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Factors affecting whale detection from large ships in Alaska with implications for whale avoidance

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ABSTRACT: In response to growing concern over lethal ship–whale collisions, a number of efforts have been developed intended to enhance the ability of ships to avoid whales. However, the effectiveness of avoidance by large ships depends upon the ships detecting whales at a distance sufficient to allow for an appropriate avoidance measure. Here we explore the issue of whale detection using over 3000 unique detections of humpback whales recorded by observers stationed aboard large cruise ships in Alaska, USA. We used point transect distance sampling methods to generate detection functions necessary to understand the probability of whale detection and how it varies with distance under different environmental and biological characteristics. Detection probability of surfacing whales decreased markedly with increasing distance from the ship. We found visibility and group size to be the most important variables influencing detection. The worst visibility conditions reduced detection probability to near 0 at 1000 m. Compared to detecting a single whale, a group of 2 or 3 whales almost doubled detection probability at 1000 m. Surface active behavior increased detection compared to spouting while showing no flukes. In southeastern Alaska, single whales that spouted during excellent visibility conditions were most commonly encountered and had a detection probability of 0.569 at 1000 m. Understanding the ability of mariners to detect whales at distances sufficient to invoke avoidance measures is a key component in the effectiveness of 'ships avoiding whales' and is germane to efforts to reduce lethal ship–whale collisions.

KEY WORDS: Humpback whale · *Megaptera novaeangliae* · Ship strike · Collision · Distance sampling · Detection probability

INTRODUCTION

The volume of commercial shipping traffic in the world's oceans now exceeds 30 trillion ton-miles (UNCTAD 2007), due largely to the near doubling of the number of large ships (>100 metric tons) in use since 1960 (Buhaug et al. 2009, Frisk 2012). Coincident with increased ship traffic has been a growing concern over the deleterious impacts shipping may have on populations of large whales, which continue to recover from near extirpation (e.g. Patenaude et al. 2007, Magera et al. 2013, Monnahan et al. 2014) following intensive unreported or unregulated levels of whaling (Ivashchenko et al. 2013, Carroll et al. 2014). For example, primary feeding areas, calving and breeding grounds, and migration routes of North Atlantic right (*Eubalaena glacialis*), humpback (*Megaptera novaeangliae*), and fin whales (*Balaenoptera physalus*) overlap with highly trafficked shipping routes to major ports along the western North Atlantic, resulting in a number of lethal ship–whale collisions each year (Vanderlaan et al. 2008, Conn & Silber 2013). Similarly, ships accessing the major port of Los Angeles/Long Beach, CA, USA, typically utilize a route that overlaps the Santa Barbara channel, an important area for blue (*B. musculus*), humpback, and fin whales (Redfern et al. 2013). Important shipping areas such as the Straits of Magellan, Gibraltar, and Panama are also areas with high concentrations of shipping traffic, whales, and subsequent reports of

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whale mortalities due to ship strikes (Acevedo et al. 2006, Clapham et al. 2008, Guzman et al. 2012). Some whale populations are in recovery (e.g. Patenaude et al. 2007) or potentially fully recovered from pre-whaling abundances (Monnahan et al. 2015), and thus may be able to sustain these added mortality events. Others remain at reduced abundance levels where even small increases in anthropogenic-caused mortality threatens population persistence (Kraus et al. 2005, LeDuc et al. 2012).

In response to the conservation concern over ship strikes, a number of national and international management entities have programs intended to reduce the likelihood of collisions, focusing mostly on shifting shipping lanes to minimize spatio-temporal overlap between ships and whales (Ward-Geiger et al. 2005, Vanderlaan et al. 2008, Irvine et al. 2014). While these methods are effective in reducing the relative and absolute risk of collisions (van der Hoop et al. 2012), they may not always be feasible, such as when the geography of an area is too narrow to provide alternatives to shipping lanes (e.g. Webb & Gende 2015) or in areas where ships approach a port of call and cannot be re-routed around high-use whale habitat (Gende et al. 2011, Guzman et al. 2012). Even when shifts in shipping lanes are used, they may result in a reduction, but not elimination, of the risk of ship–whale encounters as whale aggregations may shift within and among years with shifts in prey or oceanographic conditions (e.g. Witteveen et al. 2008, Chenoweth et al. 2011, Becker et al. 2012, Doniol-Valcroze et al. 2012, Heide-Jørgensen et al. 2012, Keller et al. 2012, Pendleton et al. 2012, Gregr et al. 2013).

When whale habitat overlaps with shipping routes, it may be incorrect to assume that whales will simply avoid the transiting ships. An acoustic 'null' may be produced in front of the ship wherein whales may have difficulty in ascertaining the ship's approach angle (Terhune & Verboom 1999, Allen et al. 2012). Whales may also be engaged in surface activities, making them less responsive to approaching ships (Morete et al. 2007, Nowacek et al. 2007). Recent data on tagged blue whales in proximity of large ships off coastal California demonstrate that whales have limited response behaviors in reaction to ships (McKenna et al. 2015). These whales used only vertical movement (descents at a slower speed than foraging dives) to avoid ships, while they showed no evidence of horizontal movement used to evade passing ships (McKenna et al. 2015). Additionally, these whales commonly failed to react until ships were relatively close (10 of 11 recorded response dives occurred when the distance between whale and ship was less than 1500 m; McKenna et al. 2015).

Consequently, a number of conservation efforts, focused mostly on technological advances, have been developed that rely, in part, on active whale avoidance by ships. For example, along the western North Atlantic, a series of passive acoustic arrays use algorithms to scan for up-calls of North Atlantic right whales. These calls are then transmitted to all ships within 5 nautical miles of the receiving buoy to 'help[ing] ships avoid endangered whales' (www.listenforwhales.org). Likewise, a recent program was developed to allow mariners in and near the Pelagos Sanctuary for Mediterranean Marine Mammals to share positions of whale sightings near shipping lanes with other mariners in real-time via a communications satellite such that mariners can more readily spot whales for avoidance (www.repcet.com). Similar applications (e.g. Whale Alert) have recently been developed with the intent of providing mariners with information on changing whale management areas and whale sightings in an area, in close to real time, with the goal of reducing the chance of collisions (www.whalealert.org).

While knowledge that whales have been spotted in an area may increase the situational awareness for mariners, ultimately active whale avoidance, defined as altering course or speed to avoid a whale, requires ship personnel ('bridge personnel') to (1) detect whales at a distance sufficient to allow for an appropriate avoidance measure owing to their limited maneuverability; and (2) determine the behavior and/or direction of the travel of the whale, thereby providing enough information to ascertain the most appropriate avoidance maneuver.

Here we explore the issue of whale detection from large ships using distance sampling and data collected by observers stationed at the bow of large cruise ships in Alaska. Most studies that have utilized distance sampling for whales were designed to estimate population density or abundance and thus produced detection functions as a means to estimate how many whales were missed during a survey. In these studies, the goal has been to maximize the probability of detection, which often entailed multiple observers stationed at multiple platforms utilizing multiple pieces of sampling equipment or procedures (e.g. simultaneous teams using naked eye surveys for distances within 500 m and 'big eye' binocular surveys for scanning 500 m to the horizon; Hammond et al. 2013). In contrast, the objective of our study was to replicate (and quantify to the extent possible) the detection process as it may apply to bridge personnel tasked with avoiding whales. We used point transect distance sampling methods applied to 8 yr of sighting data to generate the detection functions necessary to understand how the probability of detection varies with radial distance between the whale and bulbous bow of the ship. We also explored how detection probability may be affected by a variety of environmental and biological characteristics. We apply the considerable research that has been conducted and methods that have been developed for understanding the probability of detection specifically with the aim of estimating abundance (e.g. Laake et al. 1997, Barlow 2015) to quantify the probability of detection of whales from large ships in the context of whale avoidance.

MATERIALS AND METHODS

Study area

Our surveys focused on whale detection in the waters in and near Glacier Bay National Park and Preserve (GBNP), AK, USA, which is managed by the National Park Service (NPS). GBNP represents one of the largest marine protected areas in the USA and one of the few 'ocean parks' in the US National Park system owing to the park's jurisdiction over the marine waters in and near Glacier Bay proper and extending 3 miles out from the mean high tide mark. Although the park includes areas adjacent to the open North Pacific Ocean, much of the wildlife and all the tidewater glaciers, and thus the focus of visitation, occurs in the protected, 1255 km^2 Y-shaped fjord, commonly referred to as Glacier Bay (Fig. 1). The park is characterized by highly variable bathymetry containing multiple sill-basin complexes, which cause strong upwelling and complex current systems with resulting high levels of primary and secondary productivity (Hooge & Hooge 2002). The high net community productivity (Reisdorph & Mathis 2014) supports large aggregations of marine mammals including sea otters *Enhydra lutris* (Bodkin et al. 2007), Stellar sea lions *Eumetopias jubatus* (Mathews et al. 2011), and harbor seals *Phoca vitulina richardii* (Womble et al. 2010).

GBNP is also the site of a regionally important feeding aggregation of humpback whales that generally use the park and surrounding waters from late April through late September (Hendrix et al. 2012). The number of whales using park waters has increased by 4.4 % per year over the past few decades (Saracco et al. 2013), and many whales have long sighting histories in and near Glacier Bay (Neilson et al. 2015). The NPS values humpback whales owing to their ecological role, conservation status, and contribution to visitor experience.

The NPS manages visitor access to the park, which occurs almost exclusively by marine vessel, by regulating both traffic volume, via entry permits, and operating conditions once vessels enter the park (National Park Sevice 2003). For cruise ships, entry quotas are managed on both a daily (maximum of 2 ships) and seasonal basis, with the seasonal quota split into a 92 d (June–August) 'peak' season and a 61 d 'shoulder' season (May, September). The current peak seasonal quota is 153 ship entries, and thus most days the daily maximum quota (2 ships per day) is met, although on a number of days either 1 or 0 ships enter the park. The shoulder season quota is 122 ship entries, although this quota is never met as

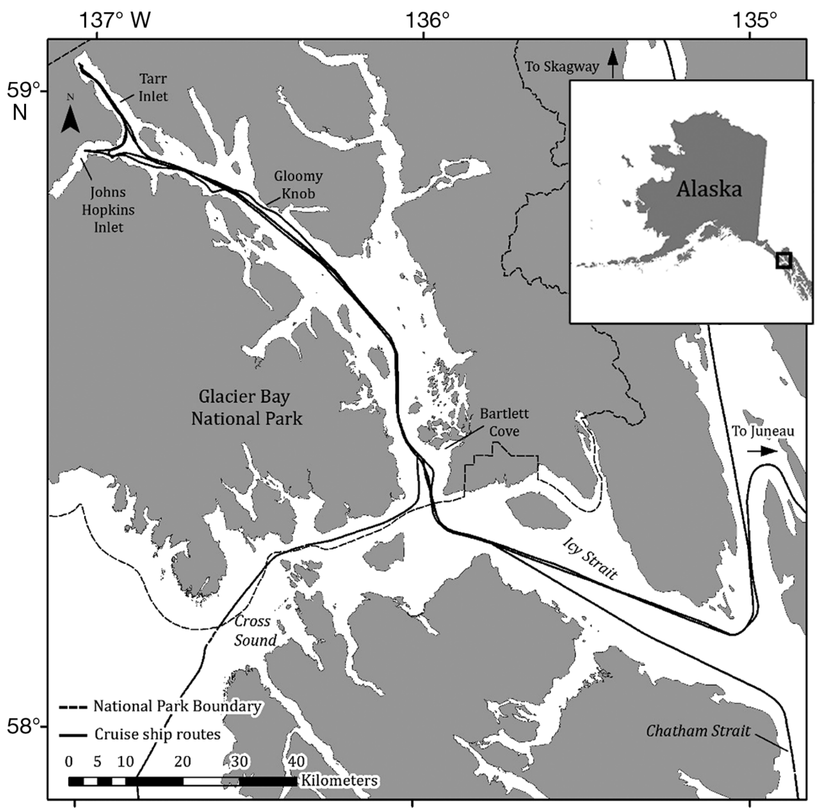

Fig. 1. Study site of Glacier Bay National Park and adjacent waters in northern Southeast Alaska, USA

the weather during the shoulder season months results in a reduced volume of cruise ships coming to Alaska. In 2014, 228 cruise ship entries into Glacier Bay resulted in more than 450 000 passengers (>95% of all visitors) accessing the park. Cruise ships thus represent an important means by which the NPS meets the mandate to allow for visitor use and enjoyment of park resources.

Due to the large number of whales and narrow geography of the park, cruise ship routes overlap high-use whale habitat, resulting in a large number of ship–whale encounters (Gende et al. 2011, Harris et al. 2012). Lethal cruise ship–humpback whale collisions have been recorded both in the park and in nearby areas (Neilson et al. 2012). The NPS has a stated goal of reducing the chance of lethal collisions, and regulations require ships to avoid approaching whales within 0.25 nautical mile (463 m). Federal regulations also require ships to operate at a 'slow, safe speed' when in the known presence of whales (50 C.F.R. § 224.103 Federal Register, https://www.law.cornell.edu/cfr/text/50/224.103). Thus, implicit in these regulations is that bridge personnel be able to actively and effectively detect whales at a sufficient operational distance, in order to comply with the federal regulations for whale avoidance.

Data collection

Cruise ships visiting Glacier Bay enter the park in the morning, generally between 06:00 and 10:30 h AST, and exit in the evening. Owing to park regulations and the relatively narrow navigational channel, cruise ships follow a nearly identical route and speed as they proceed from the park entrance at the mouth to the head of the fjord, where they stop to allow passengers to view the tidewater glaciers for several hours (Fig. 1). The ships then proceed back down to the mouth of the fjord, exiting 8 to 12 h later.

From 2008 to 2015, observers boarded cruise ships during 643 entries to record the frequency and proximity of surfacing events (encounters) of whales near the ships (see Gende et al. 2011, Harris et al. 2012; Fig. 1). For each survey, a single observer boarded the ship either within the boundary of the park via NPS transfer vessel or at the previous port of call the day prior to the ship's day in GBNP. The observer conducted surveys following 1 of 2 schedules, based on how and when the observer boarded the ship. An observer that boarded via the NPS transfer vessel started surveys upon embarkation while the ship was already within the boundaries of the park. An observer that boarded the ship the previous day began surveys at daybreak as the ship transited the waters en route to Glacier Bay, thereby enabling quantification of encounter events in areas adjacent to the park as well as the area inside the park boundary. Regardless of embarkation location, effort continued until the ship approached either Tarr or Johns Hopkins Inlet, where whale–ship encounters are rare (Fig. 1; Gende et al. 2011), and was reinitiated once the ship began its course back toward the park entrance. The observer continued until either transfer for disembarkation via NPS vessel at the southern end of the park, or until dusk, which generally occurred in Icy or Chatham Strait to the east of Glacier Bay, or into Cross Sound to the west (Fig. 1).

Survey effort varied according to observer schedule and to whether the observer embarked/disembarked via NPS transfer vessel or at ports of call. Total on-effort time for an observer that boarded via NPS transfer vessel averaged 7.0 h, typically evenly split into 3.5 on-effort hours traveling up the bay and 3.5 on-effort hours traveling back down the bay. For an observer that boarded in the port of call prior to the ship's day in GBNP, total on-effort time averaged 8.5 h. This time was split between surveying within the boundaries of GBNP (on average 5.4 h, thus typically 2.7 h traveling up the bay and 2.7 h traveling down the bay), and time spent surveying in the surrounding waters, which varied by cruise ship route and sunrise and sunset times.

To record ship–whale encounters, the observer, either immediately after boarding or at sunrise, proceeded to the forward-most bow of the ship. Forward-most bow access varied by ship, ranging from the 4th to 9th deck and averaged approximately 16.4 m above waterline. The observer then set up a tripod- (Manfrotto Distribution, 055 Series) mounted range-finding binoculars (Leica Viper II; accuracy, +1 m at 1 km;) at the rail of the ship. Configurations varied among ships, but a common feature was an unobstructed view of the waters immediately in front, and within 90° of either side, of the ship. This 180° view of the water provided an opportunity to record surfacing events in the area where whales are at risk of a collision with the bulbous bow and reflected the area that ship pilots/captains focus on for ship navigation. The observer was also equipped with Swarovski 8×42 binoculars, and continuously conducted binocular-assisted and naked eye-scans to search for surfacing whales.

Upon detecting a whale's spout, flukes or surface activity, the observer either used the rangefinders to measure or estimated the distance between the observer and the whale. The observer immediately recorded and geospatially referenced the surfacing event using a Garmin 76C× handheld GPS unit, which was also programmed to record the ship's location every 5 s, from which the track and speed (over ground) of the ship could be reconstructed. For each whale sighting, the observer also recorded the whale's direction of travel relative to the ship's course, its behavior (blow/shallow dive with no fluke showing, dive with fluke up, surface active behavior, lung feeding, etc.), and group size (Table 1). Consistent with other whale observation studies, we defined a group as 2 or more whales within 2 body lengths and coordinating their behavior and/or movement direction for at least 1 surfacing event (Ramp et al. 2010). The observer continued to follow the whale and recorded each surfacing event until it either initiated a deep dive (fluke up) and/or passed abeam of the ship.

In instances when the whale dove too quickly, the distance was too great, or inclement weather conditions prevented exact distance measurement using the rangefinder binoculars, observers estimated the distance. To determine the accuracy and presence of bias in these distance estimates, the observer recorded, on 10 different occasions during each cruise, the estimated distance to inanimate objects in the water (e.g. logs, icebergs) at varying distances and then immediately used the rangefinder binoculars to record the actual distances. The differences between actual and estimated distances were small (average was +13.3 m, 0.05% of the actual encounter distance, across all distances) and unbiased (percentage error did not change appreciably across encounter distances). Thus, no corrections were made for estimated vs. observed distances.

In many cases the observers recorded multiple encounter events between the ship and a whale, i.e. multiple surfacing events, as the ship approached the whale before passing abeam. As we were concerned with understanding the probability of detecting a

Table 1. Covariates and frequency of first sighting observations (N = 3262) at categorical covariate levels used in distance sampling analyses modeling probability of detection of humpback whales in Glacier Bay National Park, Alaska, USA, from 2008 to 2015. Covariate level in **bold** indicates baseline used for comparison to other levels of covariate. Wave heights in feet (1′ = 0.305 m)

Covariate	Description/levels	Frequency (% of total)
Distance	Continuous variable. Distance from the bulbous bow of the cruise ship directly to the whale. A continuous variable ranging from 21.4 to 4564.0 m (minimum and maximum distances after 85% right truncation). 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 to obtain the whale's or group's distance).	
Visibility	Categorical variable. Visibility at the time of the first sighting observations.	
	Excellent: no limitations to visibility	**2185 (67)**
	Good: approximately 7000 m visibility with some low-lying fog	779 (24)
	Poor: approximately 2500 m visibility with low-lying fog	265 (8)
	Poor-fog: approximately 200 m or less visibility with low-lying fog	33 (1)
Group size	Categorical variable. Number of whales counted for each first sighting observation.	
	1	**2644 (81)**
	2–3	543 (17)
	4+	75 (2)
Whale behavior	Behavior recorded as the last action of each surfacing event.	
	Blow/dive with no fluke	**2090 (64)**
	Dive with fluke	894 (27)
	Lunge feeding	10 (<1)
	Resting	93 (3)
	Surface active (including actions such as tail and pectoral fin slapping, head lobbing and breaching)	175 (5)
Wave height	Categorical variable. Height of waves that ships encountered at the time of the first sighting observation.	
	1′	**1043 (32)**
	2′	351 (11)
	3′	72 (2)
	4′	13 (<1)
	Calm	1783 (55)

whale for the purpose of whale avoidance, we used the initial detection for our analysis (e.g. first sighting), rather than the closest point of approach (CPA), when a series of surfacing events for the same whale was recorded. We note that, from a whale avoidance perspective, bridge personnel may actually need a second or third sighting in order to determine appropriate avoidance measures, as it may take several sightings to ascertain the whale's direction of travel. In that context, we view these data as a reference for whale avoidance because they only reflect the ability to detect whales with distance, not the ability to also detect direction of travel. We also recorded weather and visibility conditions at the start of each day and as the conditions changed throughout the cruise (Table 1).

The objective of our study was, to the extent possible, to replicate and quantify the detection process as it is experienced by bridge personnel tasked with avoiding whales. We thus assumed the detection process by the single observer stationed at the bow was an accurate proxy for the detection process experienced by bridge personnel. We note that while cruise ships and, to our knowledge, many other ships will often have multiple personnel present on the bridge, generally only one of them is designated as the ship's lookout. Even a ship's marine pilot, who is tasked with safe navigation of the ship and is thus constantly scanning the waters while underway, also has to search for other navigational hazards, issue security broadcasts, communicate with other vessels to arrange passage, monitor the GPS, radar and Automatic Information Systems (AIS), and engage in many other activities, all of which may distract from whale avoidance (Capt. Karl Luck, marine pilot, Southeast Alaska Pilots Association, pers. comm., 31 January 2011). An experiment comparing whale detections by dedicated observers to those by ship captains aboard fast ferries demonstrated that dedicated observers detected whales faster and at greater distances than the captain, who was often engaged in other activities (Weinrich et al. 2010). We also note that while bridge personnel are not exposed to inclement weather and possible interference by cruise ship passengers like the observer, they are also not equipped with rangefinder binoculars and nor does their search image focus solely on whales. Owing to these contrasting factors, we felt that a single observer stationed at the bow and dedicated solely to detecting whales, served as a realistic proxy for detection of whales by the ship's personnel tasked with detecting whales and initiating whale avoidance measures.

Data analysis

We estimated the probability of detection as a function of distance between the bulbous bow of the ship and the whale using point transect conventional and multiple covariate distance sampling methods (CDS and MCDS, respectively; Buckland et al. 2001) in program R ver. 3.2.1 (R Core Team 2015) and the 'Distance' package ver. 0.9.4 (Miller 2015). Because the distance data collected were from the location of the observer, the distance from bulbous bow to the whale was calculated using ship-specific distances between location of the observer and most forward point of the bulbous bow. Within the context of our study, inference on detection probability from CDS and MCDS methods are based on key assumptions including (1) all whales at zero distance from the point of observation on the vessel are detected, and (2) the distance at which whales surface from the point of observation is not influenced by the vessel itself. We recognize that not all whales at zero distance will be observed; only whales that are at the surface are available for detection, and thus our probability of detection will be conditioned on whales being present at the surface. Additionally, it is probable that whales are influenced by the presence of the vessel, and thus the distance at which they are observed may have been altered. However, the focus of our study is on understanding the realistic conditions that bridge personnel experience, and thus detection probability in the presence of a vessel is fitting.

We fit models using both CDS, including only distance as a covariate, and MCDS methods. In MCDS models, we included covariates that we predicted would affect the probability of detection: visibility, wave height, group size, and whale behavior, all of which were categorical variables and had 3 or more levels at which whale observation data were collected (Table 1). One level of each categorical covariate was used as a baseline to compare the influence of that covariate's other levels, and assessed the significance of each other covariate level using parameter estimates and variances. Exploratory analysis showed that the frequency of detections affiliated with different covariate combinations varied widely, with some combinations occurring at levels too infrequent for analysis (Table 1). Thus, we included only a single covariate in addition to distance in each MCDS model. Our final model set included a model for each covariate individually, and a model with no covariates (Table 2), although we also ultimately fit detection functions on combinations of significant covariates to explore how detection probability varied based on best, worst, and most frequent ship–whale encounter scenarios.

We right truncated observed radial distance data at the 85th percentile and fit these distances to detection functions using both the half-normal and hazard-rate parametric key functions. All models using the half-normal parametric key function failed to fit; thus, here we report only results from models using the hazard-rate key function. We incorporated the effects of covariates via the scale parameter (Marques & Buckland 2003, Marques et al. 2007, Buckland et al. 2008), which influences the rate that the detection function changes in relation to the included covariates (Marques et al. 2007, Buckland et al. 2008). We assessed model fit using visual assessment of detection function and quantile-quantile (Q-Q) plots and Cramer-von Mises goodness-of-fit tests. Although the focus of our study was not on selecting a detection function to be used in further analysis, we used Akaike's Information Criterion (AIC) to determine the detection functions that best fit our data.

Finally, to help understand the implications of the detection functions relative to whale avoidance by large ships, we present the results relative to a 1000 m reference distance (see Figs. 4–8). The purpose of this reference distance is to consider the implications of relative changes in detection probability as covariates, such as sighting conditions, change. Cruise ships and other large vessels are limited in their ability to maneuver, so decreasing the distance that whales are detected to the ship also decreases the options for avoidance, to a point where the ship is simply too close for the ship to alter course or speed. We do not assume the 1000 m distance is a minimum distance, which will vary among different operating conditions (existing speed, whether stabilizers are deployed, the degree to which course can be altered, etc.) and ship configurations (e.g. the presence of azipod thrusters), but consider the relative changes in this set distance for comparative purposes.

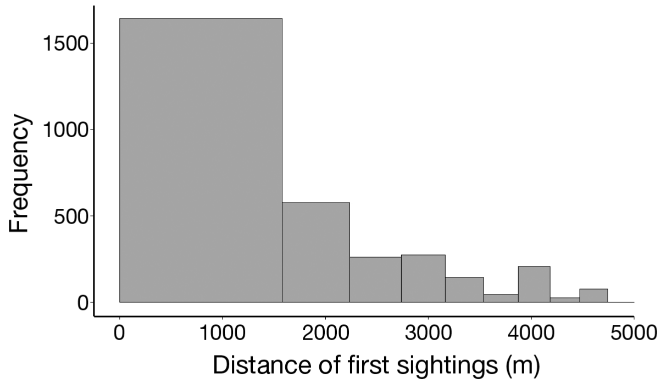

Fig. 2. Humpback whale first sighting distances (m), after 85% right truncation and removal of observations in which covariate data were missing, in and near Glacier Bay National Park from 2008 to 2015 (N = 3262). The histogram is presented in equal area bins, such that the cutpoint of each bin results in half-circle survey areas of the same size

RESULTS

From 6 May 2008 to 23 September 2015, observers boarded 28 different cruise ships that entered Glacier Bay, totaling 643 ship entries into the park. Ship length, draught, and beam averaged 260.0 m (range; 181.1–294.1 m), 7.7 m (5.9–8.5 m), and 32.6 m (25.6–38.7 m), respectively. Over the study period, at least 1 whale was detected on 91% (N = 589) of the cruises; 78% (N = 503) of cruises had 2 or more sightings.

We recorded 3852 first sightings of an individual or group of whales from 2008 to 2015. The first sighting distances ranged from 21.4 to 10 986.3 m. After removing observations where covariate data were missing and right truncating the dataset at the 85th percentile, our dataset was restricted to a maximum distance of 4564.0 m and reduced to 3262 observations (Fig. 2). Nearly 34% (N = 1097) of the 3262 detections were within 1000 m and 10% (N = 341) were within 500 m. Detections were spread across the entire 180° view of the water at different bearings from the bow (Fig. 3).

Detection probability of surfacing whales decreased markedly with increasing distance from the ship. All fitted detection functions showed a significant drop in detection at or near 500 m, including the model containing no covariates (Fig. 4A,C). Overall detection probability in the CDS model was 0.946 (95% CI: 0.912, 0.970) at 500 m, dropped to 0.496 (0.434, 0.562) at 1000 m, and fell further to 0.149 (0.125, 0.176) at 2000 m. Visual assess-

Table 2. Summary details for final model set fitted for distance sampling analyses modeling probability of detection of humpback whale first sighting observations in Glacier Bay National Park, Alaska, from 2008 to 2015. CDS: conventional distance sampling; MCDS: multiple covariate distance sampling

Analysis	Covariates	Key function	No. of parameters
CDS	Distance	Hazard rate	2
MCDS	Distance + visibility	Hazard rate	5
MCDS	Distance + group size	Hazard rate	4
MCDS	Distance + whale behavior	Hazard rate	6
MCDS	Distance + wave height	Hazard rate	6

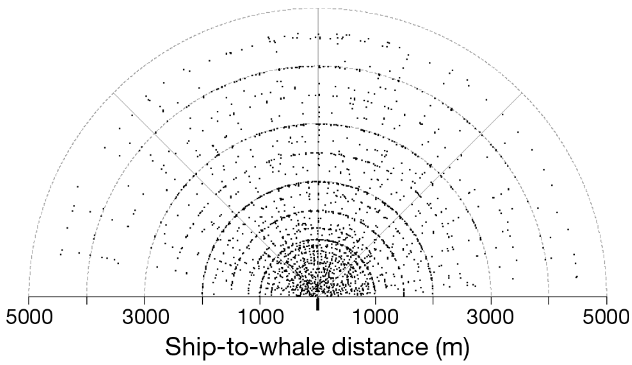

Fig. 3. Spatial distribution of humpback whale first sighting distances (m), after 85% right truncation and removal of observations in which covariate data were missing, in and near Glacier Bay National Park from 2008 to 2015 (N = 3262) in reference to front-most point of a cruise ship. Ship (thick black line on *x*-axis) is to scale based on the average length of cruise ships that enter the park (263 m)

ment of detection function plots, Q-Q plots and probability density plots (Q-Q plots and probability density plots were generated with the R package 'mrds'; ver. 2.1.15, Laake et al. 2016) indicated good fit of the models, particularly near zero distance, which is the most critical area of the model (Fig. 4 presents the Q-Q plot and probability density plot for the CDS model; Buckland et al. 2001). The Q-Q plots showed evidence of heaping of the data at rounded distances (Fig. 4B). Cramer-von Mises tests resulted in low p-values for all models, suggesting issues with model fit (Table 3). However, these results are likely due to the rather large sample size providing high power for the goodness-of-fit test to reject fit and heaping of data points noted in the Q-Q plots. Lack of fit due to the issues described is not of great concern in this application (Buckland et al. 2001). Based on AIC values, the detection functions modeled with the influence of visibility and group size were the most supported models (AIC for both models = 54 222), although the model including whale behavior also showed a significant influence of this covariate on detection. The model including wave height showed that changing levels of this covariate did not affect detection probability.

Not surprisingly, poor visibility conditions significantly reduced the probability of detection. Under

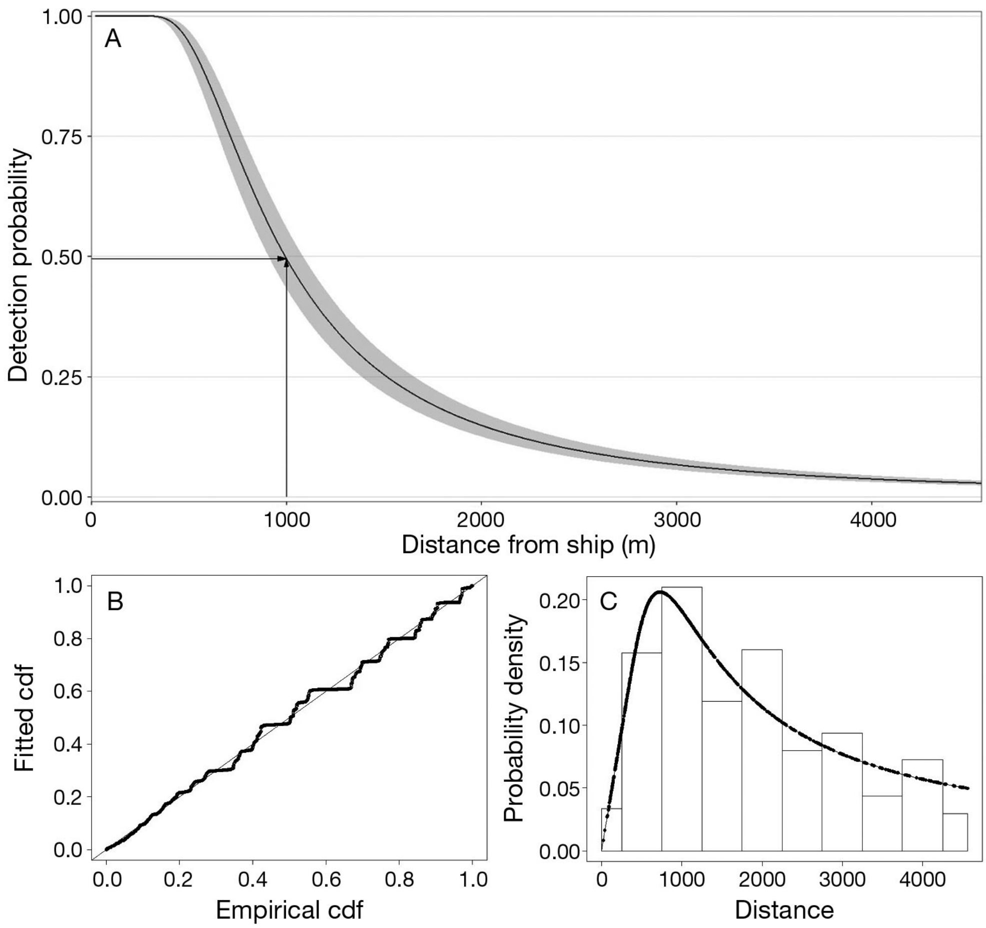

Fig. 4. Detection probability as it varies with distance (range = 0 to 4565 m) between ships and whales in and near Glacier Bay National Park from 2008 to 2015 (N = 3262). (A) Detection function. Shaded area around line indicates 95% confidence intervals. Arrows identify detection probability at 1000 m reference distance. (B) Quantile-quantile (Q-Q) plot. (C) Probability density function over radial first sighting distances binned in 10 distance classes. cdf: cumulative distribution function

Table 3. Detection function model results: goodness-of-fit (CvM: Cramer-von Mises), model selection (change in Akaike's Information Criterion, ΔAIC) values, and estimates of shape and scale parameters analyzed in distance sampling framework modeling probability of detection of humpback whale first sighting observations in Glacier Bay National Park, Alaska, from 2008 to 2015. Covariate level in **bold** text indicates baseline (intercept) for comparison to other covariate levels

Model	ΔAIC	CvM (p-value)	Shape parameter α	Shape parameter SE	Covariate level	Scale parameter β	Scale parameter SE
Visibility	0	0.006	0.780	0.024	**Excellent**	6.860	0.045
					Good	0.050	0.061
					Poor	–0.611	0.103
					Poor-fog	–1.209	0.292
Group size	0	0.008	0.766	0.024	**1**	6.673	0.046
					2–3	0.561	0.070
					4+	0.842	0.173
Whale behavior	56	0.007	0.747	0.024	**Blow/dive-no fluke**	6.732	0.048
					Dive-fluke	–0.035	0.064
					Lunge feed	0.344	0.691
					Rest	–0.105	0.184
					Surface active	0.523	0.117
Distance only	67	0.002	0.737	0.024	**Intercept**	6.727	0.045
Wave height	69	0.006	0.736	0.024	**1′**	6.720	0.062
					2′	0.042	0.099
					3′	0.306	0.202
					4′	0.587	0.577
					Calm	–0.017	0.062

'excellent' visibility conditions, which was the baseline and most common condition experienced during our surveys (67% of all sightings), detection was essentially ensured at 500 m (probability of detection = 0.983 [0.966, 0.993]) and the probability dropped greatly at 1000 m (0.594 [0.525, 0.664]). Compared to this baseline, both 'poor' and 'poor-fog' covariate levels resulted in significantly decreased detection probability (Table 3). A change in visibility from 'excellent' to 'poor' and 'poor-fog' decreased detection probability at 1000 m (0.212 [0.142, 0.309] and 0.062 [0.018, 0.200], respectively; Fig. 5). However, the most severe visibility condition ('poor-fog') occurred on only 1% of all days when surveys were conducted.

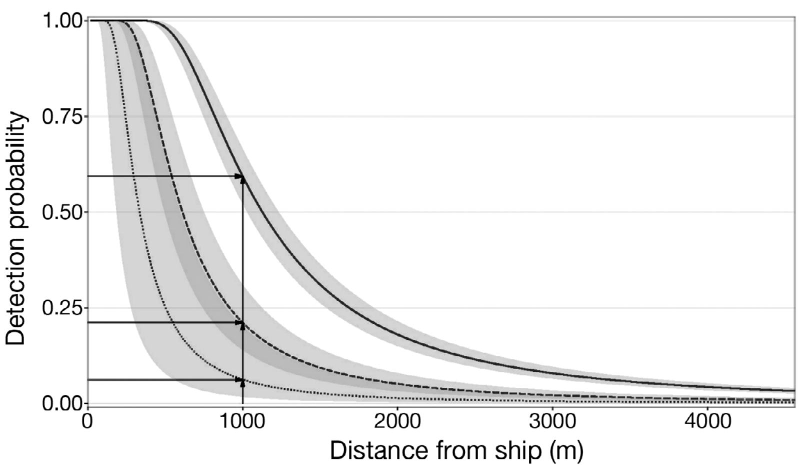

Fig. 5. Detection probability of humpback whales under different visibility conditions as it varies with distance (range = 0 to 4565 m). 'Excellent' conditions represented by the solid line (baseline, see Table 3), 'poor' conditions represented by dashed line, and 'poor-fog' conditions represented by the dotted line. Shaded area around lines indicates 95% confidence intervals. Arrows identify detection probability at 1000 m reference distance

Increasing group size significantly increased detection, probability (Table 3). Although encounters with a single whale occurred most frequently (81% of all detections), when groups of 2 or 3 whales were encountered (17% of total) the probability of detection nearly doubled at 1000 m compared to the detection probability of a single whale at 1000 m (0.453 [0.392, 0.519] and 0.867 [0.778, 0.933], respectively; Fig. 6). Further increasing group size to 4 or more whales increased the probability of detection at 1000 m to essentially 1 (0.975 [0.831, 1.000]; Fig. 6).

For most (64%) detections, whales were sighted when they spouted but did not show a fluke. Using this 'blow/dive-no fluke' as a baseline behavior, detection was again essentially ensured at 500 m (0.949 [0.913, 0.974])

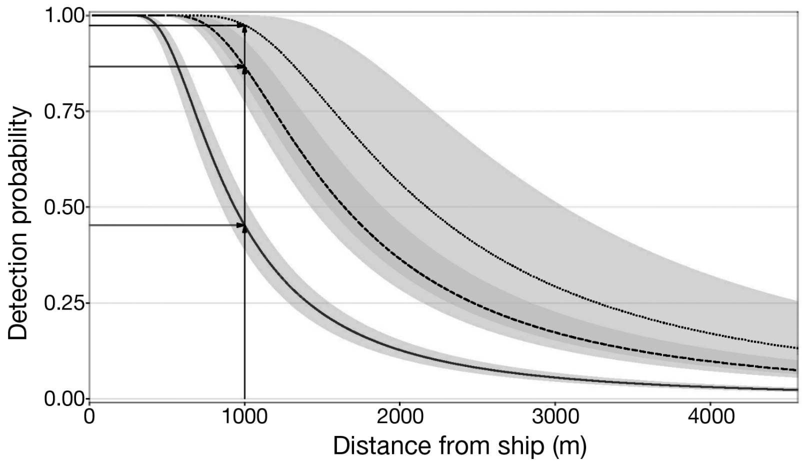

Fig. 6. Probability of detecting whale groups of different sizes of humpback whales as it varies with distance (range = 0 to 4565 m). Single whales represented by the solid line (baseline, see Table 3), group of 2 to 3 whales represented by dashed line, and group of 4 or more whales represented by the dotted line. Shaded area around lines indicates 95 % confidence intervals. Arrows identify detection probability at 1000 m reference distance

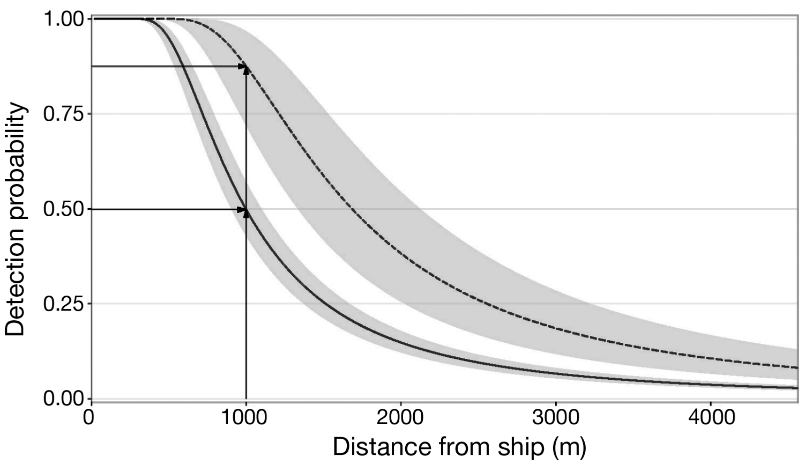

Fig. 7. Detection probability of humpback whales engaged in different behaviors as it varies with distance (range = 0 to 4565 m). 'Blow/dive with no fluke' represented by the solid line (baseline, see Table 3) and 'surface active' represented by the dashed line. Shaded area around lines indicates 95 % confidence intervals. Arrows identify detection probability at 1000 m reference distance

and again decreased markedly at 1000 m (0.498 [0.431, 0.569]). Only the 'surface active' category of whale behavior significantly, and positively, influenced detection probability (Table 3). At 1000 m, the probability of detection with the influence of 'surface active' behavior increased considerably compared to observed behavior of 'blow/dive no fluke' (0.875 [0.722, 0.966]; Fig. 7).

Finally, it is insightful to consider the best, worst, and most common conditions faced by cruise ship personnel tasked with whale avoidance when traveling the waters in and near Glacier Bay. Of all the possible covariate combinations, observers were most likely to detect a single whale during excellent visibility conditions when the whale spouted at the surface but did not show a fluke (35 % of all detections; N = 1156). Under these conditions, the probability of detection given surfacing at 1000 m was near 0.60 (0.569; Fig. 8, solid line). Detection probability was greatest (i.e. conditions where ships would have the most time to invoke a whale avoidance maneuver) when a group of 4 or more whales were engaged in surface active behavior and were encountered during excellent sighting conditions (Fig. 8, dashed line). Under this scenario, 0.60 detection probability occurred at a distance of approximately 3660 m, a distance much farther than the most common detection scenario. However, these best case scenario conditions were experienced in less than 1 % of all detections (N = 2). In contrast, for a single whale spouting and showing no fluke under the worst sighting conditions (poor-fog), detection probability of 0.60 was achieved at 268 m, a distance over 10 times closer than the best case scenario (Fig. 8, dotted line).

DISCUSSION

Generating detection functions from 3262 sightings of whales from the bow of large cruise ships demonstrated that the probability of detecting a whale was at or near 1 when whales surfaced 500 m or less from the ship, and around 0.50 at a distance of 1000 m. Larger whale group sizes and surface active behavior nearly doubled detection ability in some scenarios, while reduced sighting conditions, such as heavy fog, dropped detection ability significantly.

Our probabilities of detection were slightly lower at similar distances than those of Zerbini et al. (2006) for surveys of humpback whales conducted along the Alaska Peninsula and Aleutian Islands, but commensurate with detection functions generated for humpback and blue whales along the coasts of Washington, Oregon, and California (Ca-

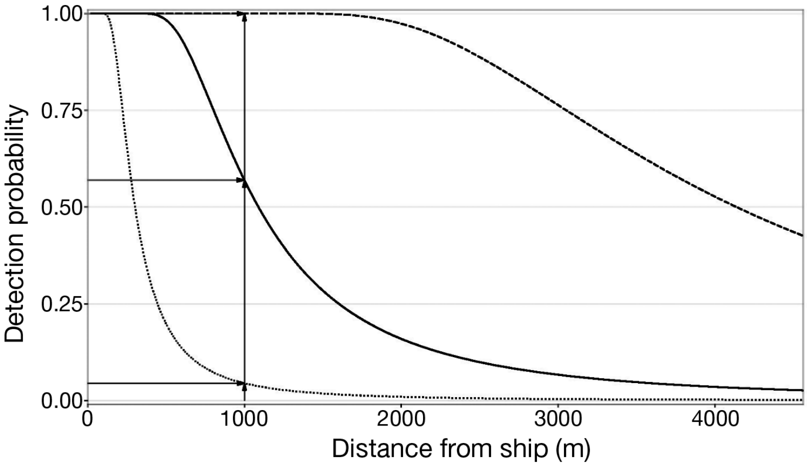

Fig. 8. Detection probability as it varies with distance (range = 0 to 4565 m) between ships and whales under the most common conditions encountered by ships: a single whale sighted under 'excellent' sighting conditions emitting a spout during a surfacing event but without having the fluke break the surface of the water (baseline, see Table 3). The dashed line indicates the best case scenario where a group of 4 or more whales are sighted during 'excellent' visibility with at least one engaged in 'surface-active' behavior. The dotted line indicates the worst case scenario of a single whale sighted under 'poor-fog' sighting conditions emitting a spout during a surfacing event but without having the fluke break the surface of the water. Arrows identify detection probability at 1000 m reference distance

lambokidis & Barlow 2004). However, unlike these previous studies, which were designed to maximize detection probability, our objectives, and thus our methods, were designed to quantify the observation process most likely experienced by bridge personnel tasked with whale avoidance.

For example, our data collection protocol was part of a larger study intended to understand multiple aspects of ship–whale encounters and related avoidance. Thus, observers were required to record multiple surfacing events of a whale to ascertain direction of travel and its closest point of approach, thereby keeping the focus on the same whale until it initiated a deep dive or passed abeam of the ship. Focusing more time on detected whales may reduce detection probabilities at greater distances, such as those on the horizon (Barlow & Taylor 2005, Barlow 2015), but reflects the operational constraints faced by the bridge personnel who also follow whales during multiple surfacing events necessary to understand the direction of travel and evaluate whether a ship maneuver is necessary for whale avoidance. Observers also remained at the bow scanning for whales for hours at a time, reflecting the time periods when pilots or bridge personnel are 'on watch'. These time periods differ from typical whale abundance surveys, which will shift duties frequently, e.g. every 15 min, to minimize the chance that observer fatigue results in missed whales (Zerbini et al. 2007, Hammond et al. 2013), though they are similar to those noted by Leaper et al. (2015) in which marine mammal observers working in seismic survey operations were tasked with visual detection of whales in injury risk mitigation efforts.

We were surprised to find that wave height did not have a significant effect on detection. Many marine mammal surveys measure Beaufort sea state, which is an index of wind speed, and its effect on detection is assumed to be influential enough to restrict survey effort during marine mammal surveys (e.g. Zerbini et al. 2006, 2007, Barlow 2015). Accordingly, we predicted that our measure of wave height would similarly affect detection probability. While high wind events do occur in and near Glacier Bay, the park and much of southeast Alaska (termed the 'Inside Passage') is a comparatively protected area. The consequences for the relationship between whale detection and wind are 2-fold. First, the area is not subject to the swells and long fetch of the open ocean, and is thus rarely subject to wave heights higher than 1′ (0.3 m) during the summer months (Table 1). The lack of a relationship between wave height and detection probability was thus more likely an artifact of low sample size in moderate sea states rather than an ability to detect whales independent of wind conditions. Second, even during strong wind conditions, when a whale's spout would dissipate very rapidly lowering detection probability, whales were often sighted close to shore, in the lee of the wind. These microclimatic conditions of calm water in the lee of islands likely increased detection probability during very windy conditions in contrast to the open ocean where wind breaks are absent.

We infer that personnel aboard large ships can be constrained in their ability to actively avoid whales, owing to the confounding factors of whale dive and respiration behavior (the availability process, e.g. Borchers et al. 2013), an imperfect observation process (our results), and the limited maneuvering capacity of large ships. Whales spend the majority of their time below the surface, which makes them unavailable to be detected, particularly in places like Alaska where water clarity is low. The surfacing events thus act as cues for bridge personnel to identify the location of whales and to assess whether they may be at risk of collision. In southeastern Alaska, the number of spouts (cues) by humpback whales has been found to vary substantially, averaging between 3.6 and 12.9 per surfacing interval (Dolphin 1987). The amount of time spent just below the surface between spouts (inter-blow interval) has also been found to be highly variable, averaging between 18 and 60 s (Dolphin 1987). Each of these behavioral metrics represents a tradeoff between detection and avoidance: more spouts equates to more opportunities for detection, but also longer periods at or just below the surface at risk of collision. Likewise, more time between spouts results in higher detection probability because ship-to-whale distances will decrease, although the closer distances provides less time for the ships to implement an appropriate avoidance maneuver. Thus, it is insightful to consider the maneuverability of large ships to understand the time necessary to avoid a whale once a surfacing cue is detected.

The International Maritime Organization (IMO) has generated a number of standards for maneuverability of large ships, including the initial turning ability (ITA). The ITA represents the distance traveled by a ship from the time a 10° change in heading is ordered and the moment that heading is achieved. The IMO requires ships over 100 metric tons, including all large cruise ships, to have ITAs of <2.5 times the ship's total length at its operational speed (International Maritime Organization 2002). For large cruise ships, which are often outfitted with azipod thrusters and thus have enhanced maneuverability, the ITA has been measured at around 1.5 of the ship's total length (Victor Ferrari, Marine Research Institute Netherlands, pers. comm.). Thus an average-sized cruise ship in Alaska (270 m; Webb & Gende 2015) will have an ITA of 405 m.

The ITA, however, only represents the distance traveled during the change in heading. As such a maneuver would also bring the stern (propeller) tens of meters out past the ship's course increasing the chance of a propeller strike, we consider 500 m to be the minimum detection distance to the whale, below which ships are significantly constrained in implementing an effective avoidance maneuver such as a 10° turn. In designating this minimum detection distance, we recognize that larger changes in heading may occur at smaller distances but highlight that avoidance maneuvers should be considered in the context of their costs and benefits; for instance, a cruise ship captain may be willing to risk the chance of multiple injuries and some structural damage by implementing a 25° turn to avoid a catastrophic collision with another vessel or a reef, but unwilling to do so to reduce the chance of a whale collision.

Bridge personnel are thus faced with the counterbalancing issues of detection and avoidance ability: decreasing distances between ships and whales, particularly in the range between 1500 and 500 m, significantly increases the chance of detection but simultaneously decreases the options for avoidance. A whale surfacing within 500 m will almost certainly be detected but at that point the opportunity to implement a safe avoidance maneuver is significantly reduced. In this context, we also highlight the role of ship speed in the detection–avoidance trade-off.

Ship speed has been demonstrated to reduce the chance that a collision is lethal should one occur (Vanderlaan & Taggart 2007) and is thus a key conservation strategy in many areas (Gende et al. 2011, Conn & Silber 2013). We did not include ship speed as a covariate in our models because in GBNP speed is spatially autocorrelated with the narrowest areas of the park. In the mid- to upper-reaches of Glacier Bay, cruise ships commonly travel 18 to 22 knots, but the NPS requires ships slow to 13 knots at the mouth of the park because this area corresponds to areas of historically high whale aggregations (Neilson et al. 2015). This area also represents some of the narrowest areas in Glacier Bay, measuring 5 km or less in places. Thus a large number of detections will occur at distances of 2.5 km or less when ships are almost always traveling 13 knots or less (Webb & Gende 2015).

Nevertheless, consider the scenario where a whale initially surfaces 650 m from the ship, a common occurrence in Glacier Bay and surrounding waters (Fig. 2). Bridge personnel have an elevated but imperfect chance of detecting the whale at this distance. For a whale with an inter-blow interval of 18 s, swimming at about 1.1 m s^{-1} (Noad & Cato 2007) and swimming toward the ship's course 5° off port, its next surfacing event will be too close for a safe avoidance maneuver (465 m) for a ship traveling 20 knots (10.28 m s^{-1}). In contrast, bridge personnel traveling on a ship at 10 knots (5.14 m s^{-1}) are afforded another opportunity for detection, and thus another opportunity to initiate an avoidance maneuver, because its second spout will still be over 550 m from the bulbous bow. While it is likely that whales will detect the ship and alter their dive behavior to avoid a collision, McKenna et al. (2015) found that blue whales failed to move laterally away from oncoming ships. These authors also noted that slower-moving ships provide more time for whales to implement a response dive

(McKenna et al. 2015). Slower speeds may thus help whales avoid ships in addition to helping ships avoid whales.

Finally, cruise ships in GBNP are required to operate at a slow and safe speed when knowingly in the presence of whales (National Park Service 2003) and must avoid approaching a whale within 0.25 nautical mile (463 m; 50 C.F.R. § 224.103 2015). Of the 3262 initial sightings, almost 10% (N = 291) were within 463 m, and thus ships are often out of compliance before they have time to initiate any avoidance measures. Our results demonstrate that these whales were not likely missed during previous surfacing events owing to the high detection probability at that distance. Perhaps more importantly, in order to remain in compliance with the federal regulations, ships must avoid approaching whales within 463 m. In instances when a 10° turn is required to avoid a whale, bridge personnel have a minimum detection distance of 868 m (463 m + 405 m ITA). Our results indicate that detection probability will be less than 0.60 at this distance. Whether the ship is able to avoid approaching within 463 m will depend upon the speed and direction of travel by the whale but nevertheless highlights that the detection ability can impede the ability of large ships to comply with these regulations. Similar to McKenna et al. (2015), we encourage more research into understanding how whale behavior is influenced by approaching ships, and integrating new understanding of the observation and detection processes into efforts designed to decrease ship–whale collisions.

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