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A Bayesian approach for understanding the role of ship speed in whale–ship encounters

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Abstract. Mandatory or voluntary reductions in ship speed are a common management strategy for reducing deleterious encounters between large ships and large whales. This has produced strong resistance from shipping and marine transportation entities, in part because very few studies have empirically demonstrated whether or to what degree ship speed influences ship–whale encounters. Here we present the results of four years of humpback whale sightings made by observers aboard cruise ships in Alaska, representing 380 cruises and 891 ship–whale encounters. Encounters occurred at distances from 21 m to 1000 m ($\bar{x} = 567$ m) with 61 encounters (7%) occurring between 200 m and 100 m, and 19 encounters (2%) within 100 m. Encounters were spatially aggregated and highly variable across all ship speeds. Nevertheless a Bayesian change-point model found that the relationship between whale distance and ship speed changed at 11.8 knots (6.1 m/s) with whales encountering ships, on average, 114 m closer when ship speeds were above 11.8 knots. Binning encounter distances by 1-knot speed increments revealed a clear decrease in encounter distance with increasing ship speed over the range of 7–17 knots (3.6–8.7 m/s). Our results are the first to demonstrate that speed influences the encounter distance between large ships and large whales. Assuming that the closer ships come to whales the more likely they are to be struck, our results suggest that reduced ship speed may be an effective management action in reducing the probability of a collision.

Key words: Alaska; Bayesian; change-point model; cruise ship; Glacier Bay National Park and Preserve, Alaska, USA; humpback whale; ship speed; ship strike; ship–whale encounters.

Introduction

Understanding the interactions between large ships and large whales has become a global conservation issue owing to the dramatic increase in commercial shipping traffic in recent decades (Andrew et al. 2002, Ross 2005) and an emerging awareness of the deleterious impacts that large vessels may have on individuals and populations of large whales. For example, shipping produces underwater sound that may disrupt vital activities for whales, such as feeding or reproduction, or hinder communication (NRC 2005, Parks et al. 2011). Whale–ship encounters may also result in lethal or sublethal collisions (Laist et al. 2001, Kraus et al. 2005). Consequently, a number of U.S. and international management entities have initiated efforts aimed at reducing these impacts, focusing primarily on reducing spatial overlap between ships and whales (e.g., Fonnesbeck et al. 2008, Vanderlaan et al. 2008). In some cases, this management approach is both feasible and effective; in the Bay of Fundy, for example, slight changes in routing of vessels can reduce the relative risk of collision by up to 62% (Vandelaan et al. 2008). In other cases, however, this management action may not be effective or appropriate, either because whale distribution may shift over time, or because ships may not be able to reroute around high-use whale habitat when approaching ports of call, or in narrow passages. In these instances, the primary management action has been to implement regulations for, or request voluntary compliance with, reductions in ship speed (National Park Service 2006, NMFS 2008, Carrillo and Ritter 2009).

Although relatively common, there is considerable uncertainty in the effectiveness of regulating ship speed in meeting whale-conservation objectives due, in part, to a paucity of data (e.g., Vanderlaan and Taggart 2007, NMFS 2008). The difficulty of applying an experimental framework, and the legal and logistical issues associated with putting observers aboard large, ocean-ranging

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vessels, have resulted in few field-based efforts and a corresponding lack of data on the role of ship speed during ship–whale encounters. Not surprisingly, the shipping industry has legitimately raised concern about the focus on ship speed in the absence of studies confirming its effectiveness (World Shipping Council 2006).

For four years (2006–2009) we used shipboard observers to record encounters between cruise ships and humpback whales in Alaska, including Glacier Bay National Park. Cruise ships make multiple ports of call in coastal Alaska, providing a logistically feasible means by which to place observers on board to record ship–whale encounters. In addition, cruise ships are one of the most rapidly expanding forms of leisure travel (Dowling 2006), overlap spatially with whale hotspots in the Caribbean, Hawaii, South Pacific Islands, Mediterranean, Alaska, and Baja California (Hoyt 2005), and consequently cruise ships have been involved in a number of collisions with whales both in Alaska and globally (Jensen and Silber 2003, Gabriele et al. 2008). Thus cruise ship–whale interactions are global in scope, likely to increase, and an emerging conservation issue.

Our objective was to better understand the nature of ship–whale encounters by recording the frequency and severity (closeness) of encounters between ships and whales. Our study included the area in and near Glacier Bay National Park, one of the largest marine mammal protected areas in the world. Given that cruise ships are essential for allowing visitor access into Glacier Bay and thus rerouting around the park is not a viable management alternative, we focused specifically on the relationship between encounter distance and ship speed. To our knowledge, this is the first large-scale study to use observers on ships for the purpose of better understanding large ship–large whale encounters, and assessing the effectiveness of ship speed in meeting conservation and management objectives.

Methods

Our study was located in southeastern Alaska and included Glacier Bay National Park and Preserve (hereafter "Glacier Bay" or "the park") and adjacent waters (approximately 58°41.127' N, 136°11.740' W; Fig. 1). Cruise ships are the primary mode of transport by which visitors access Glacier Bay: in 2009 more than 400 000 cruise ship passengers, constituting over 95% of all visitors to the area, came to Glacier Bay during 224 ship entries into the park. The U.S. National Park Service (NPS) regulates the number of all commercial and private ships in Glacier Bay, and is currently considering a >20% increase in the seasonal quota of allowable cruise ship entries (NPS 2006).

The NPS also regulates ship speed within Glacier Bay using two types of speed restrictions. *Seasonal whale waters* occur near the entrance of Glacier Bay extending from the mouth of the bay to an imaginary line between northern Strawberry Island and Lars Island (Fig. 1). All motorized vessels over 5.5 m (18 feet) must maintain speeds of 20 knots (10.3 m/s) or less while in this area from 15 May through 31 August although the time may be extended later in the season or the maximum speed may be reduced to 13 knots (6.7 m/s) depending upon management recommendations. *Temporary whale waters* may be designated in any area of Glacier Bay and this limits ship speeds to 13 knots or less when >3 whales occur for three or more days based on weekly monitoring efforts. During our study the cruise ships were subject to speed restrictions in the lower part of Glacier Bay, but not in the waters immediately adjacent to the park boundary, providing a fortuitous natural experiment to examine how speed influences encounter distances with whales.

A total of 18 different cruise ships representing four different cruise companies participated in the study. All ships were large, averaging 256 m in length (range, 181–294 m), 32 m in beam (26–37 m), and 8 m in draught (5.9–8.2 m). Most carry 1500–3000 passengers and 500–1500 crew. Most (14 of 18) of the ships used during this study had similar "diesel-electric" propulsion systems. Beginning in 2006 an observer based in Bartlett Cove (location of the headquarters for Glacier Bay) was transported to the ships as they entered the park ($n = 45$ cruises; July–September) and in 2007 two separate observers (one per ship) were transported to ships ($n = 138$ cruises, May–September). However, concurrent, independent humpback whale monitoring efforts conducted by Glacier Bay staff indicated that many ship–whale encounters (see Plate 1) were occurring just prior to, or soon after, the Bartlett Cove-based observer embarked/disembarked the ship. Thus, in 2008 and 2009, in addition to the continued effort of the Bartlett Cove-based observer ($n = 83$ cruises conducted May–September 2008; $n = 74$ cruises conducted May–September 2009), a Juneau-based observer boarded the ships at the port of call prior to Glacier Bay (either Skagway or Juneau), and recorded encounters throughout Icy Strait, Glacier Bay, and in some cases Cross Sound (Fig. 1). The Juneau-based observer then disembarked at the next port of call (Ketchikan or Sitka, Alaska), and traveled back to Juneau or Skagway to board another ship. The total number of cruises for the Juneau-based observer was 49 ($n = 20$ cruises in 2008 and $n = 29$ cruises in 2009; cruises conducted May–September).

Once aboard the ship, the protocol was the same regardless of embarkation port. The observer was positioned on the forward-most bow of the ship (generally the seventh or eighth deck on most ships) in the early morning. For the Juneau-based observer, survey effort started around daybreak (04:06–06:47 hours) somewhere in Icy Strait and ended around dusk either in Cross Sound or Chatham Strait (Fig. 1) depending upon itinerary and day length (effort ending 17:21–22:10 hours). For the Bartlett Cove-based observer effort started just after embarkation generally between 07:00 and 10:30 hours (range, 05:53–12:08

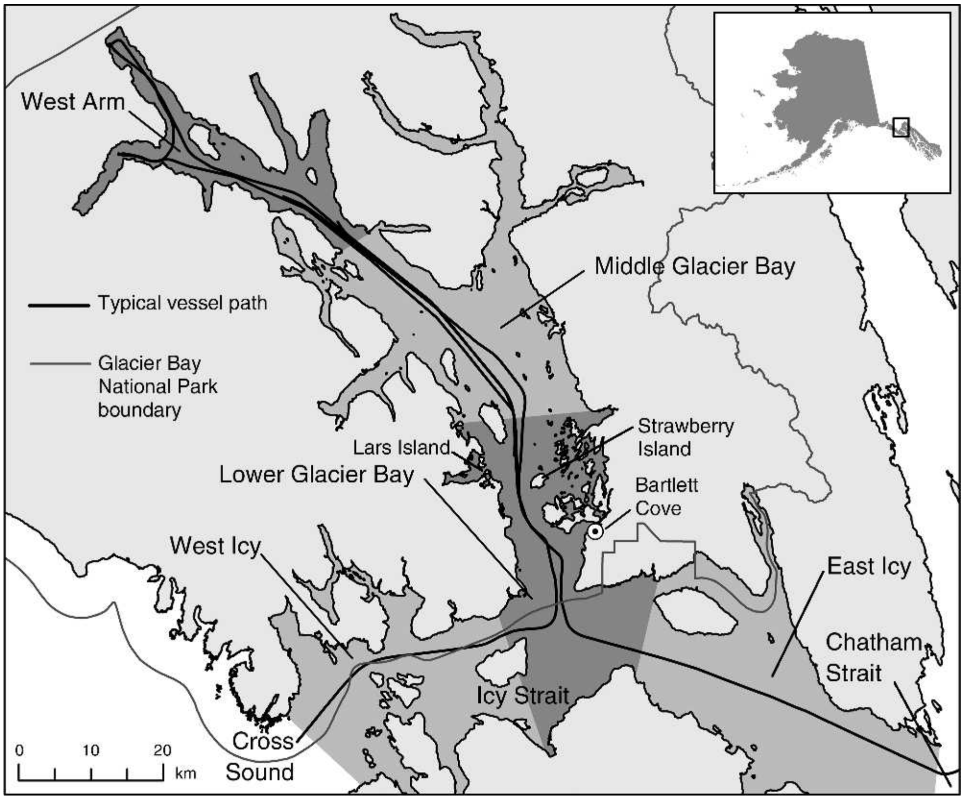

FIG. 1. Study area in southeastern Alaska, USA, showing the boundary of Glacier Bay National Park and Preserve and the five subareas designated a priori based on long-term average oceanographic conditions (Etherington et al. 2007) and historical and contemporary sighting frequency of humpback whales (Neilsen and Gabriele 2005). The five subareas are West Arm, Middle Glacier Bay, Lower Glacier Bay, West Icy, and East Icy. The heavy lines indicate typical cruise ship tracks through Icy Strait and into Glacier Bay.

hours) and ended when they disembarked with the NPS Interpretive Rangers as the ship exited the park (14:20–20:50 hours). Thus, all cruises occurred during the daylight. Only in middle to late September at the end of the cruise season are there cruise ships in Glacier Bay after dusk.

All of the large cruise ships are configured similarly, with the forward most bow of the ship ahead of the bulbous bow by an average of 13.5 m (range, 5.8–27.5 m). On average, the observer was 15.5 m above the water (range, 12–19.3 m), providing a clear 180° view of the waters surrounding the ship. Nevertheless, due to both the height of the deck railing and the overhang of the observation deck past the bulbous bow, there was a small "blind area" where observers could not see if whales surfaced within an average of 32 m of the bulbous bow.

Once at the bow, observers used Leica Viper II Rangefinder binoculars (accuracy, ±1 m at 1 km) (Leica, Charlottesville, Virginia, USA) and a Garmin 76Cx handheld GPS unit (Garmin, Olathe, Kansas, USA) to record the distance and location of encounters between ships and whales. The GPS units were set to record the location of the ship every 5 s, from which the track and speed (over ground) of the ship could be reconstructed. Observers continuously scanned the waters with naked eye or Swarovski 10 × 42 binoculars in a 180° arc around the bow of the ship. When a whale was sighted, the rangefinder binoculars were used to record the distance and bearing between observer and the whale. Sightings on the whale or group of whales continued until they were no longer seen and/or passed directly abeam of the observer, i.e., 90° from the ship's course.

In some cases, however, the whale dove before the rangefinder binoculars could be used. For these encounters (31% of total) the distances were estimated. To determine if estimating the distance biased our results, on 10 different occasions during each cruise, the observers estimated the distance to inanimate objects in the water (e.g., logs, ice bergs) and then immediately used the rangefinder binoculars to record the actual distances. This "estimation error" (difference between actual and estimated) was relatively small (average is ±12% 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.

Following each cruise, all encounter data were entered into a Microsoft Access database, and all spatial data were downloaded from the GPS units (Garmin, Olathe, Kansas, USA) using DNR Garmin (free software from the Minnesota Department of Natural Resources, *available online*).[8] The cruise-ship track data (locations automatically logged every 5 s) and whale-sighting data (waypoints taken during whale observations) were merged in ArcGIS using a Visual Basic script. Ship speed at the time of whale sighting was calculated by extracting 10 points from the track data—five ship location points immediately preceding and immediately following a whale-encounter waypoint—and summing the distance over which the ship traveled during that time and dividing by the time it took to cover that distance.

Our analytic approach was to calculate the management-relevant metric of distance of the whale to the bulbous bow (where most whale–ship collisions are likely to occur) based on the distance of the observer to the whale and the bearing of the whale to the ship. This equates to calculating the length of the line segment AC based on the triangle ΔABC with vertices of whale location (A), location of observer (B), and the bulbous bow (C). To do so, we first calculated the distance of the observer to the bulbous bow (BC), which is $\sqrt{h^2 + q^2}$ where h is the height of the observer above water and q is the distance of the bow (observer) to the bulbous bow at the water level (both of these ship dimensions were provided by the cruise companies). We then calculated the distance of the whale to the observer at water level $p = \sqrt{\mathrm{AB}^2 - h^2}$. The encounter distance (AC) $= \sqrt{p^2 + q^2 - 2pq\cos\alpha}$ where α is the bearing of the whale relative to ship direction (180° when the whale is directly in front of the ship).

If several locations were taken on the same whale, only one encounter (the minimum distance) was used for analysis to ensure independence and because minimum encounter distance was the management-relevant metric. The maximum encounter distance was limited to <1 km for three reasons. First, it was unclear at what maximum distance whale–ship interactions can still be considered biologically meaningful. Second, we felt confident that using only encounters within 1 km would ensure a near 100% detection probability, similar to what was found by Zerbini et al. (2009) using distance sampling during ship-based abundance estimates for humpback whales in the Gulf of Alaska. Nevertheless, to test this assumption on nine separate cruises we placed two independent observers (double sampling) aboard the same cruise ship, one each on the port and starboard sides of the bow, and found 100% concurrence of sighting frequency. Finally, ships are almost always at least 2 km from shore in all directions while in our study area, although in a few areas they travel to near 1 km of shore (Fig. 1). Thus, by truncating encounters to 1 km, we assumed an unbiased probability of detecting whales around the ship independent of geographic location.

We also divided the study area a priori into five separate subareas (Fig. 1) corresponding to differences in oceanographic conditions (Etherington et al. 2007). These subareas also reflected differences in whale habitat use, based on long-term monitoring efforts conducted by NPS personnel (Neilson and Gabriele 2005). No oceanographic monitoring has occurred in the West Icy subarea.

To test whether there was a change in the mean encounter distance as a function of ship speed (given the management application, the knot is the speed metric used in this analysis), we used a change-point model. Change-point models have the flexibility to identify changes in a relationship while incorporating uncertainty (Thomson et al. 2010). Our change-point model can be described as

$$Y_i \sim \log\mathcal{N}(\beta_k, \sigma^2) \qquad (1)$$

$$k = 1 + \mathrm{step}(X_i - X_{\mathrm{CP}})$$

where the Y_i are the individual encounters (each with a distance and speed) $i = 1, \ldots N$, which are modeled by the mean values β_k and variance σ^2, and X_i is the speed during encounters $i = 1, \ldots N$. Assuming a single change point (CP) is identified, the mean encounter distance can have two levels above and below X_{CP}, thus $k = 1,2$. The mean level is determined by whether the speed of the vessel is above or below the threshold with mean distance β_1 and β_2, respectively. The function step() = 1 if the value inside the parenthesis is positive and equates to 0 if negative. There are four coefficients to be estimated in the change-point model: β_1, β_2, σ^2, and X_{CP}. Of particular interest is how the speed threshold X_{CP} affects parameter estimates of β_1 and β_2. We used a log-normal distribution in the change-point analysis because all encounter distances were positive.

The change-point model was conducted in a Bayesian estimation framework that allowed us to calculate probability densities representing the uncertainty for each of the four model parameters. We used noninformative prior probabilities for all model coefficients with the goal of allowing the data to support identification of the speed threshold (change point) at which there was a difference in mean distance from ship to whale. This noninformative approach corresponded to the change-point coefficient having a uniform prior distribution between 9 and 17 knots (4.6 and 8.7 m/s) [$X_{\mathrm{CP}} \sim \mathrm{Unif}(9,17)$]. Although encounters with whales occurred at speeds faster and slower than this range, these speeds corresponded to the range where we had at least 20 observations in each 1-knot speed increment (1 knot = 0.5144 m/s). The mean distances above and below the change point were specified with a lognormal distribution with large variance [$\beta_1 \sim \log\mathcal{N}(0,1000)$, $\beta_2 \sim \log\mathcal{N}(0,1000)$] and the standard deviation of the lognor-

8 ⟨http://www.dnr.state.mn.us/mis/gis/tools/arcview/extensions/DNRGarmin/DNRGarmin.html⟩

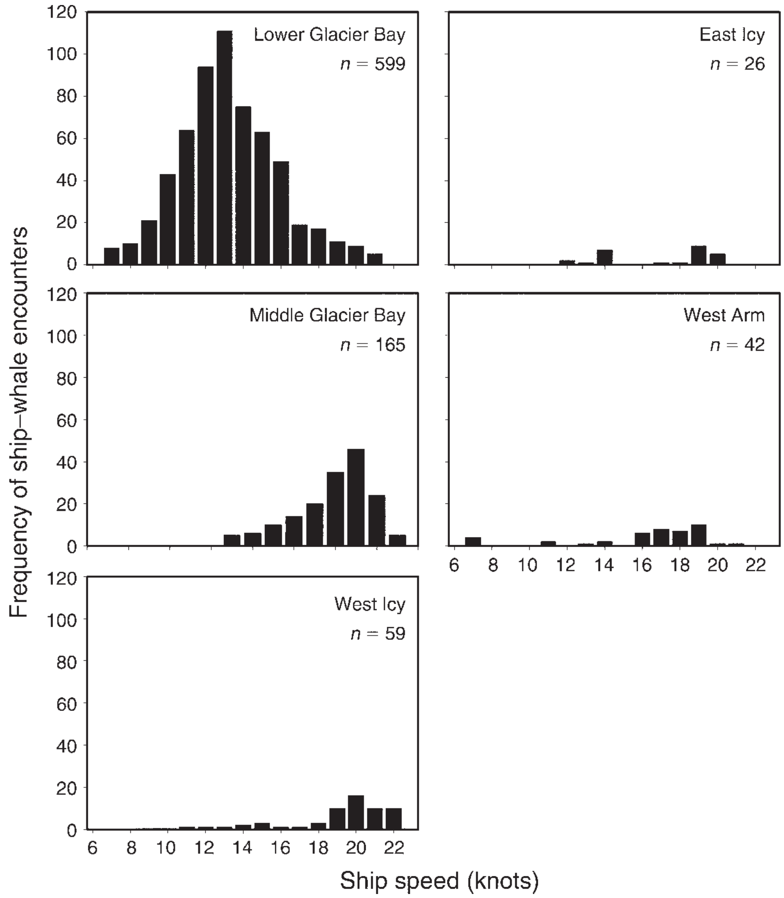

FIG. 2. Frequency of encounters between cruise ships and humpback whales, 2006–2009, by subarea and binned by 1-knot (0.5144 m/s) ship-speed increments ($n = 891$ unique ship–whale encounters).

mal observations was specified with a diffuse uniform distribution [$\sigma \sim$ Unif(0, 20)]. The coefficients were estimated through use of the Gibbs sampler, a Markov chain Monte Carlo (MCMC) algorithm implemented in WinBUGS (Spiegelhalter et al. 2003). Multiple chains were run using dispersed initial values for each model to ensure the MCMC chain converged to a stationary target distribution. Monitored parameters in all models had scale reduction factor (SRF) values that indicated samples were being drawn from the target distribution (i.e., SRF $\sim$ 1). The initial 30% of the samples were used to reach the stationary target distribution and were discarded with the subsequent samples thinned to produce approximately 1000 draws from the stationary target distributions. The 1000 draws were used to compute the posterior mean and 95% central probability intervals (credible intervals; 95% CrI). The diagnostics were implemented using the R2WinBUGS package in R (R Development Core Team 2007).

RESULTS

From 2006 through 2009 observers logged more than 2760 hours recording ship–whale encounters during 380 unique ship entries into Glacier Bay, Alaska, USA. Observations occurred aboard 18 different cruise ships and constituted ~49% of all ship entries into the park during that period. A total of 891 unique ship–whale encounters were recorded at distances ranging from 21 m to 1000 m ($\bar{x} = 567$ m, median = 576 m). Most (811) of the encounters (91%) occurred between 300 m and 1000 m although there were 61 encounters (7%) at 200–100 m, and 19 encounters (2%) within 100 m. No collisions were detected. Nearly all (754) of the encounters were with a single whale (85%) or with a group of two whales ($n = 96$ encounters; 11%); the remaining 4% of encounters occurred with group sizes of ≥ 3 whales. Encounter distances did not differ when comparing group sizes of 1 vs. >1 (group size 1 whale, $\bar{x} = 565 \pm 10$ m; group size $\geq$ 2 whales, $\bar{x} = 572 \pm 29$ m; $t = 1.96$, $P = 0.81$) and thus all analyses were considered independent of group size.

The average and range of ship speed (over ground) during encounters, as well as the frequency of encounters varied dramatically among subareas (Fig. 2). For example, in Middle Glacier Bay there was a large number of encounters recorded (165 encounters) but mostly (>76%) between 17 and 20 knots (8.7 and 10.3 m/s). In contrast, there was high variation in the speed when whales were encountered in the West Arm subarea

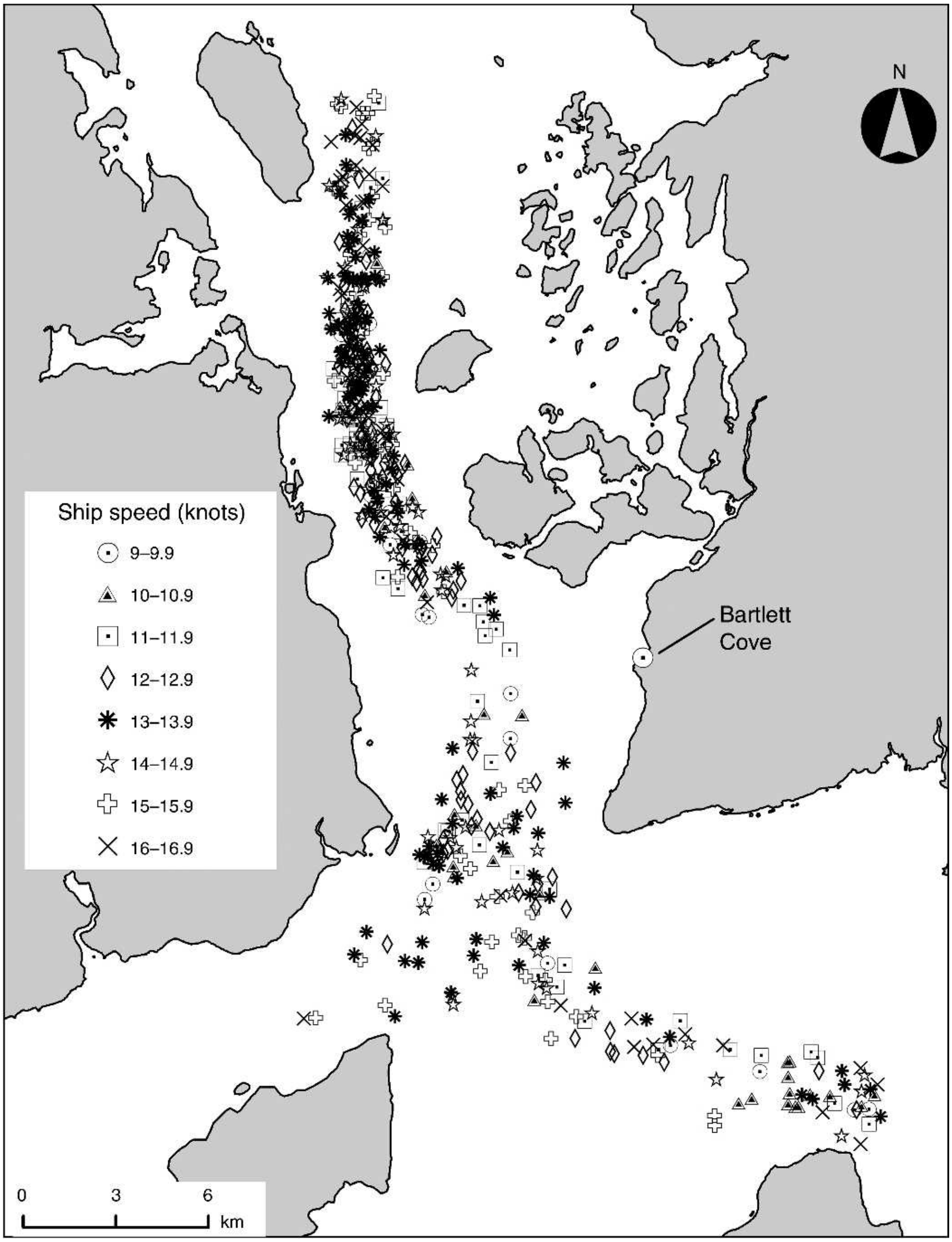

FIG. 3. Locations of humpback whales ($n = 599$) during encounters with cruise ships at different ship speeds in the Lower Glacier Bay subarea, 2006–2009. For ship speeds, note that 1 knot = 0.5144 m/s.

but very low sample size (<10 encounters) for any given speed. In contrast there were at least 20 encounters at speeds from 9 to 17 knots (4.6 and 8.7 m/s) in the Lower Glacier Bay subarea. This was due to ships slowing during transfer of NPS interpretive rangers from Bartlett Cove, speed regulations (with variable compliance), and a consistent presence of whales.

Thus, to reduce the possibility of spatial autocorrelation between speed and probability of encounter, we used only the data from the Lower Glacier Bay subarea in our Bayesian change-point model. Doing so reduced our sample size only marginally because this subarea accounted for almost 70% of all encounters recorded during the study. Within the Lower Glacier Bay subarea, there was no evidence that whale encounters were spatially aggregated at higher ship speeds (Fig. 3).

The Bayesian change-point model identified a high probability of a change in the relationship between ship speed and encounter distance around 11.8 knots (6.1 m/s) (Fig. 4A). The maximum probability of a change

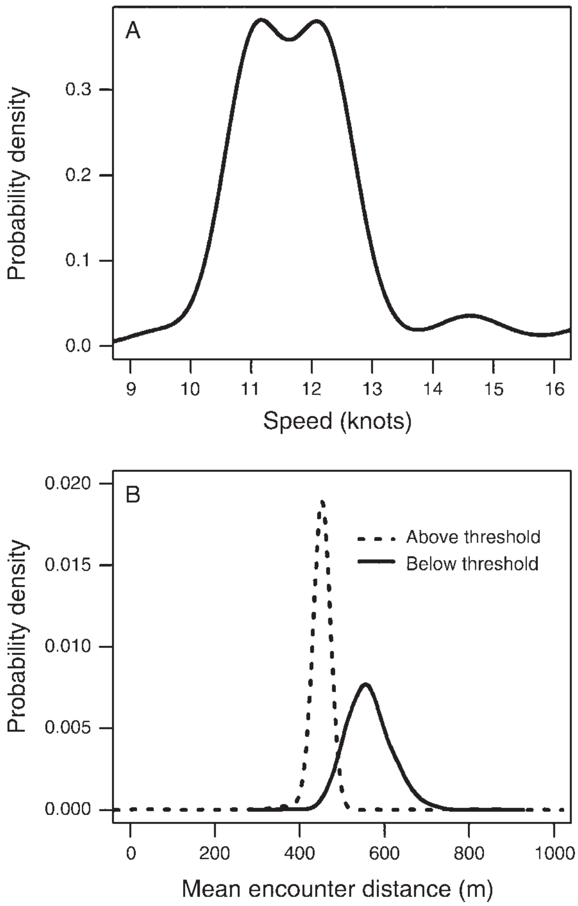

FIG. 4. Posterior probability distribution of (A) the speed threshold coefficient in the Bayesian change-point model (1 knot = 0.5144 m/s) and (B) the mean encounter distances to whales above (solid line) and below (dashed line) the speed threshold.

point occurred at 11.8 knots although there was only a slightly lower probability the change point occurred at 12.2 knots (6.3 m/s) (Fig. 4A). The probability that the change point occurred over the interval between 10 to 13 knots (5.1–6.9 m/s) was 0.88, i.e., P(10 knots $< X_{CP} <$ 13 knots) = 0.88). As a result, the highest probability for β_1 and β_2, the average encounter distances above and below the 11.8 knot change point were 448 m (95% credible interval, 398, 485) and 562 m (95%CrI, 468, 676; Fig. 4B). Binning the speeds by 1-knot (0.5144 m/s) increments clearly demonstrates that, on average, when ships were traveling faster, whales were encountered more closely (Fig. 5).

Discussion

Reducing the probability of severe injury or death as a result of a collision—a primary management objective in regulating ship speed—can occur by reducing the probability of any of the series of constituent events during a collision including the probability of (1) an encounter given a ship's presence in an area, (2) a close (severe) encounter given an encounter, (3) a collision given a severe encounter, and (4) severe injury or death given a collision. Recently Silber et al. (2010), using scale models of ships and whales in experimental flow tanks, demonstrated that under certain conditions reduced ship speed may reduce the probability of a collision given a severe encounter, and Vanderlaan and Taggart (2007) demonstrated that in the event of a collision, reduced ship speed may reduce the probability of severe injury or death. Our study is the first to demonstrate that the average distance between ships and whales decreases with increasing ship speed, confirming that speed reduction is an effective means for reducing the probability of severe encounters. If we assume that the closer that whales encounter ships the more likely they are to be struck, then, by extension, reducing ship speed may be an effective management action in reducing the probability of a collision.

It is beyond the scope of our study to identify the mechanism underlying the speed–distance relationship, although we feel the results are not likely a function of ship avoidance behavior of the whales. Cruise ships in our study area have no designated marine mammal observer on the bridge, which can influence the probability of detecting whales (Weinrich et al. 2010) needed prior to initiating avoidance measures. In addition, we regularly communicated with the ship captains/pilots and many have stated that when a whale is detected they generally retain course and speed, noting that the confined space within Glacier Bay hinders large course alterations. What is more, despite nearly 900 encounters with whales over four years we know of only two instances when ships altered course or speed in order to avoid whales (in both cases it was a group of >2 whales), and one instance when the ship captain knew of an approaching whale but took no evasive measures. In this instance, the observer radioed the ship bridge to inform them that a whale, which appeared to

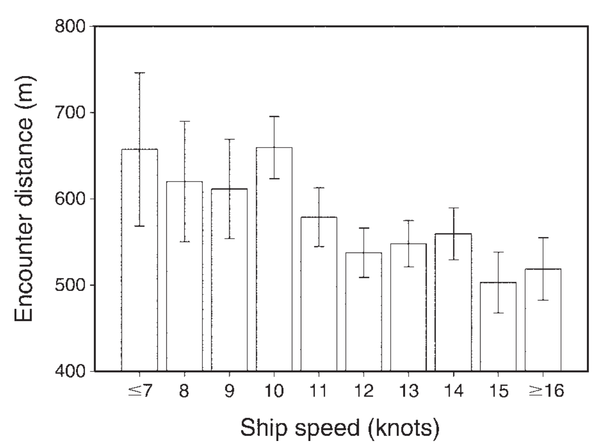

FIG. 5. Average encounter distances (mean ± SE) between cruise ships and humpback whales, binned for 1-knot speed increments in the Lower Glacier Bay subarea, 2006–2009. 1 knot = 0.5144 m/s.

PLATE 1. A humpback whale encounters a cruise ship in Glacier Bay National Park and Preserve. Photo credit: Janet Neilson, National Parks Service.

be resting at the surface, was directly in the path of the ship ~4 km away. Over the next nine minutes the observer repeatedly radioed the bridge as the ship–whale encounter distance decreased, and despite acknowledging the location of the whale, the ship captain/pilot maintained course and speed. As the ship approached to less than 70 m, the whale initiated a deep dive and a collision was narrowly avoided.

If in fact the speed–distance relationship is a function of whale avoidance behavior of the ships (as opposed to ship avoidance behavior of the whales), one scenario by which faster ships result in closer encounters could occur if whales are initiating avoidance behavior once an acoustical threshold is exceeded, and acoustic signals from ships are somewhat independent of speed. There is currently no information available regarding detection and response by large whales (cetaceans) to variation in received acoustic signals under different ship speeds (NRC 2005). Nevertheless, recent acoustic measurements of four cruise ships with diesel-electric propulsion systems recorded at the U.S. Navy's Southeast Alaska Acoustic Measurement Facility, including several ships used in our study, demonstrated that the overall sound levels emanating from these ships was similar at speeds differing by up to 8 knots (4.1 m/s) (Kipple 2002). If the acoustic signals are somewhat independent of speed, the distance between ship and whale at any acoustic threshold will thus be the same. Yet the whale will have less time to process the signal and initiate avoidance measures for the faster ships. Using the data from Kipple (2002) as an example, if a whale initiated avoidance measures at 130dB (an arbitrarily defined threshold) it would have only 8 s before collision for a ship traveling 20 knots (10.3 m/s) vs. 16 s for ships traveling 10 knots (5.1 m/s).

Regardless of mechanism, our results add to the sparse yet growing evidence that reducing ship speed may serve as an effective measure in meeting whale conservation objectives. Ultimately however, application of our results will need confirmation in other areas with different oceanographic conditions, vessel types, and whale species. Nevertheless, we highlight the effectiveness of using shipboard observers for understanding the relationship between whales and ships, and testing the effectiveness of applied management actions.

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