Spatial Pattern Analysis of Cruise Ship–Humpback Whale Interactions in and Near Glacier Bay National Park, Alaska

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Abstract Understanding interactions between large ships and large whales is important to estimate risks posed to whales by ships. The coastal waters of Alaska are a summer feeding area for humpback whales (*Megaptera novaeangliae*) as well as a prominent destination for large cruise ships. Lethal collisions between cruise ships and humpback whales have occurred throughout Alaska, including in Glacier Bay National Park (GBNP). Although the National Park Service (NPS) establishes quotas and operating requirements for cruise ships within GBNP in part to minimize ship–whale collisions, no study has quantified ship–whale interactions in the park or in state waters where ship traffic is unregulated. In 2008 and 2009, an observer was placed on ships during 49 different cruises that included entry into GBNP to record distance and bearing of whales that surfaced within 1 km of the ship's bow. A relative coordinate system was developed in ArcGIS to model the frequency of whale surface events using kernel density. A total of 514 whale surface events were recorded. Although ship–whale interactions were common within GBNP, whales frequently surfaced in front of the bow in waters immediately adjacent to the park (west Icy Strait) where cruise ship traffic is not regulated by the NPS. When ships transited at speeds >13 knots, whales frequently surfaced closer to the ship's midline and ship's bow in contrast to speeds slower than 13 knots. Our findings confirm that ship speed is an effective mitigation measure for protecting whales and should be applied to other areas where ship–whale interactions are common.

Introduction

Cruise ship tourism is the fastest growing travel sector in the world with an average annual passenger growth rate of 7.2% since 1990 (Cruise Lines International Association [CLIA] 2010). To accommodate demand, cruise ship capacity has expanded in recent years with 23 additional cruise ships scheduled to join the North American fleet between 2010 and 2014 (CLIA 2010). Although the Caribbean, Bahamas, Mediterranean, Alaska, and Mexico are the most popular cruise destinations, cruise lines continually search to expand their global ports of call. The increasing popularity of cruise ship tourism in sensitive marine areas can contribute to the degradation of the marine environment. In recent years, air and water pollution generated by cruise ships have triggered a number of national and international environmental regulations.

Perhaps less regulated and less understood are the impacts that cruise ships can have on marine mammals, particularly cetaceans. Impacts to cetaceans can occur through two primary mechanisms: though alteration of the underwater sound environment and through collisions. In

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both cases, the proximity of the whale to the ship is important. For example, the noise produced by ships, primarily through cavitation of the propellers, can mask communication or disrupt vital activities of whales (National Research Council [NRC] 2005; Southall 2005; Nowacek and others 2007; Southall and others 2007; Southall and Scholik-Schlomer 2008). In general, the closer whales are to ships, the higher level of acoustic exposure (e.g., Kipple 2002). When cruise ships and whales interact at close distances, sublethal or lethal collisions can also occur (Laist and others 2001). Collisions between large passenger ships and large whales have been documented in numerous locations worldwide (Knowlton and Kraus 2001; Laist and others 2001; Jensen and Silber 2003; Panigada and others 2006; Gabriele and others 2007; Brownell and others 2009; Carrillo and Ritter 2010). Collision rates have been reported to be increasing in places such as the Canary Islands, the Mediterranean Sea, and Alaska (Panigada and others 2006; Gabriele and others 2007; Carrillo and Ritter 2010), and although the occurrence and nature of these interactions have been summarized, few studies have collected empirical information on this important conservation and management issue.

Since the early 1980s Alaska has been a primary cruise destination regularly drawing >1 million cruise passengers annually. Cruise ships use the interconnected fjords of the southeastern panhandle of the state ("Southeast Alaska") to access major ports of call, including Skagway, Juneau, Sitka, and Ketchikan. These interconnected fjords are also prime foraging habitat for endangered humpback whales (*Megaptera novaeangliae*), which peak in abundance in the summer months May through September after migration from winter breeding grounds. Collisions between cruise ships and whales have been documented in Alaska, including a number from Southeast Alaska (Gabriele and others 2007). The population growth of the central North Pacific stock of humpback whales is currently estimated to be increasing at >5% per year (Calambokidis and others 2008), and although this robust population growth demonstrates that ship–whale collisions are not driving the population dynamics of this stock, the increasing numbers of whales and ships are likely to result in an increase in lethal and sublethal collisions. Appropriate environmental stewardship dictates that regulators and users take measures to avoid potentially lethal interactions with whales. For cruise ship companies catering to the ecotourism trade and featuring places to visit where wildlife and natural wonders are primary attractions, such actions are consistent with good business practices.

Perhaps nowhere else in Alaska is there greater attention to conflict between tourism and whale conservation than in Glacier Bay National Park (GBNP). GBNP is a Biosphere Reserve and World Heritage site, the only marine reserve in the state of Alaska, and one of the largest marine mammal protected areas in the world (Hoyt 2005). These designations, combined with its great natural beauty, make GBNP a popular destination for cruise ship tourism. Visitors to GBNP can access the marine waters of the park from tour, charter, or private vessels, including kayaks, although >95% of all visitors arrive by cruise ship (Gende 2007). The potential for ship–whale collision is of concern in GBNP because known or suspected collisions with humpback whales have occurred in recent years (Doherty and Gabriele 2001, 2004). GBNP enforces a combination of management measures to protect park resources, including speed restrictions in portions of the bay where the probability of whale presence is high ("whale waters"), mid-channel course restrictions, and daily and seasonal entry limits (Federal Register 2006). Daily entries are limited to two cruise ships per day. Seasonal entries are currently limited to 153 during the 92-day June through August "peak" season and 122 during the 61-day May through September "shoulder" season. The NPS is considering an increase to a maximum of 184 entries during peak season, allowing two ships into the park every day between June and August. Thus, the impacts that existing ship traffic have on park resources and how those impacts might change with an increase in ships permitted to enter the park are pressing management issues.

In this study, a shipboard observer stationed at the bow of cruise ships collected real-time data on how often, how close, and at what angle whales surfaced near ships as they transited waters in Southeast Alaska, including waters in GBNP. Our goal was to identify where within our study site and under what operating conditions (e.g., faster or slower speeds) whales tended to surface with relatively high frequency directly in front of the bow with the assumption that collision risk is higher when whales are at closer proximity to the ship's bow. We employed a unique analytical framework to examine the distribution of whale surfacing patterns relative to the bow of cruise ships.

Methods

Data Collection

From June 11 through September 15, 2008, and May 11 through 28 September, 2009, an observer recorded ship–whale interactions during 49 separate cruises. Observations were conducted from ships transiting Icy Strait, GBNP, and Cross Sound (hereafter Cross Sound route) or Icy Strait, GBNP, and Chatham Strait (hereafter Chatham Strait [CS] route) (Fig. 1), all of which are typical routes taken by cruise ships in Southeast Alaska. Sea state conditions within our study site never exceeded Beaufort 4 with the
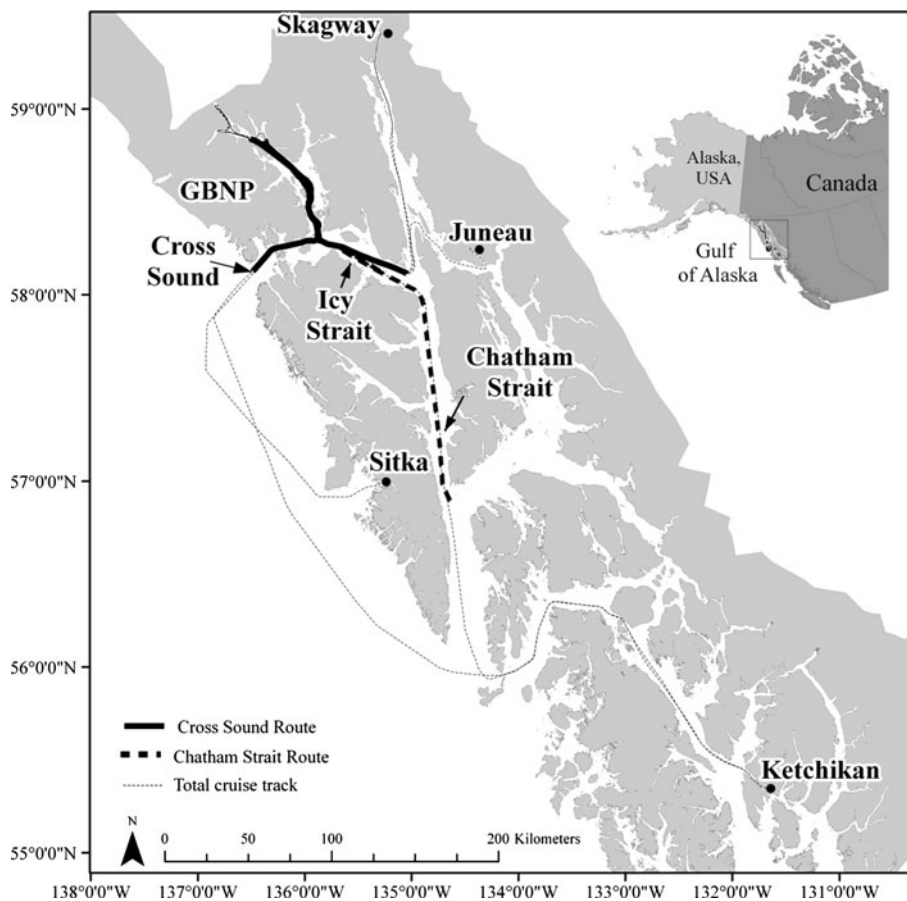
majority of observations (89%) conducted between Beaufort 0 and 2. Observers rotated between six cruise ships of the Holland America Line (Amsterdam, Ryndam, Statendam, Volendam, Zaandam, and Zuiderdam), all with similar diesel-electric propulsion systems. Ships varied in length from 219.5 m (>55,000 gross tons) to 285.3 m (>80,000 gross tons).

On each cruise, an observer spent 2 nights on the ship, embarking in Skagway or Juneau (day 1) and disembarking in Ketchikan or Sitka (day 3), respectively (Fig. 1). From daybreak of each cruise as the ship transited Icy Strait (day 2) until dusk, by which time the ship was in CS or the Gulf of Alaska (Fig. 1), the observer stood at the forward most bow of the ship (14.6 to 16.1 m above the water line) to scan the waters within 180° of the bow for whales. The only interruption in observation occurred when the ship was in the area north of Composite Island (Fig. 2) where humpback whales are rarely sighted or when fog impeded the observer's ability to see distances ≤1 km from the bow (<0.02% of the observation time), at which time observations ended until conditions improved. The daily duration of observations varied seasonally with day length (range = 5.6 to 13.0 h, $\bar{x}$ = 8.5).

During the observation period, ship location was recorded every 5 s (ship track) using a hand-held wide area

augmentation system–enabled global-positioning (GPS) unit (Garmin model 76Cx; Garmin, Ltd.; Olathe, KS). Naked-eye scans and scans using Leica Vector IV Rangefinder binoculars (> 4-km range, accuracy ± 1 m) and Swarovski hand-held binoculars (7 × 42) were used to look for whales. The rail of the ship occluded sightings <60 to 80 m from the bow (depending on the ship), although if a whale was within this distance, an observer could sometimes position themselves to see the distance between the whale and bulbous bow. When a whale was sighted, the location of the ship was recorded as a waypoint using the GPS, and the distance and bearing of the whale from the bow were recorded using the rangefinder binoculars. Distance and bearing were recorded repeatedly until the observer lost sight of the whale, the whale completed a terminal dive and was not seen again, or the ship passed the whale at an angle >90° to the port or starboard side of the bow. Note that these methods differ from those used to measure the distribution of whales for population estimation (Zerbini and others 2006).

In approximately half of the observations (51%), however, the distance between the ship and the whale had to be estimated because the whale dove before a distance reading could be made using the rangefinder binoculars. To examine if estimating the distance introduced significant

Fig. 2 The study site was divided into regions and subregions for analyses with regions including GB and AW. GB, under federal jurisdiction, is comprised of two subregions, including the UB and LB. AW, which are under state jurisdiction, were divided into west Icy Strait (an area affected by NPS management decisions), EIS, CS, and NPCS corresponding to different water bodies
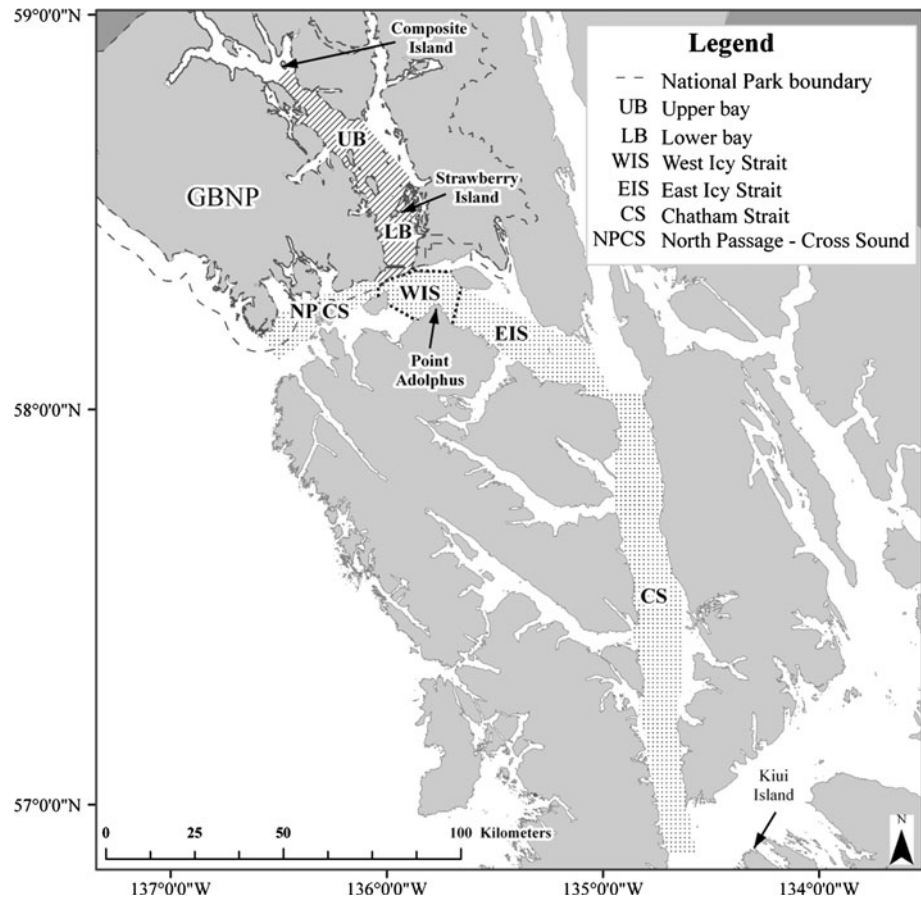
bias, during each cruise the observer estimated the distance to objects in the water (e.g., bird, vessel, iceberg) and then immediately measured the actual distance using the rangefinder binocular. We found that the difference between estimated and measured distances increased linearly with the measured distance and, on average, the observer underestimated the distance by approximately 14.9% of the actual distance (SE ± 0.64%). Therefore, estimated distances were less precise but not strongly biased and were used without correction in the analyses.

At the end of the observation day, all sighting data were entered into an MS Access database, and spatial data from the GPS (ship track and waypoint whale sightings) were downloaded using DNR Garmin (Minnesota Department of Natural Resources [MDNR] 2001; St. Paul, MN). A Visual Basic script developed by Bill Eichenlaub (NPS, Gustavus AK) was used to correct for magnetic deviation of the compass bearing and position of the whale relative to the bulbous bow. The Visual Basic script was also used to link spatial data to the whale sightings data, including estimating ship speed at the time a whale surfaced in front of the ship. To do so, the GPS waypoint taken during a whale sighting was plotted in ArcGIS 9.3 (Environmental Systems Research Institute Inc. [ESRI] 2008; Redlands, CA) on the ship track (waypoints collected every 5 s). To estimate

speed at the time of the whale encounter, the total distance the ship traveled during the five cruise ship track points before and the five track points after the whale GPS waypoint was summed and divided by the time it took to cover that distance. On 15 separate cruises in 2009, an additional GPS unit set to record ship location every 30 s was used to estimate ship speed for the total duration of the cruise. Speed was recorded in knots because this is the metric used for managing ship traffic for whale conservation purposes in Alaska and elsewhere (Federal Register 2006, 2008).

Analysis Framework

We limited analysis of ship–whale interactions to those that occurred within 1 km from the bow for several reasons. First, we could not determine a biologically based maximum distance where ship presence had no effect on the whale, and we assumed a collision was more likely when whales were closer to the ship. Second, cruise ships traveled at least 1 km from the shore during our observation periods; thus, there was equal probability for a whale to surface on all sides of the ship regardless of location within the study region. Third, Zerbini and others (2006) found that the detection probability for humpback whales was near 100% at 1-km distances from a research ship. We confirmed this

assumption when we found 100% concurrence of data when ship–whale interactions were recorded using two observers who collected data independently aboard the same ship ($n = 9$ cruises with double observers).

We developed a relative coordinate system in ArcGIS 9.3 (ESRI 2008) to analyze the spatial pattern of ship–whale interactions (hereafter surface events) relative to the bow of cruise ships. Relative coordinates were used in place of geographic coordinates because they provided a unique spatial reference in front of the ship regardless of the geographic location along the cruise track or the time during the cruise when a whale was observed to surface in front of the ship. The relative coordinate system thus allowed us to quantify the distribution of whale surface events relative to the bow of moving cruise ships. Relative coordinates for each whale sighting were calculated using distance and bearing data. From the relative coordinate framework, surface events were queried by spatial extent (e.g., Glacier Bay) or by data grouping corresponding to relevant management actions (e.g., ship speed and ship entry quotas into GBNP).

Kernel-Density Estimator

Frequency of whale surface events was modeled using the kernel-density estimator (KDE) calculated in Spatial Analyst (ESRI 2008). Whale surface events were assigned to a 2-km^2 grid with 100-m^2 resolution, which represented the total area in front of the bow. Each surface event reflected a unique location in front of the ship, and repeat observations of the same whale were included in our analysis. In the KDE calculation, a specified search radius (bandwidth) was used to estimate the probability that whales surfaced at certain locations in front of the ship (Silverman 1986; Gatrell and others 1996). In the absence of experimental data to inform our kernel-density calculation, we tested a range of bandwidth values and selected a bandwidth (100 m) that best characterized rare and spatially isolated surface events. This ensured that our analysis was conducted at a resolution appropriate to that with which the data were collected. We used the natural breaks (Jenks) method—where data are self-organized and bin sizes are determined from breaks in the probability frequency distribution—to bin surface events into three frequency classes of low (0–0.03), medium (0.03–0.06), and high (0.06–0.13) with value ranges representing the relative density of whale surface events per 100 m^2 in front of the ship's bow. To maintain comparability, we applied the same bin limits to all subsets of the data.

Analyses of Spatial Patterns of Whale Surfacing Events Relative to the Bow of Ships

Spatial pattern analysis is a quantitative parameterization of the composition (how many) and configuration (how

they are arranged) of spatial objects (McGarigal and Marks 1995; McGarigal and others 2002). For our application, spatial "objects" are whale surface events, and we analyzed spatial patterns of these events using metrics calculated in FRAGSTATS 3.3 (McGarigal and others 2002). Metrics were calculated at two levels (Table 1). At the first level, whale surface events were quantified across the full extent of the data without consideration of (whale surface) frequency class types (Table 1). At this level, the total number of all classes (N) and mean size of all classes (Table 1) were used to inform us whether whales tended to surface at numerous locations in front of the ship (larger N) and if those locations were of relatively large mean size. This latter inference has a practical application: A relatively large area of surface events positioned directly in front of the ship is more difficult for ship operators to avoid than a relatively small area positioned farther from the ship's bow. If the number and position of whale surface events occurred in one large area in front of the ship, analysis at the second level was used to inform us whether that large area was comprised of the low, medium, or high frequency class, or some combination of the three (Table 1). We examined whether a particular class was more numerous (large N), of relatively large mean size, and more clustered (small mean nearest neighbor distance [NND]) than other class types. Here the practical interpretation is that a relatively large and clustered high class area (high probability that a whale will surface in that particular location in front of the bulbous bow) will be more difficult for ship operators to avoid or maneuver around compared with a few small and dispersed high class areas positioned along the port or starboard bow. Metric values were compared relative to each other to look for differences in the pattern of whale surface events at different spatial extents or under different management actions.

Analyses by Regions and Subregions

We examined geographic differences in the spatial patterns of whale surface events in front of the ships within our study area using a hierarchical approach by dividing the study area into smaller geographic units, i.e., regions and subregions (O'Neill and others 1986; Urban and others 1987; Wu 1999). The entire study site was first divided into two regions, Glacier Bay (GB) and adjacent waters (AW) (Fig. 2). GB is under federal jurisdiction, and the NPS establishes cruise ship quota and operating requirements specifically to protect whales. AW are under the jurisdiction of the state of Alaska, and vessel traffic—including quotas, channel restrictions, and ship speed—is unregulated.

GB and AW were further divided into subregions, which allowed us to identify what spatial areas, if any, influenced

Table 1 Metrics calculated at two levels to quantify the pattern of the frequency of whale surface events across the full extent of the data without consideration of (whale surface) frequency class types (level 1) and by low-, medium-, and high-frequency class types (level 2)

Level	Metric	Description
1	N	Total no. of all classes
	Mean size (km^2)	Mean size of all classes
2	% Total area	Percentage of the total area in front of the bow by class type
	N	Total no. of each class type
	Mean size (km^2)	Mean size of each class type
	Mean NND (m)	Mean NND between classes of the same type

the pattern of whale surface events within GB versus AW. Within GB, subregions included lower bay (LB), which extended from the NPS jurisdictional boundary to Strawberry Island, and the upper bay (UB), which extended from Strawberry Island to Composite Island (Fig. 2). AW was divided into four subregions primarily based on different water bodies. These subregions included East Icy Strait (EIS), North Passage-Cross Sound (NPCS) and CS. CS was truncated to the northern tip of Kiui Island because observations were not conducted south of this point (Fig. 2). West Icy Strait (WIS) was defined as waters between the entrance to the park and Point Adolphus; this area is affected by management decisions (NPS 2003).

Analyses by Management Measures

In addition to patterns by regions and subregions, we also examined patterns of whale surface events relative to two existing management actions: ship speed and daily cruise ship entry quotas. In all areas of Alaska except GB, ship speed is unregulated for the purpose of whale-conservation measures. Consequently, ships travel at varying speeds throughout the study area as a result of varying itineraries and time constraints related to ports of call. Speed also varies as a result of NPS regulation, which limits speed to 13 knots in portions of GBNP where whale presence is high. Speed limits are often more restrictive in the lower bay simply because whales use the lower bay more often than the upper bay. Thus, we compared the pattern of whale surface events by ship speeds >13 knots or ≤13 knots.

GBNP further limits the number of ships allowed to enter the park to two per day, although there are currently a number of days when only one ship enters the park because the peak seasonal quotas (153 entries for the 92-day peak seasonal quota) limit the number of two-ship days. The number of two-ship days will increase should the seasonal quota of ship entries increase to the maximum of 184 (2

ships every day for the 92-day June through August peak season). We thus examined the pattern of whale surface events on one- versus two-ship days.

Results

Forty-nine cruises were completed during 2008 ($n = 20$) and 2009 ($n = 29$) constituting a total of 425 h of observation. Most of the cruises followed the Cross Sound route ($n = 39$; CS route $n = 10$ [2008 only]). The total linear distance traveled during observations along the Cross Sound route ($\bar{x} = 215.3$ km [range 164.7–252.8]) was less compared with the CS route ($\bar{x} = 340$ km [range 251.3–402]). Ships followed nearly the same track for each route, rarely deviating from their course. Mean ship speed (±SDs) during observation effort varied by subregion (Fig. 3). A total of 514 whale surface events within 1 km from the bow were recorded. The frequency of whales surfacing in front of the ship was highest from 900 to 1000 m, was mostly constant from 900 down to 300 m, and was decreased markedly at the closest distances (100–200 m) (Fig. 4).

Regional and Subregional Differences

The frequency and pattern of whale surface events differed by region and subregion. Although GB and AW both contained low, medium, and high (whale surface) frequency classes, the high-frequency class was more dominant, of larger mean size, more clustered, and positioned directly in front of the bulbous bow in AW compared with GB (Fig. 5; Table 2). Within GB, the patterns by subregion showed that the patterns of whale surface events within LB influenced the pattern more than in UB (Fig. 5; Table 2). In AW, WIS influenced the pattern more than any other subregion (Fig. 5; Table 2). The high class was only present in LB and WIS, although in WIS the high class comprised more total area in front of the ship and was located directly in front of the bow compared with LB (Fig. 5; Table 2).

Patterns by Management Measures

Patterns of whale surface events varied with management measures, particularly with ship speed. At speeds >13 knots, the frequency of whales surfacing at relatively high density (high class) was more numerous, of larger mean size, and more clustered compared with slower speeds (Fig. 6; Table 3). High-class surfacing events also tended to be clustered closer to the ship's midline and closer to the ship's bow when traveling > 13 knots (Fig. 6).
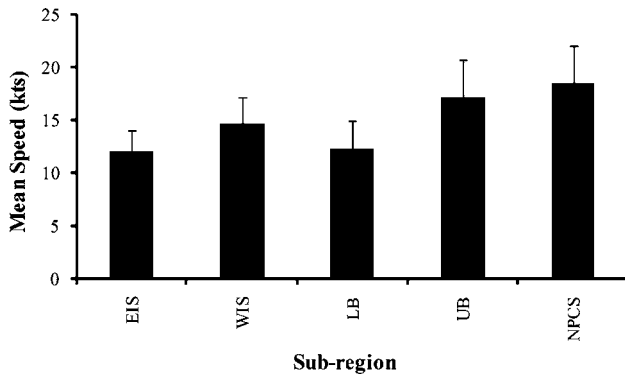
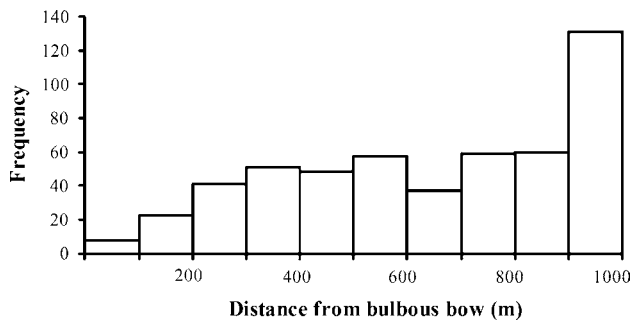Fig. 3 Mean ship speed (knots ± SE) by subregions, including EIS, WIS, UB, LB, and NPCS (2009 data only)

Fig. 4 Frequency of ship–whale interactions within 1 km of the bow of cruise ships

Of the 49 cruises, 18% were conducted when only one ship entered the park that day, and these entries were spread during the entire study period. Only the low and medium classes were present during one- and two-ship days. On two-ship days, the medium class was more numerous and more clustered compared with one-ship days (Fig. 6; Table 3).

Discussion

This is the first study to quantify whale surfacing patterns in front of cruise ships to compare differences at ship speeds >13 and <13 knots and in areas with and without conservation measures to protect whales. In our study, application of the relative coordinate system and the KDE was useful for identifying where within the study site and under what management conditions the probability for whales to surface directly in front of the ship was high.

Our first major finding showed that variation in patterns of whale surface events were spatially influenced and that the area between Point Adolphus and the GBNP jurisdictional boundary (WIS) influenced the pattern more than any other area within our study site. Although our study only spanned 2 years, and important whale habitat can shift
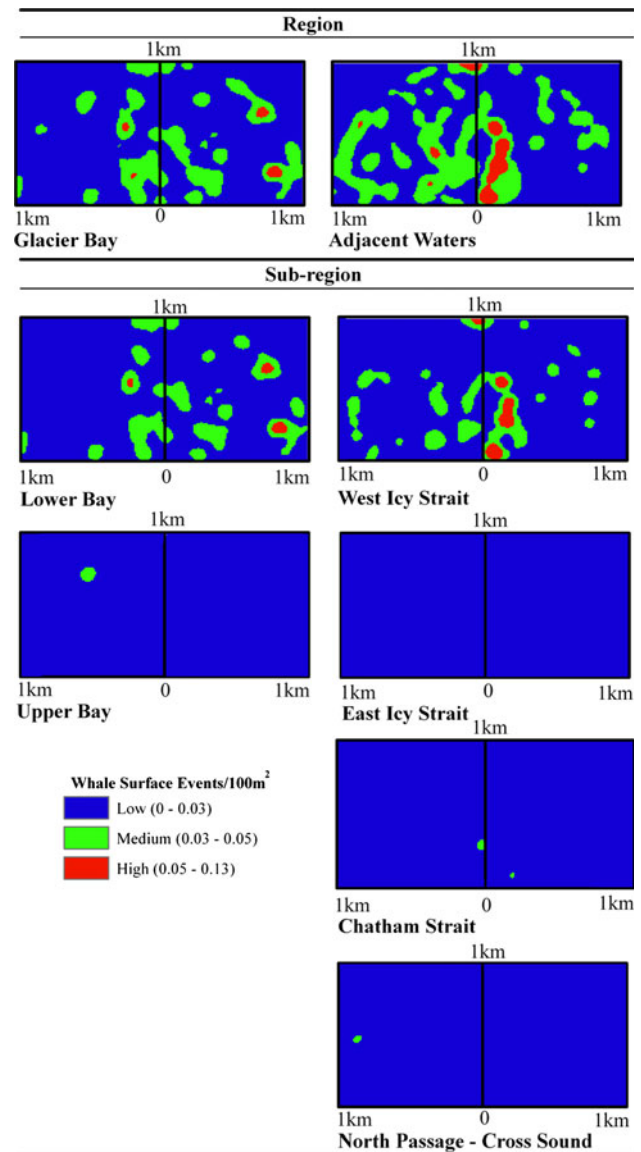

Fig. 5 Kernel-density map of the frequency of whale surface events by regions and subregions. *Blue*, *green*, and *red* indicate the locations where whales surfaced with low, medium, and high frequency within 1 km from the cruise ships' bow (0), respectively

annually with changes in prey abundance (Nielson and Gabriele 2009), the area near Point Adolphus has long been known as an area of high whale abundance, and cruise ships often go near this point for passengers to view aggregations of whales (NMFS 2001). Therefore, we expected that ship–whale interactions would be high in this area. However, it was striking that the high frequency class of whale surface events was centered almost directly in front of the path of the ship and generally within 0.5 km of the bow. Our results thus confirm that the WIS area represents an area of increased risk for ship–whale collisions and underscore the importance for ship operators to be

Table 2 Frequency of whale surface events by spatial extent were quantified across all classes combined (level 1) as total number of classes (*N*) and mean size (km²) and by individual classes (level 2) as percentage of total area (% total area), total number of each class (*N*), mean size (km²), and mean NND between classes of the same type

Spatial extent	Level 1		Level 2										
	N	Mean size (km²)	% Total area			*N*			Mean size (km²)			Mean NND (m)		
			L	M	H	L	M	H	L	M	H	L	M	H
GB	23	0.09	80.7	18.5	0.8	1	18	4	1.61	0.02	0.004	N/A	107.5	326
AW	25	0.08	69.8	27.1	3.1	3	16	6	0.4	0.3	0.1	43.3	66.2	214.3
UB	2	1	99.6	0.43	0	1	1	0	1.99	0.01	0	N/A	N/A	–
LB	21	0.1	85.2	14.1	0.7	1	17	3	1.7	0.02	0.005	N/A	106.8	533.3
WIS	22	0.09	82	11.8	1.8	1	17	4	1.73	0.01	0.009	N/A	104.4	170.4
EIS	1	2	100	0	0	1	0	0	2	0	0	N/A	–	–
NPCS	2	1	99.9	0.1	0	1	1	0	1.99	0.002	0	N/A	N/A	–
CS	3	0.67	99.8	0.22	0	1	2	0	1.99	0.002	0	N/A	247.6	–

L low, *M* medium, *H* high

When *N* = 1, mean NND is not applicable (N/A)
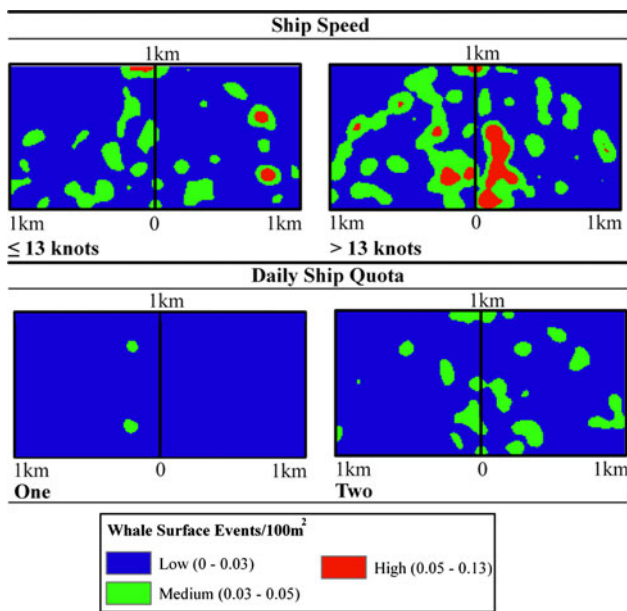

Fig. 6 Kernel-density map of the frequency of whale surface events by ship speed and by daily cruise ship entries into GBNP. *Blue*, *green*, and *red* indicate the locations where whales surfaced with low, medium, and high frequency within 1 km from the cruise ships' bow (0), respectively

attentive to the presence of whales in the area, particularly given that it is an area where ship traffic is not regulated.

It is noteworthy that the subregions in which whales surfaced in front of the bow in the highest frequency were near the entrance of GB either directly inside the park (LB subregion in GB) or immediately adjacent to it (WIS subregion in AW). These two subregions were far more similar in the frequency of whale surface events near the ship than any other subregions. Long-term monitoring of

whale abundances in GB and Icy Strait has demonstrated that whale feeding aggregations can shift between the park and Icy Strait from week to week and year to year, and individuals regularly move among these two subregions as they feed on forage fish (Nielson and Gabriele 2009). Therefore, the two subregions likely have similar whale densities because they encompass the same biological and oceanographic processes that drive whale distribution and ultimately the probability for ship–whale interactions.

Nevertheless, the frequency with which whales surfaced in front of the ships was comparatively less in LB than in WIS. One important difference is that LB is under NPS jurisdiction and ships traveling in this area are, for most of the summer cruise season, subject to speed restrictions ≤13 knots. Indeed, comparison of ship speed in LB versus WIS confirms that ships travel approximately 2 knots, on average, slower in LB compared with WIS. Thus, it is less likely that the differences in the pattern of whale surface events reflects appreciable differences in whale densities among the two subregions but more accurately reflects operational differences that covary with space.

Our analysis relative to ship speed across the entire study area confirms that speed plays an important role in the pattern of whale surface events around the bow. The frequency of high-class surface events was closer to the bow and closer to the ship's midline course, both of which would increase the chances of collisions with whales, when ships were traveling >13 knots compared with those traveling ≤13 knots. It is important to recognize that the result is clearly a function of both the density of whales and ship speed because there were several subregions, including UB and NPCS, where ships traveled on average >13 knots or, in the case of EIS, ≤13 knots, but encountered too few

Table 3 Frequency of whale surface events by ship speed and GBNP daily ship quotas quantified across all classes combined (level 1) as total number of classes (N) and mean size (km²) and by individual classes (level 2) as percentage of total area (% total area), total number of each class (N), mean size of each class (km²), and mean NND between classes of the same type

Management measure		Level 1		Level 2											
		N	Mean size (km²)	% Total area			N			Mean size (km²)			Mean NND (m)		
				L	M	H	L	M	H	L	M	H	L	M	H
Ship speed	>13	32	0.06	68.90	26.20	4.90	2	21	9	0.69	0.02	0.01	72.80	69.60	154.10
	≤13	29	0.07	84.80	14.30	0.90	1	25	3	1.70	0.01	0.006	N/A	81.40	471.40
Daily quota	One	3	0.67	99.38	0.62	0	1	2	0	1.99	0.01	0	N/A	470.96	–
	Two	18	0.11	88.78	0.11	0	1	17	0	1.78	0.22	0	N/A	123.84	–

L low, M medium, H high

When N = 1, mean NND is not applicable (N/A)

whales to generate frequency classes driven by the frequency classes found in LB and WIS. It is also important to note that ships transited EIS at speeds similar to those in LB. Although speed is unregulated in EIS, many ships traveled through this area during the early morning hours just before entering GBNP, and the slower speeds likely reflect the operational preferences established by ship operators to ensure timely arrival into the park. Ultimately it may be insightful in future analyses to adjust the parameters by which frequency classes and spatial boundaries are defined to compare whale surface event patterns in low- versus high-density whale areas.

That ship speed influenced the pattern of whale surface events was an important result because regulating or recommending decreases in ship speed in high-risk areas has been a common yet contentious management strategy where ship–whale collisions are of concern (ACCOBAMS 2005; Carrillo and Ritter 2010; Federal Register 2008). Decreased speeds are assumed to decrease the probability of lethal collisions, although there are surprisingly few studies confirming this assumption (Laist and others 2001; Vanderlaan and Taggart 2007; Silber and others 2010). Nevertheless, the effectiveness of decreasing ship speed may ultimately depend on the mechanism driving this result. For example, it is commonly assumed that decreased speed allows both whales and mariners more time to detect and initiate avoidance measures. Previous work has suggested that whales exhibit a last-second flight response when in close proximity to large vessels (Laist and others 2001), although the speed with which these last-second flight responses are exhibited is unknown or have not been reported. In addition, Nowacek and others (2003) report that North Atlantic right whales respond to an artificial alert stimulus by surfacing, but they do not respond to noise produced by ships. Whale response behavior was beyond the scope of our research. However, observers reported that responses of humpback whales in close proximity to ships

(approximately ≤300 m) was variable and whales did not always alter their course in response to the ship. Ultimately, it would be of interest to examine whale response behavior in relation to ship speed. Should the result of low-frequency surface events in front of the ship be solely a product of the ship operator detecting whales and altering course or speed to avoid the whale (compared with the whale altering behavior to avoid the ships), the effectiveness of slower speeds will then be a function of the detection ability by the ship operator, which will be decreased at night or under limited visibility. In our study, the observer was on the bow of the ship and thus not privy to the operations, communications, and detection of whales that occurred at the bridge. Nevertheless, we know of two occasions when cruise ship operators notified the observer of their intentions to alter their course to avoid a large aggregation of whales located mid-channel near the entrance of GB. Assuming that the slower speed allowed for more spatial separation between the whale and ship from detection to avoidance measures, this may be why patterns of whale surface events were less when ship speeds were slower. Clearly the mechanisms associated with ship–whale interactions and how they influence separation distances is an important avenue of future research.

For areas outside of GB, differences in ship speed appear to be a function of the distance of port of call. Our data indicate that depending on route and location, ships may travel between 9 and 20 knots when moving at night between ports of call. The average speed of ships scheduled to arrive in Ketchikan the morning after visits to GBNP was much faster ($\bar{x} = 19.7 \pm 2.70$ knots) than for ships scheduled to arrive in Sitka ($\bar{x} = 9.1 \pm 2.48$ knots). Due to time constraints, regulations decreasing ship speed within GBNP may have an impact on ship speed in other areas of the park or outside the park. During our study, cruise ships that entered GBNP operated under a concession contract that required they spend a minimum of 5 h in the upper

west arm of the park, which is the area north of Queen Inlet (just south of Composite Island). We found that ships traveled appreciably faster when traveling between seasonal whale waters and Composite Island ($\bar{x} = 17.2 \pm 1.83$ knots) than when traveling in the lower bay ($\bar{x} = 12.3 \pm 3.01$ knots), possibly to meet these multiple-ship management regulations. Thus, in some cases, restrictions in GB have the potential to affect the speed of cruise ships along different portions of the cruise.

Surprisingly, we also found that whales surfaced more frequently in front of ships on days when two ships versus one ship entered the park. We question the robustness of this comparison because the overwhelming majority of observations took place on days when two ships entered the park. Nevertheless, we have no reason to believe conditions varied considerably during the cruises that occurred on one- and two-ship days. Future work that places observers on the second ship of the day to enter the park or on ships that enter the park at the same time would provide further insight into whether patterns on two-ship days change with the order and timing of cruise ship entries.

Previous efforts to inform management measures for protecting whales from ships have focused on characterizing the spatial and temporal overlap between shipping lanes and whales (Ward-Geiger and others 2005; Merrick and Cole 2007; Firestone and others 2008). Our study used an observer at the bow to document real-time observations of ship–humpback whale interactions to model the frequency of whale surface events relative to the bow of moving cruise ships. Our results showed that whales surfaced with high frequency in front of ships in lower portions of GBNP and west Icy Strait between the park entrance and Point Adolphus. Whales also frequently surfaced in front of ships traveling >13 knots. Other whale species may vary in their response to vessel traffic, and it would be beneficial to not only conduct studies that allow for comparison of whale surfacing behavior by species, but to also allow for comparison of whale response behavior in calving versus feeding grounds or along whale migratory routes. Our research methods proved useful when applied in areas where ship–whale interaction rates varied in frequency and may be a cost-effective solution for obtaining empirical information in locations where the frequency and severity of interactions between cetaceans and vessels are of concern. Ultimately, research efforts that seek to identify the underlying mechanisms influencing the pattern of whale surface events will further guide development of management measures and vessel operating guidelines most effective at minimizing collision risks to whales.

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