Preliminary results from line transect surveys utilizing surprise encounters and near-misses as proxies of vessels collisions with humpback whales (*Megaptera novaeangliae*) in Maui County waters, Hawai'i, USA.

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ABSTRACT

The concurrent increase in abundance of certain whale populations and boat traffic in many parts of the world has highlighted the need for quantifying the probability of whale encounters and whale-vessel strikes. The number of humpback whales (*Megaptera novaeangliae*) frequenting Hawaiian breeding grounds is increasing, along with the number of reported collisions, since 1975. A study investigating the probability of vessel collisions with this endangered species was initiated in Maui County waters, an area widely used by both commercial and recreational vessels. Surprise encounters (SE) and near-misses (NM), defined as a group of whales sighted (at abeam and forward angles) within 300 m and 80 m of a vessel, respectively, were used as proxies for probability of whale-vessel strikes. Objectives included identifying any relationship between environmental (*e.g.* Beaufort sea state) or vessel-specific variables (*e.g.* speed), and the probability of a whale-vessel collision. The susceptibility of different age-classes and group compositions (*e.g.* calf presence) to vessel strikes was also investigated. Between February and April 2013, 33 line transect surveys were conducted corresponding to 86.8 hr and 1,058 n.mi. of survey effort. A total of 361 groups or 723 individuals were recorded, including 191 SE (52.9%) and 12 NM (3.3%). Higher instances of SE and NM were observed between the islands of Lana'i and Maui. Enumeration of SE and NM individuals indicated a maximum of 2 and 5 individuals/km^2 for calf and non-calf groups, respectively. The rate of SE increased with vessel speed, from 1.5 encounters/hr at five kts to 4.2 encounters/hr at 20 kts. No NM occurred at 5 kts. Little variation in the detection of encounters was found under different DSS and BSS conditions. Calves were present in 28.3% of SE and 58.3% of NM. This coincides with previous reports that calves may be more susceptible to vessel collisions. Continued research over the next 4 years will help identify frequency and trends of potential vessel collisions with humpback whales, and contribute to developing a predictive model of vessel strikes for management purposes.

KEYWORDS: HUMPBACK WHALE, VESSEL COLLISIONS, WHALE-WATCHING, MAUI, HAWAII.

INTRODUCTION

Globally, vessel collisions with cetaceans are a growing concern, and their increasing numbers constitute a substantial conservation issue (Laist *et al.*, 2001; ACCOBAMS, 2006; Douglas *et al.*, 2008). Both recreational and commercial vessels are involved in this type of collision, including tankers, cargo or cruise ships, whale-watching vessels, Navy ships, hydrofoils, sailboats, high speed ferries, fishing boats, and research vessels (Jensen *et al.*, 2004; Dolman *et al.*, 2009; Ritter, 2012). As a result, various monitoring programs have been implemented, such as the International Whaling Commission's Ship Strike Database (IWC, 2013).

Although a wide range of cetacean species are reportedly struck by vessels, larger endangered species such as humpback whales (*Megaptera novaeangliae*), North Atlantic right whales (*Eubalaena glacialis*), North Pacific right whale (*Eubalaena japonica),* fin whales (*Balaenoptera physalus*), and blue whales (*Balaenoptera musculus*) are more susceptible particularly when a) having a primary habitat overlapping areas of heavy vessel traffic; b) resting at the surface; or c) moving at a slow pace (Laist *et al.*, 2001; Lammers *et al.*, 2003; Vanderlaan and Taggart, 2007; Behrens and Constantine, 2008; Berman-Kowalewski *et al.*, 2010; DeAngelis *et al.*, 2010). Some populations of these species have begun to recover (Best, 1993; Barlow *et al.*, 2011); however, increased vessel traffic has contributed to an increased risk of whale-vessel collisions (Jensen *et al.*, 2004; Dolman *et al.*, 2006), preventing the recovery of certain populations (*e.g.* North Atlantic right whale; Kraus, 1990; Knowlton and Kraus, 2001).

Currently, our understanding of whale-vessel collisions is limited in many ways, *i.e.* the specific factors that lead to collisions are not well understood and the true frequency of collisions is still unknown (Neilson *et al.*, 2012). In the latter case, many incidents are not reported due to crew being unaware of a collision, particularly on large tanker ships, difficulty determining how an incident happened when vessels are on autopilot, and/or concerns regarding liability (NOAA, 2012). Additionally, many of the animals involved in collisions lack external signs of trauma. Internal injuries caused by blunt force trauma can only be detected via necropsies and a limited proportion of fatally wounded whales are recovered and examined. When strikes are reported, there is still a scarcity of critical details such as the fate, age-class, and sex of the animal, as well as the location and speed of the vessel (Neilson *et al.*, 2012).

Vessel speed and size are key contributors to severity and frequency of whale-vessel collisions, with faster vessels accounting for higher instances of strikes (Laist *et al.*, 2001; Panigada *et al.*, 2006; Vanderlaan and Taggart, 2007). To illustrate, Vanderlaan and Taggart (2007) estimated that if a vessel with a mass significantly exceeding that of a whale is travelling at 12 knots (kts), 50% of collisions would be lethal. Alternatively, if the same vessel is travelling in excess of 19 kts, 100% of collisions are deemed to be lethal.

The Hawaiian Islands are the most isolated archipelago in the world. Consequently, they are highly dependent on vessel traffic for commerce. Moreover, vessels are an important mean of transportation and a major source of revenue for the local economy, particularly for the tourism sector (Lammers *et al.*, 2003). In Hawaiian waters, there has been a concurrent increase in vessel traffic (commercial and recreational) and humpback whale abundance (Mobley *et al.*, 2001; Lammers *et al.*, 2003; Delfour, 2007; O'Connor *et al.*, 2009). The number of whales frequenting these mating and calving grounds is estimated at 7,469 to 10,103 individuals, increasing at an annual rate of *ca.* 5.5-7.0% (Mobley *et al.*, 1999, 2001; Calambokidis *et al.*, 2008; Allen *et al.*, 2012). This has resulted in a rise of whale-vessel collisions being reported, with calves and juveniles having a higher incidence of being struck (Laist *et al*., 2001; Lammers *et al.*, 2003). However, increased monitoring efforts over the past 20 years, through the development of the Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS, 1992; Figure 1), may account for some of the apparent rise in frequency of whale-vessel collisions and make the data challenging to interpret (Lammers *et al.*, 2003).

The majority of whale-vessel strikes reported in Hawaiian waters by the National Ocean and Atmospheric Administration (NOAA) and the HIHWNMS occur in the four island region of Maui County (Maui, Moloka'i, Kaho'olawe, and Lana'i); more specifically between Maui, Moloka'i, and Lana'i (Mobley *et al.*, 1999; Laist *et al.*, 2001; Lammers *et al.*, 2003; Barlow *et al.*, 2011). To illustrate, between 1975 and 2003, 67% of whale-vessel collisions occurred in Maui waters (Lammers *et al*., 2003). In the 2012-2013 whale season, 10 vessel strikes were reported to NOAA, of which seven were recorded off Maui and one off Lana'i (Ed Lyman, NOAA/HIHWNMS, pers. comm., May 10, 2013). This is not surprising given that the greatest density of humpback whales in Hawaiian waters occurs in this region (Mobley *et al.*, 2001), along with 50% of Hawaiian whale-watching operations (O'Connor *et al.*, 2009). The area also hosts a fleet of both commercial (*e.g.*, large cruise ships, barges, and military crafts) and non-commercial vessels including un-motorized watercrafts (*e.g.*, canoes, kayaks, and stand up paddle boards), which are becoming more popular (pers. obs.) and are occasionally involved in a collision with humpback whales (Ed Lyman, NOAA/HIHWNMS, pers. comm., May 10, 2013). Increasing reports of whale-vessel collisions in Maui County leeward waters may, however, be primarily linked to the number of whales increasing at a faster rate than vessel traffic. Indeed, between 1988 and 2006, humpback whale sightings in Ma'alaea Bay tripled while vessel traffic declined by 10% (Forestell *et al.*, 1990; Kaufman, unpublished data).

With whale-vessel collisions being a matter of concern globally, most studies have assessed the risk of whales being struck by establishing co-occurrence of the distribution of whales and vessel traffic within major shipping routes (*e.g.*, Vanderlaan *et al*., 2009; Williams and O'Hara, 2010; Redfern *et al*., 2013), which in some cases has resulted in shifting shipping lanes (*e.g.*, Merrick, 2005; Hinch and De Santos, 2010). To date, very few studies have attempted to quantify the risk of vessel strikes by taking into account the frequency of near collisions. Richardson *et al.* (2011) undertook a modeling exercise, accounting for various conditions (*e.g.*, environmental variables) to evaluate the probability of a whale-vessel collision based on data collected from whale-watching vessels as platforms of opportunity (PoP) in Maui County waters. The authors used surprise encounters (SE) and near-misses (NM) as proxies for whale-vessel collisions. SE and NM were defined as first sighting a group of whales ≤ 300 meters (m) and 80 m from a boat (abeam to forward angle), respectively. A distance of 80 m was chosen as it is less than the Hawaiian regulation, which restricts any vessel from approaching a group of whales ≤ 90 m. Richardson *et al.* (2011) model predicted a) a 8.2% increase in SE for a velocity increase of one knot (kt); b) a decrease in the likelihood of a SE with an increase in wind speed (Beaufort sea state); and c) a 5.5% chance of a NM during whale-watching trips. Given the inherent biases of sampling from PoP, the authors recommended further investigation a) using line transect surveys, with no approach restrictions, to control for certain variables (*e.g.*, effort, vessel speed, operator variability, and platform type); and b) assessing a potential age-class or sex biases associated with SE or NM. Taking into account Richardson *et al.* (2011) recommendations, this five-year study was initiated in 2013, under permit NMFS 16479, with the following objectives:

1) Model the probability of whale-vessel collisions using SE and NM as proxy data from line transect surveys to help reduce the incidence of whale-vessel collisions and allow vessels to operate more safely;
2) Test the hypothesis that sub-adults, calves, and/or specific individual whales are more susceptible to collisions in Maui;
3) Test the effects of boat speed and environmental conditions on the probability of whale-vessel collisions;
4) Compare results with Richardson *et al*. (2011) study.

METHODS

Study area

To evaluate the potential for whale-vessel collisions within the four island region of Maui County, parallel survey lines at 45° (true) North were equally spaced 1 nautical mile (n.mi.) or 1.8 kilometer (km) apart, starting at a depth of *ca.* 20 m. The study area was chosen to cover a large section of a) the HIHWNMS; and b) high vessel traffic incurred during the whale season (December – May). The total survey area covered *ca.* 176 n.mi.^{2} or 604 km^2 (Figure 1).

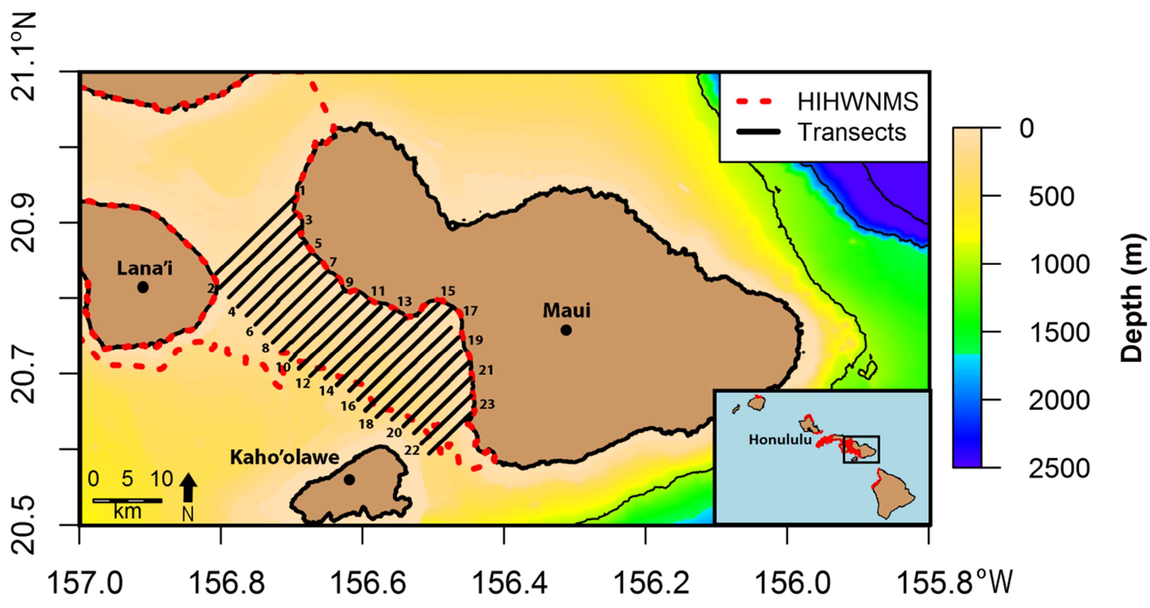

Figure 1: Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS) boundaries and the transect lines depicting survey area in Maui County waters, Hawai'i, between February and April 2013.

Data collection

Data were collected using systematic line transect surveys (Figure 1) from an 8 m fiberglass motorized catamaran research vessel, *Ocean Protector*, fitted with two 150 horse power four-stroke outboard engines. Prevailing sea (Douglas sea state (DSS) $\leq$ 5) and weather conditions influenced which part of the study area could be sampled. The subsequent direction of travel along each line (North to South or South to North) and starting speed (5, 10, 15, or 20 kts) were randomly selected using the "sample" function in 'R' (R Core Team, 2013). Weather permitting, attempts were made to survey the entire study area equally.

Surveys were primarily undertaken between 07:00 and 15:00 in order to take advantage of calmer sea conditions prior to the onset of afternoon trade winds. Weather conditions including wind speed (Beaufort sea state (BSS)) and direction, DSS, percentage cloud cover, and glare were recorded at that start of each transect line, and as they changed throughout the survey, providing detailed environmental data on covariates that might affect animal sightability (Buckland *et al.*, 2001). Global Positioning System (GPS) units (Garmin GPSmap 276C and/or Garmin 4000) tracked time and location of the vessel on a one-minute (1-min) basis.

Observations were undertaken by experienced observers using a continuous scanning methodology (Mann, 1999), by naked-eye or reticle binoculars (Bushnell 7 x 50). While on effort, one observer was stationed on the port and one on the starboard side of the helm, scanning equal sections of water (from abeam to forward, from an eye height of *ca.* 1.8 m). A third person acted as data recorder, with remaining staff, if present, at rest. With the exception of the skipper, observers regularly rotated duties to prevent fatigue. All whales sighted ≤ 300 m (abeam and forward of the vessel) were recorded with the following data: time and location (latitude and longitude) of sighting, transect number, vessel speed, group composition (number of individuals and their age-classes), group distance and bearing in relation to the boat (measured in reticles), direction the group was travelling, and the number of other vessels present ≤ 300 m of the group. Environmental variables aforementioned were also noted in addition to water depth (m). Reticles were later converted into meters following Kinzey and Gerrodette (2001) methods.

For each group, the sighting was labeled as a near-miss (NM), surprise encounter (SE), or non-surprise encounter (NO). NO is defined as an initial sighting ≥ 300 m that subsequently came ≤ 300 m of the vessel. NO could not, therefore, constitute a SE, as a vessel should have safely maneuvered around the whale(s) when initially sighted at > 300 m. When a NM occurred, attempts were made to take fluke photo-identification (photo-ID) images of each individual(s) involved, using a Canon D7 SLR camera equipped with a 100-400 mm lens. A maximum of 30 min were spent with each focal group in compliance with permit conditions (NMFS permit 16479). Initial behavioral response of the animal(s) (approach, neutral, or avoidance) was also recorded.

After 15 min on effort, the vessel would stop, and both port and starboard observers would conduct a 1-min-360° scan for humpback whales present ≤ 0.5 n.mi. or 1 km radius of the research vessel. The two observers were either assigned (on a rotation basis) as primary or secondary observer. The primary observer would scan clockwise, starting at the bow, and call out any sighting and associated information to the data recorder. The secondary observer would scan counter-clockwise, also starting at the bow, and write down their own observations. For each sighting during a scan, the following variables were recorded: group size and composition, distance and bearing of sighting (relative to bow of boat), and sighting cue (*e.g.*, blow). At the end of the scan, observers would compare their observations and note any whale(s) that were missed by either of the observers. The line transect would then resume with speed increased at increments of 5 kts, from 5 kts to 20 kts (*i.e.*, after 20 kts, the next speed would be 5 kts). Each group was only counted once while conducting transect lines and 1-min scans.

Analysis and data processing

Total distance covered while on effort during the survey period was calculated by multiplying the length of each transect line by the number of times it was completed. Owing to inconsistency in recording age-class (specifically adults and sub-adults), groups of whales were either categorized as calf or non-calf for analytical purposes, given that observers were confident that all calves were properly identified.

Kernel estimates of intensity models (Van Winkle, 1975) for calf and non-calf encounters were determined by combining the number of SE and NM. Data were projected, by convention, in Universal Transverse Mercator (UTM) coordinate system with units expressed in km and, therefore, resulting intensities as individuals/km^2. Intensities were calculated using a Gaussian smoothing kernel and graphing for kernel densities were done using the "spatstat" function in 'R' statistical software (Baddeley and Turner, 2005).

Time required to maneuver and avoid a collision was estimated at 80 and 300 m (*i.e.*, for NM and SE, respectively), using velocities of 5, 10, 15, 20, and 25 kts to represent the spectrum of boat traffic observed in the study regions.

Encounter frequency per n.mi. and per hour (hr) was standardized by calculating the distance (n.mi.) and time (hr) travelled along each transect, at each specific speed (*i.e.*, 5, 10, 15, and 20 kts). Encounter frequency with varying sea state conditions (BSS and DSS) was standardized by calculating the total number SE and NM per sea state day (*i.e.*, BSS from 1 to 5 and DSS from 1 to 4).

Data collected during 1-min-360° scans were used to determine the "miss rate" by the primary observer. Sightings were standardized by day, and confidence intervals were calculated using the "plotmeans" function (Warnes, 2012) in 'R' statistical software (R Core Team, 2013).

Graphs were generated using the "ggplot2" package (Wickham, 2009) and maps using the "raster" package (Hijmans and van Etten, 2012) in 'R'.

Finally, owing to small sample sizes and lack of multi-year data, statistical analyses were limited to descriptive statistics indicating the main trends in data collected to date.

RESULTS

Between February 2nd and April 24th 2013, 33 survey days allowed for sampling of 151 transect lines in the four island region of Maui County. Each transect line was surveyed a minimum of five and maximum of eight times throughout the study period. This corresponded to 86.8 hr and 1,058 n.mi. (1,960 km) of survey effort. A total of 361 groups of humpback whales and 723 individuals were sighted $\leq$ 300 m of the research vessel, consisting of 116 calves and 607 non-calves. The largest group observed included 12 individuals. Of all sightings, 52.9% (n = 191) were SE and 3.3% (n = 12) were NM. Owing to varying group activity and weather conditions, fluke shots for photo-ID were captured for

40% (n = 8) of the non-calves involved in NM, with no re-sights observed.

Group composition of SE and NM

Calves were present in 28.3% (n = 54) of SE and 58.3% (n = 7) of NM (Figure 2). Of all SE and NM involving calves, 54.1% (n = 33) were mother-calf pairs, 39.3% (n = 24) were mother-calf-escort groups, and 6.6% (n = 4) were single calves (*i.e.*, mother did not surface). Lone adults accounted for 39.3% (n = 75) of SE and 25.0% (n = 3) of NM, while groups consisting of ≥ 2 individuals, accounted for 32.5% (n = 62) SE and 16.7% (n = 2) of NM (Figure 2).

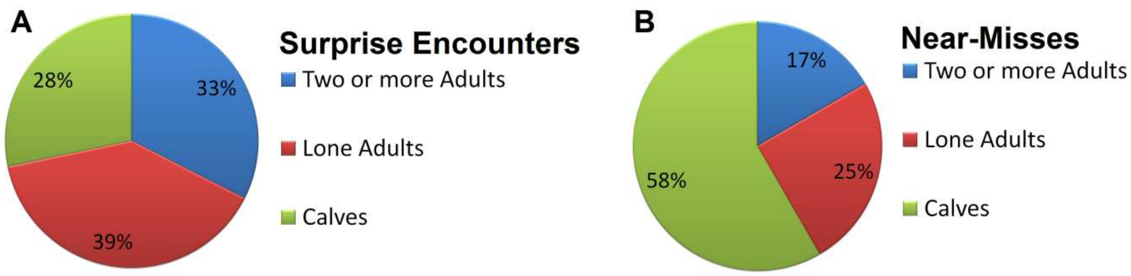

Figure 2: Percentage of surprise encounters (A) and near-misses (B) for calf and non-calf (adult) groups of humpback whales (*Megaptera novaeangliae*) in Maui County between February and April 2013.

Location of SE and NM

Occurrence of SE for calf and non-calf groups followed similar trends, with higher instances observed between Lana’i and Maui (Figure 3). Alternatively, NM with calf groups were more uniformly distributed than non-calf groups, which were more concentrated within a fairly close region off west Maui (Figure 3).

Kernel estimates of intensity of SE and NM

Kernel estimates of intensity for SE and NM with calf groups ranged from 0 to 0.5 calves/km^2 within the study area (Figure 4A). Similar analysis for SE and NM with non-calf groups indicated a maximum estimate of 1.2 non-calves/km^2 (Figure 4B). Enumeration of SE and NM individuals/km^2 indicated a maximum of 2 and 5 individuals/km^2 for calf and non-calf groups, respectively, throughout the study area.

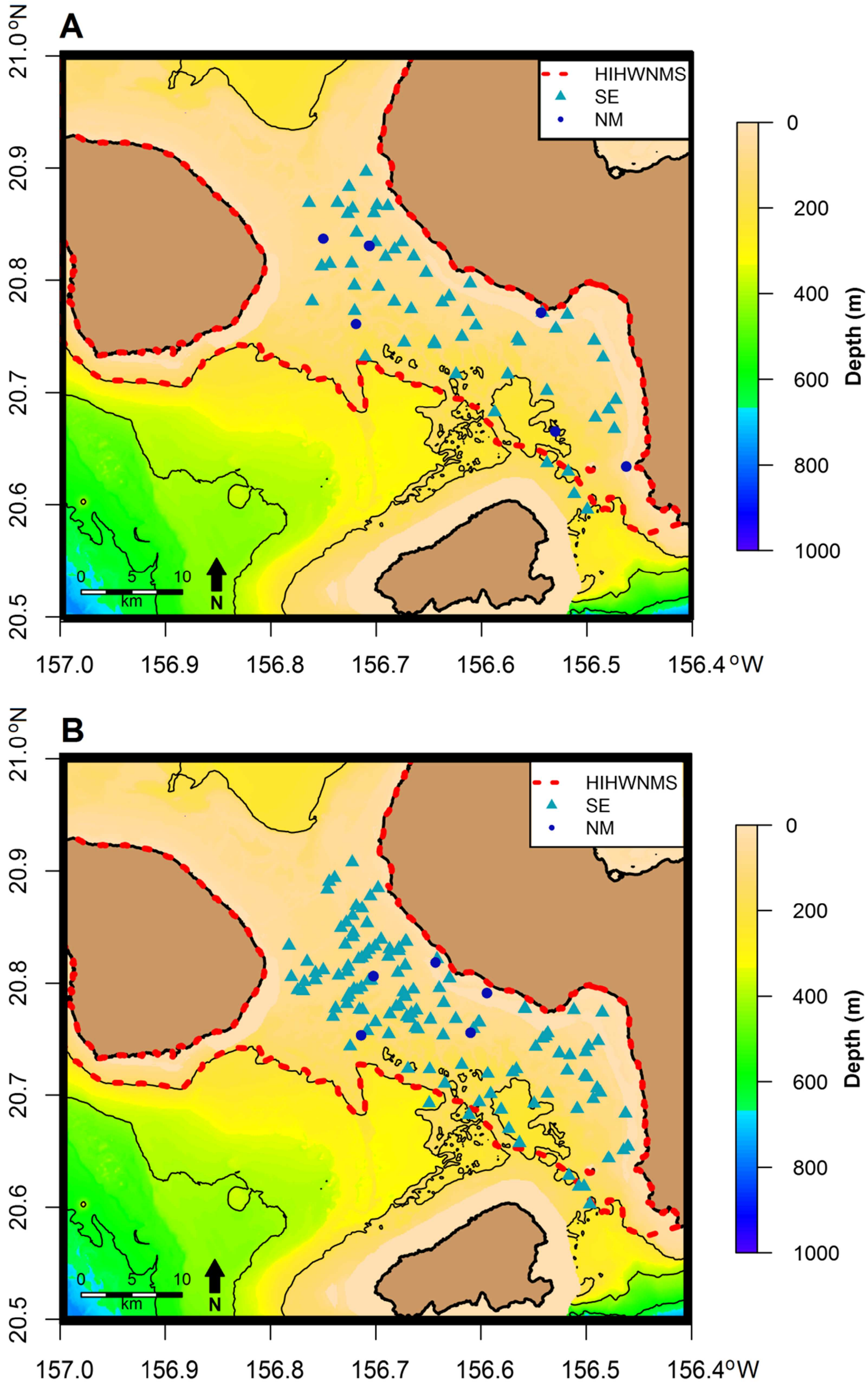

Figure 3**:** Location of surprise encounters (SE) and near-misses (NM) for groups of humpback whales with (A) calf (n = 61) and (B) non-calf (n = 142) within the boundaries of the Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS) in Maui County waters between February and April 2013.

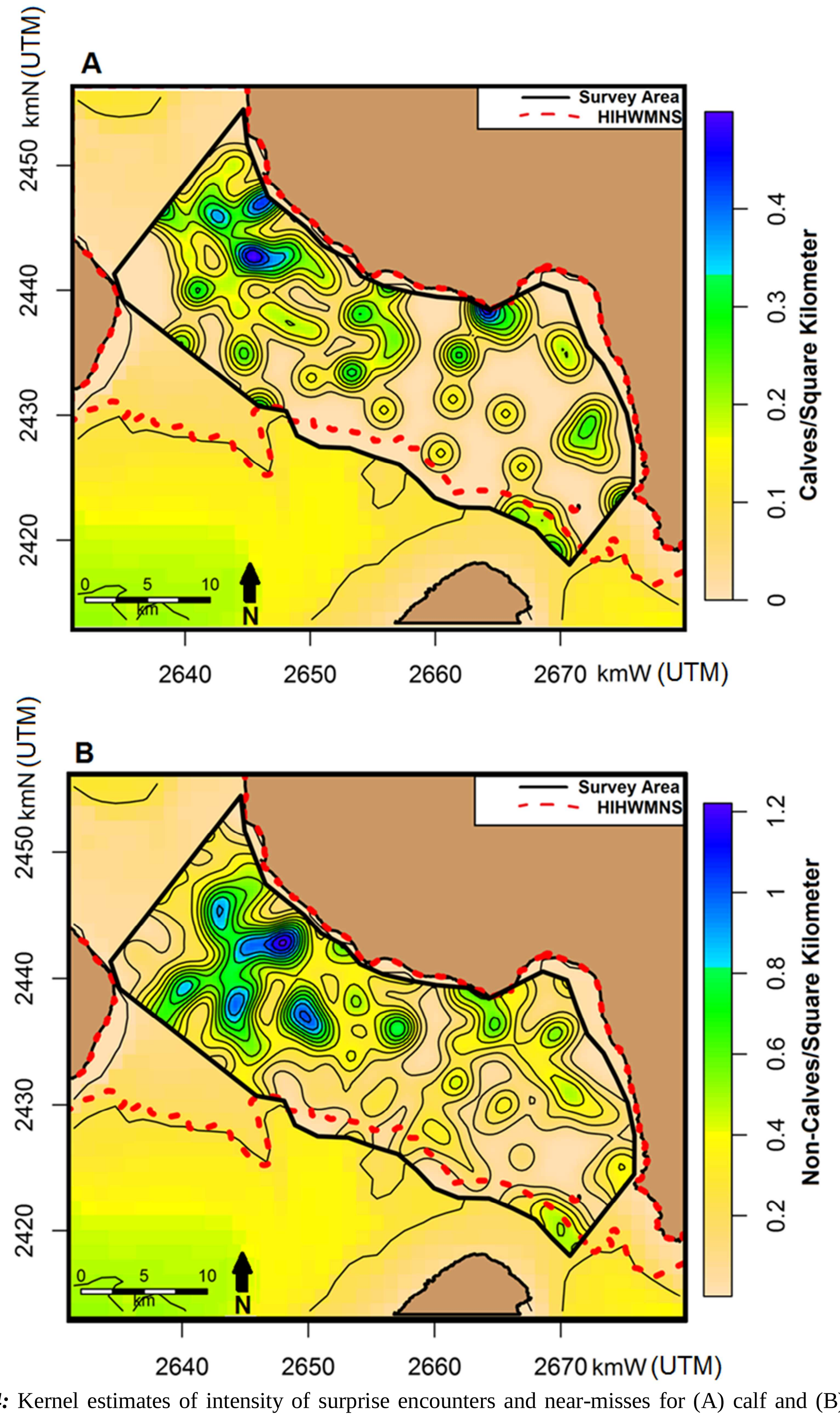

Figure 4: Kernel estimates of intensity of surprise encounters and near-misses for (A) calf and (B) non-calf humpback whales (*Megaptera novaeangliae*) within the boundaries of the Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS) in Maui County waters between February and April 2013.

Encounter frequency in relation to vessel speed

Transect lines 1-10 indicated a higher rate of SE and NM per n.mi when compared to lines 11- 23 (Figure 5). The highest SE rate occurred at line 6 with a SE expected every 2.75 n.mi.

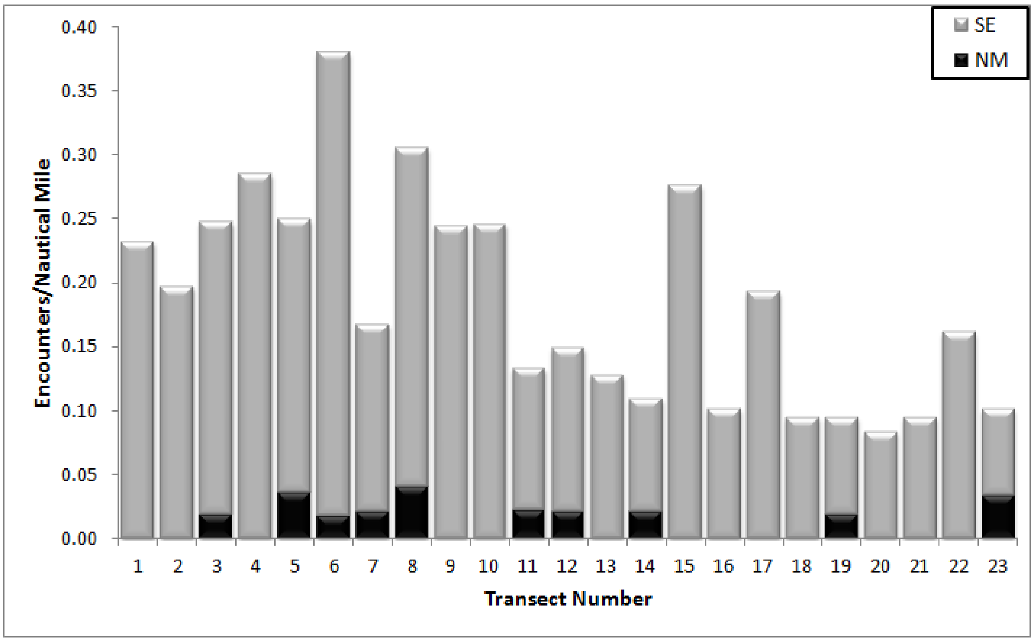

Figure 5: Rate of surprise encounters (SE) and near-misses (NM) per nautical mile with humpback whales (*Megaptera novaeangliae*) for each transect completed within Maui County waters between February and April 2013.

A 2.9 fold increase in the rate of encounters (both SE and NM) was observed when vessel speed exceeded 10 kts. Maximum encounter rates were observed at 15 kts, with a rate of *ca.* 4 encounters/hr (Figure 6). Two NM were observed at speeds of 10 kts, accounting for 18.1% of the total NM. No NM occurred at 5 kts.

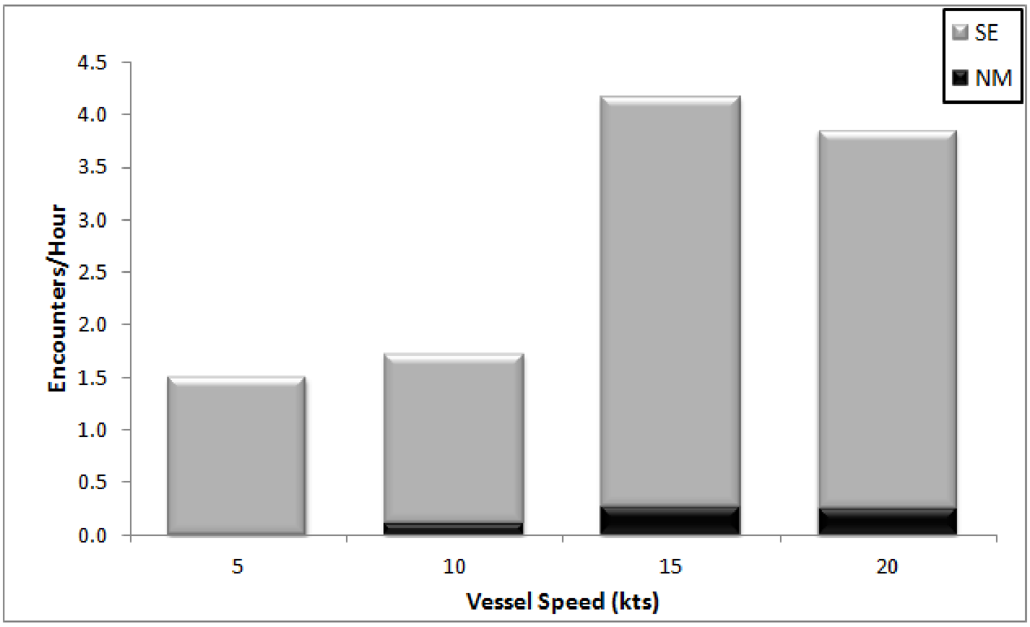

Figure 6: Rate of surprise encounters (SE) and near-misses (NM) per hour with humpback whales (*Megaptera novaeangliae*) at varying vessel speeds (kts) between February and April 2013 in Maui County waters.

The time to maneuver and avoid potential whale-vessel collisions decreased with increasing vessel speeds (Figure 7). Vessels travelling at 20 kts have only 8 seconds (sec) to avoid a whale initially sighted at 80 m, and 29 sec if the whale is sighted at 300 m (Figure 7). If travelling half that speed (*i.e.*, 10 kts), the vessel will have twice as much time to avoid a potential collision.

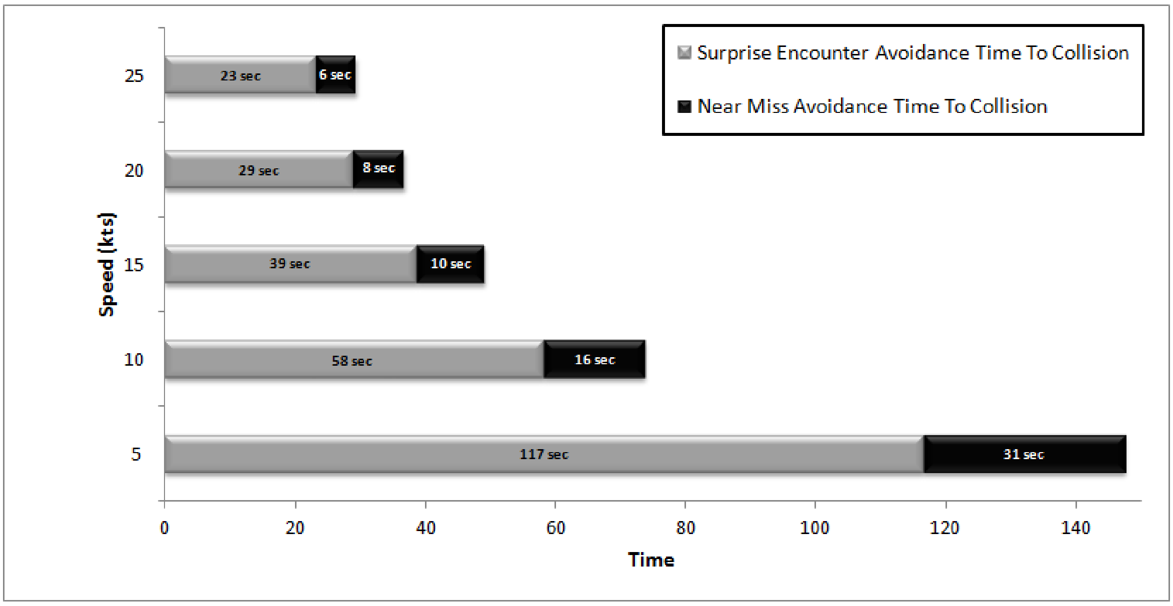

Figure 7: Time required (seconds, sec) to maneuver a vessel and prevent a collision with humpback whale (*Megaptera novaeangliae*) initially detected at 80 m (near-miss) and 300 m (surprise encounter), at varying speeds (kts).

Encounters in relation to varying sea state conditions

Little variation in the detection of encounters was found under different DSS and BSS conditions (Figures 8 and 9). There was a slight decrease in detection of SE when BSS = 5. No SE or NM were recorded at DSS = 4 nor any NM at BSS = 5. However, it should be noted that only 9.1% (n = 3) of the days had DSS = 4 and 18.2% (n = 6) of the survey days had a BSS = 5.

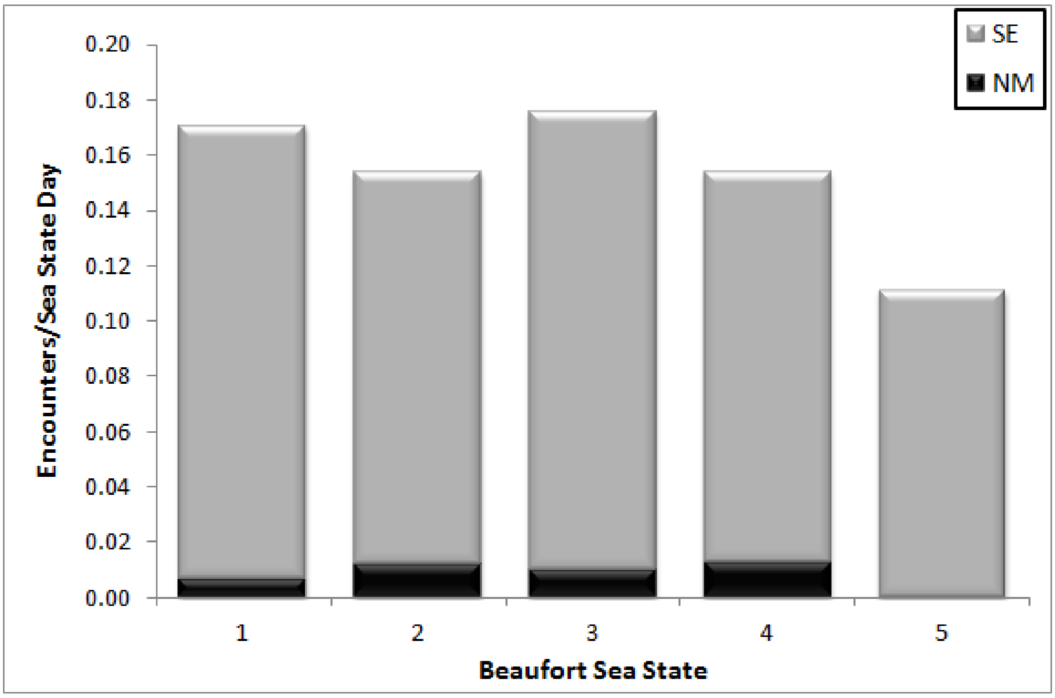

Figure 8**:** Detection of surprise encounters (SE) and near-misses (NM) per day with humpback whales (*Megaptera novaeangliae*) at varying Beaufort sea states recorded within Maui County waters between February and April 2013.

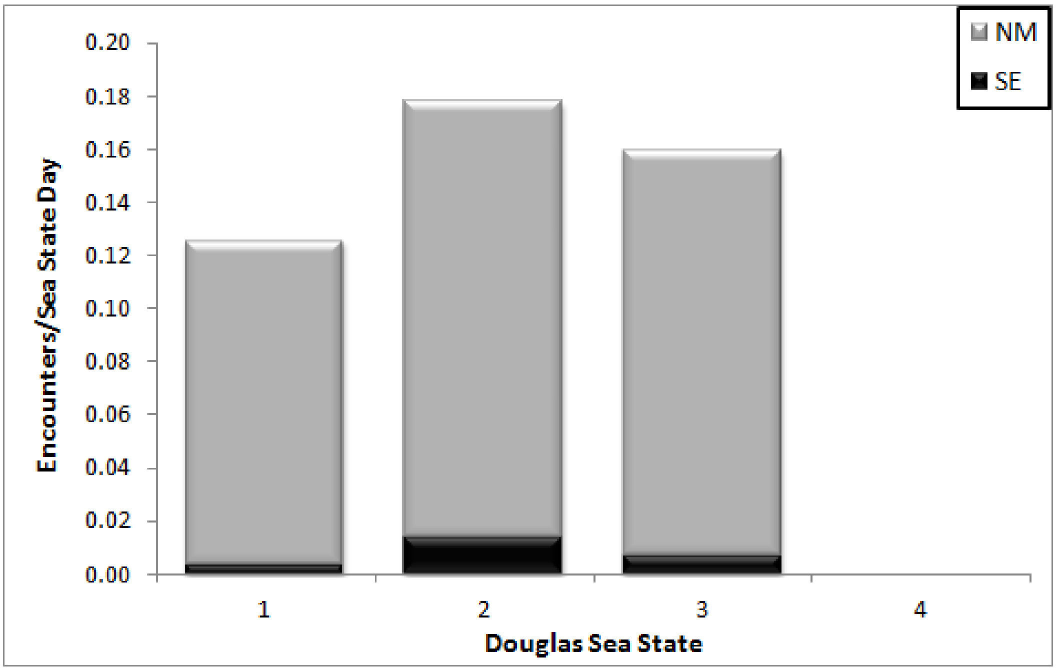

Figure 9: Detection of surprise encounters (SE) and near-misses (NM) per day with humpback whales (*Megaptera novaeangliae*) at Douglas sea states recorded within Maui County waters between February and April 2013.

Correction factor (1-min-360° scans)

Between March and April 2013, 289 1-min-360° scans were undertaken. A total of 85 groups, totaling 117 individuals, were observed within 0.5 n.mi or 1 km radius of the research vessel. Sightings per scan decreased from an average of 1.5 whales per scan in early March to zero whales per scan in late April (Figure 10). The primary observer missed 30.2% of the whales detected by the secondary observer.

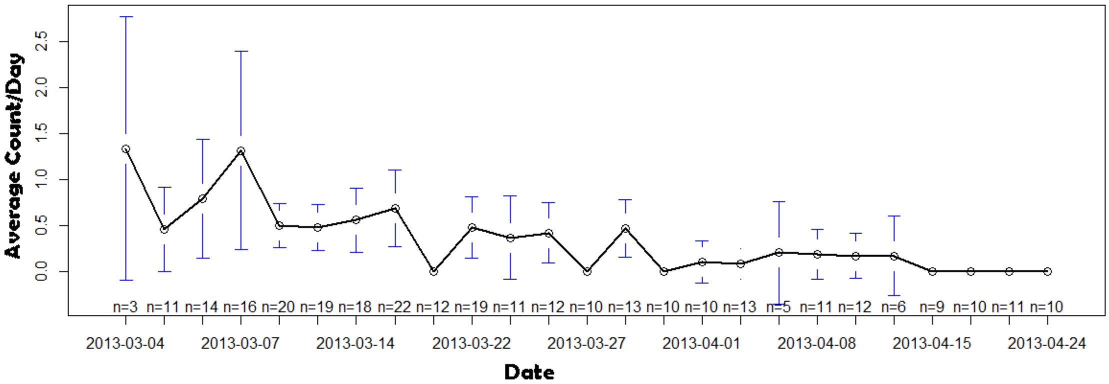

Figure 10**:** Average humpback whale (*Megaptera novaeangliae*) sightings within 0.5 n.mi or 1 km per 1-min-360° scan within Maui County waters between March and April 2013. *Note:* Vertical bars represent 95% confidence intervals.

DISCUSSION

Whale-vessel collisions are a matter of concern globally. To date, very few studies have attempted to quantify the risk of a whale being struck by a vessel by taking into account the frequency of near collisions (*e.g.*, Richardson *et al*., 2011). Most studies have assessed the risk of whale-vessel collisions by establishing co-occurrence in the distribution of whales and vessel traffic within major shipping routes (*e.g.*, Vanderlaan *et al*., 2009; Williams and O'Hara, 2010; Redfern *et al*., 2013). However, large whales, such as the humpback, can be at risk even in areas without major shipping lanes, as is the case in Maui County waters, Hawai'i (*e.g.*, Lammers *et al*., 2003). This study aimed at assessing the risk of a vessel striking a humpback whale in this region using line transect surveys and surprise encounters (SE) and near-misses (NM) following the recommendations of Richardson *et al.* (2011). Although preliminary results (initial year) of a five-year study are presented here, interesting patterns on factors influencing the likelihood of whale-vessel collisions with humpback whales in Maui County waters are already emerging.

Random *vs.* non-random surveys

Richardson *et al.* (2011) were the first to quantify the risk of whale-vessel collisions in Maui County waters using platform of opportunities (PoP). Following their recommendation, this study conducted systematic line transect surveys to quantify the probability of whale-vessel collisions in the area. Both methods led to different sighting patterns of SE and NM within Maui County waters. In the former study, two "hot spots" for SE and NM were apparent; *ca.* 1.6 n.mi. (3 km) south of Ma'alaea harbor and 6 n.mi. (11.2 km) south of Lahaina harbor. In contrast, the occurrence of SE and NM in this study was more uniform (in particular for groups with calves), the exception being that encounter rates (SE/NM) were slightly higher between Lana'i and Maui for both calf and non-calf groups than in other parts of the study area. Sampling size could have accounted for this discrepancy (204 *vs.* 33 surveys), however, more SE were recorded in this study (n = 191) than in 2011 (n = 133; Richardson *et al.*, 2011). The disparity in the location of SE and NM is due to inherent biases in the PoP sampling methods, already highlighted by Richardson *et al.* (2011). Whale-watching vessels, which were used as PoPs, were actively seeking out whales. These PoPs were further constrained by time, with most tours being two hours long. This implies that vessels would likely engage in whale-watching activities with whales encountered in close vicinity of the harbor and limit the distance travelled. Consequently, the study area was not evenly sampled, leading to bias in the results, given that effort was not taken into account. Although a PoP can provide valuable data, systematic line transect surveys should be the preferred research method employed when establishing where whale-vessel collisions are more likely to occur.

Vessel speed and the probability of collisions

Vessel speed had an effect on the rate of SE and NM observed, with a two-fold increase when speed exceeded 10 kts. The maximum encounter rate occurred at 15 kts with four encounters/hr. This concurrent increase between vessel speed and rate of SE and NM is consistent with Richardson *et al.* (2011) findings. Other studies have also demonstrated that vessel speed, as well as vessel size, influences both the frequency and severity of whale-vessel collisions (Laist *et al.*, 2001; Vanderlaan and Taggart, 2007). The probability analysis indicated that death or a serious injury to a struck whale decreases rapidly when vessel speed is ≤ 12 kts (Vanderlaan and Taggart, 2007). Consequently, vessel speed restrictions are being used in various geographic locations to reduce the occurrence or severity of whale-vessel collisions with large whale species, which have proven to be effective in some cases (*e.g.,* humpback whales in Alaskan waters (Gende *et al*., 2011) and North Atlantic right whales in American and Canadian waters (Vanderlaan *et al*., 2009; Wiley *et al.*, 2011)). This information could have important management implications to reduce the incidence of collisions in Maui County waters during whale season (December - May) given the increased risk of striking a whale at speeds ≥ 10 kts (Richardson *et al*., 2011; this study). At speeds ≥ 15 kts, reaction time to maneuver a vessel and avoid a collision is severely reduced. Lammers *et al.* (2003) reported that between 1975 and 2003, *ca*. 55% of whale-vessel collisions occurred with little or no forewarning. Furthermore, when some indication of vessel speed was provided, it ranged from 7 to 26 kts, with 62.5% travelling at 8 kts. The "Be 'Whale Aware'" code of conduct in Maui, Hawai'i developed by Pacific Whale Foundation (2013), which advises vessel operators to limit vessel speed to 15 kts and have observers on vigil at all times during whale season, should therefore be followed by both commercial and recreational vessel operators.

Environmental conditions and the probability of collisions

Richardson *et al.* (2011) found that as wind increased, the likelihood of detecting a SE decreased. In contrast, preliminary results in this study suggest that DSS ≤ 3 and BSS ≤ 5, have no adverse effect on the ability of the observer to detect whales. Detection of both SE and NM occurred at similar rates throughout all weather conditions, the only noticeable exception being that no NM were recorded at BSS = 5. There may be inherent biases in the results due a small sample size at that range and due to lack of data in the upper ranges of rough sea conditions (BSS ≥ 6) as transects could not safely be conducted in extreme weather conditions.

Age-class and susceptibility to whale-vessel collisions

SE occurred across all age-classes. A lone adult was, however, slightly more likely to be involved in a SE than a calf or a group of two or more individuals. This differs from Richardson *et al.* (2011) findings, which showed a significantly greater proportion of calves and sub-adults involved in SE than the general population. This discrepancy likely reflects differences between random and non-random survey methodology. The current study represents the minimum number of individuals observed in a SE, given that the research vessel could not stop while on effort to confirm the initial group size. Richardson *et al.* (2011), however, had more time to assess group size from a PoP, especially if the vessel stopped for whale-watching.

In terms of NM, *ca.* 60% involved a calf. This supports previous research findings indicating that calves and juveniles are more vulnerable to vessel strikes, which might be explained by their naivety to the dangers of an approaching vessel (Laist *et al.*, 2001; Lammers *et al*., 2003). In Hawaiian waters, 57% of collisions with humpback whales, in which age-class was specified, involved either a calf or juvenile (Lammers *et al*., 2003). In 2013, 50% of whale-vessel collisions reported to NOAA involved calves (Ed Lyman, NOAA/HIHWNMS, pers. comm., May 10, 2013). Finally, the whales identified in NM were all unique individuals; the sample size, however, was small (n = 8).

Future research

Whale-vessel collisions in Hawaiian waters, particularly in Maui County, are occurring with increased frequency and will likely continue to rise as the humpback whale population continues to increase, unless steps are taken to actively mitigate this issue (Lammers *et al*., 2003). The aim of this five-year study is to provide empirical data quantifying the likelihood of whale-vessel collisions in Maui County waters for effective management decisions to be implemented, such as speed reduction during certain times of the year or closure of specific high density areas of humpback whales. Continued research over the next four years will collate more data in order to help a) identify frequency and trends of potential collisions using SE and NM; b) determine if age-class or gender bias exist, or if certain individual whales are more likely to be involved in a NM; and c) establish critical distance thresholds in relation to vessel speed (as this factor may vary with type of boat, skill level and experience of the vessel operator) and weather conditions. A predictive model of vessel strikes will also be developed for management purposes, highlighting areas and conditions leading to higher risk of collision.

To reduce whale-vessel collisions, baseline data on whale distribution, vessel traffic distribution, and the frequency of near collisions are required (DeAngelis *et al*., 2010; Richardson *et al.*, 2011). The proportion of whales within a specific area that are likely to be struck is a function of whale densities, volume of vessel traffic, vessel speed, and whale behavior (Redfern *et al.*, 2013). Spatial mapping and modeling of whale densities in relation to vessel traffic in Maui County would further help pinpoint areas of overlap that have, therefore, higher risk of a whale-vessel collision. Data are, however, currently limited. Land-based observation using a theodolite would, therefore, be beneficial for monitoring both vessel traffic and humpback whale distribution in this region (*e.g.*, Bejder *et al.*, 2006).

A self-imposed speed limit of 15 kts during humpback whale season (December - May) in Maui County is warranted (Lammers *et al*., 2003; Vanderlaan and Taggart, 2007;

Richardson *et al.*, 2011; this study). Speed restrictions have proven to be efficient in reducing the number of whale-vessel collisions (*e.g.* Vanderlaan *et al*., 2009; Gende *et al*., 2011; Wiley *et al*., 2011). Furthermore, education and awareness programs (*e.g.,* "Be Whale Aware" by the Pacific Whale Foundation; Ocean Etiquette and guidelines by NOAA) should continue to be implemented to increase public awareness on the issue of whale-vessel collisions and comply with guidelines and code of conducts such as speed restrictions, which are easily quantified. As both whale and human populations continue to rise, with a concurrent increase in anthropogenic activities in the marine environment, more management, based on scientific research, will be required to ensure that both humans and animals can co-exist.

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