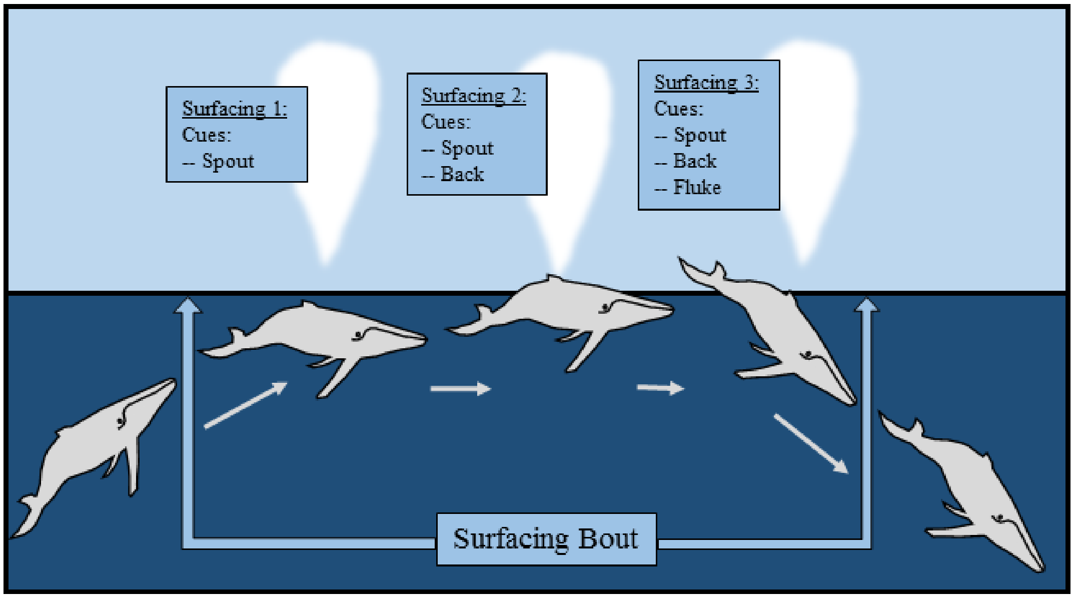

Figure 3-1. A schematic diagram of relationship between terms used throughout this document: cue (a specific whale-produced behavior used by vessel operators to determine whale presence), surfacing (one or more cues that occur consecutively each time a whale breaks the surface), and surfacing bout (a series of surfacings).

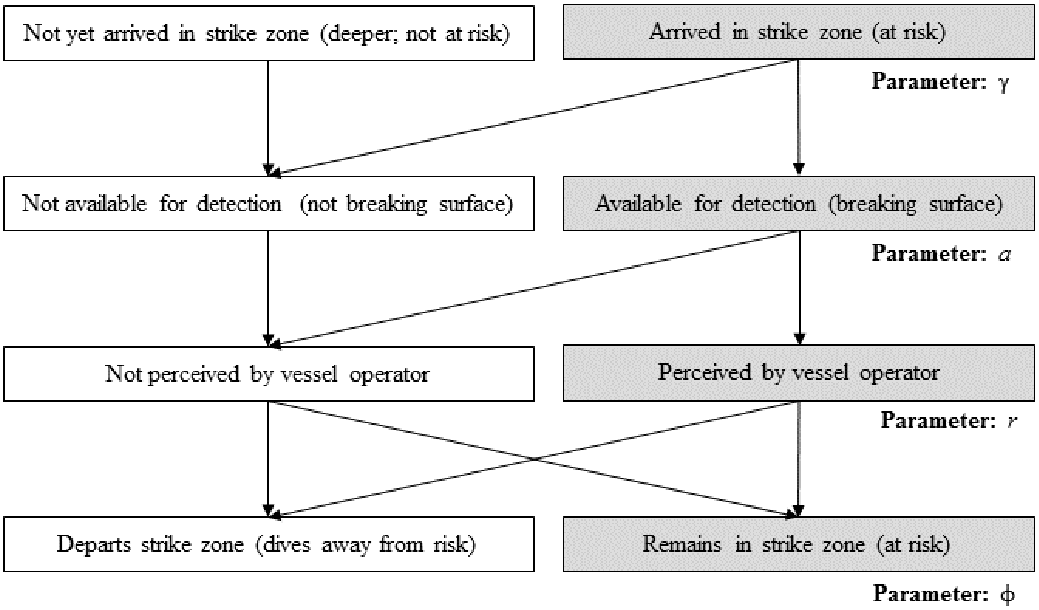

Figure 3-2. A schematic diagram of the detection and non-detection processes that drive whale observations by large ship operators.

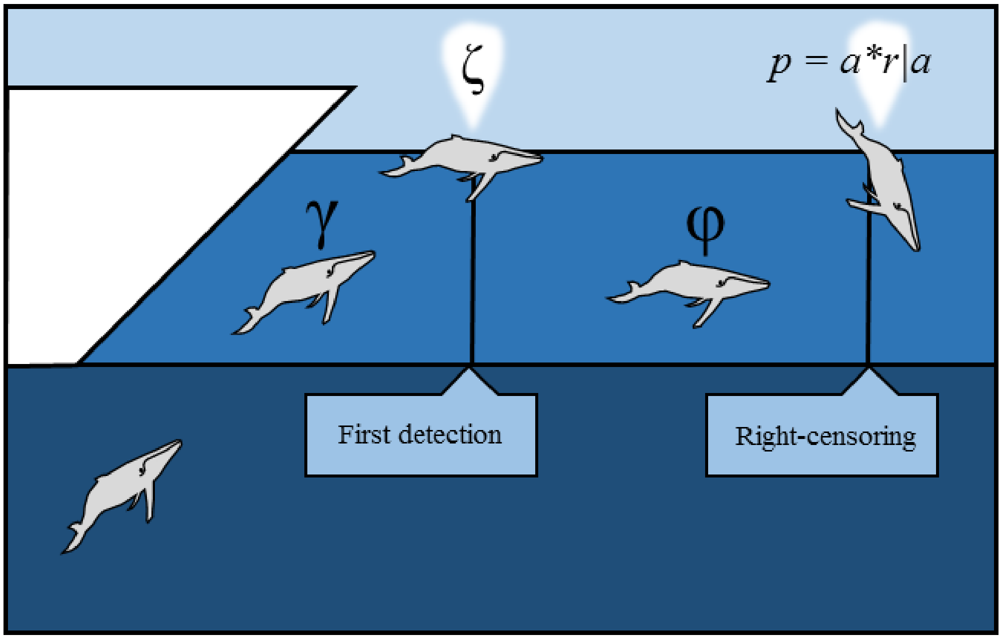

Figure 3-3. The application of the temporal symmetry model (Pradel 1996) to the study system. Gamma (γ) refers to the undetected-and-strikeable probability, zeta (ζ) refers to the initial detection probability, phi (φ) refers to the detected-and-strikeable probability, and $p = a * r|a$ refers to the probability of detection (after the initial sighting).

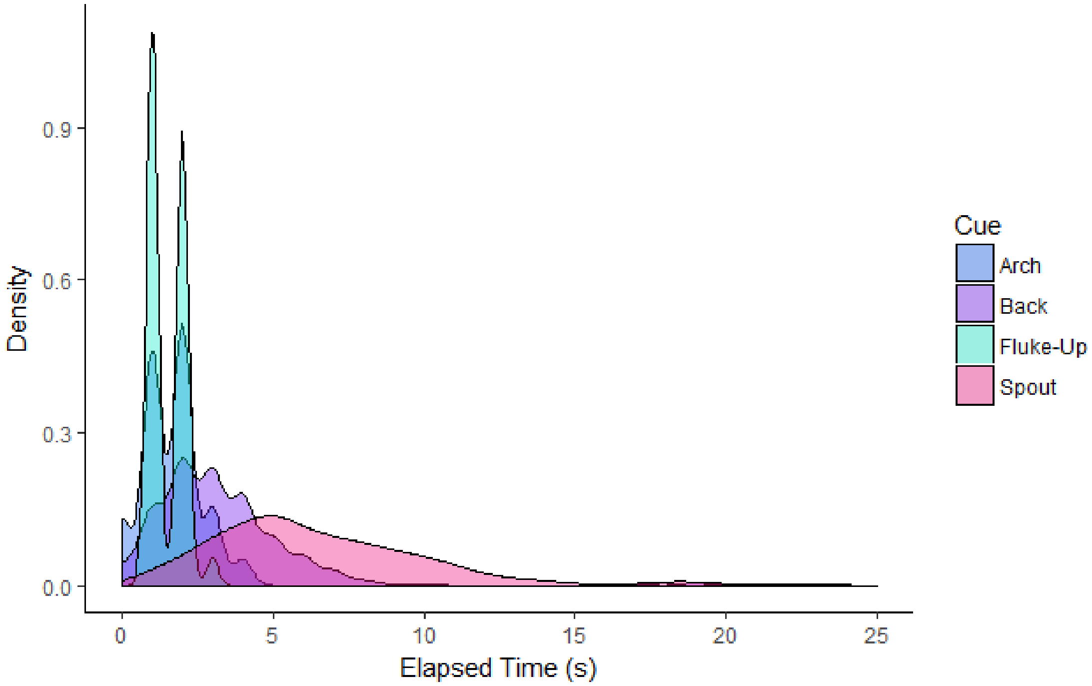

Figure 3-4. Durations of the most frequently observed cue types in GLBA in 2016 & 2017. The median duration of a fluke-up dive was 1 second (sd = 5.576), the median duration of a spout was 2 seconds (sd = 0.955 seconds), the median duration of a back was 3 seconds (sd = 3.219 seconds), and the median duration of an arch was 6 seconds (sd = 15.804 seconds).

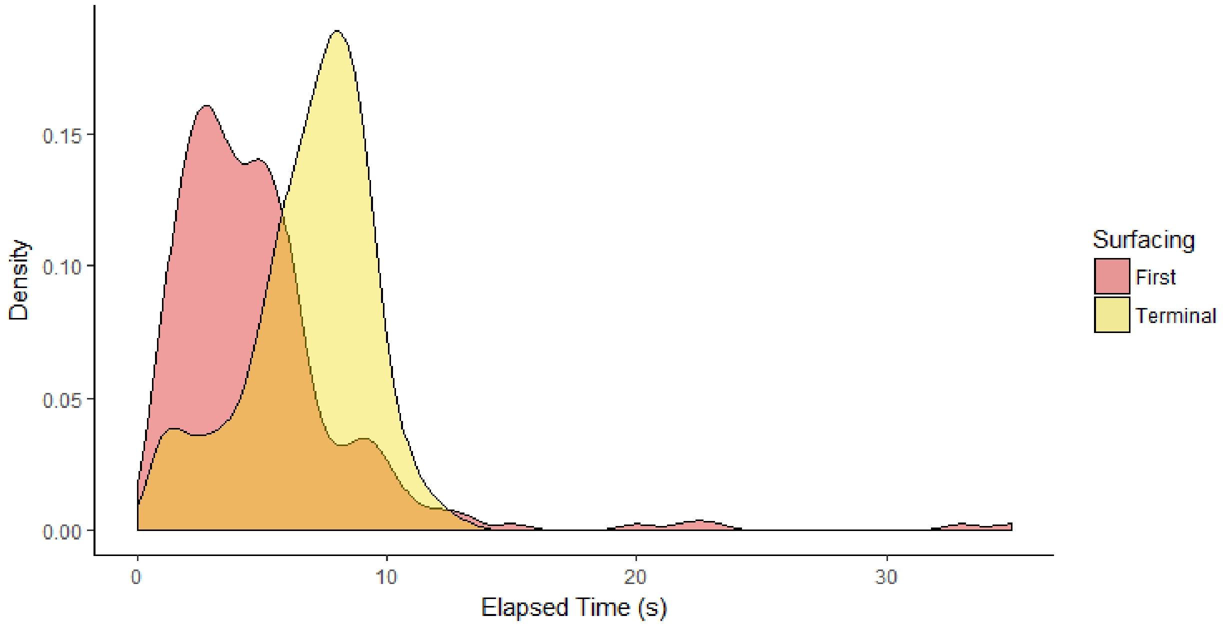

Figure 3-5. The relative durations of observed first and terminal surfacings within each surfacing bout. Surfacings may contain multiple cues (e.g. a terminal surfacing often contained a spout, back, and fluke-up). Only surfacing bouts which contained a terminal (fluke-up) dive were included in this calculation. The median duration of a first surfacing is 4.00 seconds (sd = 6.40 seconds), and the median duration of a terminal surfacing is 7.00 seconds (sd = 2.47 seconds).

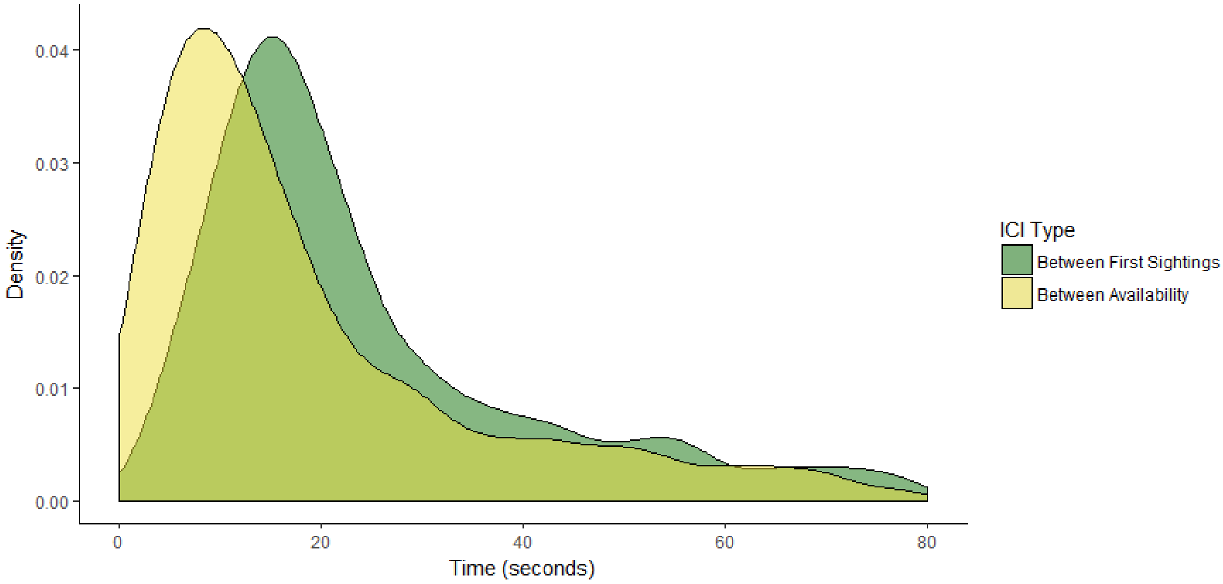

Figure 3-6. The relative durations of observed inter-cue intervals (ICI), compared across measurement types. The median ICI measured between first sightings (a typical definition of ICI in the literature) is 20.0 seconds (sd = 40.4 seconds), and the median ICI measured between the times that a whale is available to be detected (i.e. from the end of the previous surfacing to the beginning of the next surfacing) is 15.0 seconds (sd = 40.1 seconds).

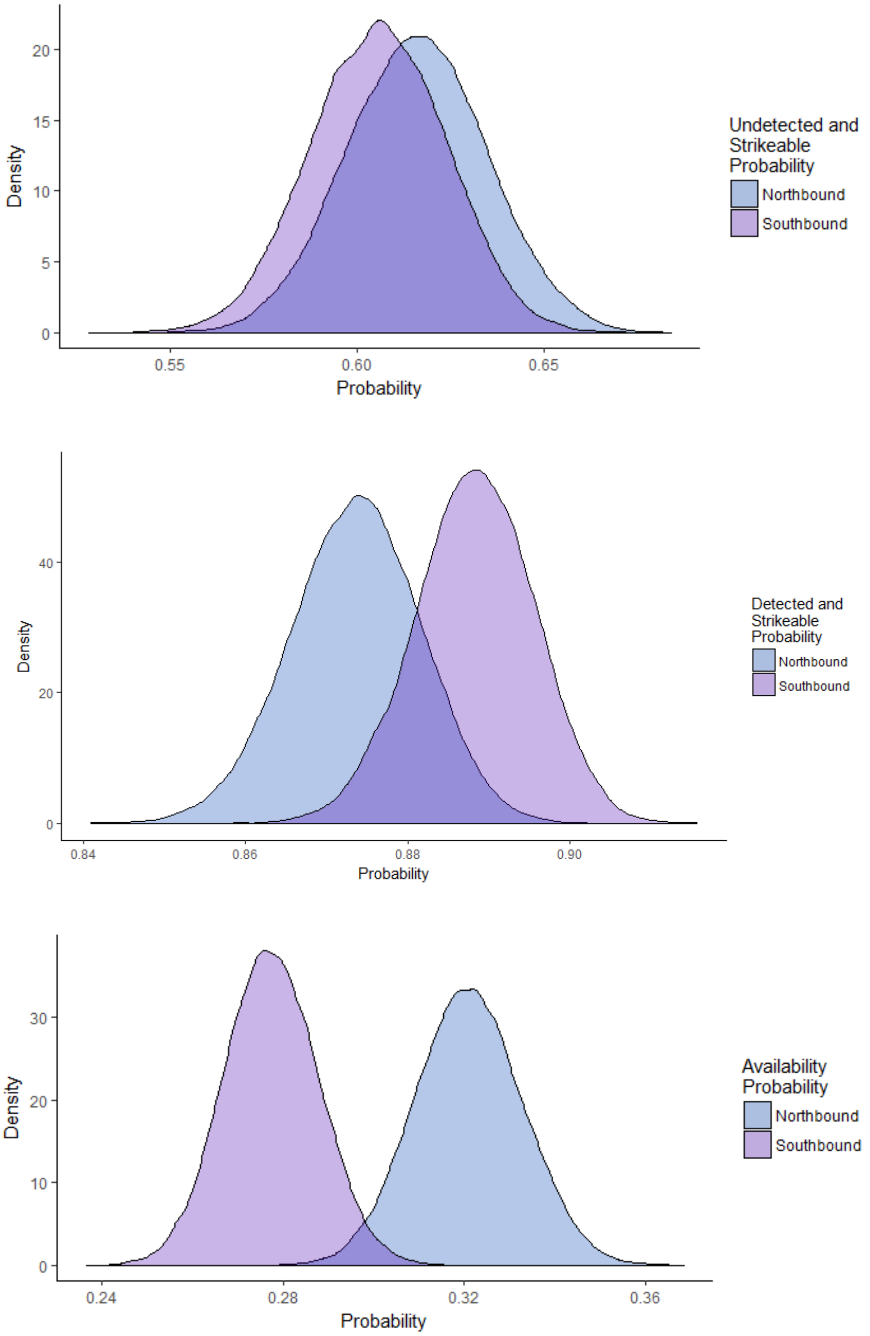

Figure 3-7. Posterior overlap between parameter estimates for availability probability, undetected-and-strikeable probability, and detected-and-strikeable probability from northbound (morning) and southbound (afternoon) transits during whale surveys in Glacier Bay.

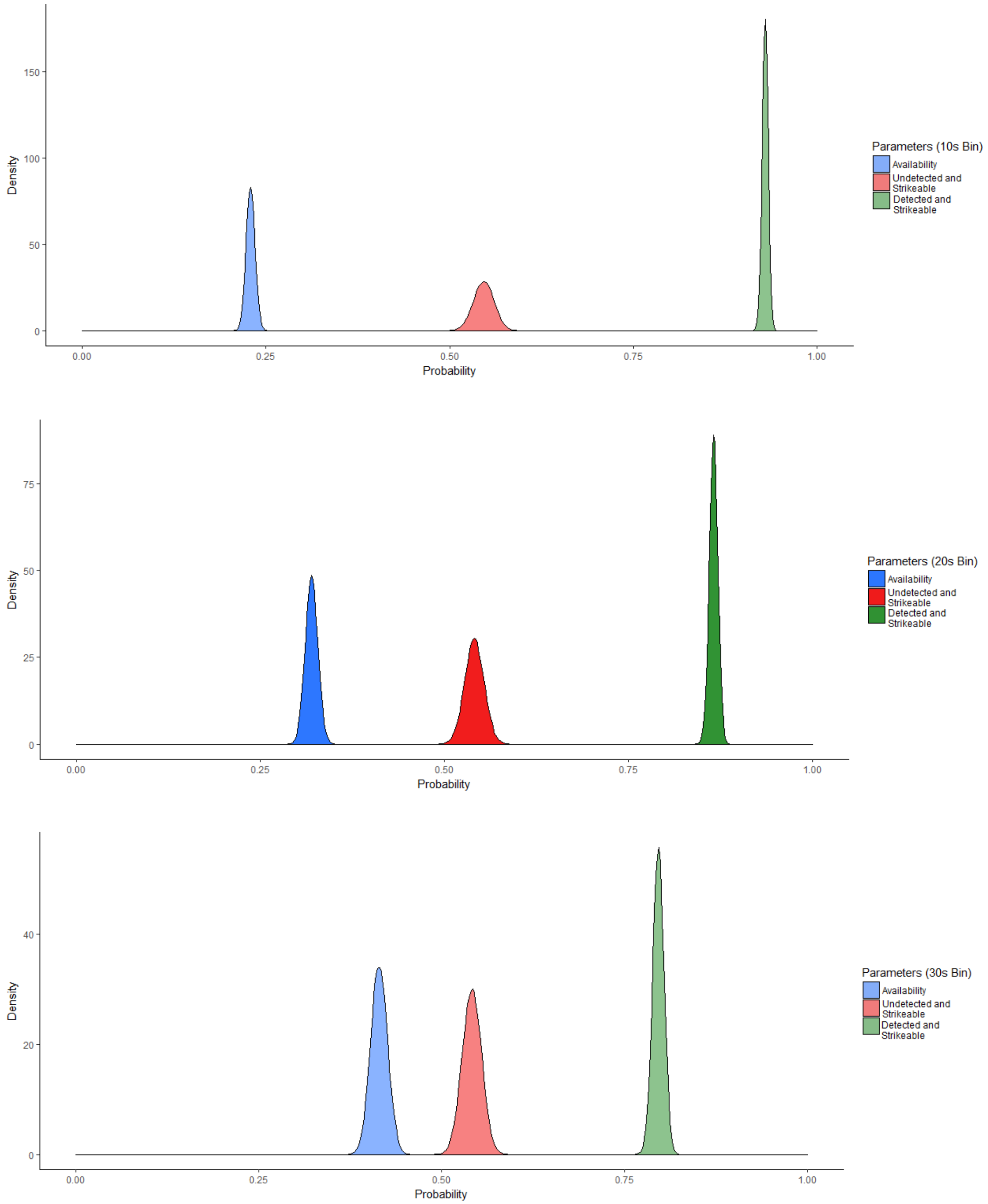

Figure 3-8. Comparison of posterior distributions of availability probability, detected-and-strikeable probability, and undetected-and-strikeable probabilities for pooled northbound and

southbound transits with encounter periods of 10s, 20s (the primary unit for analysis, presented in brighter colors), and 30s.

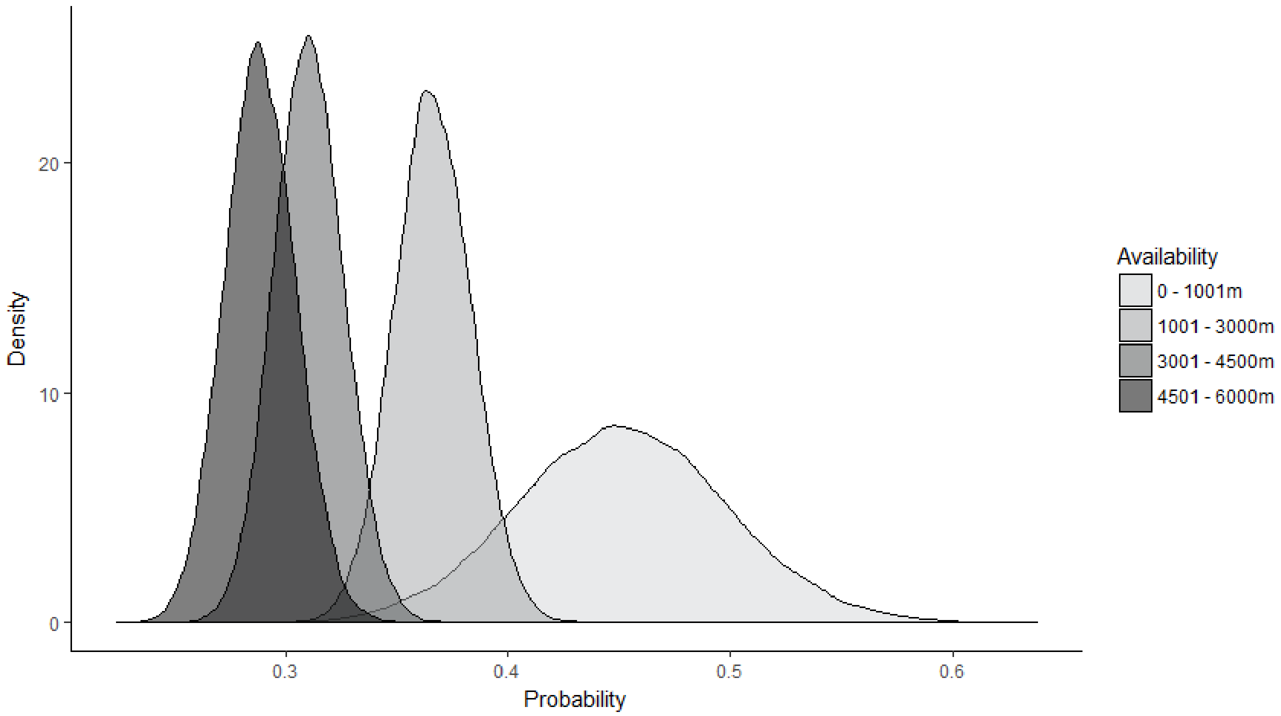

Figure 3-9. Posterior distributions of availability probability of humpback whales in Glacier Bay in 2016 and 2017, compared across binned ship-to-whale distance.

CHAPTER 4. OVERALL SUMMARY OF FINDINGS

The goal of this project was to quantify two main components of the active ship strike avoidance process, which occurs when vessel operators detect a whale in a ship's path and adjust their heading or speed in order to reduce the probability of colliding with the whale. First, we studied the ability of vessel operators to ascertain the direction of travel of whales, and second, we investigated the detection challenges faced by vessel operators as whales move through the "strike zone." Quantifying these factors that underlie active ship strike avoidance enables the development of voluntary recommendations for ship operators, and potentially enables the improvement of existing regulations by integrating whale behavioral measurements with the detection challenges faced by captains and pilots.

In studying the ability of vessel operators to determine whale direction of travel, we found that the probability of making a congruous DT assignment was higher if whales had broken the surface more times in a row, and if whales were near the ship. We also found that the probability of making any DT assignment increases as the time after the first sighting increases, with DT assignment occurring for approximately half of whales at the initial sighting.

In quantifying the probabilities of a whale entering and exiting the strike zone and the probability of the whale being available for detection, we found that whales are present and undetected in the strike zone far more frequently than they are available for detection. We found that almost half of whales will be present in the strike zone for 20 seconds prior to their initial detection, while two thirds of whales will remain in the strike zone for a full minute after their initial detection. Approximately one third of whales in the strike zone will surface in a given 20-second period.

When the results from the two studies are considered side by side, we are able to understand the probability of DT assignment in the context of the probability of a whale being in the strike zone. While our first analysis indicated that DT will be assigned for approximately half of whales at their first sighting, it also showed that it takes approximately one minute to assign DT for 75% of whales. However, our second analysis indicates that only two thirds of whales will remain in the strike zone for a full minute after their initial sighting. As our time periods lengthen, the chance of being able to assign DT before a whale dives decreases. Additionally, we know that the probability of a whale diving to depth at some point after the first sighting is equal to 1. As the time between the point at which the whale is observed and the point at which the whale dives decreases, the relevance of whale DT assignment to ship strike avoidance decreases, because the whale will soon exit the strike zone and thereby no longer be at risk of collision. Thus, DT assignment is most important for those whales that are first sighted in the cone of concern.

Ultimately, we intend to work with the National Park Service to use the results from these two studies to build recommendations for active ship strike avoidance protocols for whales first sighted under different ship-to-whale distance, ship speed, bearing, and DT scenarios.

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