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QUANTIFYING THE ECOLOGICAL PROCESSES UNDERLYING COLLISIONS BETWEEN LARGE BALEEN WHALES AND LARGE SHIPS TO EVALUATE RISK

Sara Halley Williams

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By

SARA HALLEY WILLIAMS

Bachelor of Science, Vanderbilt University, Nashville, Tennessee, 2007
Master of Science, University of Vermont, Burlington, Vermont, 2013

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Approved by:

Scott Whittenburg, Dean of The Graduate School
Graduate School

Paul M. Lukacs, Chair
Department of Ecosystem and Conservation Science

Scott M. Gende
National Park Service, Glacier Bay Field Station

Michael S. Mitchell
Montana Cooperative Wildlife Research Unit

Elizabeth C. Metcalf
Department of Society and Conservation

Jedediah M. Brodie
Department Organismal Biology, Ecology & Evolution

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Quantifying the ecological processes underlying collisions between large baleen whales and large ships to evaluate risk

Chairperson: Paul M. Lukacs

ABSTRACT

The marine environment is a major interface for human and wildlife conflict. Humans use the world's oceans for activities ranging from military operations, tourism and recreation, commercial shipping and transport, and resource extraction. These activities have a variety of impacts on marine wildlife, from alteration of the acoustic environment, displacement, changes to behavior and movement to direct physical injury or death due to collisions with vessels. Increasing awareness of human-associated negative impacts has called for research aimed at understanding the specific effects and consequences of human activity and marine wildlife overlap.

Large baleen whales are of particular research, conservation, and management interest. In past centuries, commercial whaling pressures decimated populations worldwide. Recent protection efforts and whaling restrictions have allowed for the recovery of some species, while others have yet to achieve substantial population growth (Magera et al. 013). Often, areas of intense human maritime activity heavily overlap critical large whale habitat, including feeding areas, breeding and calving grounds, and migratory routes (Block et al. 2011, Maxwell et al. 2013). Collisions between ships and whales ('ship strikes') have been documented across the globe and across large whale species (Laist et al. 2001, Jensen & Silber 2003, Neilson et al. 2012), and have grown to become one of the primary and most severe world-wide threats to baleen whale conservation (Clapham et al. 1999, Thomas et al. 2016).

Substantial research has laid the groundwork for understanding the occurrence, causes, and circumstances surrounding ship strikes (Vanderlaan & Taggert 2007, Vanderlaan et al. 2009, Gende et al. 2011, Gende et al. 2012, van der Hoop et al. 2012, Conn & Silber 2013, Redfern et al. 2013, Bezamat et al. 2014), the probability of and relative risk of ships strikes in specific areas, and the effectiveness of mitigation efforts (van der Hoop et al. 2012, Laist et al. 2014). However, much of this work has approached ship strike research from a coarse spatial and temporal scale. Understanding of ship strike occurrence and ship strike risk at a more detailed resolution is still lacking, and the best mitigation methods to reduce ship strike risk are still uncertain.

In Glacier Bay National Park and Preserve and nearby waterways, I investigated the ecological processes that underlie the risk of ship strikes between large ships and humpback whales (*Megaptera novaeangliae*). Using spatially-explicit and observation-based methods, I evaluated density and occurrence, movement, and behavioral responses to anthropogenic activity of whales in real-time overlap with large ships. Results of these assessments were incorporated in a simulation framework to evaluate ship strike risk. My aim was to provide relevant and useful information to managers, conservation practitioners, and ship operators to reduce the negative impacts of human use of the ocean on large whales.

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INTRODUCTION

Significant conservation efforts in the last half century have allowed many large whale populations around the globe to rebound from commercial whaling pressure. Simultaneous increases in whale populations and maritime large vessel traffic have resulted in increased opportunities for collisions between whales and ships ('ship strikes'), which often result in whale mortality events (Laist et al. 2001, Jensen and Silber 2003, Vanderlaan and Taggert 2007, Neilson et al. 2012, Van der Hoop et al. 2012, Conn & Silber 2013). Consequently, ship strikes and their associated impact on individual whales and populations have become a growing conservation concern over the last few decades and remain one of the leading threats to the persistence of baleen whale populations (Clapham et al. 1999, Thomas et al. 2016). In fact, the United Nations considers ship strikes a significant challenge for international sustainable development and will be addressed at the United Nations Ocean Conference in June of 2017 (United Nations Ocean Conference, preparatory meeting, 15-16 February 2017).

While substantial progress has been made in understanding the occurrence of ship strikes in a variety of regions (Laist et al. 2001, Jensen & Silber 2003, Neilson et al. 2012), the drivers of ship strikes and the degree of their overall impact on population demographics and species persistence is poorly understood. One problem is that ship strikes can be difficult to detect and are commonly unreported even when they are detected (Laist et al. 2001, Vanderlaan & Taggart 2007). Thus, investigations of ship strikes often occur long after the event occurred, limiting our understanding of the direct causes of these events. In addition to their impact on conservation efforts, ship strikes are undesirable to industry and management organizations because of the negative publicity and economic loss surrounding human-caused mortality of charismatic and iconic species such as large whales. Ecotourism is a valuable conservation tool, but may be hindered by negative publicity associated with ship strikes.

Ship strikes arise when areas of the marine environment that whales use overlaps with ship routes. Because of the characteristics of areas of ocean that whales use, these areas often overlap with heavily-trafficked routes used by large ships for commercial shipping, military operations, resource extraction, or tourism. For example, primary feeding areas, calving and breeding grounds, and migration routes of North Atlantic right (*Eubalaena glacialis*) and humpback (*Megaptera novaeangliae*) whales overlap with shipping routes to major commercial and military ports along the western North Atlantic, such as Boston, MA and Virginia Beach, VA. This overlap of whale habitat and shipping routes has resulted in whale mortalities due to ship strikes every year and has been a factor in limited population recovery of the North Atlantic right whale (Knowlton & Kraus 2001, Kraus et al. 2005, Vanderlaan et al. 2008, Conn & Silber 2013).

Recent investigation has pointed to a number of factors that may increase the risk of ship strikes and whale death in areas of habitat overlap. For example, the risk of ship strikes increases with elevated numbers of ships, when ships travel at higher speeds, and when whales are engaged in feeding behaviors (Vanderlaan et al. 2008, Parks et al. 2011, van der Hoop et al. 2012, Conn & Silber 2013). To mitigate risks, current management and conservation actions have aimed to increase situational awareness for ship operators (e.g., Whale Alert and Listen for Whales, Right Whale Listening Network), impose mandatory or voluntary speed restrictions, shift ship lanes, and create entrance restrictions for static and dynamic protected areas (Vanderlaan et al. 2008, Betz et al. 2011, Redfern et al. 2013). However, current measures to assess the risk of ship strikes often do not include data taken when ships and whales are actually in the same place at the same time. This leads to the use of probabilities of occurrence of ships and whales over potentially inconsistent temporal and spatial scales. These assessments often rely on coarse global- or regional-scale species-habitat relationships and relatively small sample sizes of tagged individuals to estimate and predict where whales are likely to occur. Evidence that these efforts actually reduce the number of strikes remains inconclusive (van der Hoop et al. 2012, Laist et al. 2014).

We currently lack insight into fine spatial and temporal scale whale occurrence patterns, particularly when whales are in the immediate proximity of large ships, and this insight is crucial for managers and ship operators to inform ship strike avoidance actions and reduce ship strike risk. Glacier Bay National Park and Preserve (GBNP) in southeastern Alaska provides a unique setting to investigate whale occurrence patterns using data of large ships and whales collected in real time.

This area is a seasonally important feeding area for a large and growing population of humpback whales. Whales congregate in GBNP, adjacent waters, and much of southeastern Alaska from May through September of each year (Neilson et al. 2015, Gabriele et al. 2017). Simultaneously, many cruise ships travel these waters to access ports of call and provide scenic cruises within the National Park. We used these cruise ships as platforms to observe encounters between large ships and humpback whales (i.e., 'ships of opportunity'). Ships of opportunity are an increasingly valuable conservation tool, allowing researchers to use industry-supported vessels as observation platforms to collect data which may be otherwise inaccessible. We investigate variables that influence whale occurrence near large ships, the expected density of humpback whales within GBNP and adjacent water ways, and how the influence of these variables and whale density change over time during the feeding season. Our main objective is to use fine scale environmental and spatial characteristics to predict whale occurrence within regularly used ship routes and to provide information that can be used by managers and ship operators to inform ship strike avoidance actions.

METHODS

Study Area

We conducted surveys for humpback whales in Glacier Bay National Park and Preserve (GBNP) and the surrounding waterways in southeastern Alaska (Figure 1). The area is made up of Glacier Bay itself, a 1,255 km^2 fjord containing several tidewater glaciers, and the adjacent narrow waterways of Chatham Strait and Icy Strait. The area is characterized by complex bathymetry, sill-basin structures, and strong upwellings and current systems (Hooge & Hooge 2002). High levels of primary and secondary productivity result in high prey availability for several species of marine mammals, and as such, GBNP serves as a seasonally important feeding ground for humpback whales from three distinct population segments of the species (Neilson et al. 2015). Humpback whales that feed in GBNP and the surrounding waters generally arrive as in late April and may remain as long as late September (Neilson et al. 2015, Gabriele et al. 2017). High site fidelity between years and generations means that many whales have long sighting histories in and near Glacier Bay (Neilson et al. 2015).

While GBNP provides critical feeding habitat for humpback whales in the North Pacific, it is also one of the largest federally-managed marine protected areas and is managed by the National Park Service (NPS). The NPS works under a dual mandate to safeguard natural resources for future generations and to provide opportunities for the visiting public to experience the unique tidewater glacial landscape and associated wildlife (National Park Service 2010). To comply with both requirements, the NPS regulates and manages all visitor access to the park, nearly all of which occurs by marine vessel. Greater than 95% of visitors enter via cruise ship. Cruise ships transit the bay and adjacent waters almost daily from late spring through early fall, leading to a large number of ship-whale encounters (Gende et al. 2011, Harris et al. 2012). To manage cruise ship entries and visitor access to the park, the NPS enacts an entry quota, which limits entries on both a daily (maximum of 2 ships) and seasonal basis (maximum of 275 ships). The seasonal quota is divided into a 'peak' season of June through August and a 'shoulder' season of May and September.

Data collection

From 2008 to 2015 we recorded the location and frequency of humpback whale surfacing events from aboard cruise ships. For each trip on the ship, or survey, a single observer boarded the ship either upon its entry into GBNP via a NPS transfer vessel, or the observer boarded the day before the ship's entry into GBNP at the port of call where the ship was located (Juneau or Skagway). Observers that boarded once the ship was already in GBNP proceeded to the bow of the ship to begin conducting surveys. Observers that boarded in the port of call prior to GBNP began surveys at sunrise on the day the ship was to enter the park and collected observations in the waterways outside the park boundary. As the ship traveled up the bay, observations were continued until the ship approached either Tarr or Johns Hopkins Inlet, where whale sightings are rare (Figure 1; Gende et al. 2011). Ships typically spend several hours in this area at the northern end of the bay to allow viewing of the tidewater glaciers. Survey effort was reinitiated once the ship started back toward the park entrance. Data collection continued until the observer disembarked via the NPS transfer vessel near the southern boundary of the park. Alternatively, if the observer boarded at a port of call, surveys continued until sunset or until the ship traveled west out of Icy Strait and into the open ocean (Figure 1).

While surveying, observers continuously performed naked eye and binocular-assisted scans, using tripod- (Manfrotto Distribution Inc.; 055 Series; Upper Saddle River, New Jersey) mounted range-finding binoculars (Leica Viper II; accuracy, +1m at 1km; Leica, Charlottesville, Virginia, USA) and 8x42 binoculars (Swarovski Optik, Absam, Austria) to search for surfacing whales in front and abeam of the ship. Once a whale or group of whales was detected, observers used the rangefinder binoculars to measure the distance between the observer and the whale and used a protractor attached to the tripod-mounted binoculars to determine the bearing of the whale relative to the ship's bow. Observers estimated the distance if it was not possible to obtain an exact distance with the rangefinders, such as during a brief surfacing event or in thick fog, Observers also estimated the distance of objects other than whales in the seas throughout the day to allow for determination of distance estimation error and bias. Differences between actual and estimated distances were found to be small and unbiased; therefore no corrections were made for estimated distances.

The location of each whale or group of whales was geospatially referenced using a handheld GPS unit (Garmin, Olathe, Kansas, USA). A group was defined as two or more whales within two body lengths that coordinated their behavior and/or movement direction for at least one surfacing event (Ramp et al. 2010). Mother-calf pairs were considered a group of two and treated as any other group. After the initial sighting, observers continued to follow the whale (or group) and recorded each resurfacing event until it left the area of view, passed abeam of the ship, or the time between resurfacing was too long to ensure that it was the same whale(s). Additionally, observers recorded weather and visibility conditions at the start of each day and as conditions changed and deployed a separate GPS unit programmed to record the ship's location every 5 seconds, from which the track and speed (over ground) of the ship was calculated.

Analysis Methods

We used distance sampling and density surface modeling (DSM) methods to estimate and predict density of humpback whales within our study area (Buckland et al. 2001, 2008, Hedley & Buckland 2004, Miller et al. 2013). Within the DSM framework, surveys are placed randomly around the study area and each survey is designated as a transect. The length of the transect is typically considered the measure of survey effort and is incorporated as an offset factor in density estimation. Transects are further divided into segments of approximately equal length, and observations gathered during surveys are assigned to the segment where they survey platform was at the time of the observation. Segments also serve as the unit at which spatial and environmental covariates are collected.

Because we used cruise ships with predefined routes as survey platforms, we were unable to randomly place transects across the study area. This led us to use model-based inference. In this context, the meaningful measure of effort in our study was the size of each segment, instead of the transects as is typical in other uses of DSM methods (R. Williams and E. Rexstad; pers. comm). Thus, we divided our survey transects into approximately equal effort lengths of 1 km.

Defining the survey area can be difficult when using ships of opportunity to assess density or abundance (Williams et al. 2006). We defined our survey area post-hoc as the area within a 1 km buffer around all cruise ship paths. Additionally, we did not include portions of the ship route over which there was not reasonable coverage of survey effort, which removed much of Chatham Strait from our survey area (Figures 1 and 2). We defined our survey area in this way for two reasons. First, because our aim was to investigate the occurrence of whales within our study area that were vulnerable to collisions, we were most interested in the density of humpback whales directly in the vicinity of the regular ship route. Second, distance sampling assumptions require that animals are distributed independently of survey transects, and density surface modeling assumptions require that survey transects be randomly placed around the study area (Buckland et al. 2001, 2008, Hedley & Buckland 2004). However, in our study area, whales tend to aggregate around coast lines (Nielson et al. 2015), and cruise ships travel nearly identical routes through deep parts of the bay. Constraining our survey area to that directly around the merged ship tracks aided in mitigating violation of these assumptions.

We first used line transect distance sampling to generate a function relating the probability of detecting a whale given increasing perpendicular distance between the whale and ship track in program R (ver. 3.3.1; R Core team 2016) using the package 'Distance' (ver. 0.9.6; Miller 2016). The detection probability we used here was different than the detection probability we reported previously (Williams et al. 2016). In our previous study, we used point transect distance sampling methods, which estimated detection probability as a radial distance from the location of the observer. In that study, our objective was to estimate the instantaneous probability of detection given increasing distance. Additionally, we were concerned with the degree that other covariates, such as weather, whale group size, and whale behavior influenced detection. In the current study, our focus was to estimate a detection probability from a ship traveling along a transect that would be further used within DSM methods. Thus, using line transect methods was appropriate.

Next, we used our detection function within a density surface modeling framework. We chose to use the count formulation for density estimation because it uses the observed counts as the response and adjusts area for survey effective effort, instead of using inflated counts as the response (Miller et al. 2013). Since the count formulation allows covariates to be included on survey segments but does not allow covariates to be included on the detection function, we used conventional distance sampling methods (Buckland et al. 2001, 2008). We evaluated the hazard rate and half-normal key functions without covariates other than distance. We selected the detection function using AIC, visual inspection, and assessment of goodness of fit using Cramer von Mises (CvM) values (Buckland et al. 2001, 2008).

After selecting a detection function, we then fit spatially-explicit generalized additive modls to our data to estimate the density of whales within our survey area and how this varies with explanatory covariates (Table 3). Because we were interested in how density of whales near the ship might change across the feeding season, we generated models for a variety of time periods (Table 2). We separated our data into six models: the first using data from the entire study period, the second and third using data from the peak season (June through July) and the shoulder season (May and September), and the fourth, fifth and sixth models using data from June, July, and August individually.

In addition to spatial variables (easting and northing), we were initially interested in using a variety of remotely-sensed habitat variables, such as temporally dynamic chlorophyll levels and sea surface temperature (SST), as covariates in our models for both density estimation and prediction. However, consistent cloud cover over southeastern Alaska during the summer months made use of these types of data difficult. To combat this, we explored sea surface temperature climatologies, which provide long term averages of sea surface temperature at monthly and annual resolutions. We generated monthly SST climatologies from ultra-high resolution (0.01 x 0.01 degree) daily SST raster layers (JPL Our Ocean Project, Global Foundation Sea Surface Temperature Analysis 2010) using the Marine Geospatial Ecology Tools (MGET; ver. 0.8a57; Roberts et al. 2010) in ArcMap (ver. 10.3.1; ESRI 2015). We used the individual monthly SST climatologies for models using data from a single month. We averaged monthly SST climatologies for models that used data from more than one month. For example, we averaged the monthly SST climatologies from May through September and used this single value for both density estimation and prediction for the model using all data. We also included distance of the segment to coast (m) as a habitat covariate in our models, as this varied across the survey area and could influence the amount and location of prey available to whales. We obtained all covariates values at the location of the spatial centroid of each segment.

We fit our density surface models using the package ‘dsm’ (ver. 2.2.12; Miller et al. 2016). We performed initial model exploration and assessment using all data from across the study period to select a distribution family and to determine if our spatial variables provided better fit as individual univariate terms or together as a bivariate term (i.e., a smooth of easting and a smooth of northing, or a smooth of easting and northing). We then fit all models beginning with all covariates and removed insignificant terms in a step-wise method based on a selected 0.05 p-value significance level. We assessed model fit by visually checking deviance residual plots. We selected our top model for each time period by removing the insignificant terms and checking for the largest deviance explained. We generated a prediction grid of 1 km^2 grid cells that we overlaid on our survey area and used the top models for each time period to predict density across this grid (Figure 2; bottom panel). Spatial and environmental covariate values were obtained for the prediction grid at the spatial center of each grid cell.

We could not use typical variance propagation and coefficient of variation methods to estimate variance because of the design of our surveys. Instead, we assessed variance within a bootstrap framework (Buckland et al. 2001, Williams et al. 2006). Using all data across all years and the top model for this data set, we randomly removed a single survey's effort and whale observations. We then refit the density surface model and estimated density for each grid cell of our study area and the total density of the survey area. We determined the maximum, median, and minimum predicted density of each grid cell across the survey area, as well as the range between the minimum and maximum estimated density per cell. We also assessed the range of summed total density across the entire survey area.

RESULTS

Observers performed 607 surveys onboard 27 cruise ships from May 6, 2008 to September 23, 2015 covering 123,478 km (Table 1). After dividing the surveys into approximately 1 km segments of equal effort, the resulting data set held 123,490 survey segments. At least one whale was observed on over 90% of cruises, and we collected 3,838 observations of unique individuals or groups in total. We right truncated our data at the 85^{th} percentile to estimate the detection function (n = 3,262). Perpendicular distance for these observations ranged from less than 1 to 2,190 m. Our survey area, constrained as noted to a 1 km buffer around the cruise ship route crossing Glacier Bay and Icy Strait, covered 1,925 km^2 (Figure 2). We used the 2,138 observations of individual or groups of humpback whales first sighted within this buffer to estimate density across our survey area.

The number of surveys and observations varied across the time periods modeled (Table 2). For the model using all data, we used all 2,138 whale observations and all 648 surveys. The perpendicular distance between the ship and whale ranged from less than 1 to 1,000 m (bounded by our 1 km buffer cutoff) and averaged 439.5 m. Group size of these observations ranged from 1 to 8 whales. For the peak season model, using data from June, July, and August of all years, we obtained 1,686 observations over 384 surveys, with group sizes again ranging from 1 to 8 whales. As expected based on the ecology of humpback whales in the area, the number of observations was lower during the shoulder season. We collected 452 observations during 145 surveys that were used to model the shoulder season of May and September across all years. During this time period, group sizes ranged from 1 to 6 whales. The models for June, July, and August used data from similar numbers of surveys (124, 132, and 128, respectively). The number of observations varied somewhat during these time periods, with the highest number of observations in July and the fewest in August (June = 529, July = 662, and August = 495). June and July both held observations of group sizes from 1 to 8 whales, while August held observations of group sizes from 1 to 5 whales.

To select a detection function that related the probability of detecting a whale to distance between the whale and the ship, we assessed the fitted detection functions. AIC values for half-normal and hazard rate key functions were similar (AIC = 49340 and 49342, respectively). Visual inspection and assessment of goodness of fit using Cramer von Mises (CvM) values showed a slight preference for the hazard rate model (CvM test statistic = 0.434, $p = 0.060$) over the half-normal model (CvM test statistic = 0.437, $p = 0.058$). Thus, we used the hazard rate detection function in our density surface models. Detection probability decreased substantially with increasing distance (Figure 3). At 500 m, probability of detection was near 0.8, while at 1,000 m, it dropped to approximately 0.5 (Figure 3).

To assess the influence of spatial and environmental covariates on the estimated density of whales in our survey area, we explored spatially-explicit density surface models fit using generalized additive modelling methods. Initial density surface model exploration indicated that a negative binomial distribution and bivariate smooth for our spatial terms provided best fit and explained the most deviance for our data. Though our survey area was constrained to the area directly around the ship, values of the environmental covariates we explored did vary across our survey (Table 3). The spatial term was significant ($p < 0.05$) in every time period’s model, but significance of environmental covariate terms varied by time period and thus different time periods resulted in different covariates selected (Table 4).

Spatial location and distance to coast were significant in estimating density for the model using all data across the duration of our study ($p \leq 0.001$ for both terms; Table 4). These terms explained 29.2% of the deviance in observed whale locations. Increasing distance from the nearest coastline had a negative influence on the estimated density of whales (Figure 5). The predicted density for survey area from this model was 20.2 whales (Table 4, Figure 4). The model using only data from the peak season across all years of the study had similar results (Table 4). Both the spatial term and distance to coast were significant, with increasing distance to coast having a similar negative influence on density ($p \leq 0.001$ for both terms; Table 4). Compared to the model using all data, the deviance explained and predicted density across the survey area were both slightly increased for the peak season model (29.5% deviance explained and 21.5 whales per km^2; Table 4, Figure 6). The model using data from the shoulder seasons across all years again resulted in the spatial term and distance to coast being significant with the same negative influence of increasing distance to coast ($p \leq 0.001$ for both terms; Table 4). However, this model explained much less variation (15.9%) and had a slightly lower predicted density (19.4 whales per km^2; Table 4, Figure 6).

The models using data from monthly spans were less similar to those using data from across months. For June, both the spatial term and the monthly sea surface temperature monthly climatology average were significant ($p \leq 0.001$ for both terms; Table 4, Figure 7). In this model, SST had little influence at the lower range of the covariate but had a negative influence as SST increased above approximately 10 C (Figure 8A). The deviance explained for this model was 30.0%, and this model was tied with July for having the highest predicted density (26.2 whales per km^2; Table 4, Figure 7). Similarly to June, the spatial term and monthly sea surface temperature monthly climatology average were again significant for the July model, ($p \leq 0.001$ for both terms; Table 4). Sea surface temperature showed a similar relationship though the negative influence on density was steeper and occurred around 10.5 C (Figure 8B). Distance to coast was also significant in this model and showed the same negative relationship between increasing distance to coast and density as in other models ($p \leq 0.001$; Figure 8B).

The deviance explained for the July model was the highest of the model set (34.2%; Table 4). Only the spatial term was significant for the model using observations from only August across all years (Table 4).

We generated 1,000 bootstrap iterations of predicted density for each grid cell of the survey area using the model with all data to assess variance. The total predicted density summed across the survey area ranged from 19.3 to 20.4 whales (median = 20.2; Figure 9). Predicted density for each grid cell did not vary widely across bootstrap iterations. The smallest difference between the minimum and maximum value for predicted density within a cell across all bootstrap iterations was 0.00006 whales per km^2 and the largest difference was 0.01558 whales per km^2.

DISCUSSION

Past research has provided insight into large spatial scale habitat use of humpback and other large baleen whales for life history activities such as breeding, calving, feeding, and migration (e.g, Calambokidis et al. 2001, Dransfield et al. 2014, Rosenbaum et al. 2014). Our study complements knowledge of large-scale habitat use by exploring the relationships between fine-scale habitat characteristics and whale occurrence and density. On average, ship operators may expect to encounter 20 whales during each transit into and out of GBNP. The highest density of whales was predicted to occur at the confluence of the entrance of the bay and Icy Strait, as well as the narrow region at the western edge of Icy Strait where islands extend into the waterway (Figure 4). This estimated density varied when constrained to specific time periods throughout the summer; for example, estimated density increased to 26 whales per transit during June and July, while in August, density decreased to 15 whales per transit. Predictions for June July highlighted areas of high density similar to those from the entire study period, however these areas of high density were more concentrated in July (Figure 7).

We found that distance to coast was an influential variable in all but two models. While cruise ships in GBNP typically travel in areas of the bay and adjacent straits that are an appropriate depth, the highly variable bathymetry of the area means that routes following deeper areas still overlie a range of distances to the nearest coast. In all models where the variable was significant, increasing distance to coast had a negative influence on estimated whale density. This result is consistent with decades of whale monitoring in GBNP, which has regularly identified large feeding groups of whales near shores (Neilson et al. 2015, Gabriele et al. 2017). Therefore, it may be useful for ship operators to increase vigilance when operating closer to the coast line.

Sea surface temperature also influenced whale density in months with the highest predicted density (June and July). In both models, increasing SST had a positive influence on density at lower temperatures. Increasing SST then had a negative influence on density above approximately 9 C for June and above approximately 10.5 C for July (Figure 8A and 8B). While sea surface temperature itself is not a direct biological driver of humpback whale occurrence, it may serve as a convenient proxy for other biologically relevant characteristics. For example, SST may reflect the influence of strong upwellings, which bring colder nutrient- and plankton-rich water to the surface (Hooge & Hooge 2002). In turn forage fish, important prey for humpback whales (Neilson et al. 2015), aggregate in dense schools in these areas to feed. Our finding that increasing SST above a threshold had a negative impact on whale density may reflect the more biologically meaningful relationship between upwellings and humpback whale prey availability. While only a proxy for other biological information, SST is a readily-available metric that managers and ship operators can use to inform real-time decisions. Additionally, humpback whales are a globally distributed species, and SST data can currently be obtained for all oceans. Thus, this proxy may be useful in prediction of whale occurrence and mitigation of ship risk across feeding grounds for other populations.

Using cruise ships as ships of opportunity to gather spatial data created a variety of constraints, which led to the violation of some assumptions of distance sampling and density surface modeling. For example, distance sampling assumes that animals do not move before detection (Buckland et al. 2001, 2008). While it is possible that whales did indeed move as the ship approached, whether deterred by noise or the physical approach of the ship, researchers have previously reported that whales typically do not respond to the approach of a vessel (McKenna et al. 2015). Defining our survey area was also a challenge due to the limitations of our survey platform. To resolve this, we constrained the area of density estimation and prediction to that of the immediate vicinity around the ship routes. This eliminates the possibility of extrapolating predicted densities across conditions that were not sampled and alleviates effects of possible differences in the distribution of whales in routes that ships travel compared to areas that the ships do not travel.

The resolution of temporal and spatial scales of estimation and prediction are important within management context. Ideally, density predictions could be made to match the temporal scale at which ships enter the study area (i.e., daily). This would allow daily adjustment of management regulations, such as speed and route restrictions. However, implementation of daily predictions models is limited by the relatively few number of observations that occur across a single day's survey effort (mean number of observations per day was 7.8). Still, density prediction over longer temporal scales, like the monthly predictions we provide here, reveal patterns of whale occurrence that are useful to ship operators. For example, the differences in predicted density between the peak and shoulder season our predictions for the month of July highlight that, while the general locations of high density areas (like the entrance of the bay as noted above) remain the same, the gradient from how to low density becomes more defined in certain sites within these areas. Yet, the predicted total density across the survey area is the same (26.2 whales per km^2) for these two months. This could indicate that whales are expected to be relatively more tightly clustered in July, while the same number of individuals may be somewhat more spread in these areas in June. The variables that influenced density also varied across the monthly temporal scale. The significance of SST in June and July alerts ship operators to the potential importance of this proxy metric's associated environmental variables during this time period. Compared to August, when SST was not significant, ship operators may find value in monitoring SST more closely during ship passages in June and July. Finally, the resolution of the spatial scale of the prediction grid must be relevant given the size of the management area. For example, Glacier Bay is quite narrow, less than 10 km wide in many locations. A prediction grid with cells of size 10 km^2 would not be useful in assessing changes in density across the ship's route through the bay. It is also important that the values of environmental covariates not vary greatly over the prediction grid cell, or the values obtained at the spatial center of the cell would not be characteristic of the entire cell. To address these concerns over spatial resolution, we used the finest grid cell size over which we were ensured reasonable survey coverage, model convergence, and representative covariates values.

In summary, our study improves understanding of whale occurrence patterns near ships within regularly-used travel routes, which can be used by managers and ship operators in conservation situations. Thus, it is important to translate our findings into methods that may mitigate the risk of ship strikes. Managers and ship operators may identify areas where the occurrence of whales is more likely by regularly monitoring SST along planned routes and being cognizant of the effect of distance to coast on whale occurrence. This information can be applied to establish management restrictions to help avoid fine-scale spatial and temporal overlap with whales in our study area and to recommend increased vigilance in areas where overlap is predicted to occur. This is particularly useful for ship operators, who simultaneously manage a variety of tasks while guiding ships through areas like GBNP and its adjacent water ways, and encounter whales in situations that require immediate decisions to enact avoidance measures.

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TABLES

Table 1-1. Number of surveys on cruise ships used as ships of opportunity to collect observations on humpback whale occurrence within survey area of Glacier Bay and adjacent water ways, southeastern Alaska from 2008 to 2015.

Ship	Number of surveys	Length of ship (m)
Amsterdam	20	238
Carnival Miracle	2	293
Carnival Spirit	4	293
Coral Princess	36	294
Crown Princess	5	294
Crystal Symphony	4	238
Dawn Princess	1	261
Diamond Princess	37	290
Golden Princess	1	290
Grand Princess	6	289
Island Princess	37	294
Noordam	7	290
Norwegian Pearl	18	294
Norwegian Sun	1	259
Oosterdam	24	285
Pacific Princess	8	181
Royal Princess (2010-2013)	6	181
Ryndam	23	219
Sapphire Princess	25	290
Sea Princess	7	261
Star Princess	5	290
Statendam	66	219
Tahitian Princess (2008)	6	181
Veendam	11	219
Volendam	99	238
Westerdam	24	285
Zaandam	59	238
Zuiderdam	62	285
Total surveys	607	

Table 1-2. Candidate model set explored to estimate factors influencing density for humpback whale occurrence within survey area of Glacier Bay and adjacent water ways, southeastern Alaska from 2008 to 2015 using observations from the foreword most bow of cruise ships. Models used observations from different time periods.

Models	Time period	Number of surveys	Number of observations
All data	May - September 2008-2015	529	2,138
Peak season	June, July, August 2008-2015	384	1,686
Shoulder season	May, September 2008-2015	145	452
June	June 2008- 2015	124	529
July	July 2008- 2015	132	662
August	August 2008- 2015	128	495

Table 1-3. Covariates explored for all models estimating density for humpback whale occurrence within survey area of Glacier Bay National Park and adjacent water ways, southeastern Alaska from 2008 to 2015 using observations from the foreword most bow of cruise ships.

Covariate	Description	Range
Spatial term	Spatially-explicit term of location within the survey area. Can be implemented as two univariate smooths (s(X) + s(Y)) or as a single bivariate smooth (s(X, Y)) (UTM).	
Easting (X)		378224 - 475661
Northing (Y)		6446123 - 6547597
Distance to coast	Distance from center of survey segment to nearest coastline (m).	Less than to 7,860
Sea surface temperature (SST)	Monthly climatology of sea surface temperature generated from 0.01 x 0.01 degree raster layers using MGET arcMap tools (degree C).	
Season average	Average of 5 monthly climatologies	8.34 to 11.41
June average	Single monthly climatology	8.23 to 12.13
July average	Single monthly climatology	8.98 to 13.03
August average	Single monthly climatology	9.89 to 14.64

Table 1-4. Model results estimating factors influencing density for humpback whale occurrence within survey area of Glacier Bay National Park and adjacent water ways, southeastern Alaska from 2008 to 2015 using observations from the foreword most bow of cruise ships.

Models	Covariates (smooths) included	Deviance explained (%)	Predicted density across survey area (whales per km^2)
All data	s(X,Y)*** s(distance to coast)***	29.2	20.2
Peak season	s(X,Y)*** s(distance to coast)***	29.5	21.5
Shoulder season	s(X,Y)*** s(distance to coast)***	15.9	19.4
June	s(X,Y)*** s(sst monthly climatology)***	30.0	26.2
July	s(X,Y)*** s(distance to coast)*** s(sst monthly climatology)***	34.2	26.2
August	s(X,Y)***	25.1	15.4

*** indicates p-value ≤ 0.001
* indicates p-vale < 0.05

FIGURES

Figure 1-1. Study area of Glacier Bay National Park and adjacent waters in southeastern Alaska where surveys were performed on cruise ships to explore factors influencing density of humpback whale occurrence within cruise ship route. Dashed line indicates boundary of Glacier Bay National Park. Solid line indicates typical cruise ship routes.

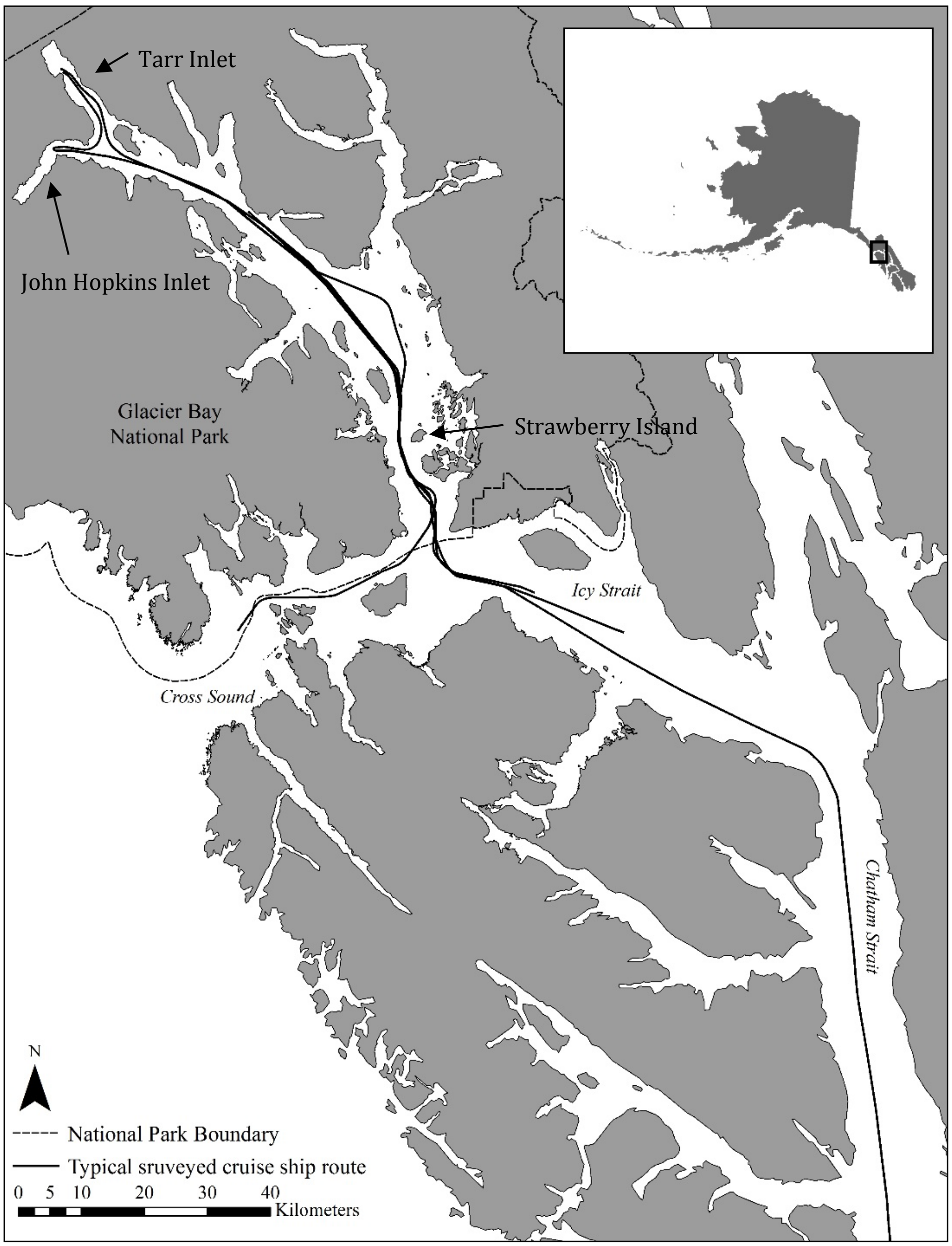
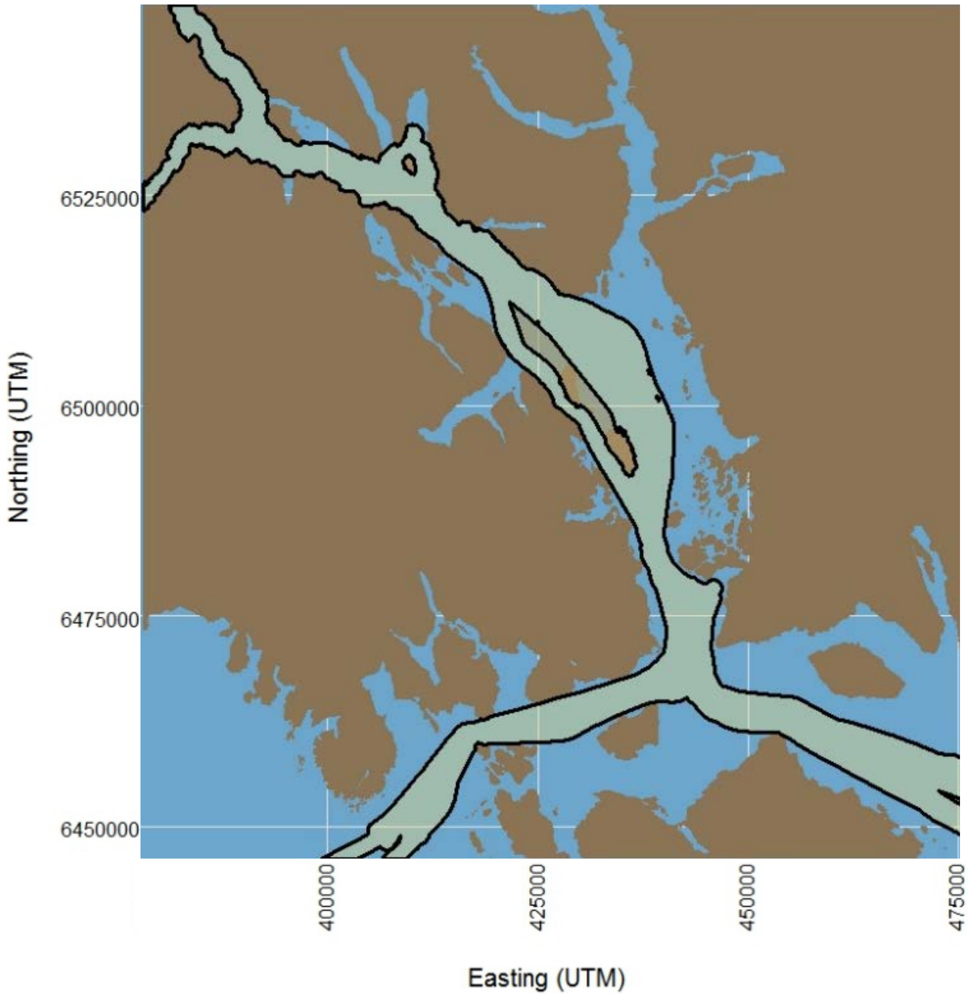
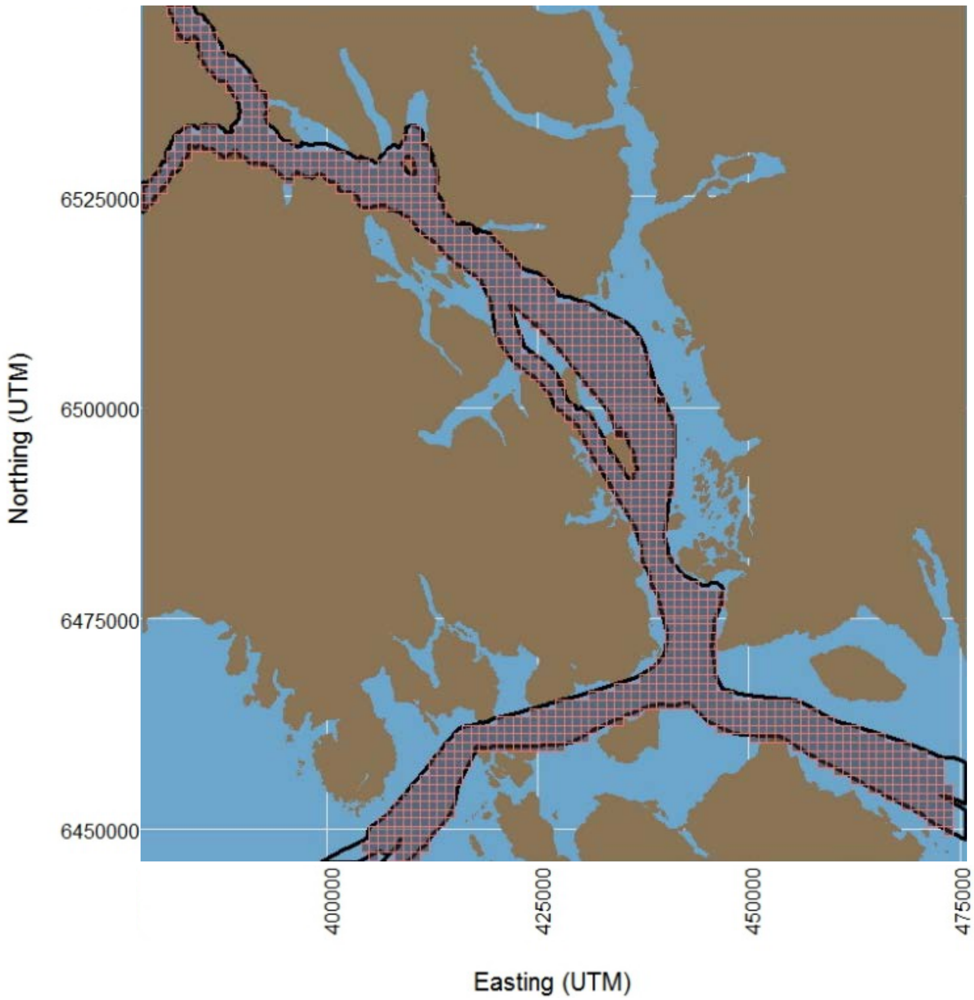


Figure 1-2. Survey area within study area suitable for humpback whale occurrence density estimation and prediction (1 km buffer around cruise ship routes; thick solid black line) in Glacier Bay National Park and adjacent waters in southeastern Alaska. Top panel shows survey area without prediction grid; bottom panel shows survey area with prediction grid (red).





6525000
6500000
6475000
6450000
Northing (UTM)
400000
425000
450000
475000
Easting (UTM)

Figure 1-3. Detection probability as it varies with distance (range = 0 to 4,565m) between ship and humpback whale observations in and near Glacier Bay National Park from 2008 to 2015 (N = 3,262).

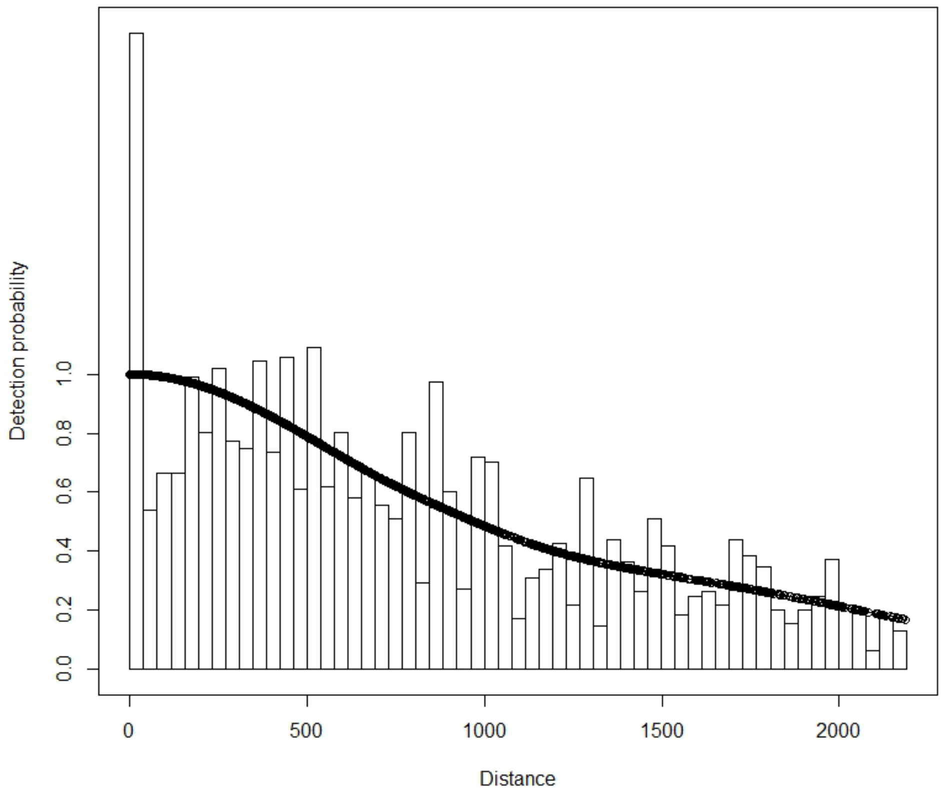


Figure 1-4. Predicted density for humpback whale occurrence within survey area of Glacier Bay National Park and adjacent water ways, southeastern Alaska using observations across all years (2008 to 2015) and months (May to September) of study. Predicted density per 1 km^2 grid in survey area.

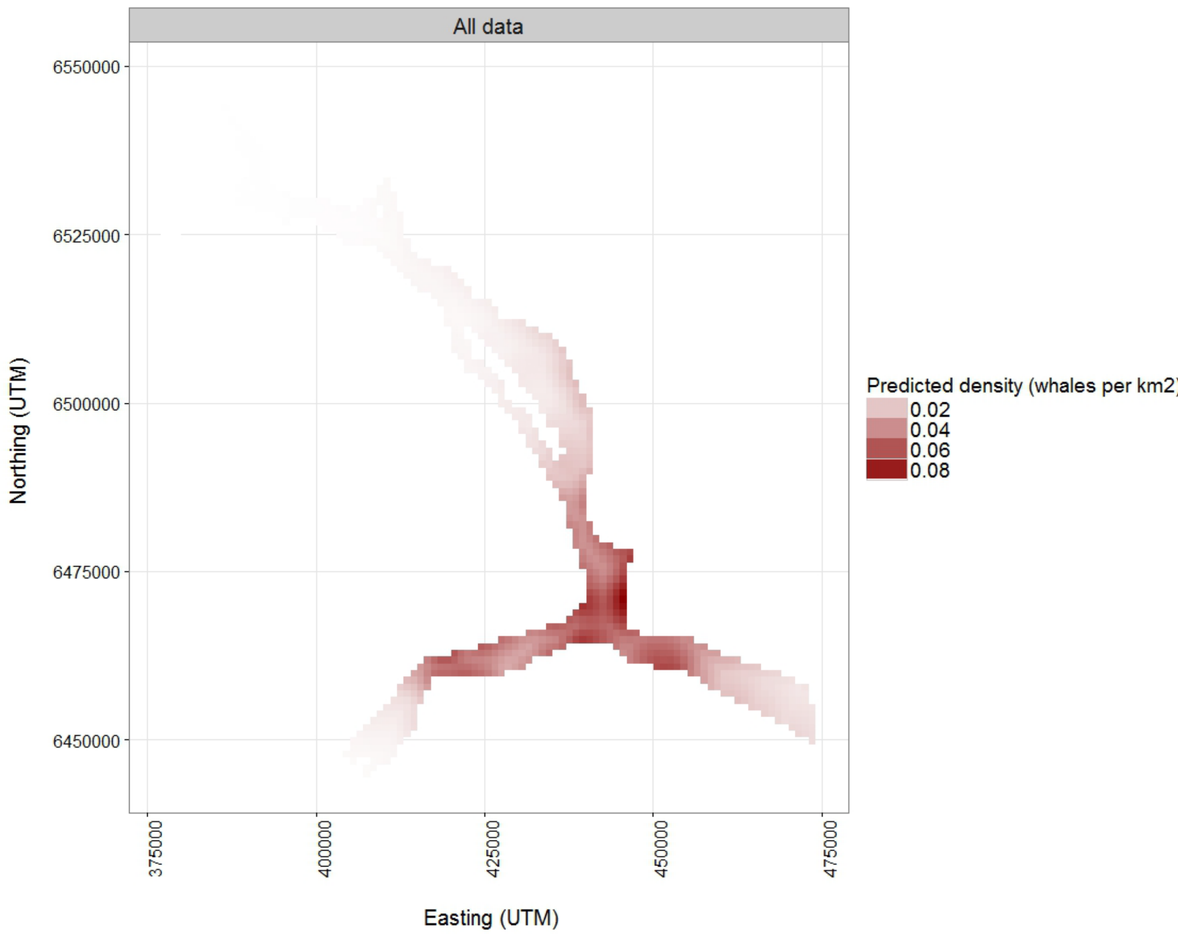


Figure 1-5. Influence of distance to coast (m) on estimated density for humpback whale occurrence within survey area of Glacier Bay National Park and adjacent water ways, southeastern Alaska using observations across all years (2008 to 2015) and months (May to September) of study. Predicted density per 1 km^2 grid in survey area.

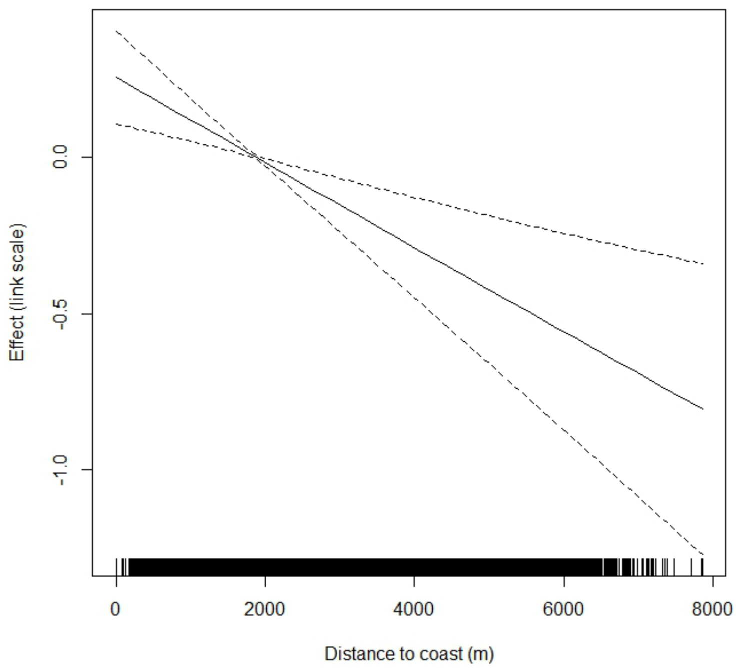


Figure 1-6. Predicted density for humpback whale occurrence within survey area of Glacier Bay National Park and adjacent water ways, southeastern Alaska using observations across all years of study (2008 to 2015) and pooled peak season (June, July, August) and shoulder season (May and September) months. Predicted density per 1 km^2 grid in survey area.

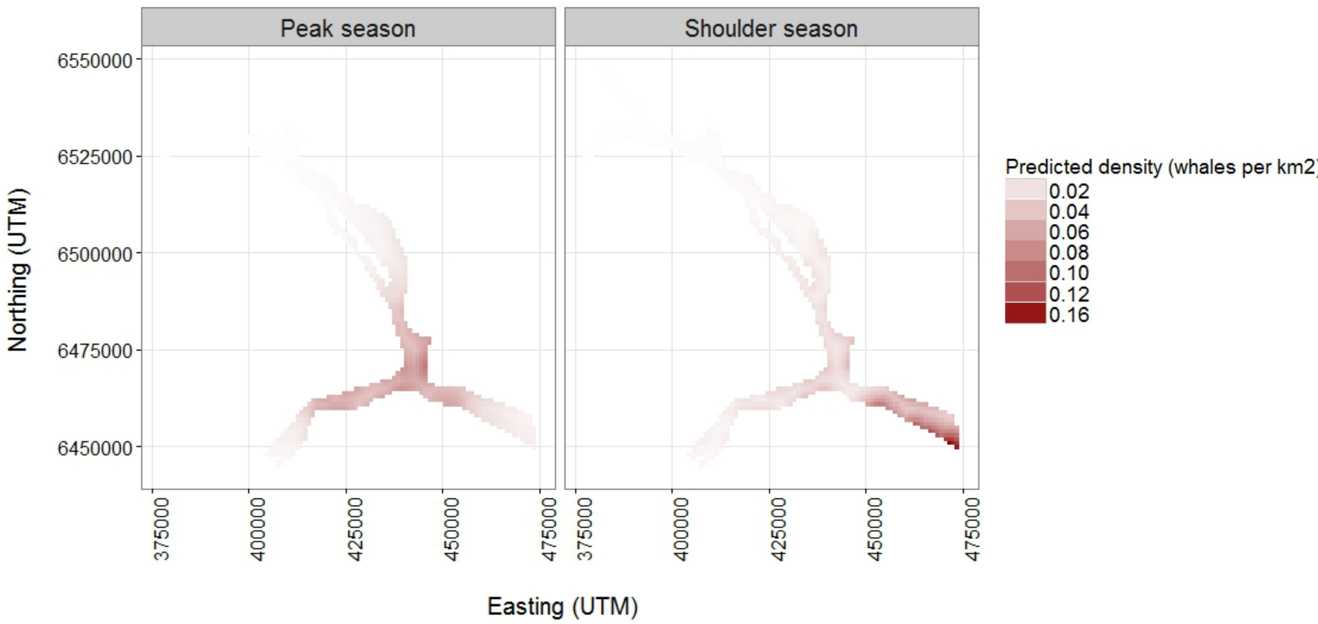


Figure 1-7. Predicted density for humpback whale occurrence within survey area of Glacier Bay National Park and adjacent water ways, southeastern Alaska using observations across all years of study (2008 to 2015) and individual peak season months (June, July, August). Predicted density per 1 km² grid in survey area.

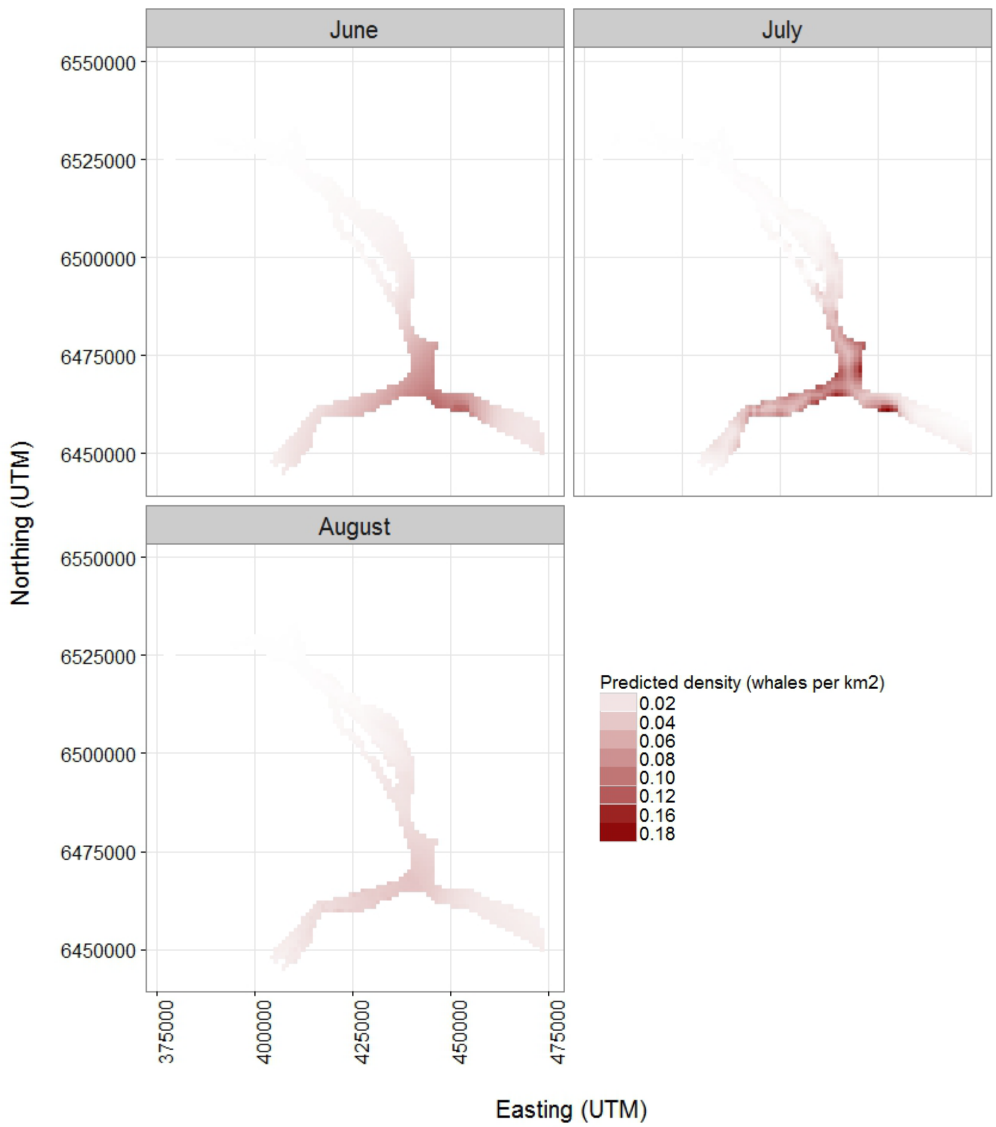
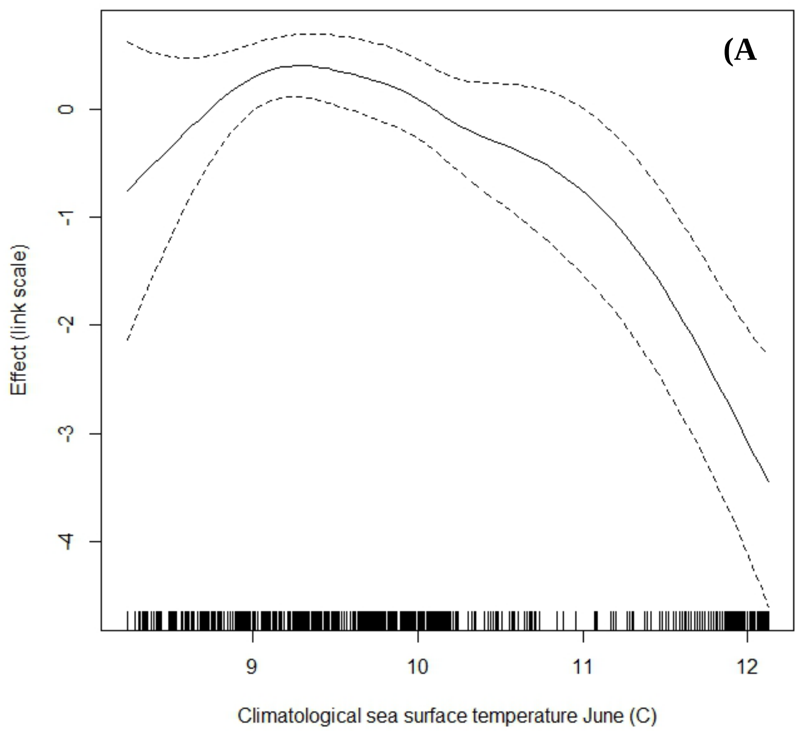
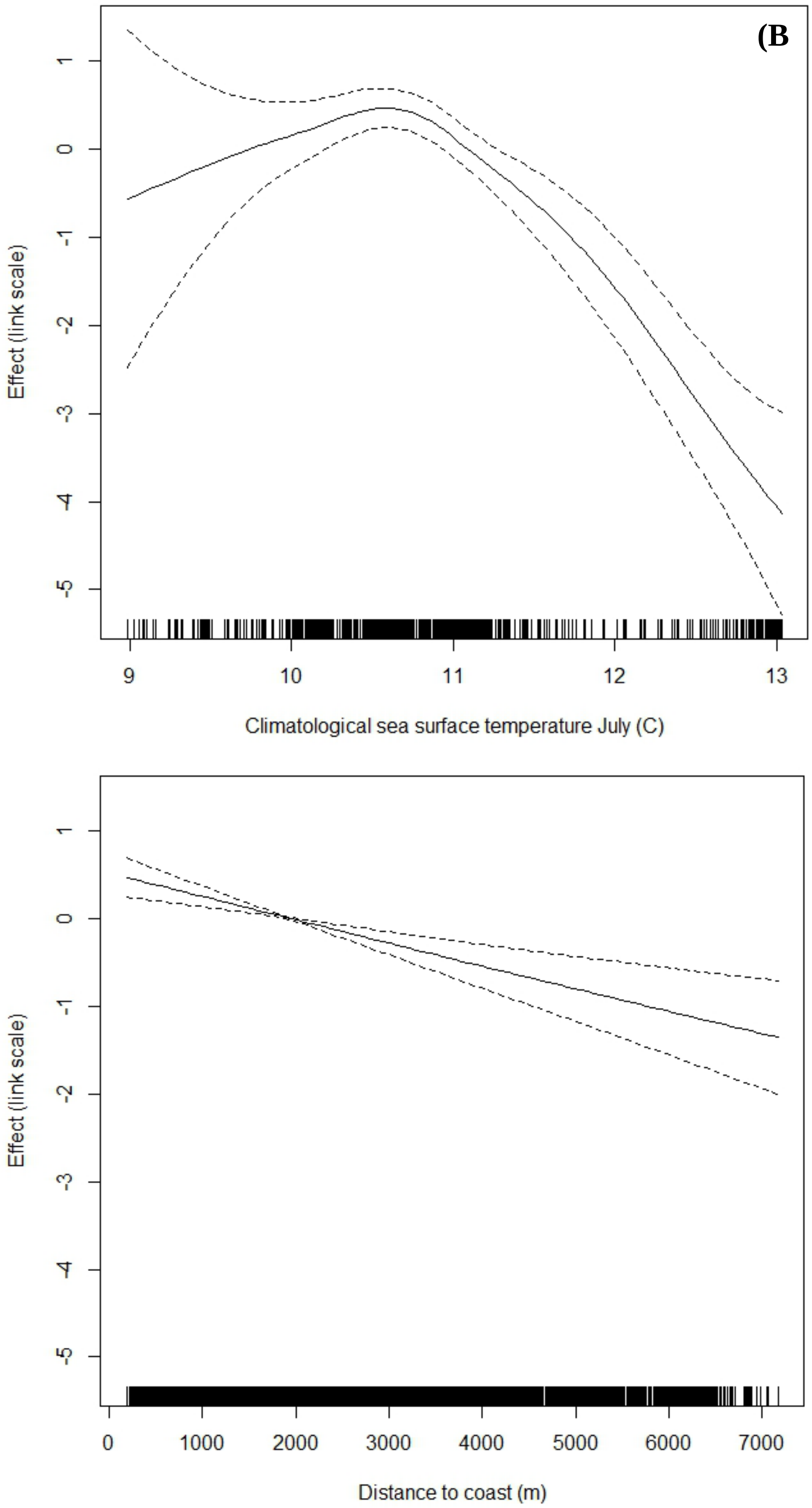


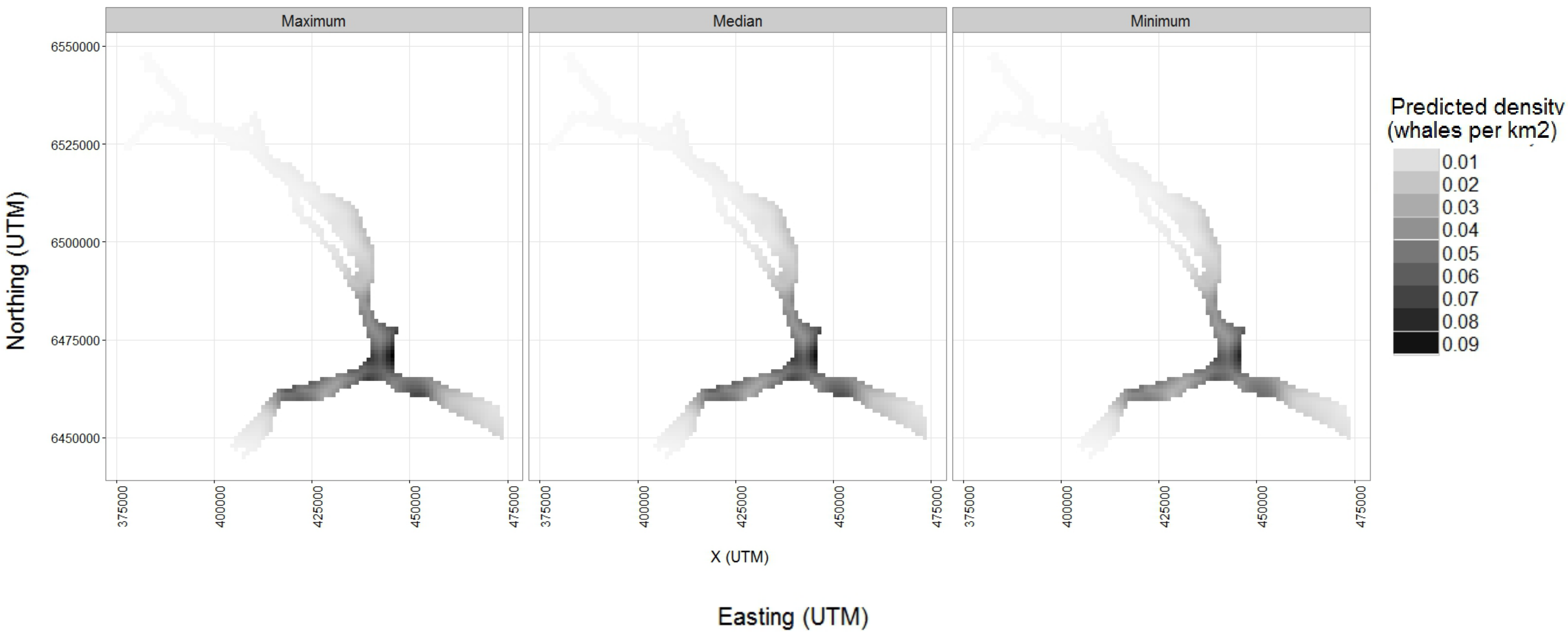
Figure 1-8. Influence of environmental covariates on estimated density for humpback whale occurrence within survey area of Glacier Bay National Park and adjacent water ways, southeastern Alaska using observations from individual months (A – June, B- July) across all years (2008 to 2015) of study.





(B
Effect (link scale)
1
0
-1
-2
-3
-4
-5
9
10
11
12
13
Climatological sea surface temperature July (C)
Effect (link scale)
1
0
-1
-2
-3
-4
-5
0
1000
2000
3000
4000
5000
6000
7000
Distance to coast (m)

Figure 1-9. Maximum, median, and minimum predicted density from 1,000 bootstrap simulations for humpback whale occurrence within survey area of Glacier Bay National Park and adjacent water ways, southeastern Alaska using observations across all years (2008 to 2015) and months (May to September) of study. Predicted density per 1 km^2 grid in survey area.



Chapter 2: Quantifying fine-scale whale movement near large ships for ship strike risk reduction

INTRODUCTION

Since the moratorium on commercial whaling in 1986, populations of baleen whales have recovered to variable degrees. Yet, whales still face a myriad of pressures, including increasing use of the world's oceans for shipping and trade, industrial operations, military exercises, and tourism and recreation. For the first time in history, shipping trade volume has surpassed 10 billion tons annually, indicating the number of large ships traveling through the oceans continues to increase dramatically, and opportunities for port development in emerging countries are expected to yield further fleet growth (United Nations Conference on Trade and Development 2016). Collisions between ships and whales ('ship strikes') have been documented across the globe and across large whale species and result in various levels of disturbance, ranging from temporary displacement to death (Laist et al. 2001, Jensen and Silber 2003). In Alaska alone, 98 definite or probable strikes have occurred from 1978 to 2011 (Neilson et al. 2015). The number of ship strikes is likely to increase as shipping volume and vessel traffic continue to grow concurrently with increasing whale populations. Areas in which whale population ranges overlap with heavy ship traffic, like port entrances or shipping lanes, are of particular concern (Thomas et al. 2016). Ship strikes remain one of the primary and most severe world-wide threats to baleen whale conservation (Clapham et al. 1999, Thomas et al. 2016).

Ship strikes are undesirable to both wildlife managers and industry for several reasons. Large whales are valued by humans as charismatic species and much effort has gone into the conservation of these flagship species already. Strikes can result in unfavorable media or news stories and possibly legal action under the Endangered Species Act or the Marine Mammal Protection Act. Strikes can cause damage to property, especially smaller vessels, and potentially to humans. Finally, for some populations or species, such as the North Atlantic right whale (*Eubalaena glacialis*), a single death due to ship strike can have a significant impact on population recovery and persistence (Knowlton and Kraus 2001, Kraus et al. 2005, Conn & Silber 2013).

Efforts to reduce the number of ship strikes have taken a variety of forms but investigation to inform these efforts have mainly focused on improving mariners' ability to avoid whales. Recent research shows that a majority of surveyed mariners in the commercial fleet actively want avoid whales and want to receive information on endangered whales and conservation measures (Reimer et al. 2016). Several current projects aim to warn mariners of the presence of whales in their vicinity (e.g., Right Whale Listening Network, Whale Alert). Other approaches have investigated how vessel speeds influence the probability of close encounters between ships and whales (Harris et al. 2012), the relative probability of ship strikes as they vary with whale habitat use and overlap with anthropogenic activity (Vanderlaan and Taggert 2007, Redfern et al. 2013, Bezamat et al. 2014, Gende et al. 2014, Rosenbaum et al. 2014), and the probability of a ship strike being lethal (Vanderlaan and Taggert 2008, Van der Hoop et al. 2012, Conn & Silber 2013).

On the other hand, investigation into whether whales avoid ships, and how effective they are at maneuvering around them, has been less explored and recent research offers conflicting conclusions. Baleen whales are highly acoustically oriented and large ships induce complex and poorly understood modifications of the acoustic environment. This may alter whales' ability to locate and navigate around ships. Even if whales are able to detect and locate an approaching vessel, it is unclear whether whales perceive the vessel as threat that needs to be avoided. A whale's physical ability to avoid ships may also be limited, especially when ships are moving at fast speeds. For example, North Atlantic right whales showed little response to sounds of approaching or passing vessels and responded to noises played by researches to alert whales to their presence by swimming strongly to the surface (Nowacek et al. 2003). A recent investigation of blue whales (*Balaenoptera musculus*) tracked in and near high traffic shipping lanes indicated inconsistent and limited avoidance of ships even at very close distances (McKenna et al. 2015). Necropsies of mortalities due to ship strikes show that healthy whales that should be able to avoid ships are often struck.

In this study, we quantified fine scale movement of whales around large ships and investigated how movement may change with varying conditions of proximity and positioning relative to a large ship, as well as whale activity. We used data on humpback whale (*Megaptera novaeangliae*) surfacing events collected from 2010 to 2015 by dedicated observers positioned at the bow of large cruise ships in southeastern Alaska. In contrast to investigations that collect data from tagged whales, which result in datasets providing detailed information on dive parameters over long periods of time but are characterized by very small sample sizes, we collected sightings from over 4,000 whales, using spouts to record location and movement of whales as ships approached them.

In our analysis, we described whale movement as two parameters: distance between surfacings (or each time the whale broke the surface of the ocean during a surfacing event) and changes in swimming direction. Our primary objective was to describe these parameters of whale movements around large ships with the aim of using these parameters to allow ship operators to predict direction and distance of movement of sighted whales in their vicinity. We developed and tested three hypotheses about whale movement and the potential influence of ships: 1) whales move in a consistent manner regardless of the activity in which they are engaged or ship presence, 2) whales move in different manners based on the activity in which they are engaged, and 3) whales move in different manners and are influenced by variables related to their position relative to or distance from the ship. We tested these hypotheses using models incorporating the distance between the whale and ship, bearing between the whale and ship, and whale activity. With this analysis, we were able to explore whether whales may actively avoid ships, which can further our ecological understanding of the impacts of ship presence on whales. Additionally, we can use insight gained from this analysis to provide important information to mariners: knowing how a whale may respond and move relative to an approaching vessel will allow mariners to undertake an appropriate avoidance action.

METHODS

Study Area

We conducted surveys for humpback whales in Glacier Bay National Park and Preserve (GBNP) and the surrounding waterways in southeastern Alaska (Figure 1). The area consists of Glacier Bay, a 1,255 km^2 fjord, and the adjacent waterways of Chatham and Icy straits. The National Park Service (NPS) administers GBNP, whose boundaries encompass the bay and extend a short distance into Icy Strait. The area is characterized by complex bathymetry, which coupled with strong tidal flux, consistently aggregates upwellings and prey. Southeastern Alaska, and GBNP in particular, is an important feeding area for migratory humpback whales from late spring to early fall (Hendrix et al. 2012). Southeastern Alaska and GBNP is also a popular destination for scenic cruises during the same time period, which produces a scenario in which large cruise ships frequently encounter whales (Gende et al. 2011, Harris et al. 2012, Webb & Gende 2015).

Data Collection

The overlap between the high density of whales and cruise ship traffic in southeastern Alaska provided a unique setting for our study and enabled us to collect data on whale movement and behavior in real time within the vicinity of large vessels. Unlike other large commercial vessels that undertake ocean-basin scale voyages, cruise ships in our study area repeatedly travel week-long scenic routes, stopping in the same ports of call on each trip. We capitalized on these relatively short but repetitive voyages and port visits, which allowed us to keep a dedicated observer onboard ships and repeatedly survey the same high-use area without the observer having to spend many days or weeks at sea outside our area of interest.

While our observations are made exclusively from cruise ship platforms, there are several reasons our insight and inferences are applicable to situations in which other large vessels encounter whales. In 2016, over 60% of the world’s commercial fleet consisted of dry bulk carriers, cargo ships, and container ships (United Nations Conference on Trade and Development 2016). These vessels range in size from 10,000 to 100,000 dead-weight tons (United Nations Conference on Trade and Development 2016), which is similar to the range of weights (approx. 28,000 to over 118,000 tons) noted in a recent review of cruise ship traffic in southeastern Alaska (Webb & Gende 2015). Changes to the acoustic environment also have the ability to largely impact whales' ability to detect and respond to approaching ships (e.g., Allen et al. 2012, McKenna et al. 2012). For both large commercial ships and cruise ships such as the ones we used as survey vessels, a major source of underwater noise is generated from propeller cavitation (Harris et al. 2012, McKenna et al. 2012), suggesting that whales may perceive and respond to these types of ships in similar ways.

Ship embarkation and surveys were performed under two possible schedules. From 2010 to 2015, a dedicated observer was based in GBNP (hereafter "GBNP-based observer"). On days of scheduled surveys, this observer embarked the ship after the ship had already entered the boundary of GBNP. The GBNP-based observer embarked and disembarked the ship via a NPS transfer vessel that carried interpretative park rangers to each cruise ship entering the park. Additionally from 2013 to 2014, a dedicated observer was based in Juneau, AK (hereafter "Juneau-based observer"). This observer embarked the ship at the port of call the on the day immediately preceding the ship's scheduled day in GBNP (either Juneau or Skagway, AK) and disembarked at the port of call immediately following the ship's day in GBNP (either Ketchikan or Sitka, AK). This embarkation and disembarkation schedule allowed the Juneau-based observer to survey the adjacent waterways of Icy and Chatham straits outside GBNP, where high concentrations of feeding humpback whales have been observed for decades (e.g., Neilson and Gabriele 2015).

Once onboard the ship, the GBNP-based observer proceeded to the bow and immediately began surveying, which typically corresponded with the ship being near Strawberry Island. The Juneau-based observer began surveying at daybreak of the ships GBNP cruise day, which typically corresponded with a starting location at or near the eastern boundary of Icy Strait. For both survey schedules, the observer continued survey effort until the ship approached either Tarr or Johns Hopkins inlets, north of which point whale sightings are uncommon (Gende et al. 2011). Ships then spent several hours allowing passengers to view tidewater glaciers at the northern end of the bay, during which time surveys were not conducted.

Surveys were reinitiated once the ship began its course south returning toward the park entrance. The GBNP-based observer continued until disembarkation via the NPS transfer vessel, and the Juneau-based observer continued survey effort until dusk or until the ship entered Cross Sound.

While surveying, the observer continuously performed naked eye and binocular-assisted scans, using tripod-mounted range-finding binoculars (Leica Viper II; accuracy, +1m at 1km; Leica, Charlottesville, Virginia, USA) and 8x42 binoculars (Swarovski Optik, Absam, Austria) to search for surfacing whales in front of the ship. The observer surveyed the entire half circle in front of the bow of the ship and scanned for cues of surfacing events, which included spouts or any portion of the body seen breaking the surface of the water. The observer used rangefinders to measure the distance between the observer and the whale and used a protractor attached to the tripod-mounted binoculars to determine the relative bearing of the whale from the bow of the ship. If it was not possible to obtain an exact distance with the rangefinders, for example due to insufficient time of the whale at the surface or thick fog, the observer estimated the distance. The observer also estimated the distance of objects other than whales in the seas throughout the day to allow assessment of estimation error and bias. Each whale location was geospatially referenced using a handheld GPS unit (Garmin, Olathe, Kansas, USA). After the initial sighting, the observer continued to follow the whale (or group) and recorded each resurfacing event until it left the area of view, passed abeam of the ship, or the time between resurfacing was too long to ensure that it was the same whale(s). These methods resulted in many cases of multiple observations of the same individual (or group).

For each surfacing event, the observer recorded the whale or group's orientation at surfacing, direction of travel relative to the ship's heading, a categorical visually-assigned behavior depending on the cue that was detected (spout/shallow dive with no fluke showing, dive with fluke up, surface active behavior, lunge feeding, resting), and group size. Additionally, the observer recorded weather and visibility conditions at the start of each day and as the conditions changed throughout the survey, and deployed a separate GPS unit programmed to record the ship's location every 5s, from which the track and speed (over ground) of the ship could be calculated.

Data Analysis

We analyzed the movement of whales using their locations obtained by each series of successive observations detected via whale surfacing cues. Spatially explicit locations were calculated using the latitude-longitude location of the ship and the distance and relative bearing between the detected whale and bow of the ship using ArcGIS. We defined the interval between two successive spatially explicit locations as a step and the change in direction between two successive steps as a turn. Thus, each step required two locations and each turn required three locations of the same whale (Figure 2). We calculated lengths of steps (m) and angles of turns (rad) in program R (ver. 3.2.3, R Core Team 2016) using the 'adehabitatLT' package (Calenge 2006). Whales in loosely associated groups may travel in the same general direction and surface at roughly the same time, however it can be difficult to visually relocate specific individuals within a group. Therefore, we constrained out analysis to data collected from single whales not within a group.

Our primary goal was to determine parameters of whale movements around large ships with the aim of using these parameters to allow ship operators to predict the future locations of whales in their vicinity. Thus, we used the derived step lengths and turn angles as input data to model whale movement and to assess if movement changed in varying conditions related to proximity to ships. Following the approach developed by Morales et al. (2004), we estimated parameters of the distributions from which step lengths and turn angles were generated over a series of candidate represented our three hypotheses described above (Table 1).

Most assessments of animal movement use datasets consisting of relatively few individuals over long time periods, resulting in many locations per individual and thus analyze data for each animal individually. However, due to the unique setting of collecting whale location data in real time within the presence of large ships, we were constrained to a dataset that included many individuals over very short time scales. This resulted in few steps and turns for each individual. Thus, we formulated our models to use combined data from individuals over the entire study to estimate parameters of movement.

We implemented our models in a Bayesian framework using the MCMC sampler JAGS via the 'rjags' package (ver. 4-6, Plummer 2016) in program R. All models were run over three chains with a burn-in period of 10,000 iterations followed by a run 30,000 iterations and a thinning factor of ten. For each model, turn angles were pulled from one or more wrapped Cauchy distributions, which are formulated by a parameter for the mean direction of turns (μ) and a concentration parameter of the distribution (ρ). Step lengths were pulled from one or more Weibull distributions, which are formulated by a shape (v) parameter and a scale parameter (λ). The variable of interest for our model with a covariate was distance between whale and ship at first sighting (m).

We visually inspected posterior distribution density plots and trace plots, using the package 'ggmcmc' (ver. 1.1, Fernández i Marín 2016), and calculated potential scale reduction values using the 'coda' package (ver. 0.18-1, Plummer et al. 2006) to assess convergence. After investigating model fit of original candidate model set, we decided split our data into subsets and further investigate our hypotheses using the best fit model. Data subsets allowed exploration of our third hypothesis (that movement occurred in two distinct modes that were influenced by whale activity or ship variables) and included: 1) whale locations that occurred near the ship vs. far from the ship, 2) locations that occurred as the whale approached from the front of the ship vs from abeam of the ship, and 3) locations that occurred while the whale was engaged in the different activities of surface interval dives vs deep dives (Table 2). We applied our simplest model to these subsets and examined distributions for differences between the parameter estimates of the subsets and to parameter estimates of the models using all data.

After fitting all models, we simulated sets of step lengths and turn angles using random samples from the posterior distributions of the parameters estimates. We applied the simulated sets to correlated random walk replicates (CRWs) to demonstrate variation in possible movement paths and future locations of detected whales (Figures 5a-c and 6).

RESULTS

From 2010 to 2015, we recorded the distance and relative bearing of 4,456 unique surface cues from 2,761 unique individuals or groups of whales while on board 406 cruises. Of these locations, 1,198 were observations of groups and were not used for further analysis. Of the remaining 3,258 locations, 1,448 consisted of a single surfacing cue and were not usable to investigate movement. Our resulting dataset consisted of 1,810 locations observed from 709 unique individuals. The average number of surface cues recorded per whale was 2.95, ranging from two to 12 sightings per whale.

From these surfacing locations, we generated a total of 1,101 step lengths and 392 turn angles. We noted some step lengths that seemed improbable given the ability to visually keep track of an individual whale while it was under water for a long time period. Thus, we chose to keep only the observations that occurred within the 95th percentile of step lengths. Our final dataset consisted of 1,046 step lengths (mean = 418.38 m, range = 4.27 – 1,942.22 m) and 381 turn angles (mean = 0.01 rad, range = -3.14, 3.13 rad). Our subsets based on proximity between whale and ship, relative bearing between whale and ship, and whale activity varied in the number of steps and turns that were assigned to each category based on characteristics at the time of observation (Table 2).

Diagnostic assessment of posterior distributions indicated that all three models in the candidate set reached convergence. For the one movement mode model, the estimate for mean direction of turns (μ) was centered closely and symmetrically on zero (mean = -0.008, 95% CI = -0.337, 0.320; Table 3, Figure 3). The concentration parameter for turns (ρ) in this model was relatively low (mean = 0.203, 95% CI = 0.127, 0.277; Table 3, Figure 3). These parameters led to simulated turns covering all possible angles (from -3.139 to 3.140 rad), but the highest probability of turn angle was clustered around zero, which suggests a relatively straight movement path (Figure 4). The posterior distributions for parameters controlling the shape (v) and scale (λ) of step lengths in this model were symmetrical and relatively wide but produced reliable estimates (mean = 1.021, 95% CI = 0.973, 1.070 and mean = 2.412, 95% CI= 2.260, 2.570, respectively; Table 3, Figure 3). These parameters led to simulated step lengths ranging from less than 1 to 4.706 km (Figure 4).

Though both models with two movement modes reached convergence, each had unsupported parameters. Posterior distributions showed that these models did not produce reliable estimates for the parameters that control turn angle in one of the two movement modes. In these models, the concentration parameter for turns (ρ) approached zero, and the posterior distribution for the parameter that formulates the mean direction of turns (μ) was nearly uniform for one of the two movement modes. Additionally, the scale parameter for step length (λ) was extremely small, held up against left boundary at zero, for one movement mode in both models with two movement modes (mean = 0.0005, 95% CI = 0.00002, 0.0001 for both models; Table 3). Such a small estimate for scale led to unrealistic simulated step lengths for that movement mode, ranging from less than 1 to over 1,500 m. However, the posterior distributions for the shape parameter (v) for step lengths for these models were reliable and provided different estimates for the two movement modes (mean = 1.669, 95% CI = 1.559, 1.783 for mode one and mean = 1.046, 95% CI = 0.960, 1.132 for mode two; Table 3), and thus did show some support for whale movement occurring as two distinct modes. Distance between whale and ship did have an influence on the probability of being in movement mode one (mean = 0.989, 95% CI = 0.674, 1.353; Table 3).

The unsupported parameters in the two movement mode models were possibly due to having too few observations per individual whale to produce reliable parameter estimates. Because of this potential limitation and because there was some signal from the step length parameters that whales were moving in two distinct modes, we decided to apply the one movement mode model to our location data separated into categories. As described in the data analysis section, we separated these categories based on either ship location or whale activity characteristics noted at the time of observation. Applying the one movement mode model to distinct data subsets allowed us to disentangle whether whales truly moved in a single manner regardless of characteristics of the ship or whale activity, or whether the models describing two movement modes were not reliably fit because of too few observations per individual.

Using the three subsets (1) surface interval activity vs deep dive activity, (2) observations near the ship vs observations far from the ship, and (3) observations from a whale approaching from the front of the ship vs the side of the ship), we saw differences in parameters of movement in all scenarios (Table 4, Figure 5a). For the first data subset comparison, the estimate for the mean direction of turns (μ) was centered on zero for surface interval activity and had a much narrower distribution compared to deep dive activity (mean = -0.036, 95% CI = -0.775, 0.705 and mean = 0.502, 95% CI = -2.847, 2.872, respectively;

Table 4). Additionally, the concentration parameter for turns (ρ) was larger for surface activity compared to deep dive activity (mean = 0.175, 95% CI = 0.044, 0.295 and mean = 0.074, 95% CI = 0.003, 0.202, respectively; Table 4). The scale parameter for step lengths (λ) varied substantially for these two subsets (mean = 7.103, 95% CI = 5.959, 8.346 for surface interval activity and mean = 1.457, 95% CI = 1.316, 1.606 for deep dive activity; Table 4). The shape parameter (v) for step lengths also varied within for these two subsets (mean = 1.009, 95% CI = 0.925, 1.094 for surface interval activity and mean = 1.627, 95% CI = 1.502, 1.757 for deep dive activity; Table 4). The differences in these two parameters between the two subsets resulted in larger step lengths for deep dive activity observations (Figure 5a).

For the second data subset comparison, turn angle parameters (μ and ρ) did not show differences between observations near the ship compared to observations far from the ship (Table 4). However, estimates for both step length parameters did differ. The scale parameter (λ) was substantially larger for observations near the ship (mean = 6.226, 95% CI = 5.132, 7.460; Table 4) than that for observations far from the ship (mean = 1.640, 95% CI = 1.477, 1.808; Table 4). The shape parameter (v) also varied between the subsets (mean = 0.996, 95% CI = 0.901, 1.092 for observations near the ship and mean = 1.304, 95% CI = 1.202, 1.410 for observations far from the ship; Table 4). These differences in estimates of parameters for step length resulted in shorter steps for observations that occurred near the ship but in similar turn angles for both subsets (Figure 5b).

For the third data subset comparison, step length parameters (λ and v) did not vary substantially between observation of whales approaching from the front of the ship and those approaching from the side of the ship (Table 4). Thus, simulated step lengths were similar (Figure 5c). Additionally, the mean estimates for parameters controlling turn angle did not vary. However, the posterior distribution for the mean direction of turns (μ) was considerably narrower for observations of whales approaching from the front of the ship than those approaching from the side (mean = 0.056, 95% CI = -0.296, 0.414 and mean = -0.254, 95% CI = -3.053, 3.049, respectively; Table 4, Figure 5c).

DISCUSSION

Understanding the patterns in which whales move is critical to conservation efforts, such as identifying important habitats to protect and reducing the risk of collisions in habitats in which whales and ships overlap. Investigation of movement has thus far been focused on large-scale movement, such as migrations between feeding and breeding areas, using remotely-collected telemetry data (e.g., Zerbini et al. 2006, Pendleton et al. 2012, Irvine et al. 2014, Kennedy, Zerbini, Vasquez, et al. 2014, Rosenbaum et al. 2014). However, understanding of the fine-scale manner in which whales move, especially while in the presence of anthropogenic disturbance, has been lacking. This knowledge is particularly important because large-scale studies have revealed that whales make individual decisions regarding fine-scale movement, leading to high variability in movement patterns (Kennedy, Zerbini, Rone, et al. 2014).

We quantified the movement of individual humpback whales at a very fine spatial and temporal scale while in the presence of large ships. Our study is unique in that we used visually collected location data as whales and ships were in real-time overlap, instead of remotely-collected whale and ship data that may not coincide temporally. There are several practical advantages of this type of data for movement analysis. First, visual observation allows access to animals or populations that are difficult to approach for physical tagging, are vulnerable to injury during the tagging process, or are protected by international or federal restrictions. Second, the sample size of individuals can be increased using visually collected observation data compared to remotely-collected data. Our study involved over 700 unique humpback whales, which may allow increased coverage and understanding of the variation of fine-scale movement existing within a population. Finally, our method of data collection allowed us a unique opportunity to assess movement while whales were in the presence of large ships. This enabled us to assess the potential impact of varying conditions of the encounter between whale and ship on whale movement.

Overall, we found that whales showed considerable variation in fine-scale movement. Considering the population as a whole moving under a single mode of movement, there was some probability associated with turns of every direction and steps up to 5 km. However, whales on average move very short distances and make little change in direction between surfacings (Figure 4).

Dividing the study population into subsets based on characteristics of the surfacing revealed some important differences within movement patterns. When whales were separated into 'deep dive' and 'surface interval' groups based on the time between subsequent surfacings, we found differences in both estimated step length and turn angle for these groups and these metrics for the population as a whole. For the deep dive group, step lengths were longer and turn angles were more broadly distributed around 0 rad (no turn or change in direction). For the surface interval group, step lengths were much shorter (often less than 0.5 km) and turn angles were more narrowly focused around 0 rad. This indicates that whales in a surface interval moved shorter distances and more often continued moving in the same direction than the population as a whole or whales in a deep dive. It may not be surprising that step lengths from the surface interval group were shorter than those from the deep dive group, as one might expect that whales under water for a longer period of time would move further. However, more time spent underwater does not necessitate a greater movement in horizontal distance. It is possible that whales may be making complex movements at depth under the ocean surface while staying in or returning to the same spatial location. This is important within the context of strike avoidance as whales are vulnerable to ship strikes when at the surface. Thus, prediction of movement is relevant to reveal the next surfacing location of a whale, while movement patterns at depth are less critical.

Whales separated into groups based on the conditions of their encounter with a ship also signaled some differences in movement patterns. Assessment of whale movement relative to the distance between the whale and ship revealed that whales nearer to ships moved shorter distances than whales farther from ships. The direction of turns was not different between these groups. When comparing movement of whales in regard to relative bearing to the ship, the direction of turn was considerably more broadly distributed for whales that were more on the side than the front of the ship. For these groups, there was no difference in the distance of movement. We hypothesize the dissimilarities in movement between these groups may underlie interesting drivers of the response of whales to ships. It may be that whales nearer to ships surface more frequently because they have become aware of the presence of the ship and are attempting to determine its location. This would be consistent with the behavior of North Atlantic right whales exposed to an acoustic alert stimuli, who surfaced more frequently when the alert was present (Nowacek et al. 2004). Whales are likely influenced by acoustic noise propagation from ships as they approach. Complexity in the spatial propagation of ship noise, including an acoustic null or shadow effect that prevents noise from being directed in front of the ship, may be driving the differences in turning direction of whales in front of compared to the side of the ship. Whales to the side of ship were more likely to make turns of all directions, which may indicate whales attempting to respond to and avoid ships as they approach.

The scale of our analysis is an important complement to analyses of movement on longer time scales and larger spatial scales. Ship operators seeking to reduce their risk of striking a whale are concerned with the movement of animals in their immediate vicinity. The data available to vessel operators are usually obtained visually and over very short time periods, the length of which vary according to the ship's speed. In our study area, travelling speeds of cruise ships fluctuate and thus the amount of time the observer (and vessel operators) have to observe whales at multiple surfacings also varies. Within the boundaries of GBNP, ships are often travelling at reduced speeds of 10.0 kts or less, where they operate under NPS-mandated speed and course restrictions, however the average travelling speed outside of the park is 16.8 kts (Webb & Gende 2015). This means that a ship travels a distance of 1 km in either 3.2 or 1.9 min (for a ship travelling at 10.0 and 16.8 kts, respectively). Assuming a maximum humpback whale swimming speed of 13.0 kts, a whale moving in a straight line at maximum speed could only possibly travel up to 1.3 km in 3.2 min or 0.8 km in 1.9 min. Whales moving more slowly, perhaps while engaged in stationary behaviors like feeding, would travel even less distance.

While the context and data collection methods of our study provided us with the opportunity to assess movement at a very fine scale, the use of visual collection of location data does present challenges. First, data collection is contingent upon resighting the same individual or group over the time span in which they are being observed. This may be difficult when many animals or groups are moving within the same area or spending longer lengths of time underwater out of view. Second, the lack of convergence of our more parameterized models may indicate that estimation of movement parameters switching between multiple modes is not possible at the very short temporal scale over which we observed individual whales and groups. However, ship operators are constrained to a similar scenario of short time scales and must make decisions within seconds to minutes of observing a whale for only a few surfacing events. Thus, we feel our results are useful in providing information on whale movement at the scale of the conservation problem.

Adjustments to observation and data collection protocols may be able to alleviate some of the challenges presented above. We suggest further investigation is needed to target individuals or groups such that the entirety of a surfacing event is observed and possible switches between movement modes can be assessed. Movement paths observed in real time over a slightly longer time scale (e.g., four or more locations for many individuals) may allow more complex models to be fit and in turn, access to further understanding of the physiological and environmental drivers of movement. We recommend that future research target information about time between individual surfacings of a surfacing event and overall time spent at the surface during the course of a surfacing event. These data could be used to explore modifying whale locations for models that use regularly spaced time steps. Finally, we suggest that efforts be directed toward collecting data on environmental factors and ephemeral ocean characteristics at observation locations to complement more complex models. While remotely-sensed data are useful in coarser spatial and temporal scale investigations of movement, research such as ours, done over relatively short periods of time and within small areas, would benefit from covariate information at similar scales.

Our results provide insight on the probability of direction and distance of movement between surfacings. From the perspective of ship operators, knowledge of movement patterns and the probabilities associated with a variety of movement metrics can aid them in making more informed decisions as to if, when, and how to change ship course or speed when in the presence of whales. When a whale is observed that may or may not come into the ship’s path, ship operators must make rapid decisions based where they believe the whale will next appear. We provide information on the probabilities of the direction and distance of the next location, and how these probabilities vary with conditions of the encounter between the whale and ship.

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TABLES

Table 2-1. Candidate model set explored for whale movement data analyzed using observations of humpback whale surfacings in Glacier Bay National Park and adjacent water ways, Alaska from 2010 to 2015.

Hypothesis/model	Biological interpretation	Mathematical model description
One movement mode	Whales move in a consistent manner (mode) regardless of the activity they are engaged in or the presence of a ship.	A single distribution for each step length and turn angle parameter.
Two movement modes	Whales move in different modes based on the activity (surface interval vs deep dive) they are engaged in.	Two distributions for each step length and turn angle parameters, one for each movement mode.
Two movement modes with covariate	Three, whales move in different modes based on the activity (surface interval vs deep dive) they are engaged in and re influenced by variables related to their position relative to or distance from the ship.	Two distributions for each step length and turn angle parameter, one for each movement mode, with a covariate (distance between whale and ship) influencing the probability of being engaged in one movement mode.

Table 2-2. Categories and resulting sample sizes of data subsets for further exploration of hypotheses using single movement mode mathematical mode for movement analysis of humpback whales in Glacier Bay National Park and adjacent waters in Alaska from 2010 to 2015. Data subsets include ship proximity, relative bearing, and whale activity.

Data subsets	Number of individuals	Number of locations	Number of steps	Number of turns
All data (used for all models in original candidate set; Table 1)	709	1,810	1,046	381
Whale activity				
Surface interval dive: Less than 50s between sightings	224	456	295	143
Deep dive: More than 120s between sightings	331	583	386	88
Distance from ship Near ship: first sighting within 1,000m of ship	154	208	206	53
Far from ship: first sighting farther than 3,000m of ship	236	395	381	152
Relative bearing to ship Approach from front: first sighting's relative bearing less than 20°, port or starboard, from bow of ship	487	794	783	301
Approach from side: first sighting's relative bearing greater than 40°, port or starboard, from bow of ship	163	207	200	42

Table 2-3. Estimates for turning angle and step length distribution parameters from candidate model set using all data for movement analysis of humpback whales in Glacier Bay National Park and adjacent waters in Alaska from 2010 to 2015. All estimates show mean and 95% credible interval.

Model	Turn angle parameters		Step length parameters		Mode assignment parameter	Covariate
	μ	ρ	v	λ	β_0	β_1
One movement mode	-0.008 (-0.337, 0.320)	0.203 (0.127, 0.277)	1.021 (0.973, 1.070)	2.412 (2.260, 2.570)	NA	NA
Two movement modes						
Mode 1	0.019 (-2.984, 2.984)	0.028 (0.011, 0.065)	1.669 (1.559, 1.783)	0.00005 (0.00002, 0.0001)	0.587 (0.460, 0.714)	NA
Mode 2	0.031 (-0.814, 0.929)	0.152 (0.035, 0.269)	1.046 (0.960, 1.132)	2.391 (2.124, 2.670)		
Two movement modes with covariate						
Mode 1	0.019 (-2.985, 2.980)	0.022 (0.0008, 0.061)	1.676 (1.571, 1.784)	0.00005 (0.00002, 0.0001)	-4.805 (-4.994, -4.347)	0.989 (0.674, 1.353)
Mode 2	0.022 (-0.915, 1.007)	0.147 (0.023, 0.266)	1.032 (0.946, 1.119)	2.344 (2.085, 2.626)		

Table 2-4. Estimates for turning angle and step length distribution parameters one movement mode model using all data and data subsets for movement analysis of humpback whales in Glacier Bay National Park and adjacent waters in Alaska from 2010 to 2015. All estimates show mean and 95% credible interval.

Data subsets	Turn angle parameters		Step length parameters	
	μ	ρ	v	λ
Whale activity				
Surface interval: Less than 50s between sightings	-0.036 (-0.775, 0.705)	0.175 (0.044, 0.295)	1.009 (0.925, 1.094)	7.103 (5.959, 8.346)
Deep dive initiation: More than 120s between sightings	0.502 (-2.847, 2.872)	0.074 (0.003, 0.202)	1.627 (1.502, 1.757)	1.457 (1.316, 1.606)
Distance from ship				
Near ship: first sighting within 1,000m of ship	0.188 (-0.652, 1.098)	0.259 (0.041, 0.460)	0.996 (0.901, 1.092)	6.226 (5.132, 7.460)
Far from ship: first sighting farther than 3,000m of ship	0.006 (-0.934, 1.005)	0.146 (0.023, 0.264)	1.304 (1.202, 1.410)	1.640 (1.477, 1.808)
Relative bearing to ship				
Approach from front: first sighting relative bearing less than 20°, port or starboard, from bow of ship	0.056 (-0.296, 0.414)	0.212 (0.129, 0.294)	1.035 (0.978, 1.091)	2.415 (2.242, 2.597)
Approach from side: first sighting relative bearing greater than 40°, port or starboard, from bow of ship	-0.254 (-3.053, 3.049)	0.095 (0.004, 0.271)	1.041 (0.932, 1.155)	2.424 (2.084, 2.795)

FIGURES

Figure 2-1. Study site of Glacier Bay National Park and adjacent waters in southeastern Alaska.

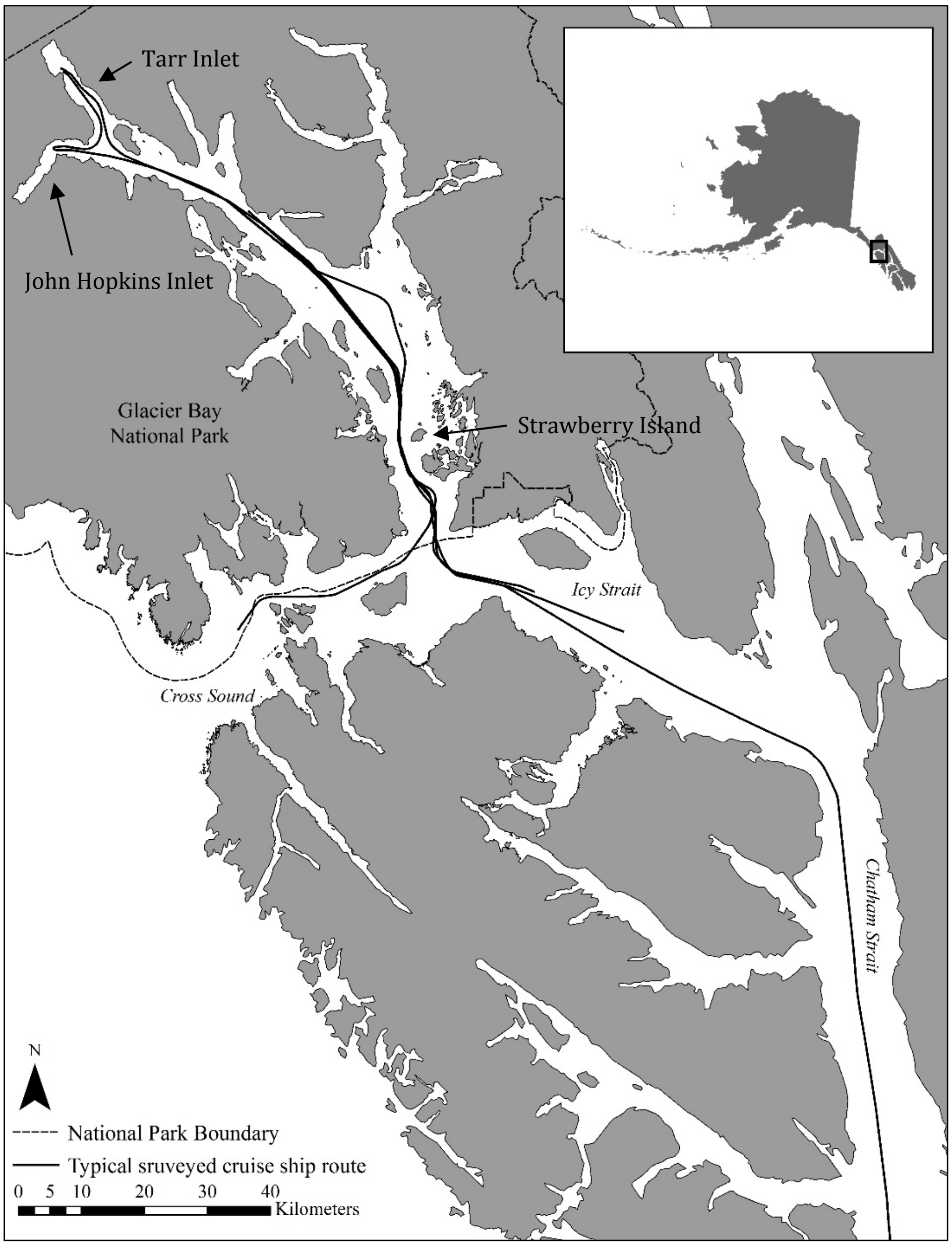


Figure 2-2. Conceptual diagram illustrating movement metrics of step length and turn angles across 3 whale surfacing locations.

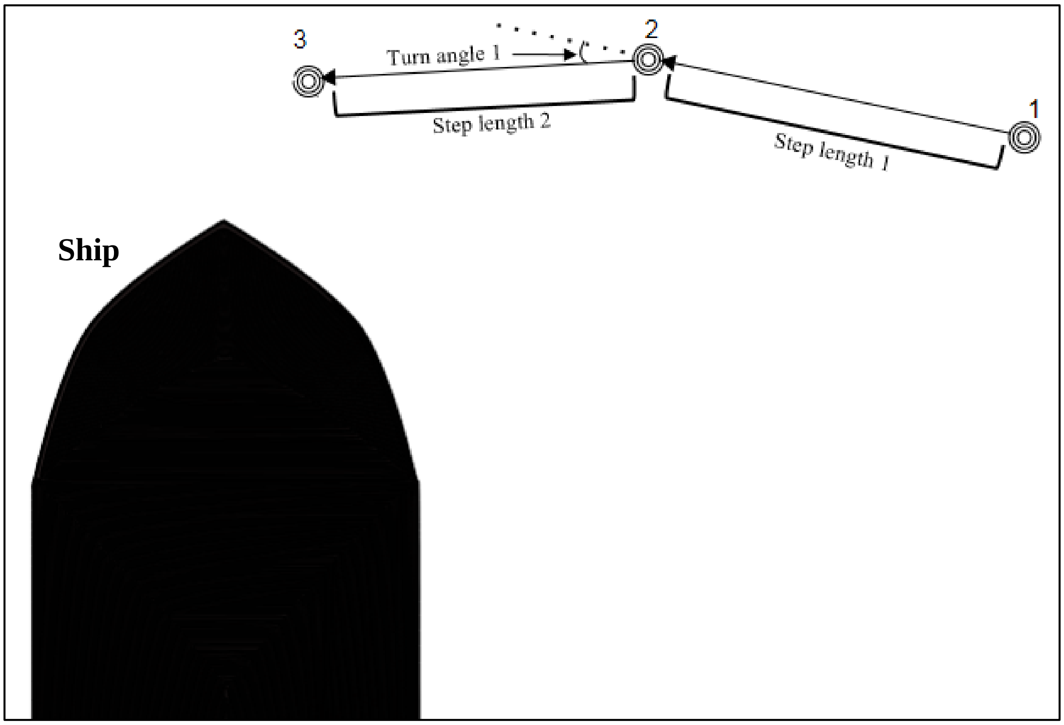


Figure 2-3. Posterior density plots and MCMC trace plots of parameters from one movement mode model using all data from humpback whale locations in Glacier Bay National Park and adjacent waters, Alaska collected from 2010 to 2015.

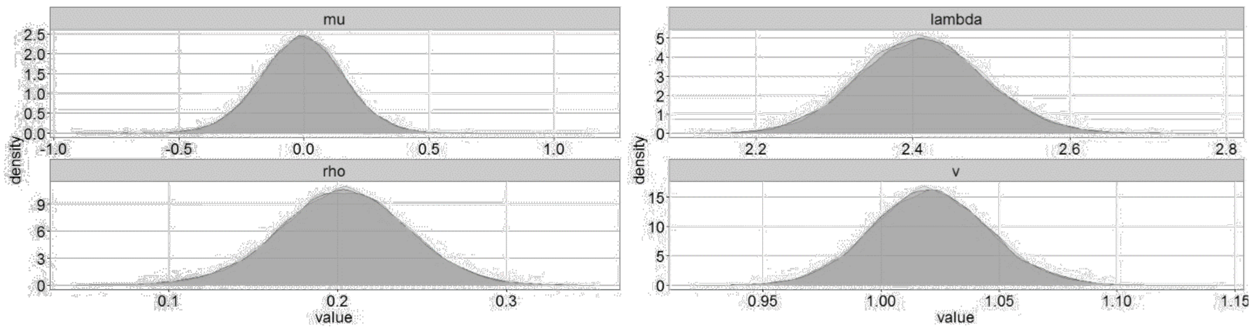


Figure 2-4. Simulated step lengths and turn angles generated from parameter posterior distributions from one movement mode model from humpback whales locations in Glacier Bay National Park and adjacent waters, Alaska collected from 2010 to 2015. Dashed line indicates mean step length or turn angle.

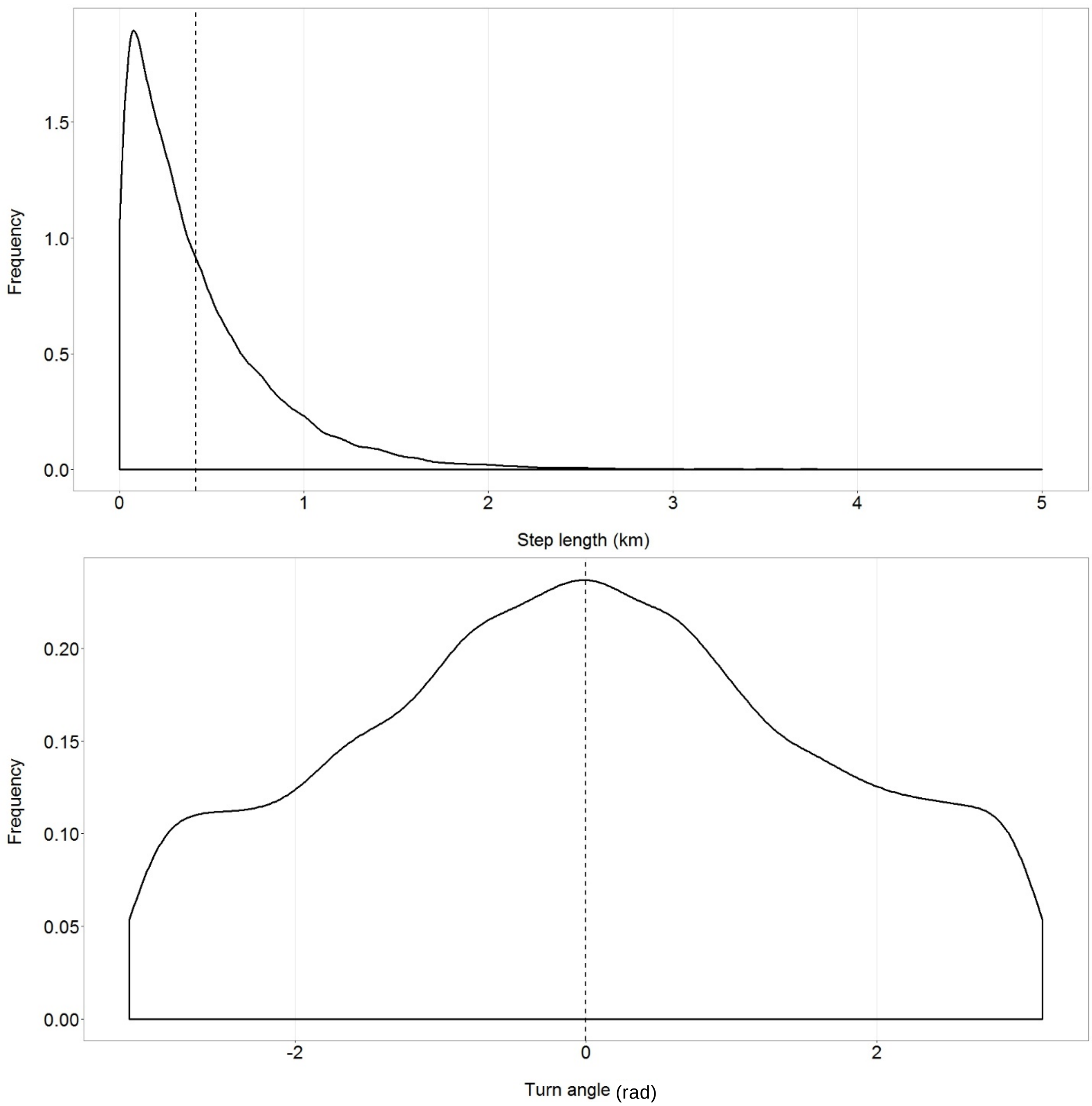
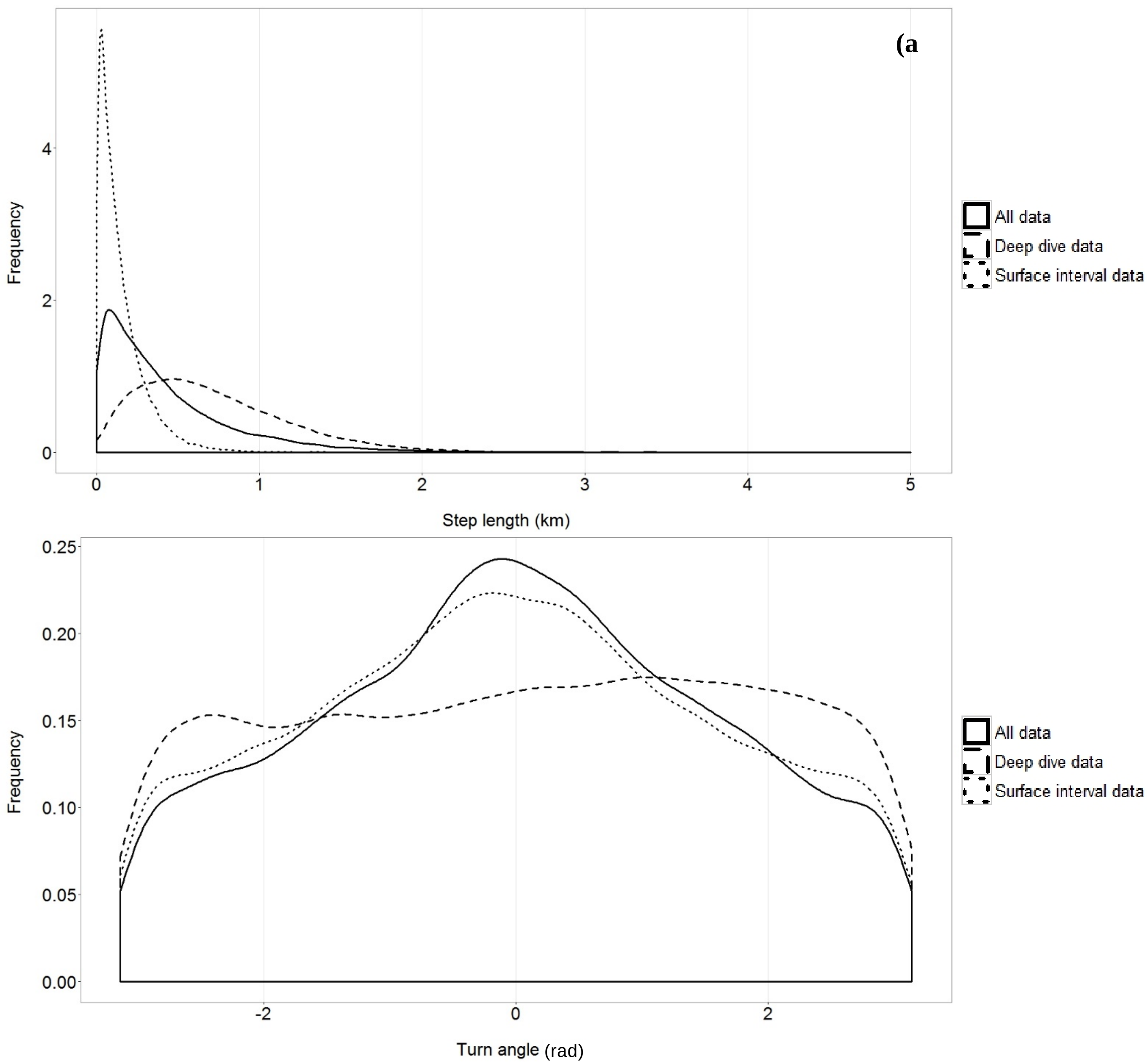
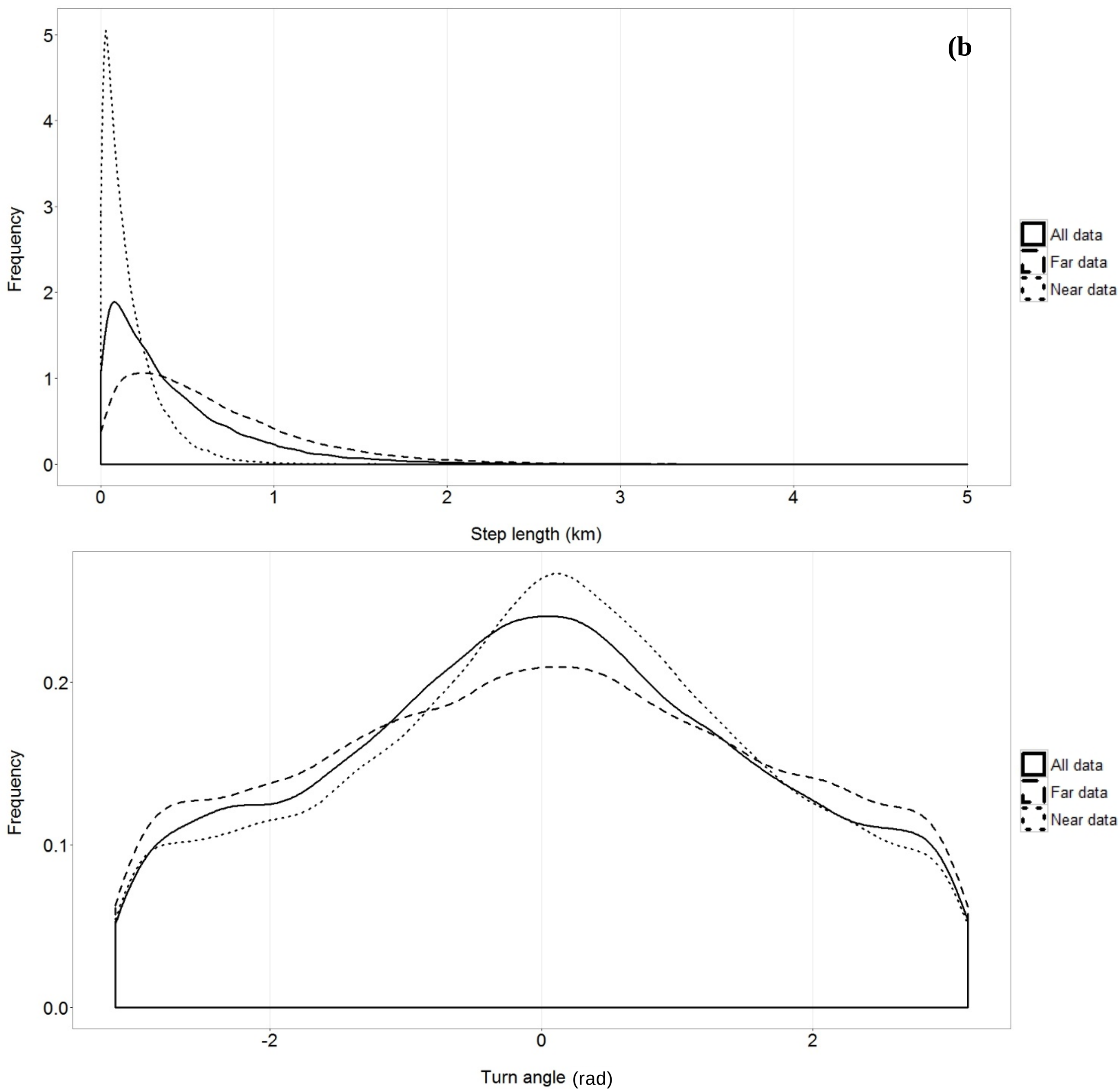


Figure 2-5. Simulated step lengths and turn angles generated from parameter posterior distributions from one movement mode model applied to data subsets from humpback whales locations in Glacier Bay National Park and adjacent waters, Alaska collected from 2010 to 2015. Solid line in each figure is step lengths or turn angles generated from entire data set for comparison to subsets. (a) Data from surface interval activity (less than 50s between sightings; dotted line) and data from deep dive activity (more than 120s between sightings; dashed line), (b) data from location near ship (first sighting within 1,000m of ship; dotted line) and data from location far from ship (first sighting farther than 3,000m of ship; dashed line), and (c) data from location approaching from the side of ship (first sighting relative bearing greater than 40°, port or starboard, from bow of ship; dotted line) and data from location approaching from the front of ship (first sighting relative bearing less than 20°, port or starboard, from bow of ship).


(a
Frequency
Step length (km)
All data
Deep dive data
Surface interval data
Frequency
Turn angle (rad)
All data
Deep dive data
Surface interval data


(b
Frequency
Step length (km)
All data
Far data
Near data
Frequency
Turn angle (rad)
All data
Far data
Near data

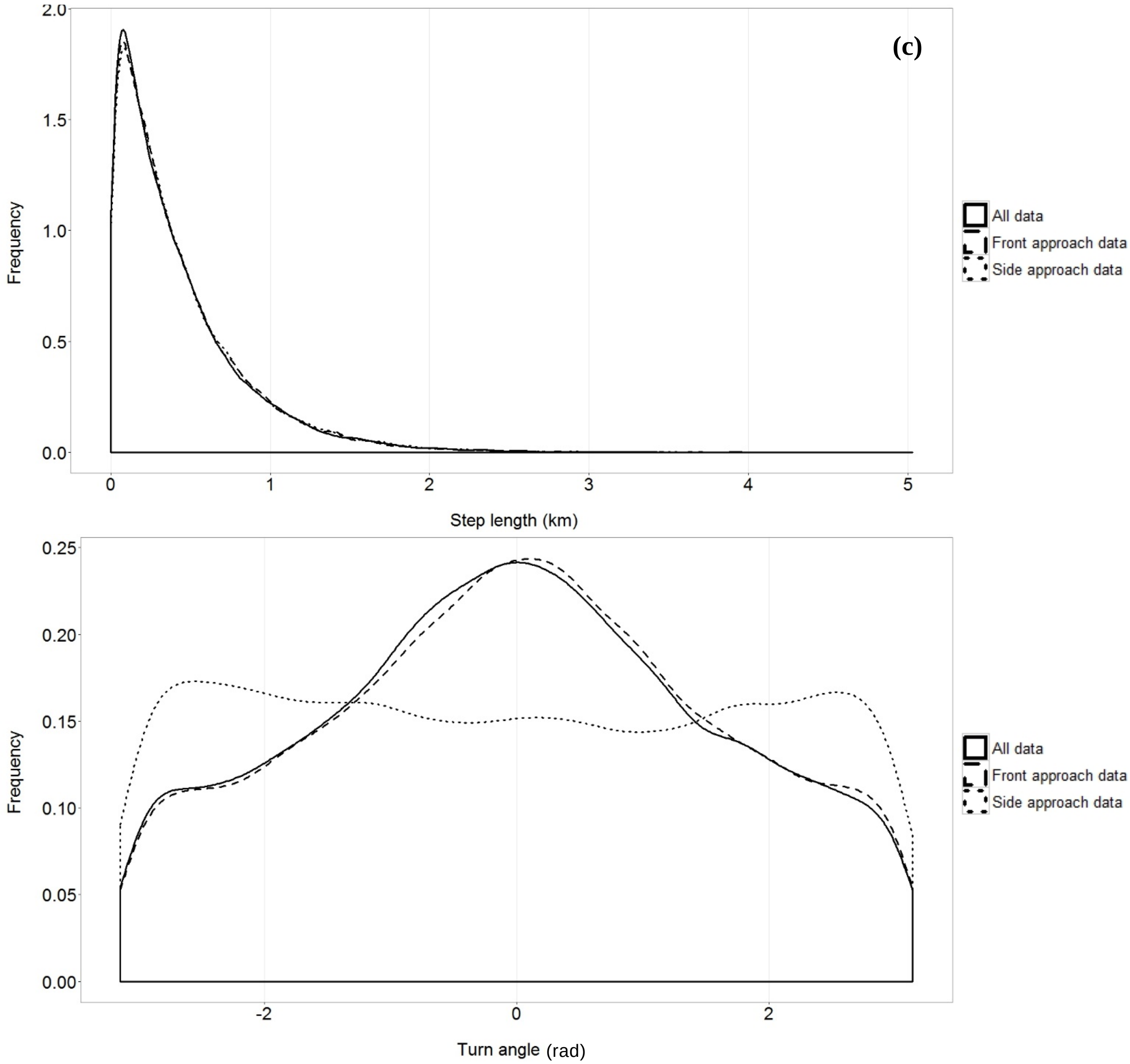
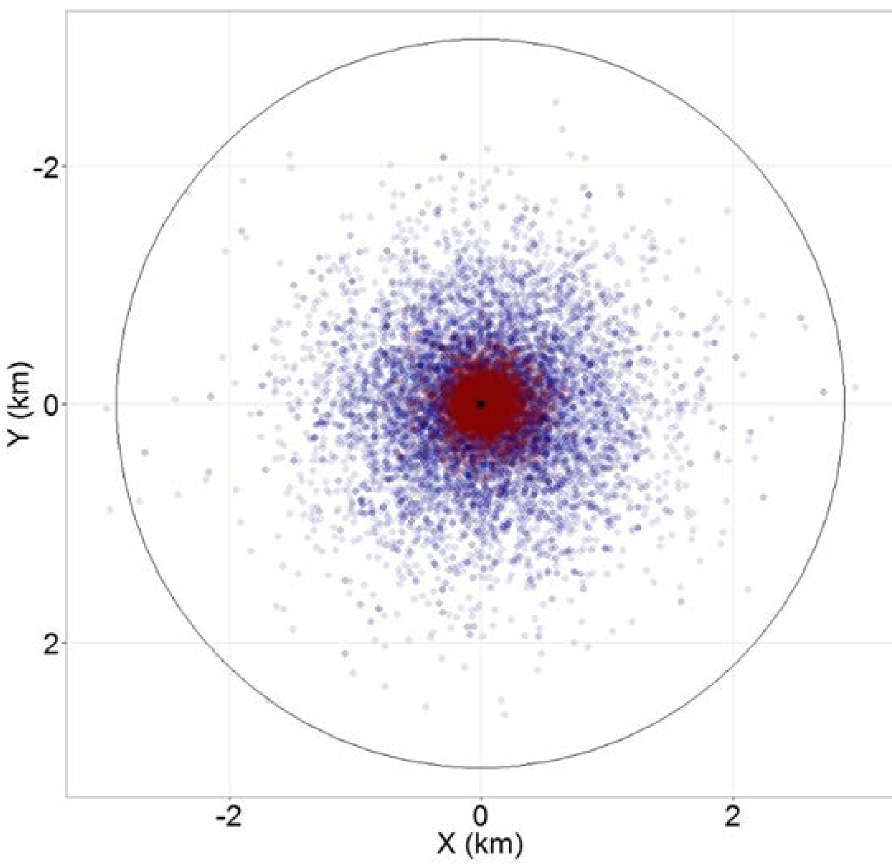

(c)
Frequency
Step length (km)
All data
Front approach data
Side approach data
Frequency
Turn angle (rad)
All data
Front approach data
Side approach data

Figure 2-6. Next location of sighted whale from 10,000 step length and turning angle iterations from single movement mode posterior distribution for surface interval activity (red) and deep dive activity (blue). Black dot at center is location of whale at first sighting.



Chapter 3: Investigating the influence of large ships on behavior change in humpback whales (*Megaptera novaeangliae*) within a regulated ship route in Glacier Bay National Park and Preserve, southeastern Alaska

INTRODUCTION

Conflicts between humans and wildlife are increasingly widespread, and understanding their exact effects is important for effective management and conservation. In the marine environment, areas of intense human maritime activity heavily overlaps critical large whale habitat across the globe (Block et al. 2011, Maxwell et al. 2013). This overlap leads to a variety of anthropogenic threats that impact individual whales as well as whale populations. Threats may occur as direct impacts that cause immediate injury or mortality, such as ship strikes and entanglement with fishing gear, or as indirect impacts that cause accumulated harm over time, such as stress from noise, chemical pollution, and displacement from preferred habitat (Clapham et al. 1999, Thomas et al. 2016).

Proximate impacts for different species and populations vary. While some whale populations have recovered significantly since the end of commercial whaling (Patenaude et al. 2007, Magera et al. 2013, Monnahan et al. 2015), other populations remain critically small (Kraus et al. 2005, LeDuc et al. 2012). For recovered species, growing populations allow for more opportunities of human-whale overlap and conflict. For example, the distinct population segment (DPS) of humpback whales (*Megaptera novaeangliae*) that breeds in the West Indies has recovered sufficiently to be considered no longer at risk under the Endangered Species Act (NOAA 2016). Some whales from this DPS migrate northward along the Atlantic coast of North America to summer feeding grounds in the northern North Atlantic Ocean (Bettridge et al. 2015), overlapping with the extremely busy commercial shipping and military ports in the Chesapeake Bay. The growing number of whales moving through this area and overlap with high marine traffic areas has led to four known whale mortalities in less than two months during 2017, and all necropsies thus far have determined these mortalities to be the result of ship strikes (Virginia Aquarium & Marine Science Center, Stranding Response Team, media report, 2017).

For unrecovered species with small populations, a single incident may have significant and lasting impacts on population persistence, especially for a relatively long-lived and slowly reproducing species. For instance, the North Atlantic right whale (*Eubalaena glacialis*) has been shown to be particularly vulnerable to ship strikes (Conn & Silber 2013). With an estimated abundance of only 500 individuals, a single ship strike mortality or reduction in reproductive success, due to stress or being displaced to suboptimal feeding conditions, may have severe population-level impacts.

To mitigate the impacts of threats to whales, it is critical to understand whether whales respond to large ships in perceivable and predictable ways. For example, within the context of the direct impact of mortality due to ship strikes, understanding if and how a whale may respond to a ship as it approaches may allow ship operators to predict future movement and locations of the whale relative to the ship's route and to execute more informed avoidance actions. Additionally, knowledge of whales' responses to ships will advance the assessment of cumulative or long-term indirect anthropogenic impacts, such as altered feeding or breeding behavior in response to approaching ships and their associated noise . Understanding these impacts can inform seasonally- and provisionally- regulated management actions, such as temporarily instated protected areas or restrictions on ship speeds.

Current investigations of whale responses to ships have been inconclusive. The responses of blue whales (*Balaenoptera musculus*) traveling near high-traffic shipping routes to large commercial shipping vessels were assessed by investigating changes to movement and diving patterns (McKenna et al. 2015). Results show that these whales lacked any lateral movement response to approaching vessels and that they evoked only limited vertical responses once the ships were in close proximity (McKenna et al. 2015). Investigation of North Atlantic right whales showed that whales did respond to an auditory alert stimuli, by increased surfacing behavior, but they did not respond to the sound of approaching vessels or the presence of vessels themselves (Nowacek et al. 2004, 2007). Additionally, most current investigations of whale responses to ships have been conducted using remotely-collected data, such as archival acoustic recording tags, GPS tags, or underwater acoustic monitors. Data collected whales using these methods typically constrains studies to relatively small sample sizes. These data are then considered in combination with ship information, such as number of occurrences, routes, or noise output, which are also remotely-collected. Thus, the overlap between whales and ships being assessed is not actually occurring in real time. Of the investigations observing the responses of whales to marine traffic in real-time, most have been conducted from small research or tourism vessels (e.g., Morete et al. 2007, Stamation et al. 2010). Studies of whale responses observed in real-time while in the vicinity of large ships is lacking.

In the current study, we examined behavioral responses of humpback whales in the vicinity of large cruise ships during real-time overlap in regularly-used and high-traffic ship routes. We used cruise ship passages within Glacier Bay National Park and Preserve (GBNP) and its adjacent water ways to record observations of whale activity and behavior in an area where whales often encounter large ships (Gende et al. 2011, Harris et al. 2012). We explored how characteristics of these encounters, such as the distance and relative bearing between the whale and ship, may have influenced the probability of changes to the behaviors that whales are engaged in utilizing a multistate model approach that estimated transition probabilities between behavioral states and the effects of covariates on those transitions. Our main objective was to provide further understanding of the direct and indirect impacts of the anthropogenic threats resulting from overlap between areas that whales occur and ship routes, and to generate evidence-based recommendations for ship operators to consider within avoidance actions.

METHODS

Study Area

We conducted surveys for humpback whales in Glacier Bay National Park and Preserve and the surrounding waterways in southeastern Alaska (Figure 1). The combination of complex bathymetry, strong current systems, and numerous upwellings results in highly productive waters in this area during the summer months. Availability of prey makes GBNP, as well as much of southeastern Alaska, an important summer feeding grounds for several marine mammal species, including humpback whales from the Hawaiian-breeding DPS. Humpback whales that feed in GBNP and the surrounding waters generally arrive as early as late April and remain as long as late September (Hendrix et al. 2012). During this time, whales must consume enough to generate stores to sustain themselves throughout subsequent migrations and breeding periods; for females, these stores may also need to be plentiful enough to cover pregnancy and lactation (Clapham 2000).

The National Park Service (NPS) has conducted a rigorous humpback whale monitoring program in GBNP since 1985 (Neilson et al. 2015). Results from monitoring efforts indicate that humpback whales in this area exhibit high site fidelity for their summer feeding grounds between years and across generations (Neilson et al. 2015). Additionally, many of these whales (over 60% of adults in the monitored population) are considered "residents" of the study area, spending ≥ 20 day spans in the GBNP and nearby waterways (Gabriele et al. 2017). Monitoring results have also shown that this population has undergone strong growth in the last several decades, particularly from 2002 to 2011 (Gabriele et al. 2017). Recent abundance estimates yielded an average rate of increase over the last three decades of 4.8% annually (Gabriele et al. 2017), which is similar to population growth rates found in the rest of southeastern Alaska (Hendrix et al. 2012).

While Glacier Bay National Park and the surrounding area is a critical summer feeding ground for a growing humpback whale population, it is also a popular and highly-visited National Park and Preserve and World Heritage Site (National Park Service 2016). GBNP has received more than 500,000 recreation visits annually since 2013, and most visitors arrive via cruise ship during the summer months (NPS, US DOI, Visitor Use Statistics Reports, 2016). The National Park Service manages entry of cruise ships through permits distributed to cruise lines, and through regulations on operating conditions once ships enter the park. Cruise ship entries are restricted to park-set quotas on both a daily (maximum of 2 ships) and seasonal basis. Seasonally, the park restricts entries to a maximum of a total 275 ship passages, split over a 'peak' season (June-August; 153 cruise ships entries permitted) and a 'shoulder' season (May, September; 122 cruise ship entries permitted). Because of the large number of whales and temporal overlap between humpback whale occurrence and cruise ship visitation in the park, a large number of encounters between ships and whales occur in the area (Gende et al. 2011, Harris et al. 2012). These encounters provide a unique context to investigate the impacts of large ships on humpback whale behavior.

Data Collection

Cruise ship-based observers surveyed for humpback whales and recorded the location and frequency of encounters between ships and whales from 2008 to 2015. Encounters were observed and recorded in real time via visual observations of whale surfacing events as ships moved through the study area. Surveys were conducted during the humpback whale summer feeding season and covered both the 'peak' and 'shoulder' cruise ship entry quota seasons (April through September).

We used two methods for observers to embark cruise ships and carried out two associated survey schedules. The first embarkation method was employed by an observer that was based in GBNP (hereafter, GBNP-based observer). This observer embarked the ship via a NPS transfer vessel while the ship was in transit and had already entered the park boundary (Figure 1). The GBNP-based observer would immediately station themselves on the bow of the ship upon embarkation and begin surveys. This observer disembarked, also via NPS transfer vessel, as the ship transited back down the bay and neared the southern end of the park.

The second embarkation method was employed by an observer based in Juneau, AK (hereafter, Juneau-based observer). This observer embarked the ship while it was docked at a port of call on the day immediately preceding the ship's scheduled day in GBNP (either Juneau or Skagway, AK). The Juneau-based observer disembarked while the ship was docked at the port of call the day after the ship's transit through GBNP (either Ketchikan or Sitka, AK). Once onboard the ship, the GBNP-based observer proceeded to the bow and immediately began surveying, which typically corresponded with the ship being near Strawberry Island. The Juneau-based observer began surveying at dawn during the ship's

GBNP cruise day, typically near the eastern boundary of Icy Strait. This observer schedule allowed for continued survey effort until dusk or the ship entered Cross Sound. In either method, only one observer was on board for any given survey.

Once the survey began, the observer continuously performed naked eye and binocular-assisted scans, using tripod-mounted range-finding binoculars (Leica Viper II; accuracy, +1m at 1km; Leica, Charlottesville, Virginia, USA) and 8x42 binoculars (Swarovski Optik, Absam, Austria). Upon detecting a surfacing whale, the observer used the rangefinders to measure the distance between the observer and the whale (or estimated the distance if conditions made the range-finder binoculars unusable, such as the whale being above surface for too little time or excessive fog) and used a protractor attached to the tripod-mounted binoculars to determine the relative bearing of the whale from the heading of the ship. Each whale location was geospatially referenced using a handheld GPS unit (Garmin, Olathe, Kansas, USA). After the initial sighting, the observer continued to follow the whale or group and recorded each resurfacing event until it either left the area of view, or the time between resurfacing was too long to ensure that it was the same whale or group.

For each whale location, the observer also recorded the whale or group's orientation at surfacing, direction of travel relative to the ship's course, group size, and a categorical visually-assigned behavior (blow/shallow dive with no fluke showing, dive with fluke up, surface active behavior, lunge feeding, resting; Table 1). We defined a group as two or more whales within two body lengths and coordinating their behavior and/or movement direction for at least one surfacing event (Ramp et al. 2010). For our analysis, groups of more than one whale were treated as a unit that engaged in behavior in concert. We considered mother-calf pairs as a group size of two and treated them as any other group. The observer recorded pertinent environmental covariates, such as weather and visibility, at the start of each day and as the conditions changed throughout the survey. We deployed a separate GPS unit programmed to record the ship's location to reconstruct the ships route.

Data analysis

We used a multistate model approach implemented within a Bayesian framework to assess the probability of transitioning between visually-assigned behavior categories and to assess how characteristics of the encounter influenced this probability. We used distance between whale and ship (m) and relative bearing between the whale and heading of the ship (deg; Table 2) as covariates describing the conditions of the encounter. We hypothesized that these covariates may be significant in 1) prompting a response from whales that would possibly cause a behavioral change, and 2) having an influence on the amount and direction of sound propagating from the ship, which may be one stimuli whales use to assess location of an approaching ship. Covariates were scaled and centered for use in our model, and we used the absolute value of relative bearing, as we did not expect differences between observations of whales on the port and the starboard side of the ship.

We designated the visually-assigned behaviors for each observation of a surfacing whale into two states: those associated with "transit" activities, or those activities for which the whale was likely traveling some distance (dive with fluke showing or spout and dive with no fluke showing; Table 1), and those associated with "stationary" activities, or those activities for which the whale was likely to stay in a relatively small area (lunge feeding, resting/logging, surface activity, which included pectoral fin slapping, breaching, and tail lobbing; Table 1) over the course of the encounter. We then developed an encounter history for each surfacing per whale or group from these data. Every individual or group's encounter history began on its initial observation and continued for as many subsequent surfacings of that whale or group that was observed.

The multistate model approach that we used consisted of four possible transitions: (1) transition to stationary behavior given that a whale or group was seen initially in transit behavior ($P(\Psi_{TS})$), (2) remaining in transit behavior given that a whale or group was seen initially in transit behavior ($P(\Psi_{TT}) = 1-P(\Psi_{TS})$), (3) transition to transit behavior given that a whale or group was seen initially in stationary behavior $P(\Psi_{ST})$, and (4) remaining in stationary behavior given that a whale or group was seen initially in stationary behavior ($P(\Psi_{SS}) = 1-P(\Psi_{ST})$; Figure 2). Transition probabilities (1) and (3) were parameters estimated by the model, and transition probabilities (2) and (4) were derived parameters. As our model was conditioned on initial sighting, there was no probability associated with the behavior that the whale or group was engaged in at initial sighting. We fit the multistate model in program R (ver. 3.3.1; R Core Team 2016) using the package 'rjags' (ver. 4.6; Plummer 2016). We assessed model convergence and reliability of parameter estimates by visual inspections MCMC chains and posterior distribution plots that we generated using the package 'ggmcmc' (ver. 1.1; Fernández i Marín 2016).

RESULTS

From 2008 to 2015, we recorded 7,645 observations of individuals or groups of humpback whales from onboard cruise ships. Each observation coincided with a surfacing of the individual or group and had associated characteristics of the encounter with the ship (distance and relative bearing between whale and ship). Some (N = 2,848) of these observations were of a whale or group that was seen only a single time, and thus were not useable in our assessment of behavior changes. Additionally, we were not able to determine behavior or other covariate of importance (distance or relative bearing between ship and whale) for some encounters, so these observations were also not used for our analysis. Our final data set consisted of 4,470 observations of 1,671 unique individuals or groups whales. These observations occurred over encounters between the whale(s) and ship that lasted between 2 and 12 surfacings and ranged in group size from 1 to 15 whales.

Visual assessment of MCMC chains and parameter estimate posterior distribution plots indicated good model convergence and reliable estimates of parameters from our model (Figure 5). Whales were seen much more frequently in a transit than stationary behavioral state at initial observations (N = 1,489 and 182, respectively; Table 1). In respect to transitions between behaviors, most often, whales that were seen engaged in transit behavior remained in transit behavior, and this accounted for a large number of our observations (N = 2,293; Table 1).

Overall, probabilities of transition to a different behavior than the behavior that was initially observed were quite small (($P(\Psi_{TS})$ = 0.002, 95% CI = (0.0004, 0.006) and $P(\Psi_{ST})$ = 0.078, 95% CI = (0.003, 0.240); Table 3). These results show that, on average, we would expect that whales seen initially in transit behavior would stay in transit behavior in over 99 out of 100 observations, and that whales seen initially in stationary behavior would stay in stationary behavior in 89 out of 100 observations. Though the probabilities of switching behavior between initial and subsequent observations low, there was considerable relative difference between the two probabilities; the probability of switching behavior given that a whale was initially observed in stationary behavior was nearly 40 times higher than the probability of switching behavior given that a whale was initially observed in transit behavior.

The conditions of the encounter between the whale(s) and ship that we investigated had varying influences on transition probabilities (Table 3). Neither distance nor relative bearing between whale and ship influenced the probability of a whale switching from stationary to transit behavior (Table 3). However, both covariates did influence the probability of switching to stationary behavior given that the whale was initially in transit behavior (Table 3). The distance between the whale(s) and ship had a positive influence on the transition probability of going from transit to stationary behavior (mean = 0.542, 95% CI = (0.418, 0.668), Table 3). In other words, as distance increased, the probability of switching from transit to stationary behavior also increased (Figure 3). However, the relative bearing between the whale(s) and ship had a negative influence on the transition probability from transit to stationary behavior (mean = -0.193, 95% CI = (-0.296, -0.090), Table 3). This indicates that as encounters between the whale(s) and ship were increasingly abeam of the ship (i.e., further on either side of the ship than in front of the ship), the probability of transitioning from transit to stationary behavior decreased (Figure 4).

DISCUSSION

Overall, our results show that there is low probability of whales switching behaviors when in the vicinity of and encountering large ships. This supports previous evidence that large whales show little avoidance or response to the presence or sound of oncoming ships (Nowacek et al. 2004, McKenna et al. 2015). We suggest two possible explanations for the overall low probability of switching behaviors as a response to large ships.

First, our study area serves as an important summer feeding ground for humpback whales (Neilson et al. 2015, Gabriele et al. 2017). As seasonal feeders and capital breeders, these whales must develop enough energy stores during their summer feeding period to sustain themselves for the duration of the year. Their annual life cycle includes several thousand mile migrations to and from low latitude breeding and calving grounds, as well as the several month residency at this habitat. For females, energy stores may also need to be plentiful enough to support a nursing calf and growing fetus for part of the year. Many of the humpback whales that we observed were likely engaged in feeding-associated behavior, in the form of transit to areas of high prey availability or in the act of feeding itself. Perhaps focus on finding and consuming enough prey was paramount to response to or avoidance of approaching ships. This may be an underlying biological driver for their low probability of switching between behaviors.

Our second explanation for the low probability of switching between behaviors centers on alteration of the acoustic environment, though it does not exclude the first explanation focused on the importance of feeding. Because of the regulated entry of cruise ships throughout the summer, whales in our study area are exposed to ship noise on a regular and consistent basis (www.nps.gov/articles/humpback-acoustics.htm). It may be that whales in our study have become desensitized to increased noise as an indicator of approaching ships. It is also possible the relatively constricted nature of the narrow waterways of Glacier Bay and Icy and Chatham Straits, in addition to the complex ways that noise is propagated from large ships, results in acoustic alterations that are not easily interpretable by whales. Even if whales are alerted to the presence of large ships, perhaps they are unable to determine the location of the approaching vessel from the ship's noise output and thus do not undertake a behavioral response.

This explanation surrounding alterations of the acoustic environment is supported by our finding that the relative bearing between whale and ship influenced the probability of transitioning from transit to stationary behavior, such that there was a decreased the probability of switching when whales with increasing relative bearing. Researchers have suggested that ships produce an acoustic null directly ahead of them, though sound is readily propagated to the sides of ships (Allen et al. 2012). In our study, whales were more likely to stay in transit behavior when they were more abeam, or to the side of the ship, than when they were directly ahead of the ship. This suggests that perhaps noise propagated from the sides of the ship alerted whales, and decreased the probability that they would switch from transit to stationary behavior, in essence facilitating continued movement away from the ship.

The probability of transition from stationary to transit behavior was much higher than the probability of transition from transit to stationary behavior. This indicates that, of the relatively few times that a whale does change behavior, it is more often going to switch from stationary to transit behavior. Together with our result that neither covariate of the encounter between ships and whales had a significant influence, the heightened probability of switching to transit behavior may indicate that whales are willing to flee under any conditions of an encounter with a ship. Conversely, the probability of switching from transit to stationary behavior was extremely low and was influenced by the both conditions of the encounter that we investigated. Biologically, this may indicate that whales stop, presumably to feed, only under particular sets of conditions regarding ship presence. While feeding behavior is primarily driven by prey availability, the distance and relative bearing between the ship and whale may impact whether a whale will stop given that it is in an area of prey. This result indicates that indirect impacts of ship presence may occur, as whales could experience reduced feeding rates or efficiency when they encounter ships.

The results of our study inform management and ship strike avoidance decisions. As we discussed above, our results support the hypothesis that acoustic nulls directly in front of large ships may prohibit whales from being alerted to the presence of oncoming ships. Ship operators may be able to use this information to combat ship strike risk with slight and temporary adjustments of the heading of the ship so that the ship is briefly oriented at an increased relative bearing to the whale. This may allow noise radiating from the side of the ship to better alert the whale of the ship's approach. Additionally, the knowledge that whales are very likely to remain in the behavior that they are initially observed in is useful to ship operators in predicting future movement and appropriate avoidance maneuvers. Finally, our results indicate that humpback whales in our study area may be experiencing indirect impacts of ships with respect to feeding behavior. Managers of important feeding areas can use this knowledge to more accurately assess long-term impacts of high volume ship traffic on whale populations.

Our study provides an important step forward in assessing whale responses to large ships. While our work advances the understanding whale responses to ships, and the possible indirect impacts resulting from the changes to behavior, future research can address constraints that were present in our study. First, though the distance between the ship and whale at initial observation was considerable in some cases (some occurred at over 10 km), it is possible that whales had already been influenced by the presence of the ship by the time of our initial observations, and may have already responded and changed their behavior. Additionally, it is likely that initial behavior and group size influenced the distance at which we were able to detect whales (Williams et al. 2016), and this may have influenced our assessment of probability of switching between behaviors. It would be beneficial for future work to observe whales while ships were at even further distances, such that investigators could be certain that initial behavior had not yet been influenced by the presence of the ship. An additional constraint of our study was that encounter histories of each individual or group of whales spanned a relatively short time period. While the time span of our encounter histories typically encompassed observations of the whale or group until the ship had passed, future work could strive to obtain longer encounter histories, which could provide a fuller picture of whale behavior changes.

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TABLES

Table 3-1. Humpback whale behavioral observations collected on surveys aboard cruise ships in Glacier Bay and adjacent water ways, southeastern Alaska from 2008 to 2015.

Behavioral state	Specific behaviors observed	Number of initial sightings in state	Number of transitions to same state	Number of transitions to other state
Transit	Dive with fluke showing, spout and dive with no fluke showing	1,489	2,293	185
Stationary	Lunge feeding, resting/logging, surface activity (including pectoral fin slapping, breaching, and tail lobbing)	182	181	140

Table 3-2. Covariates used in multistate model assessing probability of transition between behavioral states of humpback whales in Glacier Bay and adjacent water ways in Alaska from 2008 to 2015.

Covariate	Description	Range
Distance to ship	Radial distance from the bulbous bow of the cruise ship directly to whale or group. Distance was either obtained directly from rangefinder binoculars or estimated when distance could not be obtained from range finder binoculars (e.g., there was not enough time above the water's surface to obtain the whale's or group's distance).	11 to 10,986 m
Relative bearing to ship	Relative bearing from forward route of cruise ship to whale or group. Directly in front of ship was 0 deg relative bearing, starboard side covered measurements from 0 to 180 deg, and port side covered directions from 0 to -180 deg. For reference, 90 and -90 deg correspond with directly abeam of ship on either side. Absolute relative bearing was used as data in the models, as we were not concerned with port vs starboard influence but relative position on either side. Measured using protractor attached to tripod-mounted rangefinder binoculars.	0 to 180 deg

Table 3-3. Multistate model estimates of transition probabilities and covariates for behavioral states humpback whale observations in Glacier Bay and adjacent water ways in Alaska from 2008 to 2015.

Behavioral States	Transition probability	Derived probability	Covariate influence on transition probability	
	(Ψ: switch behavioral state)	(1 - Ψ: stay in behavioral state)	Distance to ship (m)	Relative bearing to ship (deg)
Transit	0.001 (0.0003, 0.004)	0.999	0.571 (0.473, 0.670)	-0.276 (-0.358, -0.194)
Stationary	0.109 (0.005, 0.290)	0.891	0.059 (-0.185, 0.303)	-0.049 (-0.242, 0.152)

FIGURES

Figure 3-1. Study area of Glacier Bay National Park and adjacent waters in southeastern Alaska where surveys were performed on cruise ships to explore changes between behavioral states of humpback whales. Dashed line indicates boundary of Glacier Bay National Park. Solid line indicates typical cruise ship routes.

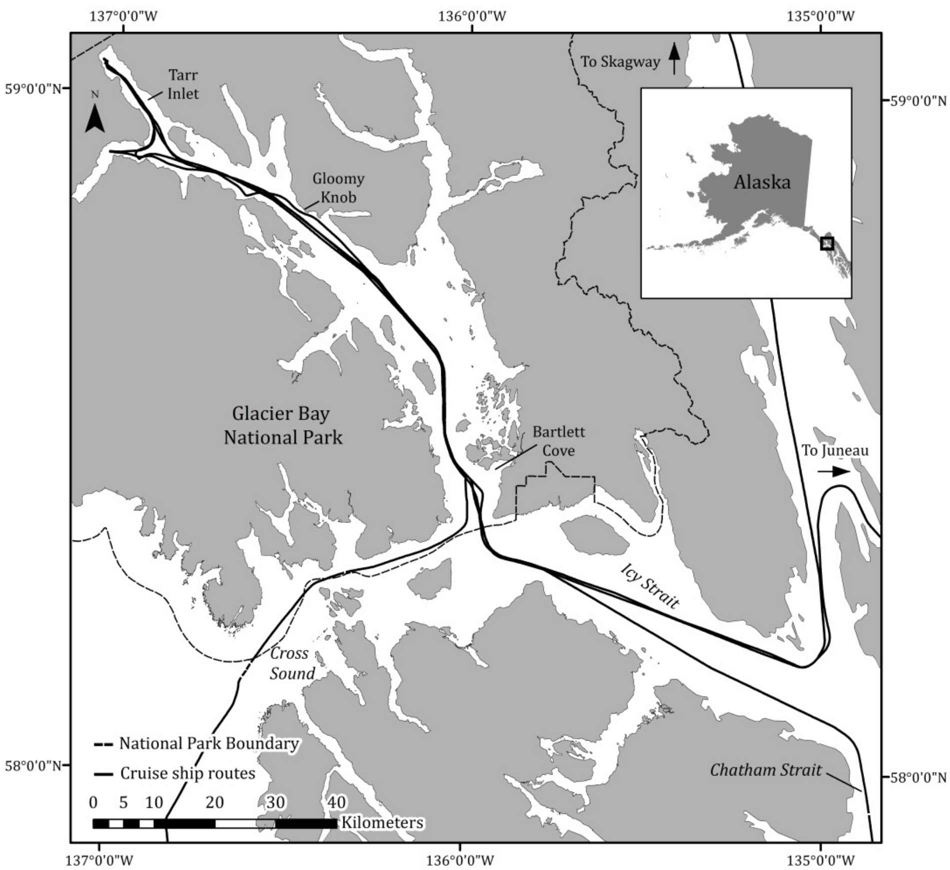


Figure 3-2. Conceptual design of multistate model implemented to assess probability of transition between behavioral states of humpback whales within cruise ship route. Dashed line indicates boundary of Glacier Bay and adjacent water ways in southeastern Alaska from 2008 to 2015.

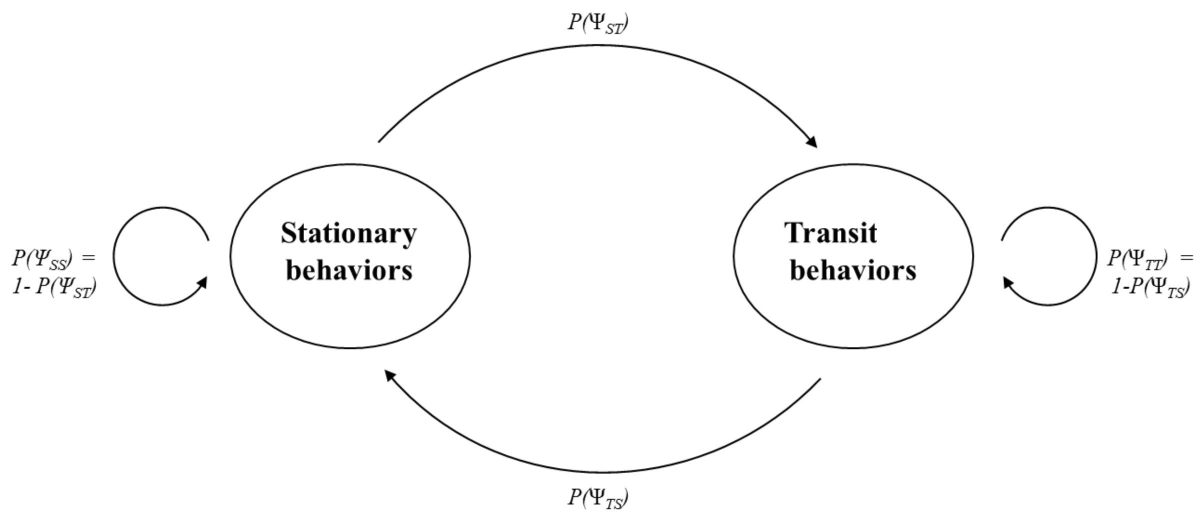


Figure 3-3. Influence of distance between ship and whale(s) (m) on probability of transition from transit to stationary behavior from multistate model estimates using humpback whale observations in Glacier Bay and adjacent water ways in Alaska from 2008 to 2015. Solid black line uses mean parameter estimate for the effect of the covariate. Grey lines are draws from MCMC iterations to show breadth of possible values.

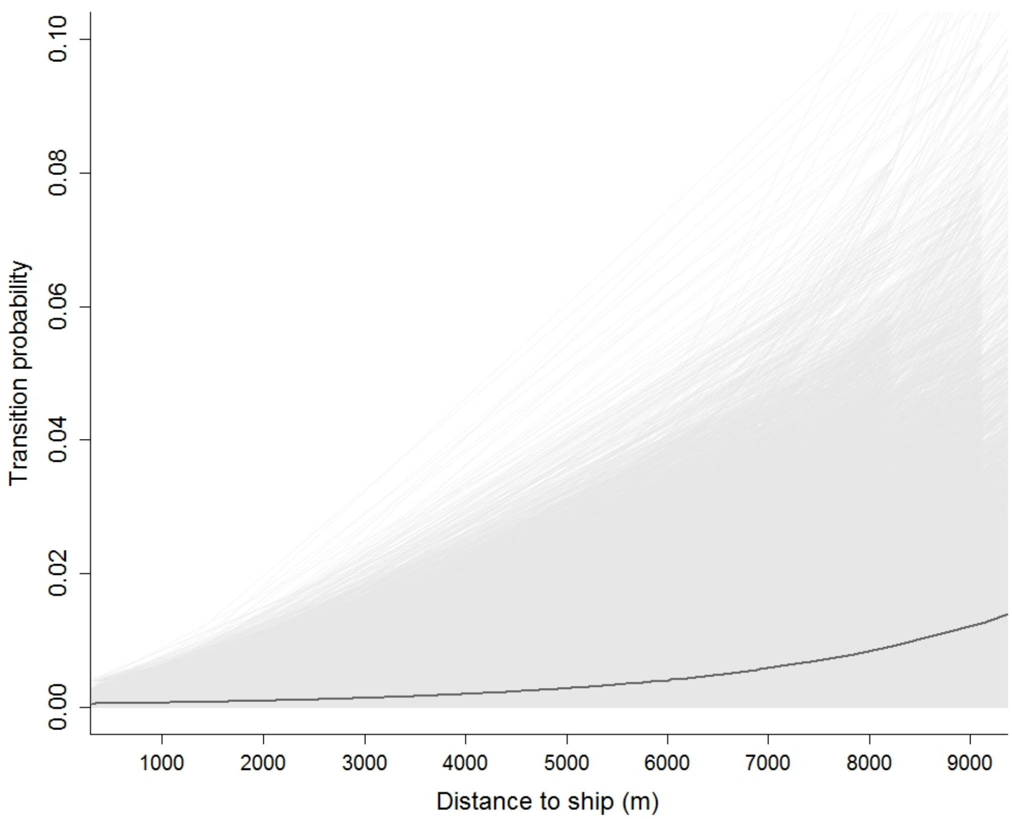


Figure 3-4. Influence of relative bearing between ship and whale(s) (deg) on probability of transition from transit to stationary behavior from multistate model estimates using humpback whale observations in Glacier Bay and adjacent water ways in Alaska from 2008 to 2015. Solid black line uses mean parameter estimate for the effect of the covariate. Grey lines are draws from MCMC iterations to show breadth of possible values.

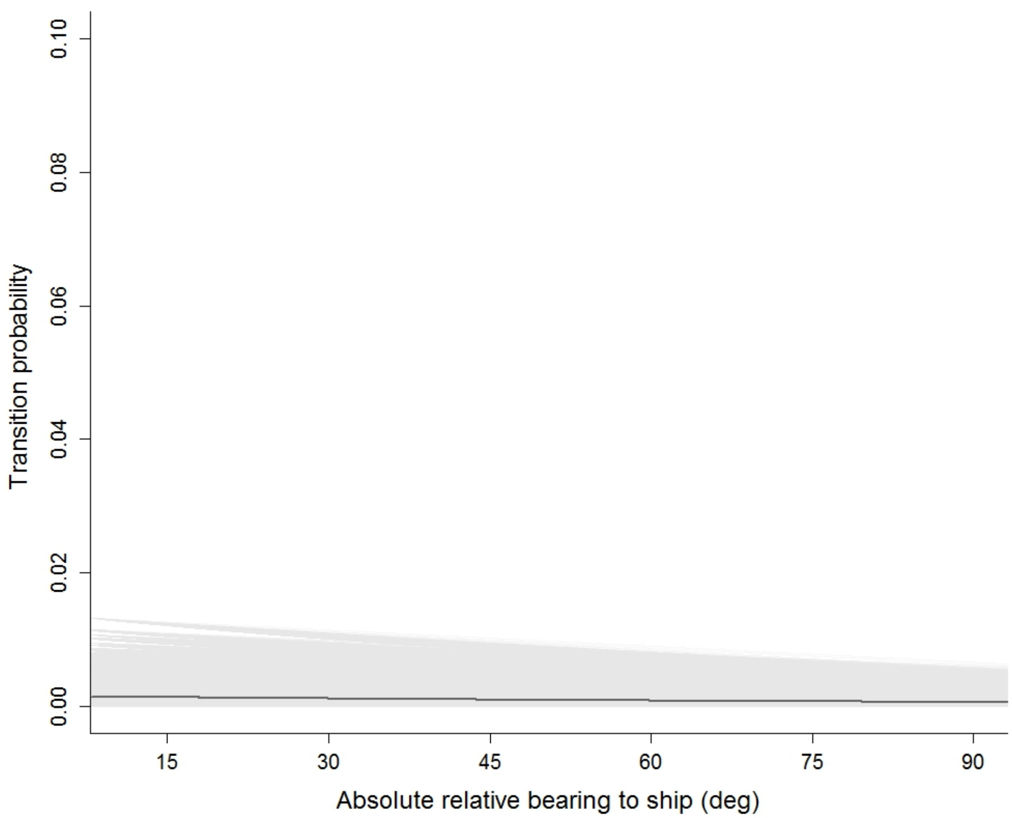
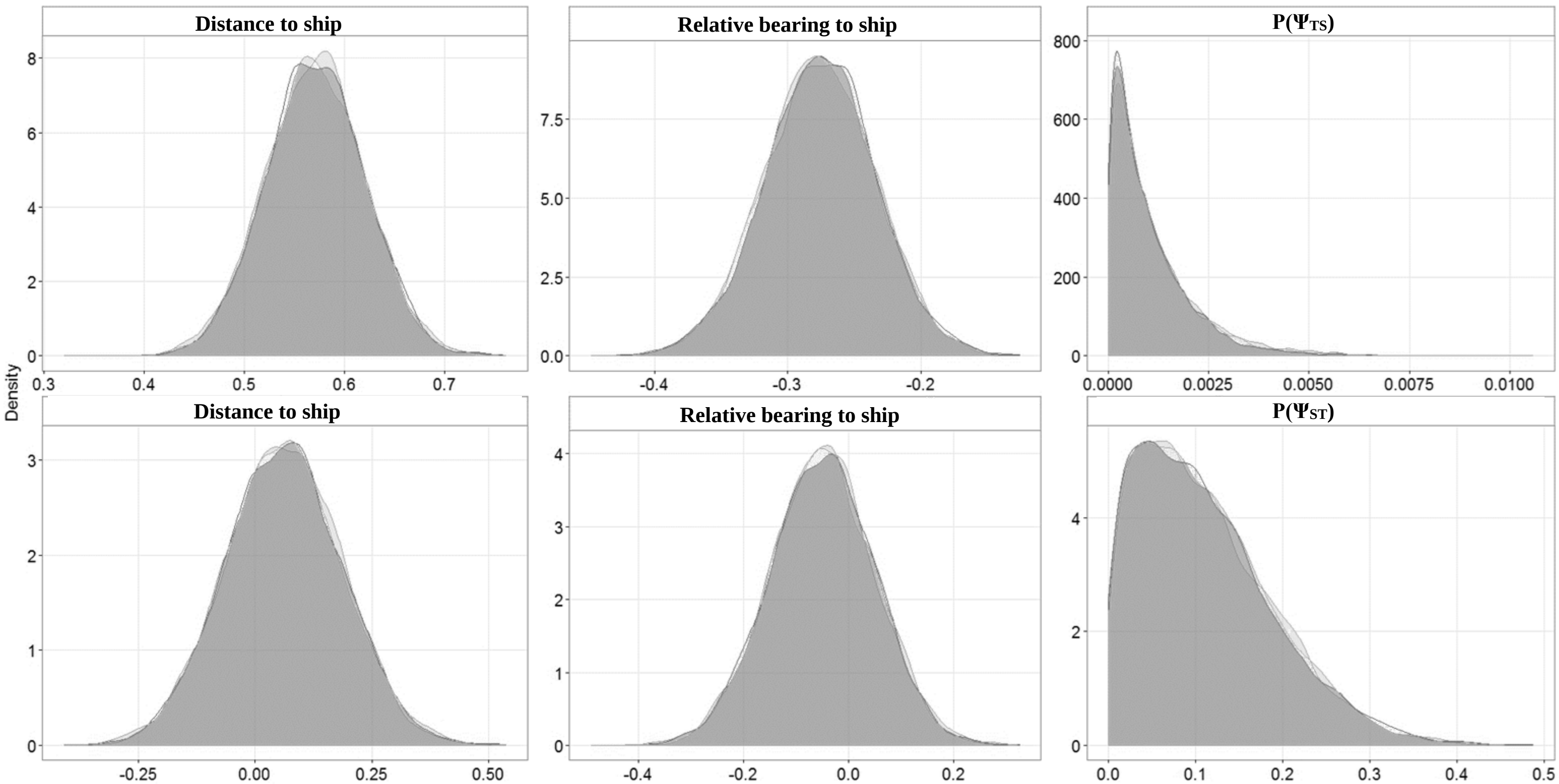


Figure 3-5. Posterior density plots of parameters from multistate model using humpback whale observations in Glacier Bay and adjacent water ways in Alaska from 2008 to 2015.



Chapter 4: Evaluating ship strike risk of humpback whales (*Megaptera novaeangliae*) in Glacier Bay National Park and Preserve using spatially-explicit model-based estimates of density, occurrence, whale movement and ship movement

INTRODUCTION

Collisions between ships and whales ('ship strikes') are a growing conservation concern for baleen whale species across the globe (Laist et al. 2001, Jensen & Silber 2003, Douglas et al. 2008, Gende et al. 2014, Neilson et al. 2015). Ship traffic has increased steadily over the last several decades and is expected to continue with increasing global development, particularly in developing countries (United Nations Conference on Trade and Development 2016). Currently, many whale populations are recovering from near extinction from commercial whaling pressure in the 20th century and are experiencing positive population growth rates (e.g., Calambokidis et al. 2008). As a result of increased ship traffic and concurrently growing whale populations, mortality due to ship strikes has become one of the primary global threats to baleen whale conservation, threatening their continued recovery and long term persistence (Clapham et al. 1999, Thomas et al. 2016).

Given the gravity of ship strike threats, conservation and management research has invested a great deal of effort into understanding the incidence and occurrence of ship strikes. Primarily, research has focused on revealing patterns of where and how often strikes have occurred in the past (Laist et al. 2001, Jensen & Silber 2003, Douglas et al. 2008, Neilson et al. 2015). Another research focus has been assessing the influence of ecological and anthropogenic factors, such as whale behavior or sex and ship speed, on past ship strikes and future risks, and how these factors affect the probability of mortality resulting from a ship strike (Vanderlaan & Taggert 2007, Gende et al. 2011, Wiley et al. 2011, Conn & Silber 2013). More recently, researchers have begun evaluating the probability of ship strikes in spatially-explicit contexts of overlap between whale habitat and ship traffic (Vanderlaan & Taggert 2008, Vanderlaan et al. 2009, Guzman et al. 2012, Harris et al. 2012, Bezamat et al. 2014), as well as assessing the impacts of management actions aimed at reducing the occurrence of ship strikes, particularly for critically small populations (van der Hoop et al. 2012).

However, there is still much uncertainty surrounding ship strike occurrences. For one, ship strikes are underreported for a variety of reasons, including fear of repercussions, lack of detection of a strike, or negligence or ignorance of reporting protocols (Laist et al. 2001, Conn & Silber 2013). Even when ship strikes are reported, inconsistent or poorly-enforced reporting protocols often preclude collection of information from both the vessel and the animal at the time of the collision. In many cases, only data regarding the operating conditions of the vessel at the time of the strike are recorded, rather than diagnostic information detailing the specific cause of the strike and the activity of the whale at the time the strike occurred. Meta-analyses and reviews of ship strikes often rely on historical data and indicate that most injury and mortality information is obtained after the event from either observations of injured/stranded animals or necropsies, not at the time of the vessel strike (Laist et al. 2001, Vanderlaan & Taggart 2007). Furthermore, reviews commonly assert that the overall number of strikes is underreported for a variety of reasons, including fear of repercussions, lack of detection that a strike has occurred, or negligence or ignorance of reporting protocols (Laist et al. 2001, Conn & Silber 2013).

Ship strikes result from spatial and temporal overlap between whale activity and human maritime activity (e.g. commercial shipping, transport, military operations, natural resource extraction, tourism and recreation) and are the outcome of a series of biological and anthropogenic processes. Biologically, ships strikes are influenced by the processes underlying whale occurrence, movement, and behavior, all of which are interrelated. Previous research has provided a solid background on these processes whale distribution, habitat preferences, and migration routes (e.g., Zerbini et al. 2006, Keller et al. 2012, Pendleton et al. 2012, Gregr et al. 2013). The results of this research have been used to inform conservation and management decisions, such as the enactment of seasonal protected areas and shifts in ship lanes (e.g., Vanderlaan and Taggert 2007, Becker et al. 2012, Redfern et al. 2013, Bezamat et al. 2014, Dransfield et al. 2014, Rosenbaum et al. 2014, Gende et al. 2014, Brillant et al. 2015). However, given general spatial and temporal overlap, whales and ships must encounter each other at a finer spatial scale for a strike to occur. This means that within an area of general whale habitat, whales must occur specifically within locations that ships travel. Environmental and oceanographic variables, prey abundance, and interactions with other whales often drive fine-scale whale occurrence and the related biological processes of movement and behavior.

When fine-scale encounters between whales and ships do occur, strikes can be avoided by either the whale responding to the ship, or by ship personnel undertaking an appropriate avoidance action. For the first course of strike avoidance (i.e., by whales), a whale must perceive a ship's approach, determine its location, and respond to the ship with an evasive movement. From the perspective of ship operators, ship strike risk is driven by the operating conditions of the ship, such as route and speed, as well as onboard mitigation efforts, such as dedicated observers in place to detect whales in the ship's path or speed reductions. For the second course of strike avoidance (i.e., by ship operators), a ship operator must first detect the whale, then predict where the sighted whale will move or occur in the future, and finally adjust the ships operating conditions appropriately to avoid the whale. A ship operator must accomplish any avoidance action while maintaining overall safety of the ship and its passengers.

Both courses of ship strike avoidance have been the focus of recent research. Understanding if and how whales respond to fine scale encounters can be particularly challenging. Studies have assessed changes in whale behavior or movement when in close proximity to ships to evaluate whale responses to ships and the effectiveness of responses to avoid ships strikes (e.g., Nowacek et al. 2004, 2007, Morete et al. 2007, McKenna et al. 2015, Williams in prep.). Researchers also have assessed components of ship operator strike avoidance, such as evaluating the effectiveness of dedicated observers in reducing strike risk (Weinrich et al. 2010), understanding how the probability of detecting a whale is influenced by conditions of the fine-scale encounter (e.g., Williams et al. 2016), and if ship strikes can be reduced by warning ship operators with real-time communications of nearby whales (e.g., Right Whale Listening Network, Whale Alert). However While previous research has investigated ship strike avoidance from perspectives of both the whale and the ship operator, wide-scale assessment of encounters between whales and ships using data collected on both they were in the same location at the same time is still lacking.

In light of the uncertainty surrounding ship strikes, and the dearth of information on the exact causes of and circumstances under which fine-scale encounters and strikes occur, conservation practitioners and managers remain underequipped to make informed decisions to reduce ship strike risk. In this study, we examined strike risk of humpback whales (*Megaptera novaeangliae*) observed on summer feeding grounds while in the presence of large ships. Our primary goal was to assess spatial variation in ship strike risk in a region that is both important whale habitat and receives consistent ship traffic. Notably, we incorporate model-based estimates of whale occurrence, movement, and behavior, as well as actual ship location, route, and speed, from real-time data collected at the study area when whales and ships were occurring simultaneously. We used simulations to assess ship strike risk over a variety of time scales and translated our findings to visualizations that are relevant to ship operators and managers.

METHODS

Study Area

We evaluated ship strike risk in Glacier Bay National Park and Preserve (GBNP) and the surrounding waterways in southeastern Alaska (Figure 1). Our study area is made up of Glacier Bay itself, a 1,255 km^2 fjord, and the adjacent waterways of Chatham and Icy straits. Southeastern Alaska, and GBNP in particular, is an important feeding area for migratory humpback whales from late spring to early fall (Neilson et al. 2015, Gabriele et al. 2017). The majority of whales that spend the summer here are from the Hawaiian distinct population segment (DPS; NOAA 2016). This DPS has been undergoing population growth over the last several decades (Hendrix et al. 2012, Saracco et al. 2013) and exhibits strong seasonal site-fidelity (Gabriele et al. 2017).

GBNP is one of the largest federally-managed marine protected areas and is administered by the National Park Service (NPS). The NPS functions under a dual mandate to 1) safeguard natural resources for future generations, and 2) provide opportunities for the visiting public to experience the unique tidewater glacial landscape found in the park and to view wildlife (NPS 2010). To provide for visitor experience and simultaneously protect natural resources, which includes wildlife such as humpback whales, the NPS regulates and manages all visitor access to the park. The vast majority of GBNP visitors arrive by cruise ships entering the park from late spring through early fall. Cruise ship routes are constrained by the narrow geography of the bay, and all ships follow nearly identical routes entering and leaving the bay (Figure 1). As a result, these ship routes are often nearby or overlap high-use whale habitat leading to a large number of ship-whale encounters (Gende et al. 2011, Harris et al. 2012). Whale mortalities resulting from strikes by cruise ships and other large vessels have been documented in GBNP as well as in the surrounding water ways (Neilson et al. 2012, 2015).

Data Collection

Because of the concurrent regular, highly-managed cruise ship traffic and intense whale use during the summer months, this system provides a unique context to investigate ship strike risk. We used cruise ships as survey platforms to observe humpback whales as they were approached by these ships throughout GBNP itself, as well as within the adjacent waterways. We observed and recorded whale surfacing events on surveys from 2008 to 2015 during the months of April through September. For each survey, a single observer embarked the ship via two possible schedules: 1) upon the ship’s entry into GBNP via a NPS transfer vessel, or 2) on the day before the ship’s entry into GBNP at a port of call on the cruise ship’s itinerary (either Juneau or Skagway). Observers that boarded via the first schedule proceeded to the bow of the ship to begin conducting surveys immediately upon embarkation. Observers that boarded via the second schedule began surveys at sunrise on the day the ship would enter GBNP. This allowed the observer to collect data on whale occurrence, movement, behavior, and encounters between the ship and whales within the waterways outside of the park boundary.

For both embarkation schedules, the observer continued surveying for whale surfacing events until the ship approached either Tarr or Johns Hopkins inlets, where whale-ship encounters are rare

(Figure 1; Gende et al. 2011). After the ship departed this area and began transit back toward the entrance of the bay, the observer reinitiated the survey and continued surveying until either disembarkation via the NPS transfer vessel near the southern boundary of the park (for observers that embarked in this method), or the observer continued survey effort until sunset or until the ship traveled west out of Icy Strait and into the open ocean (for observers that embarked via the second method).

During survey effort, the observer continuously performed naked eye and binocular-assisted scans using tripod-mounted range-finding binoculars (Leica Viper II; accuracy, +1m at 1km; Leica, Charlottesville, Virginia, USA) and 8x42 binoculars (Swarovski Optik, Absam, Austria) to search for surfacing whales. Upon detecting a whale or group of whales, the observer used the rangefinders to measure the distance between the observer and the whale and used a protractor attached to the tripod-mounted binoculars to determine the bearing of the whale from the bow of the ship. If it was not possible to obtain an exact distance with the rangefinders (e.g. the whale's body breaking the surface for an insufficient amount of time or thick fog), the observer estimated the distance. Each whale location was geospatially referenced using a handheld GPS unit (Garmin, Olathe, Kansas, USA). The observer continued to follow the whale and recorded each resurfacing event after the initial sighting until it left the area of view, passed abeam of the ship, or the time between resurfacing was too long to ensure that it was the same whale being sighted.

For each whale sighting, the observer recorded the whale's or orientation at surfacing, direction of travel relative to the ship's course, a categorical visually-assigned behavior (blow/shallow dive with no fluke showing, dive with fluke up, surface active behavior, lunge feeding, resting), and group size. We defined a group as two or more whales within two body lengths and coordinating their behavior and/or movement direction for at least one surfacing event (Ramp et al. 2010). We considered mother-calf pairs as a group size of two and treated them as any other group.

The observer also recorded weather and visibility conditions at the start of each day and as the conditions changed throughout the survey. We deployed a separate GPS unit programmed to record the ship's location every 5s, from which the track and speed (over ground) of the ship could be calculated.

Data Analysis

To assess ship strike risk, we incorporated estimates obtained from previous work modeling several biological and ship operational processes into a cohesive simulation framework. Though data was collected throughout the bay, we constrained our assessment of ship strike risk to an area of a 1 km buffer around merged ship tracks for two reasons (Figure 2). First, this made the area of our assessment consistent with the area covered by our previous studies, which we model estimates from for simulation inputs. Second, while whales in our study area often aggregate very near coastlines. But, these whales are not vulnerable to ships strikes when they are initially located near coasts and remain there, as ships cannot travel in these shallow areas.

Our simulation covered the time period of a single ship transiting into and out of our study area and consisted of 6 steps. Several biological and anthropogenic processes were incorporated into our simulation (Table 1). For step 1, we used the output two-part distance sampling and density surface modeling approach to select the number of whales to place in the study area based on the mean density of humpback whales estimated to be in the survey area (Williams et al., in prep.). In step 2, we placed these whales in initial locations within the study area based on the relative probability of occurrence for each cell of the prediction grid derived from the density surface model (Figure 3).

In step 3, we simulated whale movement away from initial locations and predicted future locations (Figure 4). To accomplish this, we had each whale move along a correlated random walk. From the initial location onward, each subsequent surfacing was the result of movement, or in other words, a combination of step length (distance traveled) and turn angle (direction traveled). We used results from previously developed models fit to observed whale movements to populate movement metrics and correlated random walk parameters (Williams et al. in prep.)

Next, in step 4, we determined the locations of a ship moving along a transit route into and out of the study area. To do this, we used our 5 s interval GPS ship locations to reconstruct actual ship tracks into and out of the bay. Though there was slight variation in ship routes, most tracks were within very close proximity to each other. We randomly selected 1 of 300 ship routes transiting from south to north into the study area and bay, as well as 1 of 300 ship routes traveling from the northern end of the bay back to its entrance and exiting the study area. From the randomly selected tracks, we determined the length of track from its starting and ending location and determined the specific spatial location of the ship at specific time intervals (described in step 5) and distance travelled at two regularly used speeds for ships within the study area (13 knots and 20 knots).

In step 5, we assessed the spatial and temporal overlap of moving whales with moving ships. One assumption of our simulation is that we considered a whale to be vulnerable to a ship strike when it was at the surface of the water. Thus, we made the assessment of overlap between the whale and the ship at the interval of median time between surfacings (or surfacing interval) of whales across all of our observations (89 s). To obtain the appropriate ship locations, we divided the length of the randomly selected ship route (described above) by the distance the ship travels at each ship speed during the median surfacing interval. Thus, a ship traveling 13 knots (6.69 m/s) travelled approximately 595 m during each surfacing interval, and a ship travelling 20 knots travelled approximately 915 m. This calculation determined the number of locations for the ship and for the whale that occurred within the amount of time required for the ship to travel its route into and out of the study area. For example, a ship moving at 13 knots along a randomly selected route 104,000 m long would require the amount of time equivalent to 174 surfacing events to reach the end of its route. Thus, the overlap between the location of the whales placed in the study area and the ships was evaluated at 174 time steps. Finally, in step 6, we calculated the distance between the location of each whale and the ship at each time step and determined if this distance was within a designated encounter distance.

To provide conservation and management relevant data visualizations, we assessed a variety of scenarios (Table 2). We varied the distance between encounters that we considered at risk for ship strike: 10m, 25m, and 50m. We simulated the number of times and locations that encounters occurred at each of these distances over a variety of time spans: 1 year, 10 years, and 50 years under the current management vessel quota of 275 ships per year. We also evaluated the amount of time it took to reach a single encounter at each distance and generated density plots using 1,000 replications at each distance and ship speed. We generated maps and density plots to visualize the outcomes of our simulations. We prepared specialized scripts for our simulations and data visualization in program R (ver. 3.3.1; R Core team 2016).

RESULTS

We assessed ship strike risk by simulating the encounters between whales and ships at a variety of distances and time spans (Table 2). We also varied ship speed and route based on collected ship data (Table 2). Overall, the cumulative number of encounters at each evaluated distance was relatively small, and unsurprisingly, fewer encounters occurred at 10 m than either 25 m or 50 m distance scenarios (Table 3, Figure 5 a-f). Even at a number of ship transits into and out of the study area equivalent to 50 years, only 7 and 9 encounters occurred at a distance of 10 m between whales and the ship at the 13 knot and 20 knot ship speeds, respectively. Compared to a 10 m encounter distance, the number of encounters that occurred 50 m for each time span increased considerably (274 and 184 over a 50 year time span at 13 knot and 20 knot ship speeds, respectively). However, compared to the number of ship transits that occur over a 50 year time period (13,750 transits into and out of the study area), the number of encounters at 50 m is still relatively low.

The number of iterations of the simulation it took to reach the first encounter at each distance scenario revealed a consistent pattern that very close encounters do not occur frequently (Table 4, Figure 6 a-b). At the 10 m encounter distance, 91 and 218 repetitions failed to reach a first encounter within the 2,750 iteration limit at both the 13 knot and 20 knot ship speed, respectively. The other repetitions of the simulation at 10 m showed an encounter of 10 m would not occur for almost 3 years for the 13 knot ship speed and for over 4.5 years for the 20 knot ship speed. At the 25 m and 50 m encounter distances, the first encounter was reached for all repetition within the 2,750 iteration limit. The median number of iterations to reach the 25 m and 50 m encounter distances from all repetitions occurred within the equivalent to a single year for both ship speeds (Table 4).

Simulations iterated to provide the locations of encounters between ships and whales indicated similar occurrence numbers and patterns. To highlight variation in the overall numbers of encounters and variation in the locations that had higher densities of encounters, we mapped all encounter distances over each time span individually (e.g., all encounters at 10 m, 25 m, and 50m over 1 year, etc.; Figure 7 a-f). Again, the number of encounters, even at the largest encounter distance of 50 m, was small. At the 13 knot ship speed, there were only 12 encounters across all distances within 1 year. At the 20 knot ship speed, there were even fewer (6 encounters). For both ship speeds, the encounters that did occur over a single year time span were clustered at the southern end of the bay and its confluence with Icy Strait (Figure 7 a-b). Over 10 years, there were 74 and 40 encounters across all distances for the 13 knot and 20 knot ship speed, respectively. Locations of these encounters were spread more evenly along the ship route, though there were still dense clusters of encounters at the southern end of the bay and confluence with the adjacent waterway (Figure 7 c-d). The areas of denser encounter occurrences over this time span spread further east and west into Icy Strait. Finally, at the 50 year time span, the number of encounters increased substantially (367 and 247 at the 13 knot and 20 knot ship speeds, respectively). The locations of these encounters spread through almost the entire length of the ship routes into and out of the study area (Figure 8 e-f). However, high density encounter areas were clear, again, at the southern mouth of the bay. The spatial representation of simulated encounter locations showing the highest number of encounters (50 years at 13 knot ship speed) revealed a triangular shape of high encounter density extending in the bay and strait confluence area, and a high density of encounters at the western part of this confluence (8e).

DISCUSSION

Precise methods to assess ship strike risk are critical to managing the growing conservation issue of ship strikes. A strong foundation of research has provided insight on whale occurrence and movement, as well as overlap with anthropogenic activity. Understanding gained from this work has been critical in evaluating ship strike risk in a variety of settings (e.g., Vanderlaan et al. 2008, van der Hoop et al. 2012); however the focus thus far has been mainly at large spatial scales. Information on encounters between whales and ships and strike risk at a finer and more detailed scale has been limited and has not often been incorporated into ship strike risk assessment. Here, we quantified ship strike risk at a management-relevant fine spatial-scale by simulating the number of encounters that occurred at a range of close proximities (Table 2). We used a spatially-explicit simulation method, incorporating results from observationally-based models of occurrence and movement, as well as site specific data on ship speed and routes (Table 1).

Our results indicate that the number of encounters at close distances between whales and ships are relatively rare. Within the time span of 50 years, our simulations resulted in 7 and 9 encounters within 10 m, for 13 knot and 20 knot ship speeds respectively (Table 3). This is consistent with results from an assessment of ship strikes in Alaskan waters (Neilson et al. 2012). In this study, investigators determined 86 definite or probable ship strikes between ships and humpback whales over a 33 year time period. Under these circumstances, we would expect the occurrence of only approximately 2.5 ship strikes per year over the entirety of Alaskan waters.

Uncertainty regarding the number of ship strikes that go unidentified or unreported is a concern commonly raised by researchers, managers, and conservation practitioners. The consistency between our results and those of known strikes in Alaskan waters suggests that the number of ship strikes that actually occur is similar to the number determined through reports or found carcasses. However, the consistency in these quantities may be due to specifics of the study area. In southeastern Alaska, a variety of ships (commercial shipping and transport, tourism, and military) use narrow waters ways, resulting in large overlap between areas of high density whale occurrence and ship use. However, the constricted nature of many of these waterways and bays may mean that strikes that do occur are more likely to be noticed and reported. Additionally, carcasses from undetected or unreported strikes may be more likely to be found in areas like southeastern Alaska; due to the number of ships and boats on the water and increased chances of being washed ashore than in areas of open ocean. Furthermore, a strong focus on humpback whale conservation in GBNP, and southeastern Alaska as whole, may mean that a larger percentage of ship strikes that occur in this area are detected or revealed. While this consistency between expected and known ship strike numbers may be less reliable in other contexts, our results suggest that few ship strikes go unnoticed in our study area of southeastern Alaska, and this may be true for similar regions.

One method to reduce the risk of ship strikes, and to reduce the likelihood of mortality in the event a ship strike occurs, is restricting ship speed (Vanderlaan & Taggert 2007, Vanderlaan et al. 2009, Gende et al. 2011, Wiley et al. 2011, Conn & Silber 2013). Our simulations routinely showed that more ship strikes occur over time periods when the ship was moving at the slower (13 knot) ship speed. While this was initially surprising, our methods reveal why fewer close encounters or ship strikes may occur when ships travel at faster speeds. One assumption of our model was that whales were vulnerable to ship strikes only at the times of their surfacing events, and we used only one value for the time whales spent underwater between surfacing events. Ships traveling at a faster speed spent less total time transiting the study area, and thus ships were present for fewer whale surfacings. While a relatively fast speed may reduce the amount of time the ship is present in the area and thus able to be involved in encounters or strikes, increased speeds may prohibit whales from successfully performing evasive responses. Maximum humpback whales swimming speeds at short bursts may near 13 knots (Noad & Cato 2007). However, it is unlikely that a whale could swim and maneuver at a great enough speed to avoid ships travelling at 20 knots.

Our results revealed spatial variation in the density of simulated encounters, and thus, areas of higher ship strike risk. In particular, the confluence of Glacier Bay and Icy Strait had many simulated encounters across time periods and ship speeds. This is consistent with findings from long-term humpback whale monitoring program that have often noted large aggregate feedings groups in this area (Neilson et al. 2015). However, these feedings groups are frequently very close to shore, where prey abundances are high. Our simulations reveal that ship strike risk is high this same area, but it also shows that this high risk extends across the width of the waterway and is not restricted to near shore.

Another important result revealed by our spatial representation of strike risk is a particularly dense area of encounters near Lemesurier Island (Figure 1). Increased awareness and vigilance by ship operators may be critical to counter high ship strike risk in this area for two reasons. First, this area is especially narrow, and ship routes and maneuver options are therefore restricted. Second, ships transiting this area have just exited the boundary of GBNP and are no longer under operating restrictions put in place by park managers. Speed or route restrictions in the bay could potentially have unintended consequences for ship operation just outside the park in this high ship strike risk area. For example, ship operators may feel required to increase speed just outside the park to make up time and ensure they stay on schedule.

Further investigation on fine-scale whale movement, surfacing intervals, and response behaviors may reveal insights to improve our simulation framework and results. It is critical to obtain a more detailed understanding of several components of these biological processes, including: the range of duration between whale surfacings, if time between surfacings is influenced by encounters with ships, and if whales are spending time just below the surface but still at a depth where they are vulnerable to ships strikes. Advances in our knowledge of these components will allow for more comprehensive simulation of fine-scale encounters and for more accurate assessment of ship strike risk. Additionally, increased understanding of if and how whales respond to ships and possible avoidance maneuvers will be critical in assessing tradeoffs between increased ship speed, which reduces the time ships are present in an area and able to cause encounters or strikes, and decreased ship speed, which allows more time for whales and ships to enact avoidance measures.

Though our results suggest that close encounters and ship strikes, are relatively rare, the gravity of this conservation threat is not diminished. Our simulations indicate that actual ship strike occurrence in our study area may be similar to the number of strikes reported and identified. However, GBNP is strongly-protected and highly-managed area of overlap between maritime activity and important whale habitat. Ship operators in this area are aware of this overlap and are strongly dedicated to aiding in whale conservation. Additionally, though the ship traffic through our study area is regular, the number of ships travelling through the area is relatively small compared to major transportation ports. In areas of heavy ship traffic, fewer protections, and less buy-in from ship operators, the occurrence of ship strikes and ship strike risk may be substantially higher.

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TABLES

Table 4-1. Biological and anthropogenic processes included in simulation and sources of model estimates or data used as input for simulation to assess ship strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska.

Process	Agent	Input data description
Density	Whale	Number of whales to place on study area based on total estimated abundance from density surface model (chapter 1)
Initial location	Whale	Initial locations determined based on probability of occurrence within a cell of grid covering study area derived from density surface model (chapter 1)
Movement	Whale	Pulls from distributions of step length and turn angles to calculate future locations from estimated from single movement mode model (chapter 2)
Surface interval	Whale	Median time between surfacings across all whale observations (observed data)
Route	Ship operator	Derived ship track from coordinates of locations every 5 sec for 300 ship routes each of transit up and down study area
Speed	Ship operator	Typical ship speeds from park restrictions

Table 4-2. Range of scenarios addressed in simulations to assess ship strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska.

Temporal scales	Encounter distances	Ship speeds
1 year: 275 ship transits each up and down study area	10 m	13 knots (6.69 m/s)
10 years: 2,750 ship transits each up and down study area	25 m	20 knots (10.29 m/s)
50 years: 13,750 ship transits each up and down study area	50 m	

Table 4-3. Results of simulations to determine the number of encounters at various distance and temporal span scenarios to assess ship strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska.

Temporal scales	Number of encounters at each distance		
Ship speed	10 m	25 m	50 m
1 year			
13 knots	0	0	4
20 knots	0	1	1
10 years			
13 knots	4	18	60
20 knots	2	6	43
50 years			
13 knots	7	66	274
20 knots	9	44	184

Table 4-4. Number of iterations of the simulation required to reach first encounter various distance and ship speed scenarios (repeated for 1,000 repetitions per scenario) used in assessing ship strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska.

Ship speed	Median number of iterations to reach first encounter			Range of number of iterations to reach first encounter		
	10 m	25 m	50 m	10 m	25 m	50 m
13 knots	797	125	130	4 - 2,750	1 – 1,141	1 – 2,047
20 knots	1,252	222	197	6 – 2,750	1 – 2,252	1 – 1,698

* 91 and 218 repetitions never reached the first encounter at 10 m by the 2,750 iteration limit at 13 knot and 20 knot ship speed, respectively

FIGURES

Figure 4-1. Study area of Glacier Bay National Park and adjacent waters in southeastern Alaska.

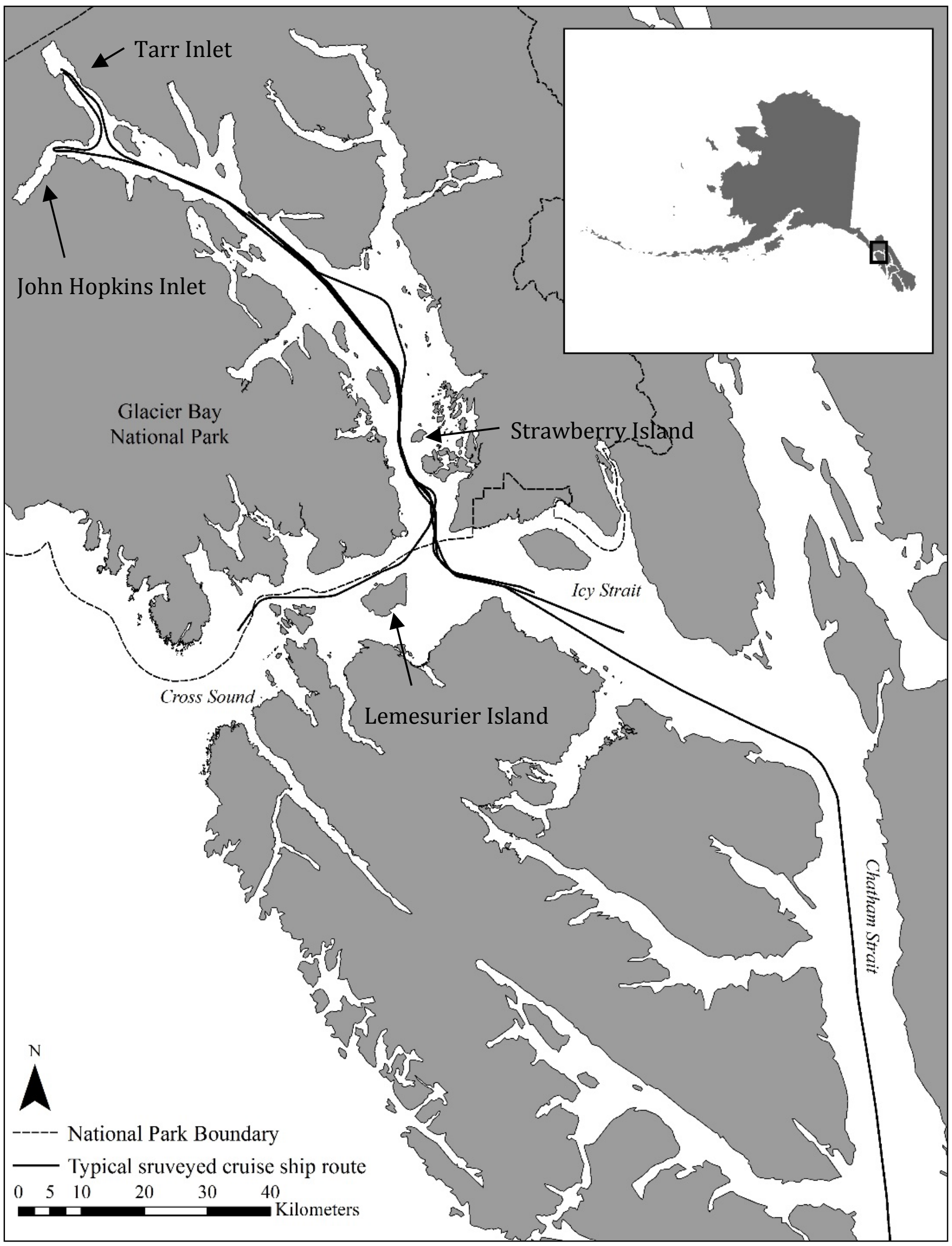


Figure 4-2. Reduced area for simulations to assess spatially-explicit ship strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska.

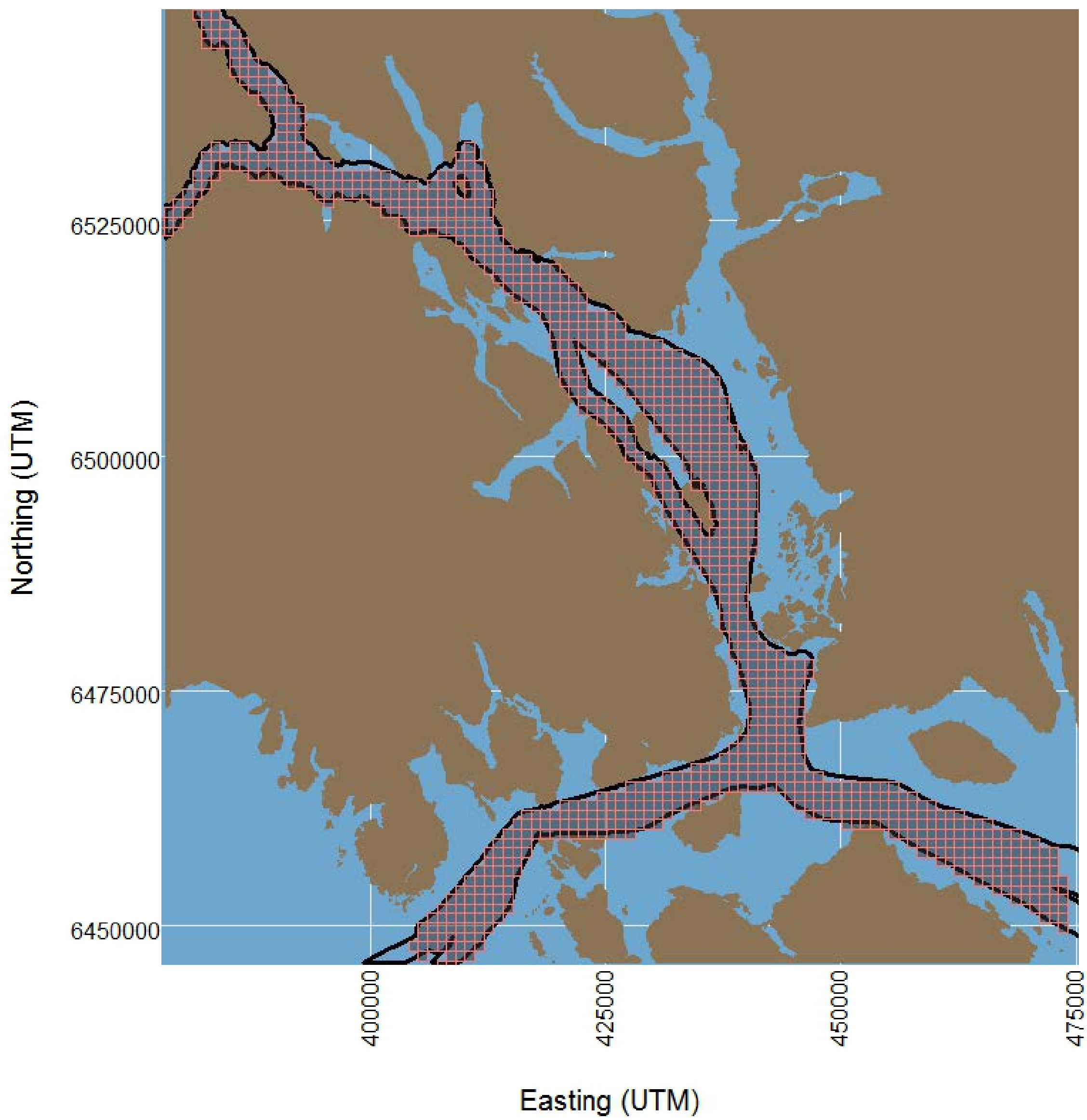


Figure 4-3. Example initial whale location placement (N = 20 whales; accomplished in step 2 of simulation) for a single iteration of the simulation to assess spatially-explicit ship strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska.

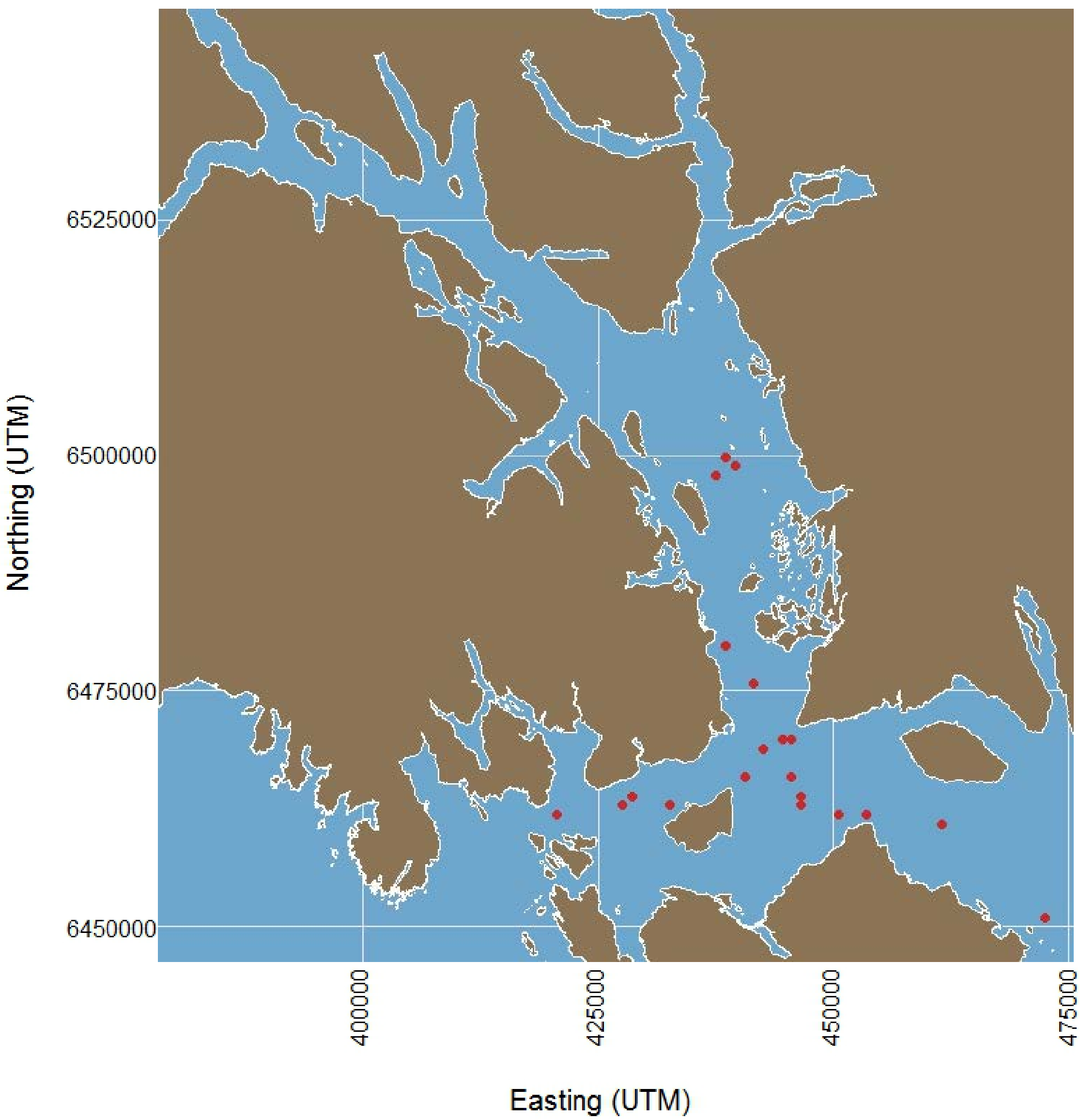


Figure 4-4. Example of simulated future locations for a single whale resulting from movement steps (accomplished in step 3 of the simulation) during a single iteration of the simulation to assess spatially-explicit ship strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska.

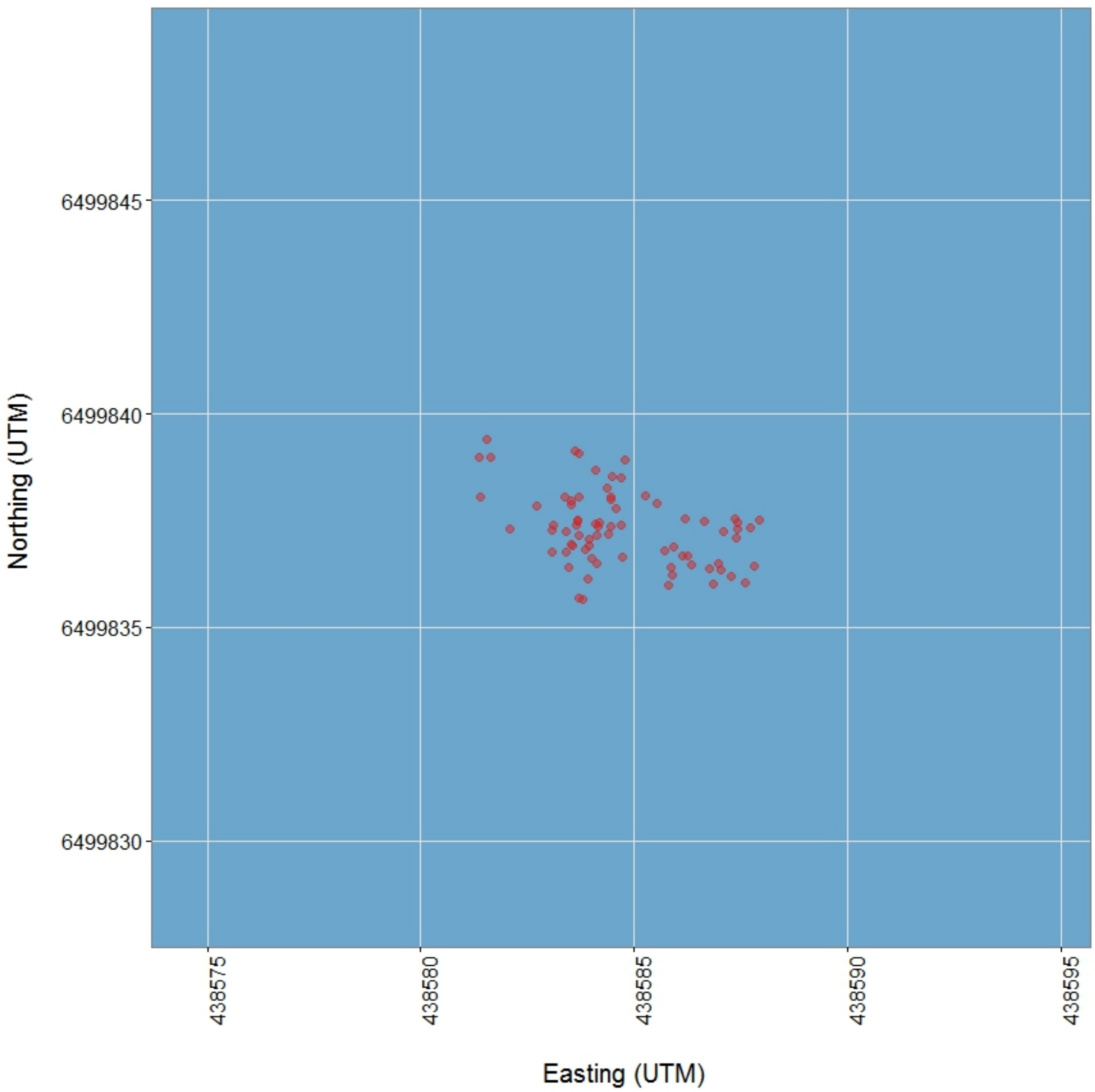
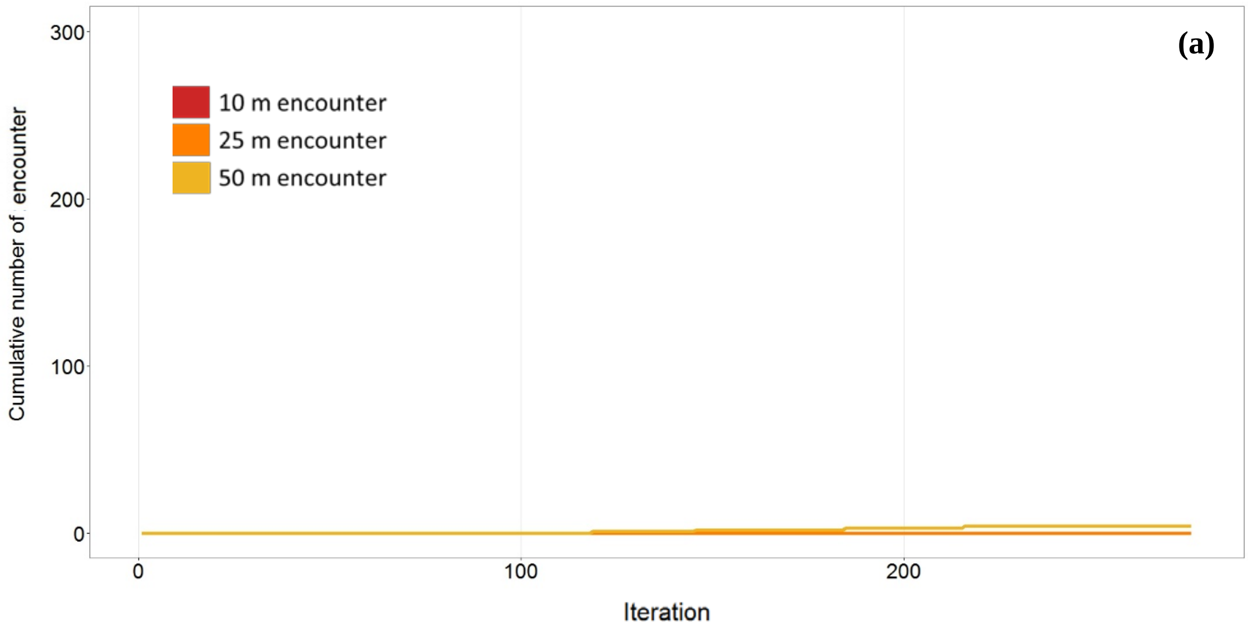
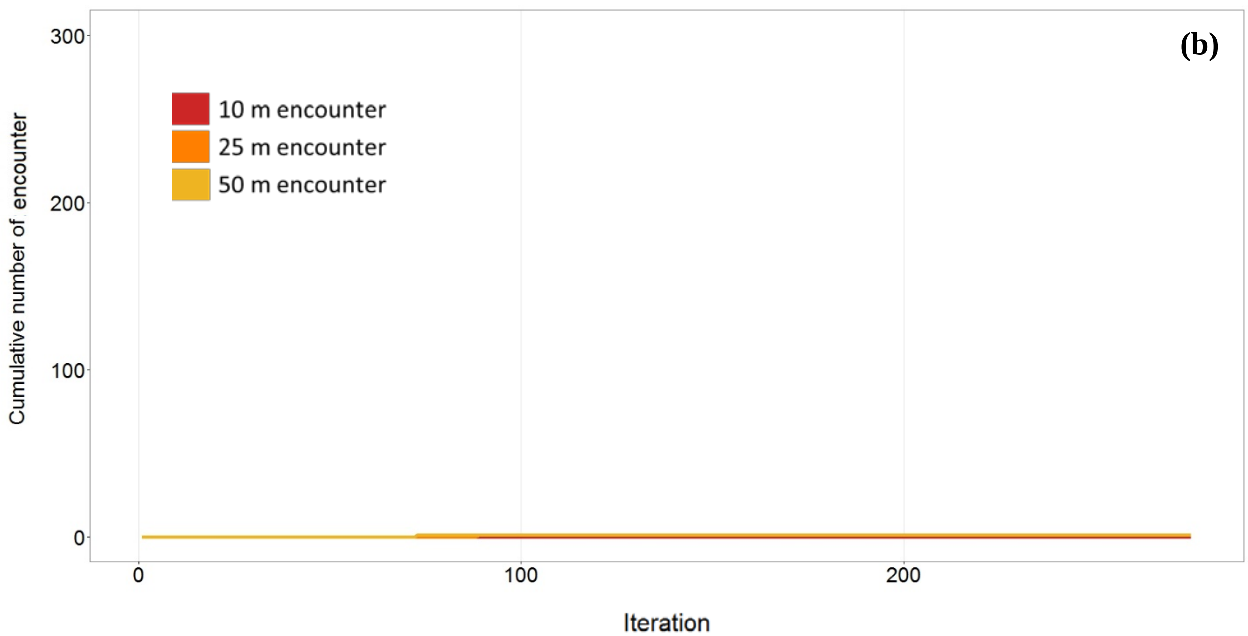
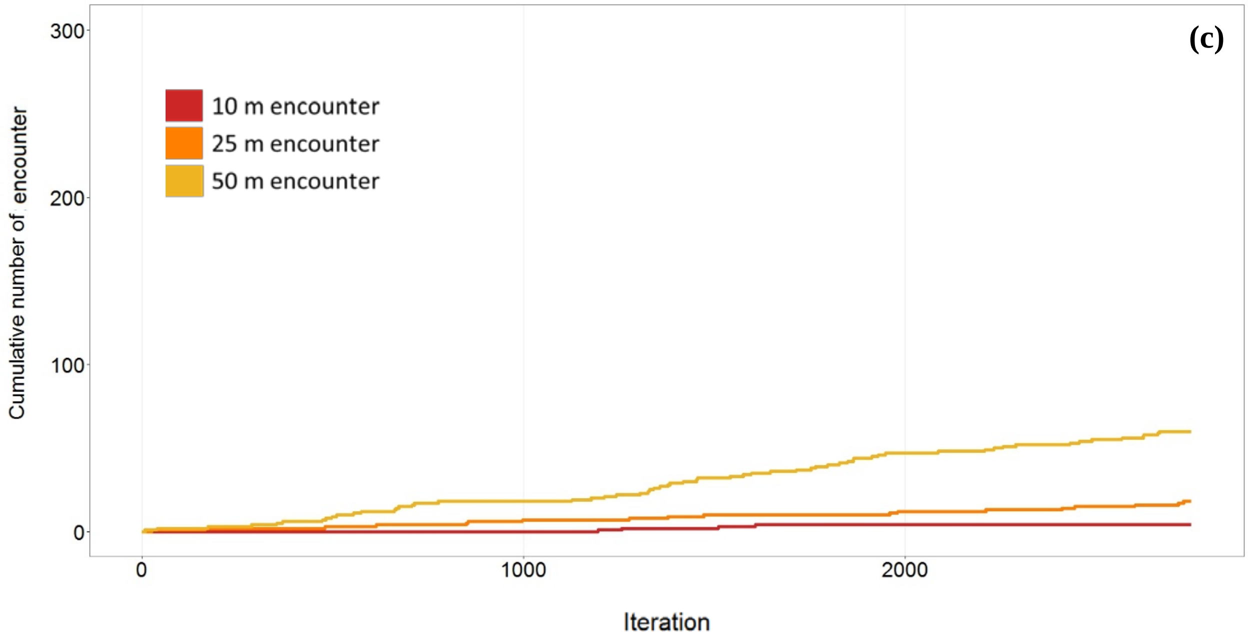
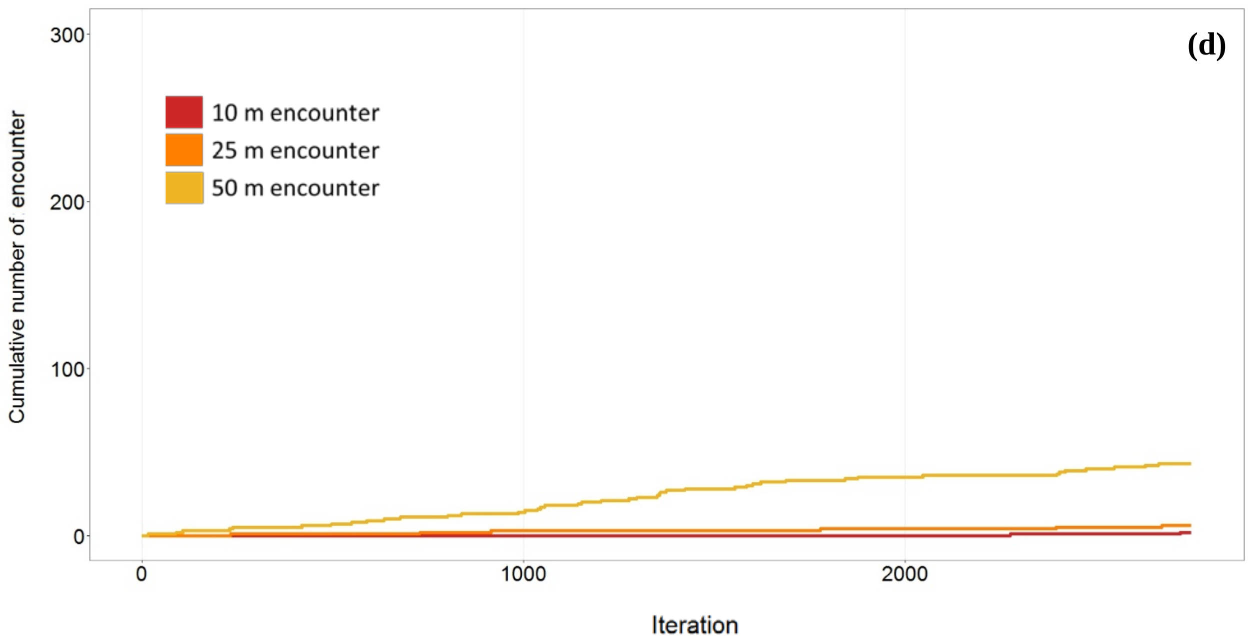


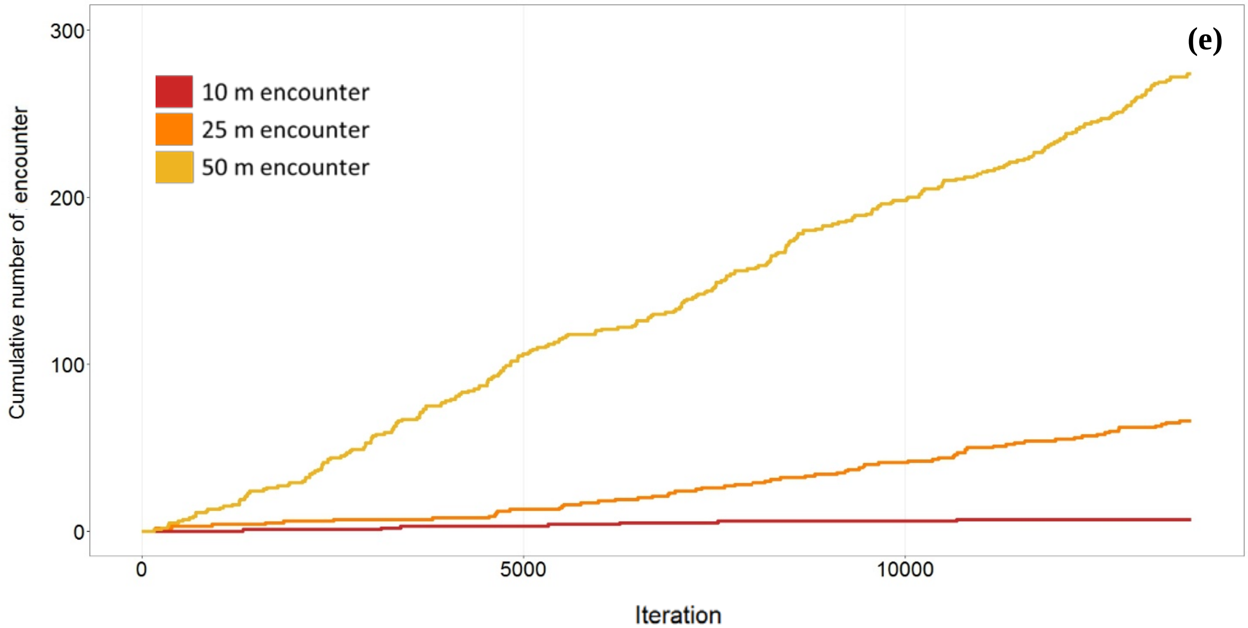
Figure 4-5. Number of cumulative ship strikes at a range of scenarios to assess strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska. Scenarios simulated are: (a) ship strikes at 10 m, 20 m, and 50 m over iterations equivalent to 1 year of ship transits (275 trips) for 13 knot ship speed, (b) and 20 knot ship speed, (c) ship strikes at 10 m, 20 m, and 50m over iterations equivalent to 10 years of ship transits (2,750 trips) for 13 knot (d) and 20 knot ship speed, and (e) ship strikes at 10 m, 20 m, and 50m over iterations equivalent to 50 years of ship transits (13,750 trips) for 13 knot (f) and 20 knot ship speed.




(b)
10 m encounter
25 m encounter
50 m encounter
Cumulative number of encounter
300
200
100
0
0
100
200
Iteration


(c)
10 m encounter
25 m encounter
50 m encounter
Cumulative number of encounter
Iteration


(d)
10 m encounter
25 m encounter
50 m encounter
Cumulative number of encounter
Iteration


(e)
10 m encounter
25 m encounter
50 m encounter
Cumulative number of encounter
300
200
100
0
0
5000
10000
Iteration

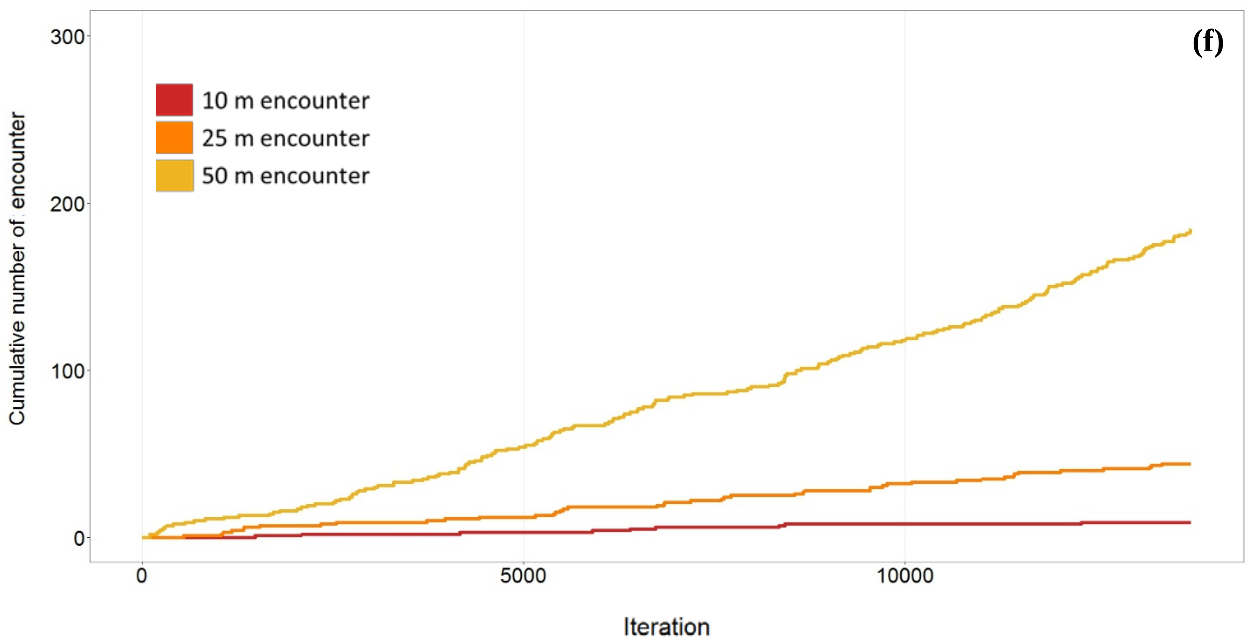

(f)
10 m encounter
25 m encounter
50 m encounter
Cumulative number of encounter
300
200
100
0
0
5000
10000
Iteration

Figure 4-6. Number of iterations of simulation required to reach first encounter at a range of scenarios to assess strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska. Density is plotted over 1,000 repetitions of simulations to reach first trike over each scenario. Scenarios simulated are: (a) ship strikes at 10 m, 20 m, and 50 m for 13 knot ship speed, (b) and 20 knot ship speed.

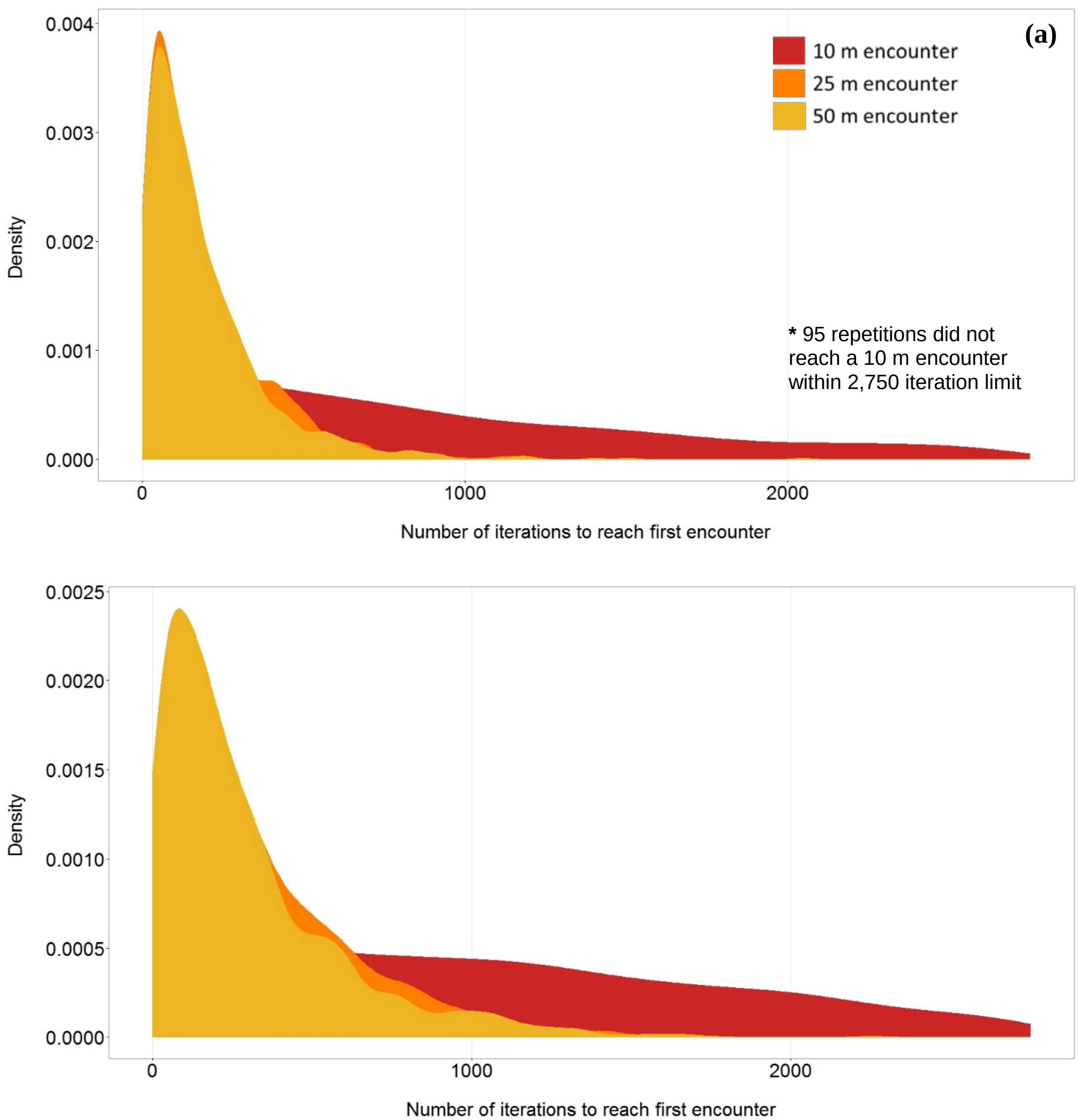
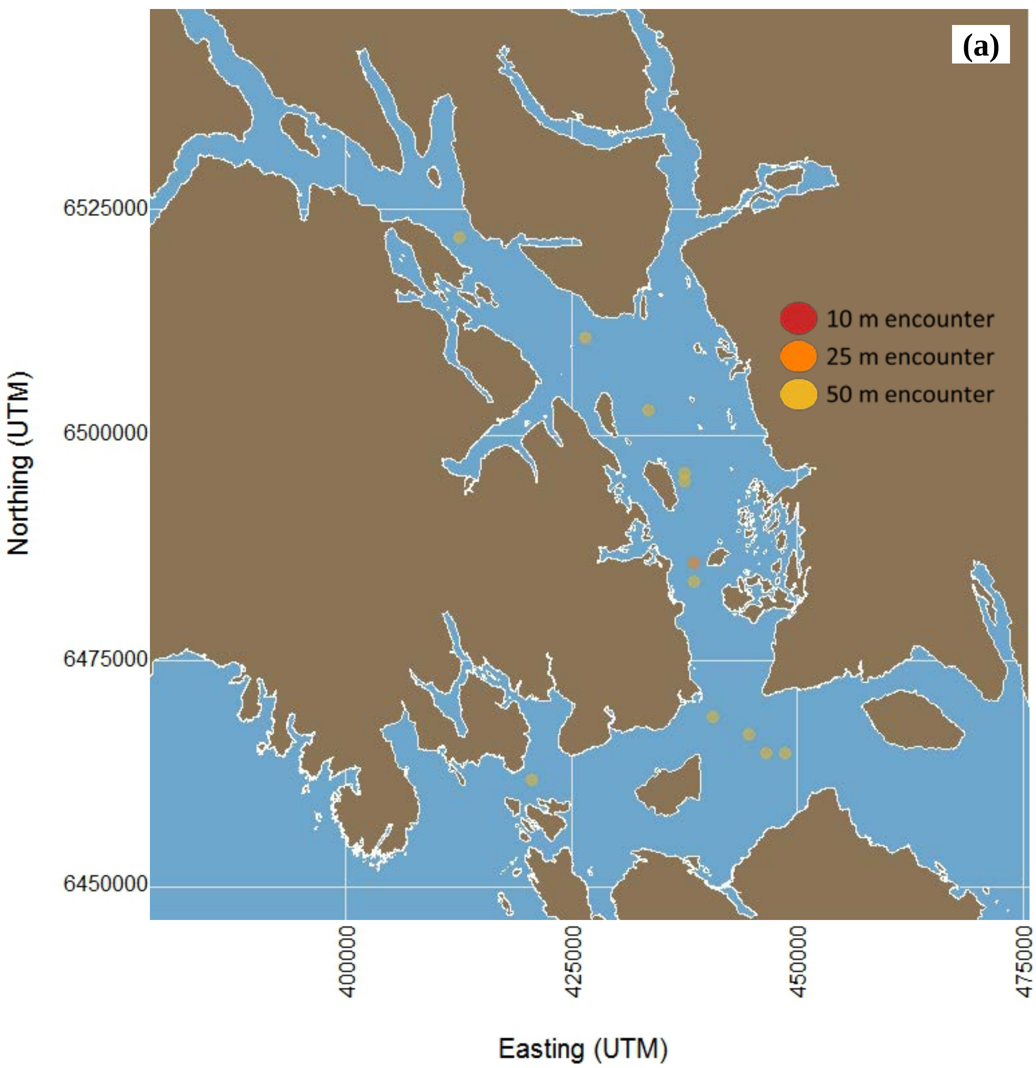
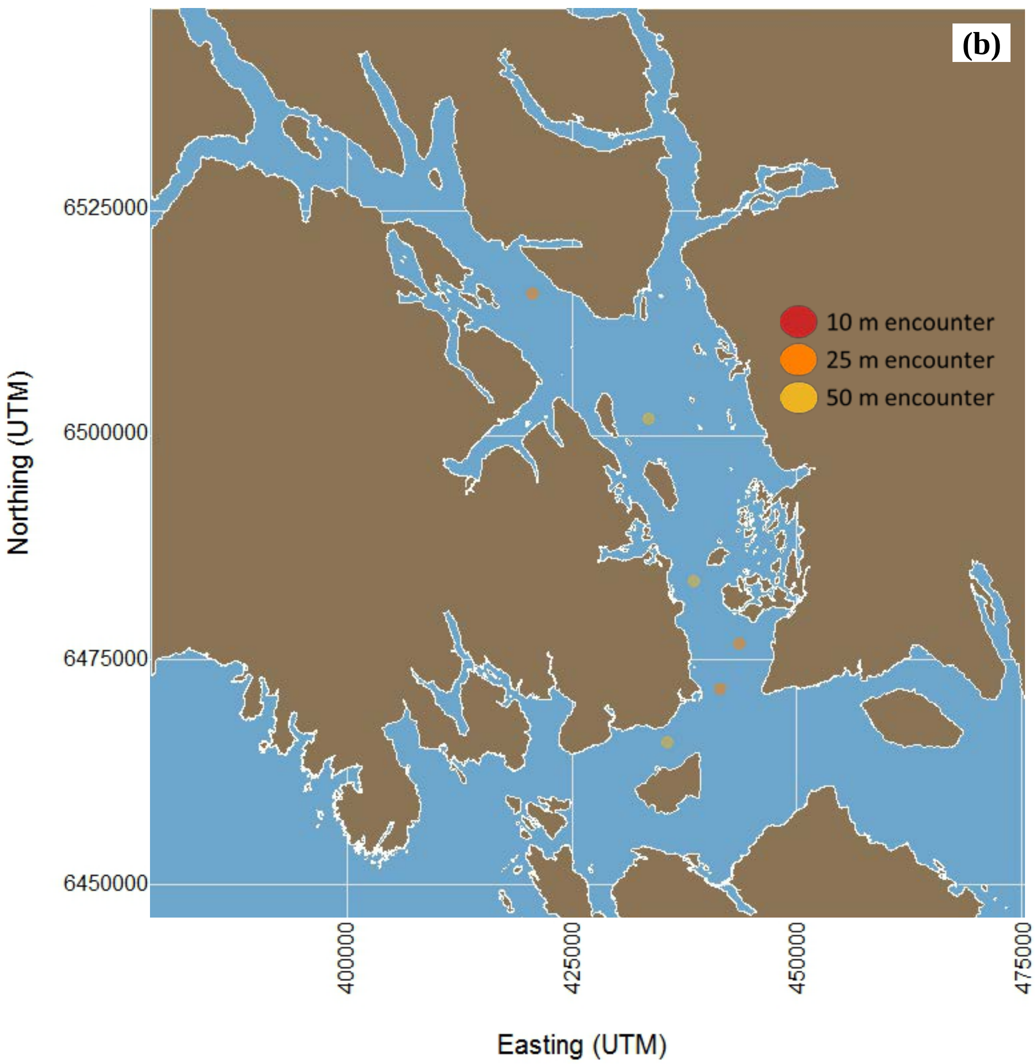
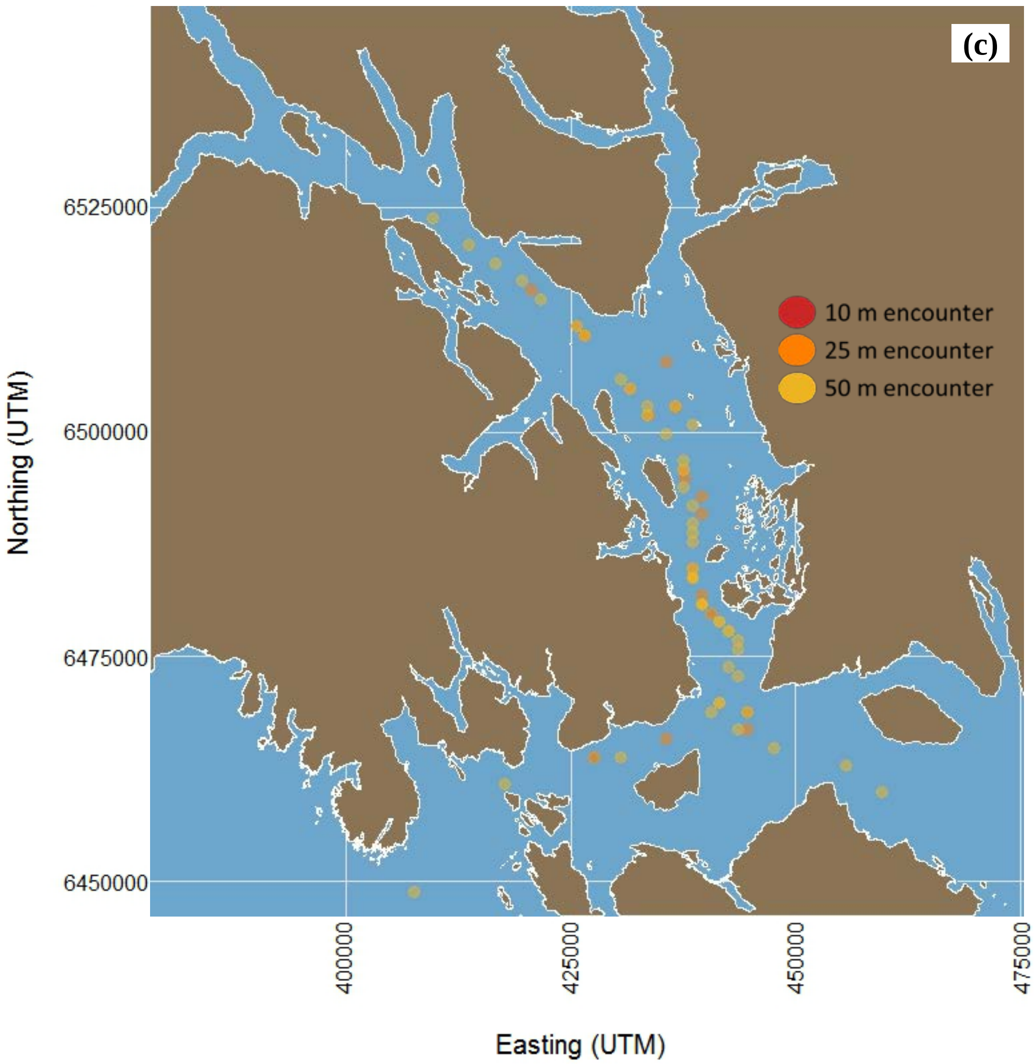
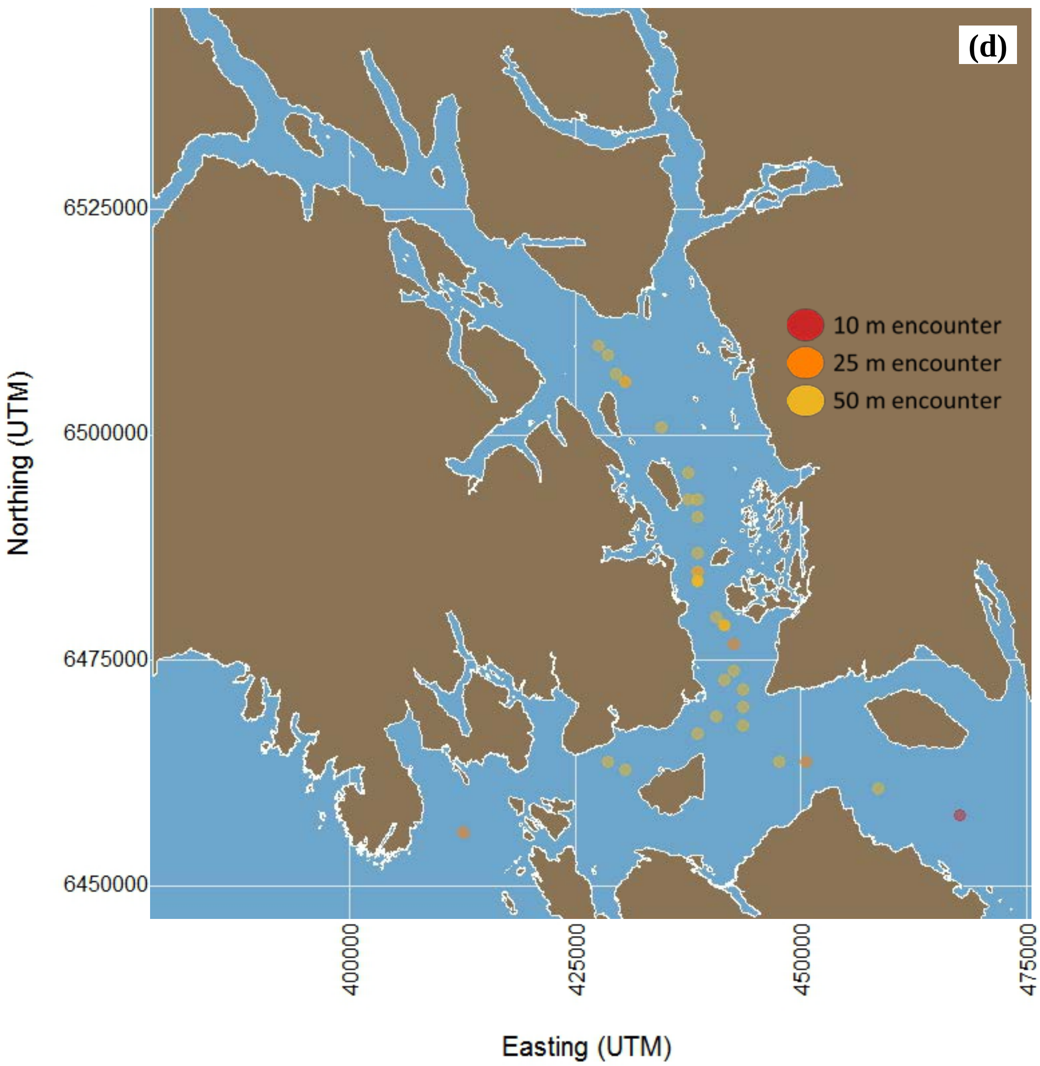


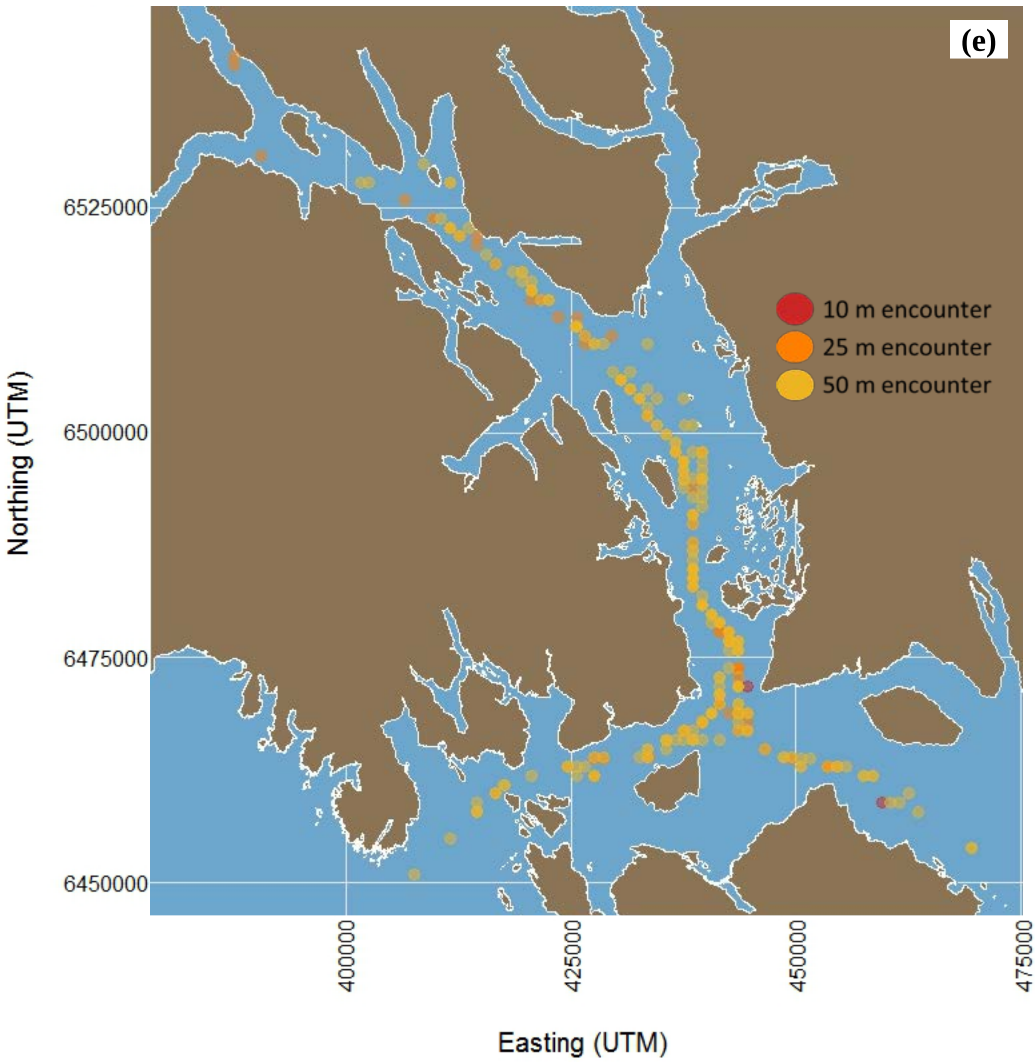
Figure 4-7. Locations of simulated encounter locations at a range of scenarios to assess strike risk based on observations of humpback whale surfacings in Glacier Bay National Park and adjacent waters in southeastern Alaska. Scenarios simulated are: (a) ship strikes at 10 m, 20 m, and 50 m over 1 year for 13 knot ship speed, (b) and 20 knot ship speed, (c) ship strikes at 10 m, 20 m, and 50m over 10 years for 13 knot (d) and 20 knot ship speed, and (e) ship strikes at 10 m, 20 m, and 50m over 50 years for 13 knot (f) and 20 knot ship speed.

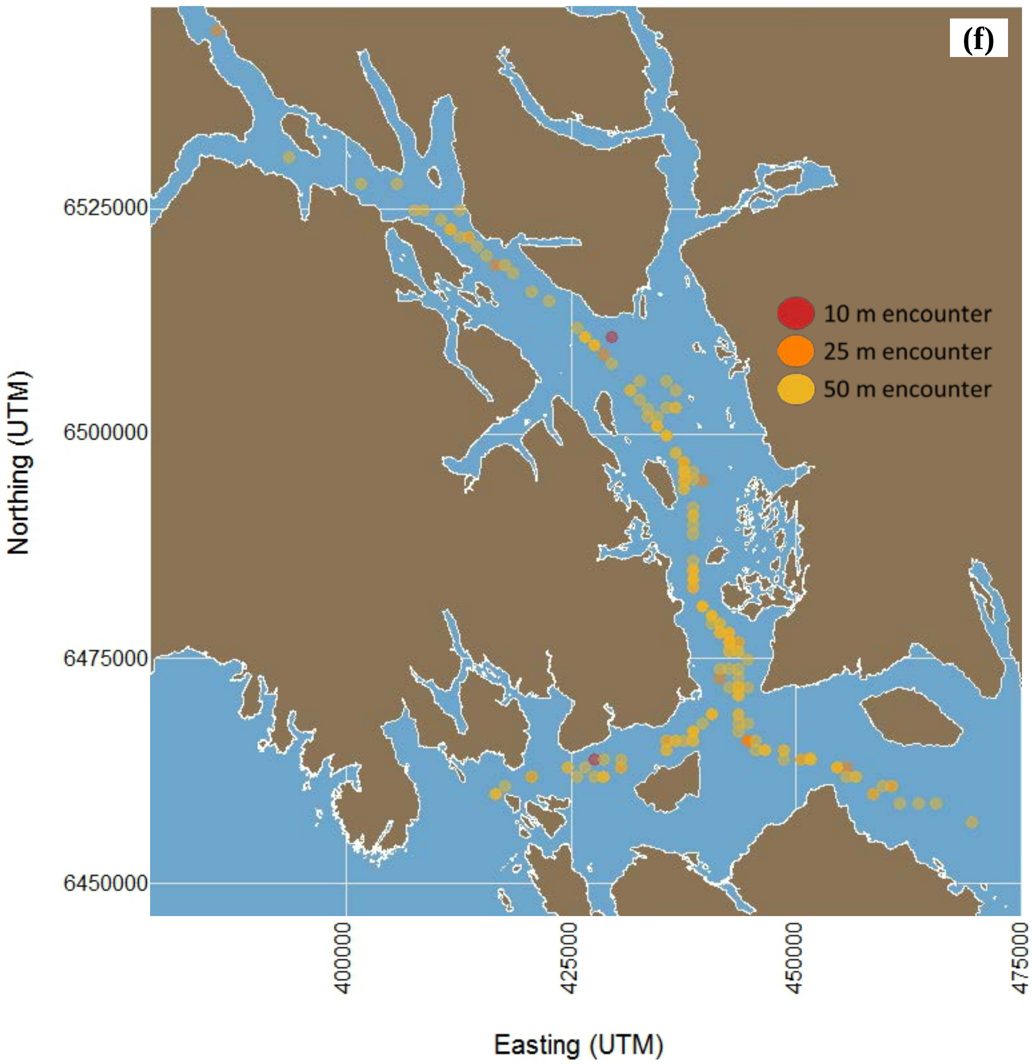



(b)
10 m encounter
25 m encounter
50 m encounter
6525000
6500000
6475000
6450000
Northing (UTM)
400000
425000
450000
475000
Easting (UTM)


(c)
10 m encounter
25 m encounter
50 m encounter
6525000
6500000
6475000
6450000
Northing (UTM)
400000
425000
450000
475000
Easting (UTM)


(d)
10 m encounter
25 m encounter
50 m encounter
Northing (UTM)
6525000
6500000
6475000
6450000
400000
425000
450000
475000
Easting (UTM)


(e)
10 m encounter
25 m encounter
50 m encounter
Northing (UTM)
6525000
6500000
6475000
6450000
400000
425000
450000
475000
Easting (UTM)


(f)
10 m encounter
25 m encounter
50 m encounter
6525000
6500000
6475000
6450000
Northing (UTM)
400000
425000
450000
475000
Easting (UTM)

APPENDIX 1. Program R scripts for simulation described in chapter 4.

```
# Sara Williams
# 3/18/2017
# Whale ship strike risk simulation - set up code that need to be run once first before running simulation
#   function
##################################################################################

#  Load packages
#  Load data

#  Load functions
#  Wrapped Cauchy distribution function
rwcauchy <- function(n, mu = 0, rho = 0) {
  u = runif(n)
  V = cos(2 * pi * u)
  c = 2 * rho/(1 + rho^2)
  t <- (sign(runif(n) - 0.5) * acos((V + c)/(1 + c * V)) + mu)%%(2 * pi)
  return(t)
}

# Function to generate relative probability of whale occurrence for each grid cell
probsel <- function(probrast, ni){
            x <- getValues(probrast)
            x[is.na(x)] <- 0
            vec_cells <- seq(1:length(probrast))
            samp <- sample(vec_cells,  ni, replace = F, prob=x)
            samprast <- raster(probrast)
            samprast[samp] <- 1
            samp_pts <- rasterToPoints(samprast, fun = function(x){x > 0})
            samp_pts <- SpatialPoints(samp_pts)
            crs(samp_pts) <- UTM
            return(samp_pts)
            }

#   Assign relative probability from each grid cell from relative predicted density
sa <- predgrid_plot %>%
     dplyr::select(X, Y, Nhat)
sa_rast <- rasterFromXYZ(sa)
probrast  <-sa_rast/sum(getValues(sa_rast), na.rm=T)

# Make study area and ship route, movement
UTM <- CRS("+proj=utm +zone=8 +datum=WGS84")
crs(segs_sm) <- UTM
e <- extent(segs_sm)

s_big <- crop(s_big2, extent(e))
s_big@data$id <- rownames(s_big@data)
s_big_points <- fortify(s_big, region="id")
s_big_df_tmp <- join(s_big_points, s_big@data, by="id")
s_big_df <- s_big_df_tmp %>%
            mutate(fill = as.logical(ifelse(hole == "TRUE", "FALSE", "TRUE")))

s <- crop(s2, extent(e))
s@data$id <- rownames(s@data)
```

```
s_points <- fortify(s, region="id")
s_df_tmp <- join(s_points, s@data, by="id")
s_df <- s_df_tmp %>%
        mutate(fill = as.logical(ifelse(hole == "TRUE", "FALSE", "TRUE")))

track <- crop(track2, extent(e))
track@data$id <- rownames(track@data)
track_points <- fortify(track, region="id")
track_df2 <- join(track_points, track@data, by="id")
track_df <- track_df2 %>%
            separate(transct, c("A", "B", "C", "D", "E"), sep="-", remove = FALSE)
track_df$id <- as.numeric(track_df$id)
all_track_df_up <- track_df %>%
                    filter(E < 2) %>%
                     dplyr::select(long, lat, id)
all_track_df_up$new_ID <- all_track_df_up %>% group_indices(id)
all_track_df_down <- track_df %>%
                      filter(E > 10) %>%
                      dplyr::select(long, lat, id)
all_track_df_down$new_ID <- all_track_df_down %>% group_indices(id)
####################################################################################
####################################################################################


# Sara Williams
# 3/18/2017
# Whale ship strike risk simulation - function to run simulation for 13 knot ship speed
#   Have to load script: sim_once_to_start.R before running this one
####################################################################################

sim_ship_strike_fun_13k <- function(strike_dist){

#### STEP 1 ####
#  Determine number of whales present in ship route area
#  These are placed initially within the area of the prediction grid of the DSM (so within 1 km on either
#    side of ship route)
#   Predicted abundance in that area: 20.22758, mean from iterations (mat_predgrid) 20.17342, sd
#    0.1281257
#  Whales are only placed within that small buffer around ship, and if they leave that buffer, they don't
#   return.
ni_tmp <- rnorm(1, 20.17342, 0.1281257)
ni <- round(ni_tmp)

#### STEP 2 ####
#  Place the number of initial whales (ni) in grid cells based on the predicted density of that cells used as
#   probabilities
#  Sample ni initial locations for whales using the relative probability of each grid cell
init_locs <- probsel(probrast, ni)
init_locs_df <- as.data.frame(init_locs)
#plot(init_locs_df$x, init_locs_df$y)
####################################################################################

#### STEP 3 ####
#  Set ship locations
#  Pick a ship transect for up and down bay
rand_up <- sample(1:300, 1)
```

```
one_track_df_up <- all_track_df_up %>%
                      filter(new_ID == rand_up) %>%
                      dplyr::select(long, lat)
rand_down <- sample(1:300, 1)
one_track_df_down <- all_track_df_down %>%
                        filter(new_ID == rand_down) %>%
                       dplyr::select(long, lat)
one_track_pts_up <- SpatialPoints(one_track_df_up)
crs(one_track_pts_up) <- UTM
one_track_pts_down <- SpatialPoints(one_track_df_down)
crs(one_track_pts_down) <- UTM

#  Set ship start and end location for one passage
start_up_bay <- as.data.frame(one_track_df_up) %>%
                 filter(lat == min(lat)) %>%
                 dplyr::select(long, lat)
end_up_bay <- as.data.frame(one_track_df_up) %>%
                 filter(lat== max(lat)) %>%
                 dplyr::select(long, lat)
start_up_bay_xy <- SpatialPoints(start_up_bay)
crs(start_up_bay_xy) <- UTM
end_up_bay_xy <- SpatialPoints(end_up_bay)
crs(end_up_bay_xy) <- UTM

start_down_bay <- as.data.frame(one_track_df_down) %>%
                    filter(lat == max(lat)) %>%
                    dplyr::select(long, lat)
end_down_bay <- as.data.frame(one_track_df_down) %>%
                   filter(lat == min(lat)) %>%
                   dplyr::select(long, lat)
start_down_bay_xy <- SpatialPoints(start_down_bay)
crs(start_down_bay_xy) <- UTM
end_down_bay_xy <- SpatialPoints(end_down_bay)
crs(end_down_bay_xy) <- UTM

#  Ship speed limits: 13 knots (6.68778 m per sec, 1000 m in 149.5 sec)
#  Time for ship to travel up, down, total at two speeds
one_track_up_ln <- spLines(one_track_pts_up)
crs(one_track_up_ln) <- UTM
track_up_length <- gLength(one_track_up_ln)
one_track_down_ln <- spLines(one_track_pts_down)
crs(one_track_down_ln) <- UTM
track_down_length <- gLength(one_track_down_ln)
tm_sec_up_13k <- (track_up_length)/6.68778
tm_sec_down_13k <- (track_down_length)/6.68778
tm_sec_total_13k <- tm_sec_up_13k + tm_sec_down_13k # 482 min, 8 hr

#   Time between surfacings, based on data from movement analysyis: median(89 sec), mean (124 sec)
med_surface_int <- 89
#mu_surface_int <- 124

#  Move ship up and down bay along route and determine locations based on distance moved in amount
of time between surfacings
dist_ship_move_per_surf_13k <- 6.68778*med_surface_int

num_ship_locs_up_13k <- floor(track_up_length/dist_ship_move_per_surf_13k)
```

```
ship_locs_up_13k <- sp::spsample(one_track_up_ln, n = num_ship_locs_up_13k, type = "regular")
ship_locs_up_df_13k_tmp1 <- as.data.frame(ship_locs_up_13k)
ship_locs_up_df_13k_tmp2 <- ship_locs_up_df_13k_tmp1[-1,]
ship_locs_up_df_13k_tmp3 <- ship_locs_up_df_13k_tmp2[-nrow(ship_locs_up_df_13k_tmp2),]
ship_locs_up_df_13k <- ship_locs_up_df_13k_tmp3 %>%
                                bind_rows(start_up_bay, end_up_bay) %>%
                                arrange(lat) %>%
                                mutate(loc_num = 1:n())

num_ship_locs_down_13k <- floor(track_down_length/dist_ship_move_per_surf_13k)
ship_locs_down_13k <- sp::spsample(one_track_down_ln, n = num_ship_locs_down_13k, type =
"regular")
ship_locs_down_df_13k_tmp1 <- as.data.frame(ship_locs_down_13k)
ship_locs_down_df_13k_tmp2 <- ship_locs_down_df_13k_tmp1[-1,]
ship_locs_down_df_13k_tmp3 <- ship_locs_down_df_13k_tmp2[-nrow(ship_locs_down_df_13k_tmp2),]
ship_locs_down_df_13k <- ship_locs_down_df_13k_tmp3 %>%
                                  arrange(desc(lat)) %>%
                                  bind_rows(start_down_bay, end_down_bay) %>%
                                  arrange(desc(lat)) %>%
                                  mutate(loc_num = 1:n())

#  Designate number of whale locations during time it takes ship to move up and down bay
nobs_whale_up_13k <- num_ship_locs_up_13k
nobs_whale_down_13k <- num_ship_locs_down_13k
##################################################################################

#### STEP 4 #### only use this step to switch between movement modes for different behaviors
#  Select initial behavior of whale at initial sighting based on proportion observed: 1489/1671 = 0.89;
#   Transit, 182/1671 = 0.11; Station
#  For coding, 1 = Transit
beh <- as.data.frame(rbinom(ni, 1, 0.89))
colnames(beh) [1] <- "beh_tmp"
init_locs_tmp1 <- as.data.frame(init_locs)
init_locs_tmp2 <- bind_cols(init_locs_tmp1, beh)
init_locs_df <- init_locs_tmp2 %>%
                    mutate(beh = ifelse(beh_tmp == 1, 1, 2)) %>%
                    dplyr::select(x, y, beh = beh)
##################################################################################

#### STEP 5 ####
#  Generate simulated step lengths and turn angles for whale movements from parameter
#   estimate posterior distributions from movement analysis
#  Currently using single dive movement mode - this is "single_fit_dive"
niter <- 11000
nsamp <- 5000

keep_1 <- sample(1:niter, nsamp, replace = F)
keep_2 <- sample(1:niter, nsamp, replace = F)
keep_3 <- sample(1:niter, nsamp, replace = F)
chain_1 <- single_fit_dive[[1]]
sims_1 <- chain_1[keep_1, c(2, 3, 4, 1)]
chain_2 <- single_fit_dive[[2]]
sims_2 <- chain_2[keep_2, c(2, 3, 4, 1)]
chain_3 <- single_fit_dive[[3]]
sims_3 <- chain_3[keep_3, c(2, 3, 4, 1)]
sims <- rbind(sims_1, sims_2, sims_3)
```

```
steps <- numeric(length = nrow(sims))
turns <- numeric(length = nrow(sims))

for(i in 1:nrow(sims)){
  steps[i] <- rweibull(1, sims[i,3], (1/sims[i,4])^(1/sims[i,3]))
  turns[i] <- rwcauchy(1, sims[i,1], sims[i,2])
 }

mod <- as.data.frame(cbind(steps, turns))
mod$turns[mod$turns>pi]=mod$turns[mod$turns>pi]-2*pi

#  Generate CRW from simulated steps and turns for movement UP bay for 13k speed restriction
#   Matrices to hold simulations for whale movement UP bay 13k
mat_X_up <- matrix(nrow = nobs_whale_up_13k, ncol = ni)
mat_Y_up <- matrix(nrow = nobs_whale_up_13k, ncol = ni)

for(j in 1:ni){
     keep <- base::sample(1:nrow(mod), nobs_whale_up_13k, replace = FALSE)
     # make distributed steps
     steps_sim <- mod[keep, 1]
     # make clustered turning angles
     theta_sim <- mod[keep, 2]
     # cumulative angle (absolute orientation)
     phi_sim <- cumsum(theta_sim)
     # step length components
     dX_sim <- steps_sim*cos(phi_sim)
     dX_sim[1] <- init_locs_df$x[j] # make each whale start at location selected above
     dY_sim <- steps_sim*sin(phi_sim)
     dY_sim[1] <- init_locs_df$y[j] # make each whale start at location selected above
     # actual X-Y values
     X_sim <- as.matrix(cumsum(dX_sim))
     Y_sim <- as.matrix(cumsum(dY_sim))
     mat_X_up[,j] <- X_sim
     mat_Y_up[,j] <- Y_sim
   }

#  Data from for locations for whales moving UP bay
df_X_up_tmp <- as.data.frame(mat_X_up)
df_Y_up_tmp <- as.data.frame(mat_Y_up)
df_X_up <- melt(df_X_up_tmp)
df_Y_up <- melt(df_Y_up_tmp)
loc_num_whale_u <- as.data.frame(rep(1:nobs_whale_up_13k, ni))
df_XYwhales_up_tmp <- dplyr::bind_cols(df_X_up, df_Y_up, loc_num_whale_u)
names(df_XYwhales_up_tmp) <- c("whale_ind_num", "X_whale", "walk_num_rep", "Y_whale",
"loc_num_whale")
df_XYwhales_up <- df_XYwhales_up_tmp %>%
                              dplyr::select(whale_ind_num, X_whale, Y_whale, loc_num_whale) %>%
                              dplyr::arrange(loc_num_whale)
#plot(df_XYwhales_up$X_whale, df_XYwhales_up$Y_whale)

#  Generate CRW from simulated steps and turns for movement UP bay for 13k speed restriction
#   Matrices to hold simulations for whale movement DOWN bay 13k
mat_X_down <- matrix(nrow = nobs_whale_down_13k, ncol = ni)
mat_Y_down <- matrix(nrow = nobs_whale_down_13k, ncol = ni)

for(k in 1:ni){
```

```
    keep <- base::sample(1:nrow(mod), nobs_whale_down_13k, replace = FALSE)
    # make distributed steps
    steps_sim <- mod[keep, 1]
    # make clustered turning angles
    theta_sim <- mod[keep, 2]
    # cumulative angle (absolute orientation)
    phi_sim <- cumsum(theta_sim)
    # step length components
    dX_sim <- steps_sim*cos(phi_sim)
    dX_sim[1] <- init_locs_df$x[k] # make each whale start at location selected above
    dY_sim <- steps_sim*sin(phi_sim)
    dY_sim[1] <- init_locs_df$y[k] # make each whale start at location selected above
    # actual X-Y values
    X_sim <- as.matrix(cumsum(dX_sim))
    Y_sim <- as.matrix(cumsum(dY_sim))
    mat_X_down[,k] <- X_sim
    mat_Y_down[,k] <- Y_sim
  }

#  Data from for locations for whales moving DOWN bay
df_X_down_tmp <- as.data.frame(mat_X_down)
df_Y_down_tmp <- as.data.frame(mat_Y_down)
df_X_down <- melt(df_X_down_tmp)
df_Y_down <- melt(df_Y_down_tmp)
loc_num_whale_d <- as.data.frame(rep(1:nobs_whale_down_13k, ni))
df_XYwhales_down_tmp <- dplyr::bind_cols(df_X_down, df_Y_down, loc_num_whale_d)
names(df_XYwhales_down_tmp) <- c("whale_ind_num", "X_whale", "walk_num_rep", "Y_whale",
"loc_num_whale")
df_XYwhales_down <- df_XYwhales_down_tmp %>%
                              dplyr::select(whale_ind_num, X_whale, Y_whale, loc_num_whale) %>%
                              dplyr::arrange(loc_num_whale)
################################################################################


#### STEP 6 ####
#  Combine whale movement and ship movement
df_XYship_up <- ship_locs_up_df_13k[rep(1:nrow(ship_locs_up_df_13k),each=(20)),]
df_XYboth_up <- bind_cols(df_XYwhales_up, df_XYship_up) %>%
                       dplyr::rename(X_ship = long, Y_ship = lat)

df_XYship_down <- ship_locs_down_df_13k[rep(1:nrow(ship_locs_down_df_13k),each=(20)),]
df_XYboth_down <- bind_cols(df_XYwhales_down, df_XYship_down) %>%
                           dplyr::rename(X_ship = long, Y_ship = lat)
################################################################################


#### STEP 7A #### To count number of “strikes”
#  Count overlaps within critical distane (“strike_dist”, which is passed to function)
up_dists_whales <- cbind(df_XYboth_up$X_whale, df_XYboth_up$Y_whale)
up_dists_ship <- cbind(df_XYboth_up$X_ship, df_XYboth_up$Y_ship)
up_dists <- as.data.frame(raster::pointDistance(up_dists_whales, up_dists_ship, longlat = FALSE))
colnames(up_dists)[1] <- "dist_btw"

sim_strikes_up <- df_XYboth_up %>%
                        bind_cols(up_dists) %>%
                        mutate(sim_strike = ifelse(dist_btw <= strike_dist, 1, 0))
```

```
down_dists_whales <- cbind(df_XYboth_down$X_whale, df_XYboth_down$Y_whale)
down_dists_ship <- cbind(df_XYboth_down$X_ship, df_XYboth_down$Y_ship)
down_dists <- as.data.frame(raster::pointDistance(down_dists_whales, down_dists_ship, longlat =
FALSE))
colnames(down_dists)[1] <- "dist_btw"

sim_strikes_down <- df_XYboth_down %>%
                    bind_cols(down_dists) %>%
                    mutate(sim_strike = ifelse(dist_btw <= strike_dist, 1, 0))

tot_sim_strikes_up <- sum(sim_strikes_up$sim_strike)
tot_sim_strikes_down <- sum(sim_strikes_down$sim_strike)

tot_sim_strikes <- tot_sim_strikes_up + tot_sim_strikes_down
return(tot_sim_strikes)
}


#### STEP 7B #### To obtain locations of “strikes”
#  Count overlaps within certain distance!!!!
up_dists_whales <- cbind(df_XYboth_up$X_whale, df_XYboth_up$Y_whale)
up_dists_ship <- cbind(df_XYboth_up$X_ship, df_XYboth_up$Y_ship)
up_dists <- as.data.frame(raster::pointDistance(up_dists_whales, up_dists_ship, longlat = FALSE))
          colnames(up_dists)[1] <- "dist_btw"

sim_strikes_up <- df_XYboth_up %>%
                  bind_cols(up_dists) %>%
                  mutate(sim_strike = ifelse(dist_btw <= strike_dist, 1, 0)) %>%
                  dplyr::filter(sim_strike==1) %>%
                  dplyr::select(X_whale, Y_whale)

down_dists_whales <- cbind(df_XYboth_down$X_whale, df_XYboth_down$Y_whale)
down_dists_ship <- cbind(df_XYboth_down$X_ship, df_XYboth_down$Y_ship)
down_dists <- as.data.frame(raster::pointDistance(down_dists_whales, down_dists_ship, longlat =
FALSE))
colnames(down_dists)[1] <- "dist_btw"

sim_strikes_down <- df_XYboth_down %>%
                    bind_cols(down_dists) %>%
                    mutate(sim_strike = ifelse(dist_btw <= strike_dist, 1, 0)) %>%
                    dplyr::filter(sim_strike==1) %>%
                    dplyr::select(X_whale, Y_whale)

strike_locs <- as.data.frame(bind_rows(sim_strikes_up, sim_strikes_down))
return(strike_locs)
}
##################################################################################
###################################################################################
```