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Whale surprise encounters and near misses: proxies of vessel strikes in Maui County waters.

RICHARDSON, D.T., SILVA, I.F., MACIE, A., RANKIN, R.W., MALDINI, D., AND KAUFMAN G.D.

Pacific Whale Foundation, 300 Ma'alaea Rd., Suite 211, Wailuku, Maui, HI, USA 96793

ABSTRACT

Quantifying the probability of striking a whale is becoming increasingly important as whale abundance and boat traffic increase in many areas of the world. We undertook a modeling exercise based on data collected systematically from a fleet of whalewatching vessels in Maui County waters, Hawaii during the 2011 humpback whale breeding season (Jan-Apr). We estimated humpback whale density around the vessels during 15-minute scans and recorded a 'surprise encounter' each time a whale surfaced within 300 m from the vessel without being detected by observers and crew. We recorded 2,464 humpback whale sightings including 133 (3%) surprise encounters. The proportion of calves and sub-adults in the 'surprise encounter' sample was significantly greater than the proportion found in the general population. Wind speed influenced detectability of surprise encounters and likely drove the counter intuitive inverse relationship between the increase in wind and decrease in the odds of detecting a 'surprise encounter'. The model predicted an 8.2 % increase in the odds of a surprise encounter for a velocity increase of one knot. Vessel type influenced the odds of a 'surprise encounter' but there were confounding factors in this prediction. We estimated the number of near misses both based on a naïve value that implied 8% of surprise encounters were near misses, and on a corrected value which suggested a 5.5% chance of 'surprise encounters' becoming likely whale-vessel interactions.

KEYWORDS: VESSEL STRIKE, MODELING, HAWAII, WHALEWATCHING, HUMPBACK WHALE

INTRODUCTION

Globally, strikes between vessels and cetaceans are of increasing concern. A wide range of cetaceans have been involved in vessel strikes, but studies have shown that the large whales species are the most susceptible, especially endangered mysticetes such as humpback whales (*Megaptera novaeangliae*), northern right whales (*Eubalaena glacialis*), fin whales (*Balenoptera physalus*), and blue whales (*Balenoptera musculus*) (Laist *et al.,* 2001; Lammers *et al*., 2003; Jensen and Silber*,* 2003; Vanderlaan and Taggart*,* 2007; Constantine and Behrens, 2008; DeAngelis *et al*., 2010). A variety of vessels are involved in collisions with whales, including tankers, cargo or cruise ships, whalewatching vessels, navy ships, hydrofoils, sailboats, high speed ferries, fishing boats and research vessels (Jensen and Silber, 2003; Dolman *et al*.,2006; Ritter,2009).

The reduction of whaling on some endangered large whale specie has resulted in increases in abundances of several whale populations. Simultaneously ship traffic has increased worldwide at a rate of at least 3% (Schwehr and McGillivary, 2007). The coincident recovery of some large whale populations, coupled with an increase in ship traffic, enhanced the threat of whale-ship collision (Best, 1993; Bannister, 1994; Stevick *et al*., 2003; Branch *et al*., 2004; Ward *et al.,* 2006; Gerber *et al*., 2007).

The North Pacific humpback whale stock has increased in size, following the cessation of commercial whaling, with recent population estimates ranging from 18,000 to 20,000 whales (Calambokidis *et al*., 2008). Studies have shown that this population has been increasing at an annual rate of about 5.5-7% (Mobley *et al.*, 1999; Mobley *et al.*, 2001; Calambokidis *et al*., 2008). Hawaii is one of the primary breeding grounds for the North Pacific humpback whale, and close to 12,000 whales, or nearly 60% of the North Pacific population, migrate to Hawaii each year to mate and give birth (Calambokidis *et al*., 2008).

The increase of humpback whales in Hawaiian waters has also been mirrored by an increase in the number of ships operating in the area due to increased human population and commercial interests (Lammers *et al*., 2003; Delfour,2007; O'Connor *et al.*, 2009). However, whalewatch vessel traffic has not increased (Lyman, pers. comm.).

Data on vessel strikes in Hawaiian waters are difficult to interpret because the apparent increase in number of vessel strike reports between 1979 and 2010, (n=64; NOAA Fisheries and HIHWNMS, unpublished data) is partly the result of increased monitoring due to the creation of the Hawaiian Islands Humpback Whale National Marine Sanctuary (HIHWNMS). In fact, there were five reported strikes in 2009 but only two in 2011 (Lyman, pers. comm.).

The majority of reported cases involved vessels (but not whalewatching vessels) traveling in Maui County waters (Lammers *et al*., 2003, NOAA Fisheries and HIHWNMS, unpublished). Sub-adult whales and calves appear more susceptible to vessel strikes, representing about 68% of known reports (Lammers *et al*., 2003, NOAA and HIHWNMS, unpublished).

Maui County waters have one of the highest densities of humpback whales in Hawaii during breeding season (October- May) (Mobley *et al*., 1999; Mobley *et al*., 2001). Waters between the islands of Maui, Molokai, Lanai and Kahoolawe (the Four-Island area) are an ideal habitat for breeding humpback whales because of easy access to sheltered shallow-waters (Aki *et al.*, 1994).

The waters of Maui County are also home to a fleet of both commercial and non-commercial vessels, including regular visits by several large cruise ships, barges and military crafts. Maui County is also home to over 50% of Hawaii-based whalewatching operations (O'Connor *et al*., 2009). It should be noted, however, all whalewatching vessels operating in Maui waters are small passenger vessels, 65 feet or less in length, with low tonnage (most under 20 tons), and are not classified as ships (Laist *et al*., 2001).

Although reports suggest that vessel strikes on whales are increasing worldwide, to date no attempt has been made at quantifying the risk of a whale being struck by a vessel. Silber (2010) suggests that two types of data are needed to reduce vessel strikes on whales: (1) data on whale distribution and (2) data on vessel distribution. We argue for a third element: data on the frequency of near misses. Therefore, the main objectives of this study were to (1) quantify the potential for near misses between whalewatching vessels and humpback whales using a model as well as empirical data, and to (2) define if the probability of unexpected encounters ('surprise encounters') with humpback whales depended on factors such as time of day, environmental variables, vessel behavior, and whale abundance.

We argue that these surprise encounters and near misses can be used as a proxies of ship strikes, and thus provide a complimentary dataset to actual whale-mortalities and ship strikes to answers questions about what conditions and vessel attributes may result in more potential strikes.

Data were collected utilizing whalewatching vessels as Platforms of Opportunity (PoP) during the course of day-to-day whalewatch operations in Maui County waters. Whalewatch PoPs used in this study were already following self-imposed best-practices guidelines for operation around humpback whales in Hawaiian waters that were more stringent that Federal and State humpback approach regulations and operational guidelines.

METHODS

Study Area

The study was undertaken in Maui County waters between the islands of Maui, Molokai, Lanai and Kahoolawe (the Four-Island Area), and, specifically, within the HIHWNMS's Maui region boundaries (Figure1). The two areas of operation for the whalewatching fleet were approximately 201.61 km^2 and 223.40 km^2 offshore the harbors of Maalaea and Lahaina respectively. The maximum distance from shore traveled was about 7 km, or the half-way point between the Island of Lanai and the Island of Maui for the vessels used during the study period.

Data Collection

An observer was deployed on one of five whalewatching vessels: three departing from Maalaea Harbor (Ocean Odyssey, 65 foot aluminum power catamaran, 149 passengers; Ocean Spirit, 65 foot aluminum power catamaran, 148 passengers; and Ocean Intrigue, 65 foot aluminum power catamaran, 141 passengers); and two from Lahaina Harbor (Ocean Discovery, 65 foot aluminum power catamaran, 149 passengers; and Ocean Quest, 65 foot power catamaran, 147 passengers). An equal number of trips were scheduled on vessels departing from each harbor during three different time slots (0630-1030; 1030-1430; 1430-1830). To maximize efficiency and avoid the observer being distracted by written data collection, data were collected by using a digital voice recorder and a hand-held GPSMap276C unit and subsequently entered into a database.

Observers collected data during the course of routine whalewatching operations and never interfered with the vessel crew or dictated vessel behavior, speed, direction or course of action. All current Federal and State humpback whale approach regulations in place for Hawaiian waters were followed.

The National Marine Fisheries Service (NMFS) has specific regulations for Hawaiian waters (50 C.F.R. § 222.31) and the State of Hawaii regulates interactions with whales through Endangered Species Act (ESA) under statute 195D-4(a), and statutes 195D-4(e)(2) and 195D-2 which defines a take to include harassment, harm, pursuit, hunting, shooting, wounding, killing, trapping, capturing or collecting whales. In addition, the HIHWNMS issues specific guidelines to the public and to commercial operations (hawaiihumpbackwhale.noaa.gov/explore/whale_guidelines.html).

A maximum self-imposed boat speed limit of 15 knots was maintained at all times. Vessel speeds were further reduced to 6 knots from 402.33 m (440) yards on approach to a pod, with the vessel coming to a complete stop at 91.44 m (100 yards).

Every 15 minutes, a 360°-one-minute scan for individual humpback whales found within a one kilometer radius off the vessel was conducted and the waypoint where the scan was started was taken. Distances were estimated using a Bushnell 7x50 reticle binocular and angle was read from the binocular's compass.

Each whale observed was counted only once during the scan. Additional variables collected were visibility, percent cloud cover, Beaufort sea state, Douglas sea state, percent glare on both sides of the vessel, water depth, vessel speed, and distance and angle of the sighting to the vessel.

When a whale was detected the boat would maneuver to either avoid the whale or approach it. To approach a whale, the captain slowed vessel speed to a minimum and halted at ≤91.44 m from the whale (as per NMFS/DLNR regulations and determined using a Bushnell© Legend 1200 Rangefinder).

We used the term 'surprise encounter' to describe when a whale was detected for the first time at a distance ≤300 m from the vessel. We used the term 'near miss' to describe those surprise encounters which surprise encounters which occurred off the bow of the moving vessels, and at a distance of ≤ 80m.

When this occurred, we recorded GPS location, exact distance from the boat using a Bushnell© Legend 1200 Rangefinder, angle of the sighting, boat speed at the time of detection, water depth, any change in environmental conditions, numbers of whales involved, whale behavior at first surfacing and any reaction to the boat. These encounters could occur either during scans or outside of scanning periods.

Data Analysis

Detectability

Prior to making inferences about environmental covariates and surprise encounters, or building a model of near misses, we employed the popular approach of distance-sampling to try and account for those animals that went unseen due to imperfect detectability with distance. The estimation of a detectability curve, using the Program DISTANCE 6.0 (Thomas *et al.*, 2010), served to contextualize the results for further analyses, as well as provide parameters for modeling.

We tested various key functions (half-normal, hazard), adjustment expansions series (*e.g.*, hermite function, simple polynomial, cosine function), and environmental covariates that may have influenced the scale parameter of the key function (Observer, Vessel Type, Percent Cloud Cover, Visibility, Wind Speed, and Pod Size).
Final model selection was based on overall goodness-of-fit and on the Akaike Information Criterion (AIC). The effect of environmental covariates on detectability served as a context for modeling the covariates of surprise encounters, while the distance-specific estimates of the probability of detection served as correction factors in the estimate of the number of near misses.

Modeling the Covariates of Surprise Encounters
Using surprise encounters as a proxy for potential ship strikes, we made inferences about which environmental conditions and whalewatching vessel attributes were closely associated with surprise encounters by building a multivariate regression model. We modeled the probability that at least one surprise encounter will occur between 15-minute whale-sighting-scan intervals, using a Generalized Additive Mixed Model (GAMM) with a Quasi-Binomial distribution, and employing a backwards step, variable-selection procedure.

All modeling was performed using the 'R' statistical software (R Development Core Team, 2011) and the "mgcv" package, which provides additional functions for GAMMs (Woods, 2006; Woods, 2011). Candidate environmental covariates included in the model were percent cloud cover, visibility, Beaufort Wind-Speed classes, water depth, glare off the water surface, vessel type, vessel velocity, Julian day of year, and time of day. Douglas sea-state was excluded because of being highly correlated to other variables. Numerical variables were tested as linear variables, or with a regression spline transformation (Harrell, 2001), or as what we perceived to be sensible two-way interactions.

We included, *a priori*, a variable for the total number of sightings during the nearest whale scan, which was not subject to model selection, reasoning that the probability of a surprise encounter should increase with increasing number of whale sightings. All observations with neither a whale sighting nor a surprise encounter were discarded. Because of the close proximity in time of both whale observations and environmental covariate measurements, we included a temporal autocorrelation structure for the model residuals, using a continuous autoregressive process over time within each boat trip. We also included boat trips as a grouping factor for random-intercepts.

In order to eliminate conditions and attributes which are not associated with surprise encounters, we employed a backwards stepping model-selection procedure. We began by constructing a full model with all covariates, and sequentially dropped variables with Type I error rates greater than a 0.20. We used the variable error rate rather than other more popular model-selection procedures, such as the AIC, because of the lack of a Likelihood value for the Quasi-likelihood distribution.

Number of Near misses

Surprise encounters, as defined in this study, are a rough proxy of potentially injurious interactions with whales. A more restricted definition is required to approximate the actual number of near misses (*i.e.*, those surprise encounters which had a high likelihood of becoming a hit). Firstly, we estimated the naïve number of near misses (see definition in methods).

Secondly, we employed a more sophisticated calculation of the number of near misses, which elaborate upon the above naïve criteria, and include a correction factor to account for errors due to imperfect detectability of whales estimated during radial scans. The formula for near misses includes the following adjustments to the number of surprise encounters:

a) The proportion of surprise encounters which occurred off the vessels' bow, where surprise encounters are more likely to become injurious (18.2% of surprise encounters). We used an empirically estimated proportion, because whales may avoid or be attracted to the bow of vessels, and may not be random in relation to vessel orientation;
b) An estimate of missed surprise encounters due to declining detectability with distance, calculated by inflating the number of surprise encounters by the inverse probability of detection;
c) A correction factor accounting for the effects of vessel velocity on the number of surprise encounters by reducing the importance of surprise encounters, which occurred beyond velocity-dependent "critical distances." We consulted the whalewatching vessel captains who drove during the study to estimate the "critical distance", at various vessel velocities, for which a surprise encounter may become a near miss. Furthermore, we tried to incorporate some 'fuzziness' in the critical distances, upon the recommendation of sea captains, who expressed concern that considerable variability is introduced to the notion of "critical distances" due to whale behavior and sea conditions. Rather than having a 'crisp' threshold for each boat velocity, we used a fuzzy membership function based on an inverse Weibull Growth Curve (Weibull, 1953) to represent high probabilities of a Near miss near the critical distances estimated, and declining further away from the boat (Figure 4). The curve was calculated as:
d)

$$\text{Near} - \text{Miss Fuzzy Membership} = e^{-\left(\frac{Distance_i - f_{Critical\ Distance}(Vessel\ Velocity_i)}{\beta}\right)^{\alpha}}$$

where $Distance_i$ is the distance of the i^{th} surprise encounter observation; $f_{Critical\ Distance}$ is the asymptotic function to estimate the critical distance based on the *vessel* $velocity_i$ and α is the shape parameter, arbitrarily set to 2 to promote a sigmoidal shape, which has a steeper decline at closer distances. β was solved for each velocity so as to arbitrarily set the 50% Near miss membership level to 2 times the estimated critical distance (Figure 3). We applied this function to correct the number of Near misses based on their distance to the whale-watching boat, and the vessels' velocity at the time of encountering the surprise encounter.

Combining these three correction factors, we calculated the number of Near misses according to the following formula:

$$Total\ Near\ Misses = \left[\sum_{i}^{n} \frac{f_{fuzzy\ membership}(Distance_i, Vessel\ Velocity_i) \times nPod_i}{f_{Detectibility}(Distance_i)}\right] \times 18.2\%,$$

where n is the total number of surprise encounters; $f_{Critical\ Distance}$ is the near miss fuzzy member function which estimates the probability of the i^{th} surprise encounter becoming a Near miss based on $Distance_i$ of the surprise encounter, and the $Vessel\ Velocity_i$ during the encounter; $nPod_i$ is the pod size of the i^{th} surprise encounter; $f_{Detectibility}$ is the probability of detecting any surprise encounter at $Distance_i$: 18.2% is the empirical estimate of the percentage of surprise encounters that occur off the bow of whale-watching vessels where a surprise encounter is likely to become a hit or near miss.

RESULTS

Between 11 January and 4 April 2011, 204 vessel-based surveys were conducted on board of whale-watching vessels across three different time blocks (06:30-10:30h; 10:30-14:30h; 14:30-18:30h): 114 trips departed from Lahaina Harbor (Lat:20°47'26" N; Long: 156°30'44"W) and 90 from Maalaea Harbor (Lat:20° 52' 19" N; Long: 156° 52' 19"W) (Figure 1). In the course of the survey, over 384 hours of effort were logged and over 3,845.53 km were traveled. We recorded 2,464 whale sightings: 3,410 adults, 175 sub adults, 612 calves and 396 individuals of unknown age group. Of all of the sightings133 (3%) were surprise encounters (Figure 2). In terms of individuals, surprise encounters involved interactions with 169 adults, 20 sub adults, 43 calves and 6 whales of unknown age.

Demography of Surprise Encounters

The proportion of calves and sub-adults in the surprise encounter sample was significantly greater than the proportion found in the general population (Chisq=15.099, df=2, p-value=0.0005). The test excluded whale sightings with an unknown age class (Table 1).

Detectability

There was strong evidence of declining detectability of surprise encounters with distance. Based on AIC and goodness of fit, the best detectability model included a half-normal key with no adjustment terms, and included a covariate for surprise encounter Pod Size (Figure 2). The model with second lowest AIC value (ΔAIC = 1.54) also had a half-normal key function model, with covariates for surprise encounter Pod Size and Beaufort Wind-Speed classes. This provides some evidence that wind speeds may be influencing the probability of surprise encounters by two opposite and confounded processes: 1) by potentially obscuring the crews' ability to monitor and track and 2) by reducing the detectability of surprise encounters (thereby reducing the number of *observed* surprise encounters).

Modeling the Covariates of Surprise Encounters
Our final multivariate regression model included four variables which influence the probability of surprise encounters: Beaufort Sea State, Vessel Velocity, Julian Day and Vessel Type (and total number of whales, which was not subject to variable selection). Only Beaufort Sea State, Boat Speed, and Vessel Type had significant effects (p-values 0.003, 0.0001, and 0.0001 respectively). Overall, the model only explained a small fraction of the overall variation, with an adjusted R-squared of 0.0414.

Beaufort Sea State (Wind Speed)
Beaufort Sea State was used as a proxy for wind speed as the scale is based on this parameter. Hereafter, we will refer to Wind Speed as the variable. The model estimated that an increase in one class of Wind Speed resulted in a 51.7% decrease in the odds of a surprise encounter (during any 15-minute interval). The interpretation of this effect is counterintuitive, as one might expect that rougher seas (caused by stronger winds) would increase the chances of not seeing a whale (*i.e.*, increase the chance of a surprise encounter). However, rougher conditions may also reduce our ability to detect a surprise encounter (*e.g.*, a declining detectability with distance). As stated earlier, the detectability model which included Wind Speed as a covariate (ΔAIC = 1.54), revealed a slight decrease in the detectability of surprise encounter with increasing wind speed (one class increase in wind speed reduced the Effective Detection Radius from 142 m to 139m). This small and possibly non-significant effect on whale detectability may, nonetheless, be the effect driving the counter intuitive relationship between wind speed and the probability of a surprise encounter.

Boat Speed
The model predicted an 8.2 % increase in the odds of a surprise encounter for a velocity increase of one knot. The interpretation of this relationship is intuitive, and has the obvious implication that the chances of a strike increase with boat speed. The most frequent travelling speed of the whale watching vessels was 5 knots, while the maximum is 15 knots. Using the model estimate, an increase from 5 knots to 15knots increases the odds of an surprise encounter by 2.2 times.

Vessel Type
Some vessels were 3x more likely to have a surprise encounter, making the variable the most influential term in the multivariate model. Overall, the interpretation of vessel type effects is difficult, as boats vary by their length, tonnage, viewing platform, and captain and crew. Furthermore, some of the vessels used in the study only went out at certain times of the day, confounding the influence of time of day and vessel type. Future study designs should carefully consider vessel types, and perhaps directly model vessel attributes, such as tonnage.

Number of Near misses
We estimated only 16 naïve Near misses over 204 whalewatching trips. This implies that 8% of surprise encounters were Near Misses.

However, using the formula which included adjustments for the proportion of surprise encounters which occurred off the bow (18.2%), distance-specific inflations due to imperfect detectability (Figure 3), and the velocity-specific critical distances (Figures 4 and 5), we estimated 14 Near misses over the course of the study.

We performed a 2,000 iteration bootstrap to estimate a standard error of 3.13. This suggests that 5.5% of surprise encounters could become likely whale-vessel interactions.

DISCUSSION

Overall, several factors seem to influence the probability of Near misses during whalewatching operations in Maui County waters under the current speed limit guidelines and operational guidelines used by the whalewatching fleet used in this study. It is important to recognize that many factors were difficult to control and/or model such as observer variability and vessel directionality as whalewatching vessels tend to remain in areas of high whale density and target whales for viewing. However, interesting patterns emerged that will be useful in guiding further studies and suggest more systematic sampling protocols.

The relationship between age-class and increased risk of strike was already suggested based on strike data (Laist *et al.*, 2001; Best *et al.*, 2001; Lammers *et al.*, 2003). Although we did not model the demography of surprise encounters, our data suggests that humpback whale sub-adults and calves were more prone to be involved. This result is not surprising as sub-adults and calves tend to be more curious and less experienced and are therefore more prone to approach a boat to investigate it. In addition, juveniles and calves spend more time at the surface than adults.

It is unclear, in our data set, whether some specific individuals were more prone to become repeated surprise encounters. In addition, animals involved in surprise encounters tended to surface and then dive again or move away from the area immediately after the event.

The large drop in the probability of a surprise encounter with increasing wind speed, as stated in the results, is counterintuitive and the influence of lower detectability was smaller than would be expected. This may be because of inherent biases in the model and the lack of data in the upper ranges of rough sea conditions as whalewatch cruises generally get cancelled in extreme weather. There may also be behavioral differences in the whale response to vessels in rougher weather, which our data could not model.

The significance of vessel speed in our findings is consistent with other studies which reported that vessel speed and size influence both the frequency and severity of ship strikes and reported that large whales may be critically injured at a speeds of 10 -14 knots, with near 100% mortality at speeds greater than 20 knots when the mass of the vessel significantly exceeds the whale (Laist *et al.*, 2001; Vanderlaan and Taggart, 2007).

Panigada *et al.* (2007) reported that the mean vessel speed which resulted in injury or mortality of fin whales in the Mediterranean Sea was 18.6 knots, and the speed of most vessels involved in strikes ranged between 13 and 24 knots. According to Kite-Powell *et* *al.* (2007), models suggest that more than half of right whales located in or swimming into the path of an oncoming ship traveling at ≥15 knots are likely to be struck even when they do take evasive action.

Our model predicted an 8.2 % increase in the odds of a surprise encounter for every boat speed increase of one knot. Note that in our study, boat speed affected the probability of a surprise encounter even at the lower speeds dictated by current self-imposed whalewatching speed restriction guidelines (≤15 knots). This information is important for the purpose of regulating vessel speed in Maui County waters during whale breeding season and more research is needed on critical distance thresholds in relation to vessel speed, as this factor may vary with type of boat, captain's skill level and weather conditions. This finding, however, supports the regulation of vessel speeds for all watercraft in Maui waters, and suggests any vessel travelling at a speed greater than 15 knots (Dec – May) is a higher strike risk to a whale. It is therefore important to understand vessel speed patterns for vessels other that whalewatching boats in Maui County as most operators (especially private crafts) do not self-impose speed limits.

Overall, our model predicted a 5.5% chance of a near miss during whalewatch trips in 2011. This prediction is specific to PWF's whalewatch vessels under the conditions sampled and with all the inherent biases of sampling from a Platform of Opportunity. It should be noted that there were no strikes recorded by any vessels involved in this study. Controlled experiments performed during systematic transects from a research vessel with no approach restrictions would be recommended to control certain parameters such as effort, boat speed, operator variability, and platform variations. Further investigation is needed to determine if there is a whale age class or sex bias, or if certain individual whales are more likely to approach vessels and become involved in surprise encounters or near misses.

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Table 1 – Proportion of age-class sightings for surprise encounters versus the general humpback whale population sampled during scans

	Surprise Encounters	**Non-Surprise Encounters**
Calves	0.18	0.14
Sub-Adults	0.08	0.04
Adults	0.71	0.74

Table 2 – (*) reports the maximum coefficient.

Variable	**Coefficient (logit scale)**	**SE**	**P-value**
Beaufort Wind Speed	-0.728	0.248	0.0034
Boat Speed	0.079	0.021	0.0001
Vessel Type	1.111*	0.289	0.0001
Total Sightings	0.028	0.037	0.2420
Julian Day	-0.005	0.004	0.1170

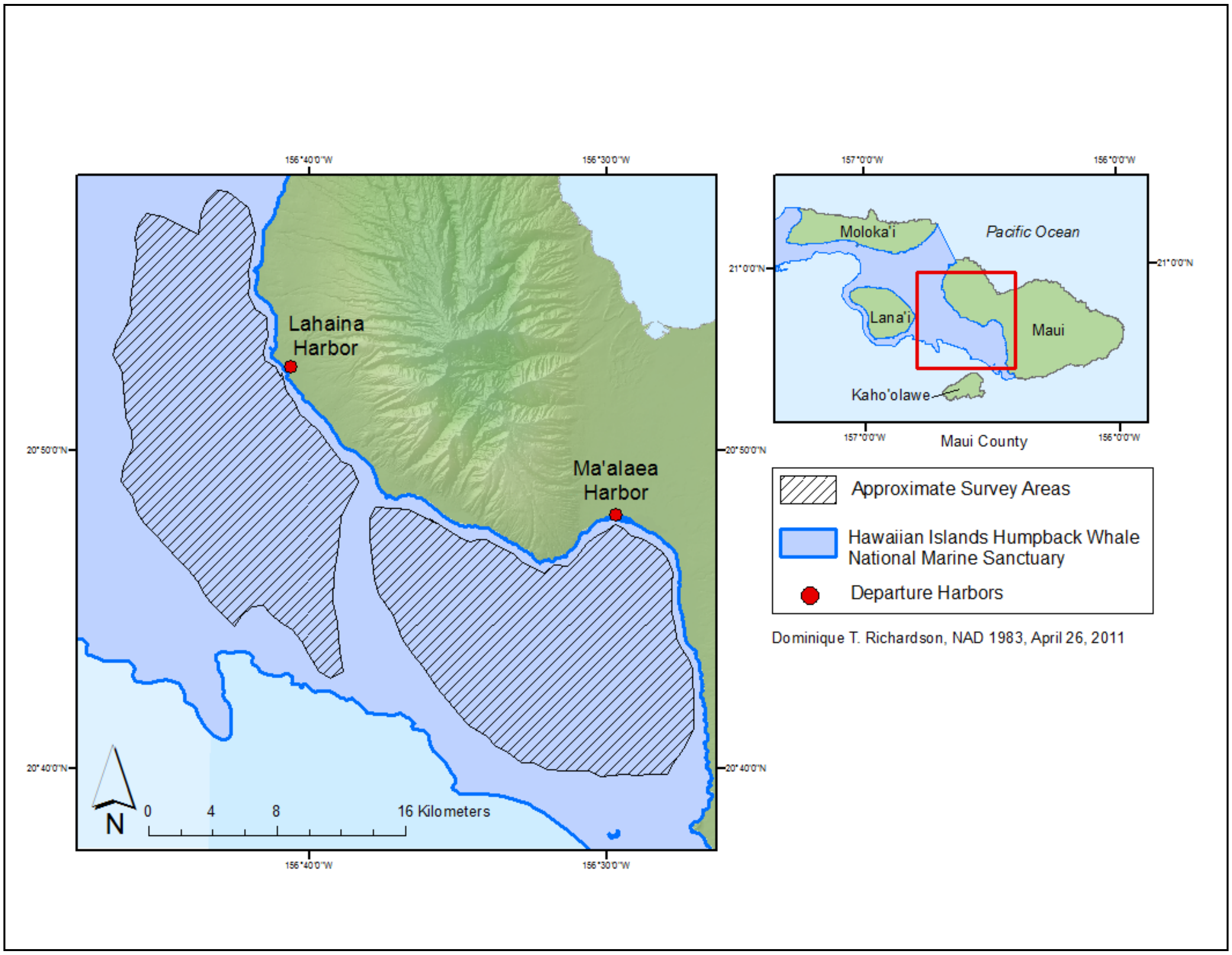

Figure 1. Surprise encounters Survey area. Approximate survey area for Pacific Whale Foundation's Research On Board Surprise Encounter Survey, January-April 2011

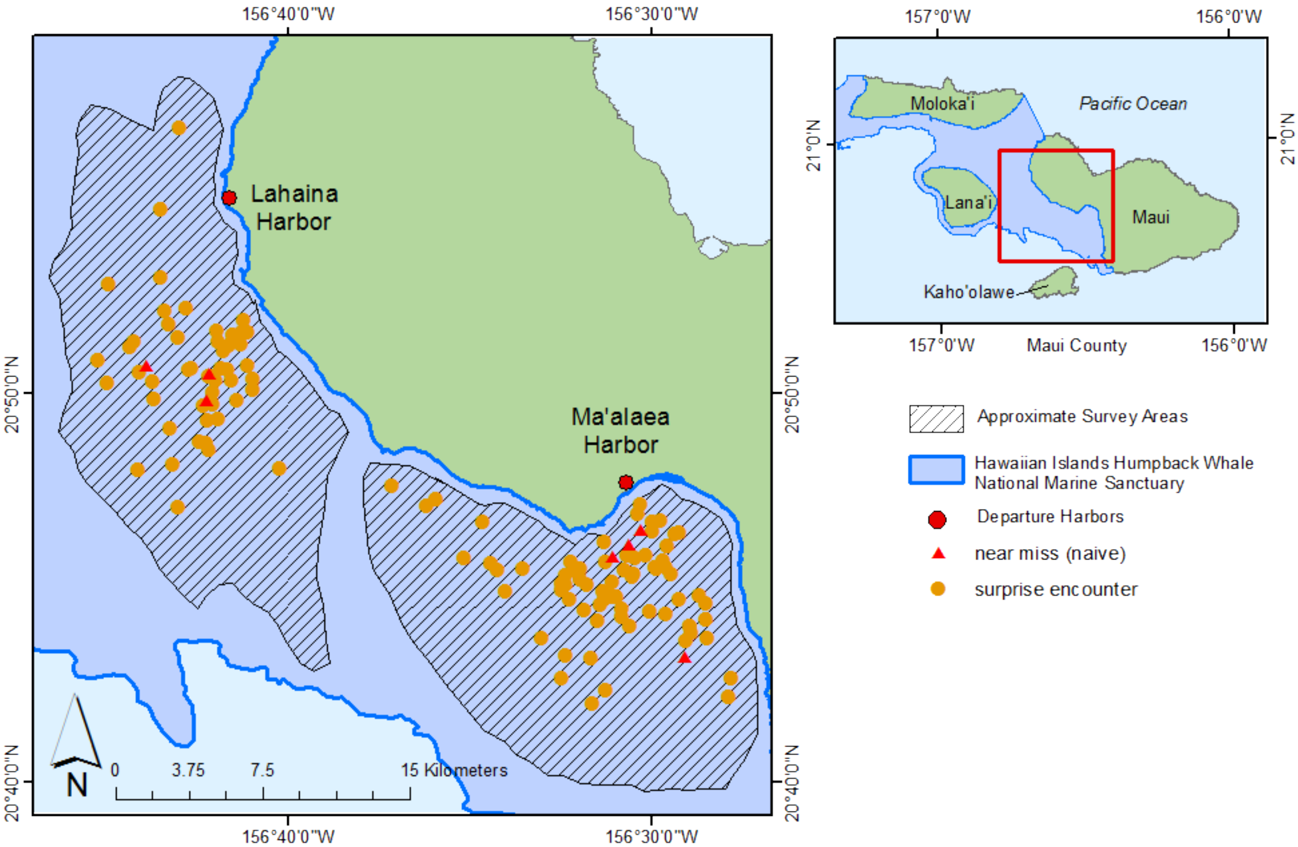

Figure 2 – Summary of locations where surprise encounters occurred during our study (orange circle) and locations where Near misses occurred (red triangle).

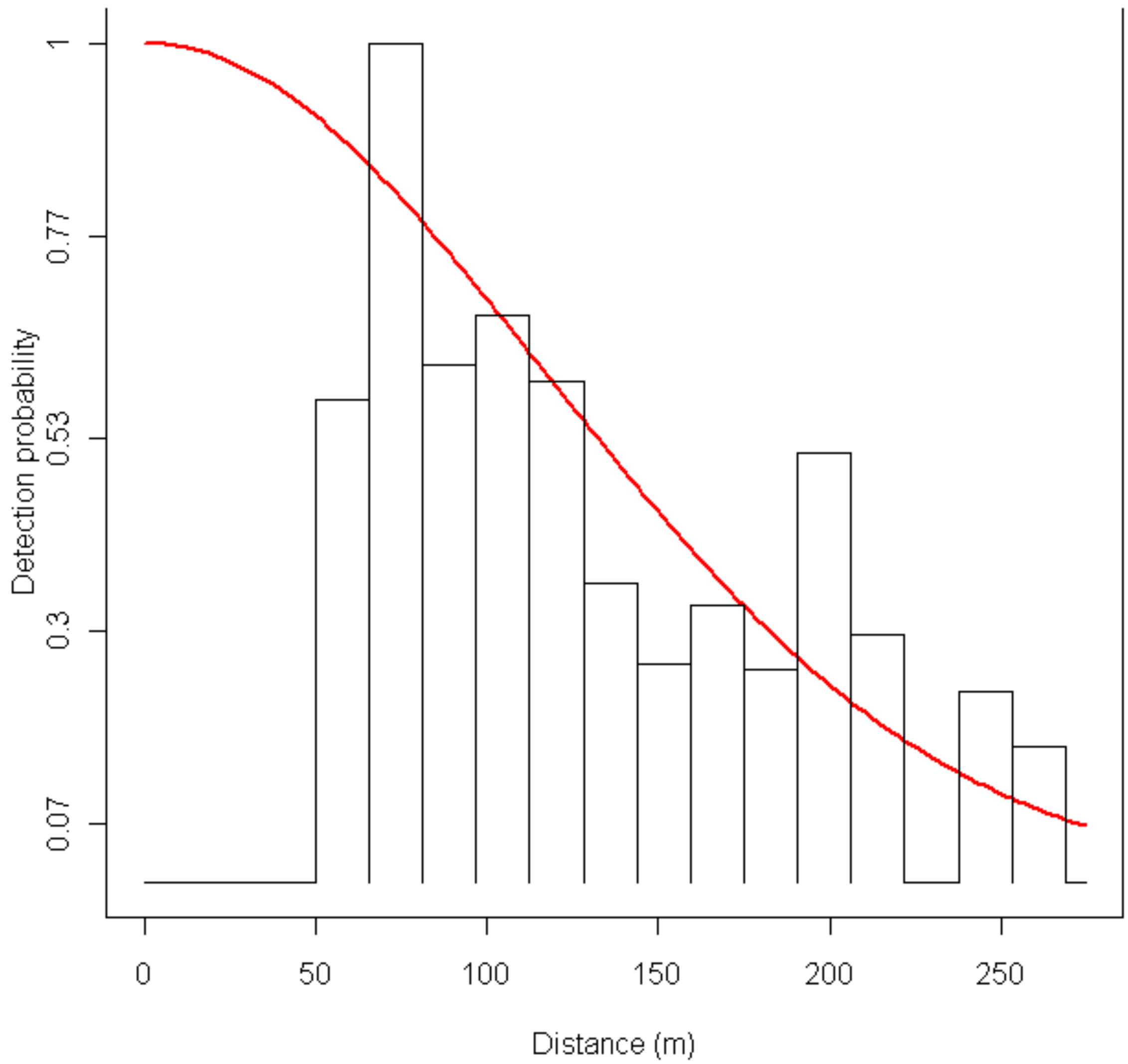

Figure 3 - Half-normal detectability function of Surprise Encounters.

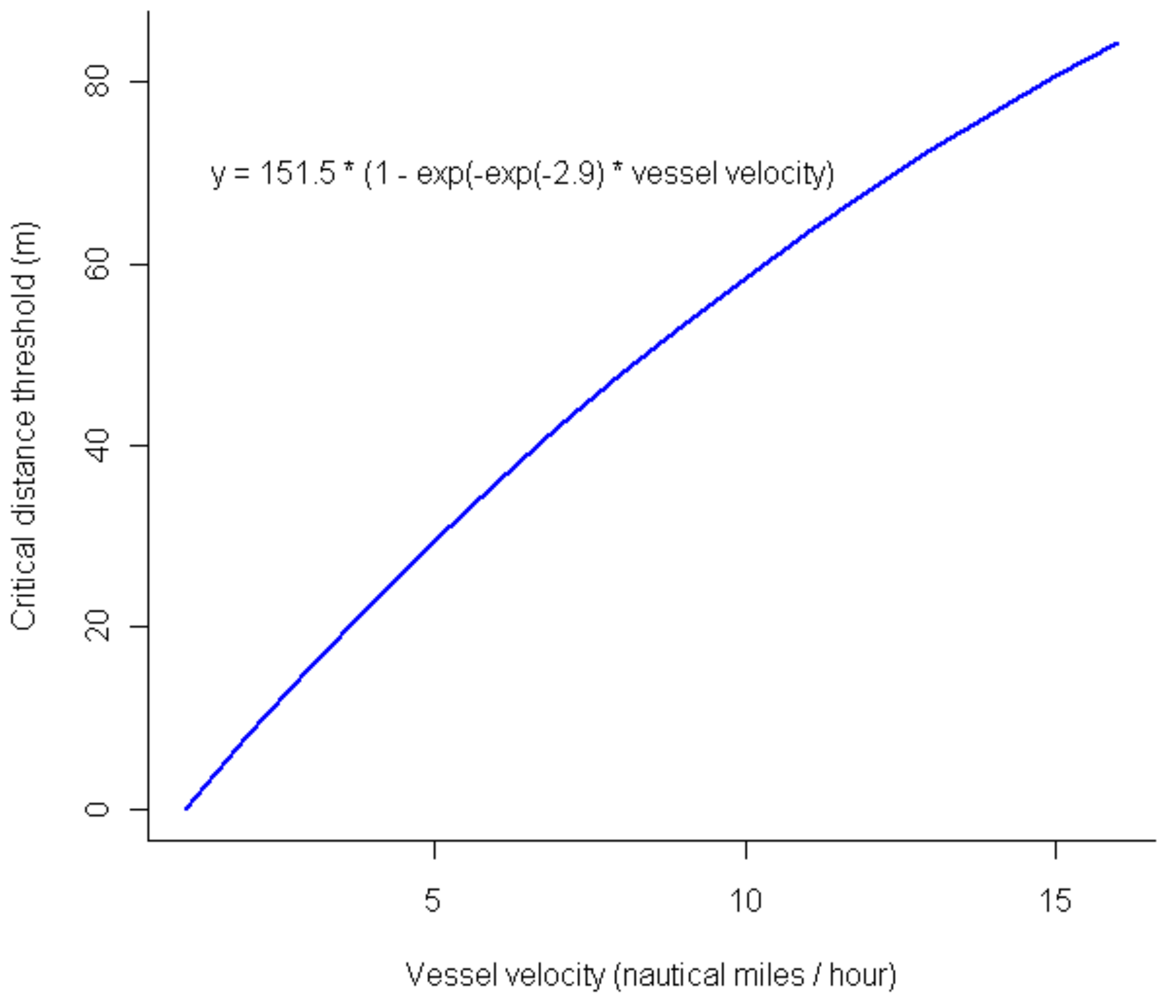

Figure 4 - Critical threshold under which a Surprise Encounter may become a hit or "near miss" and beyond which the encounter is not dangerous

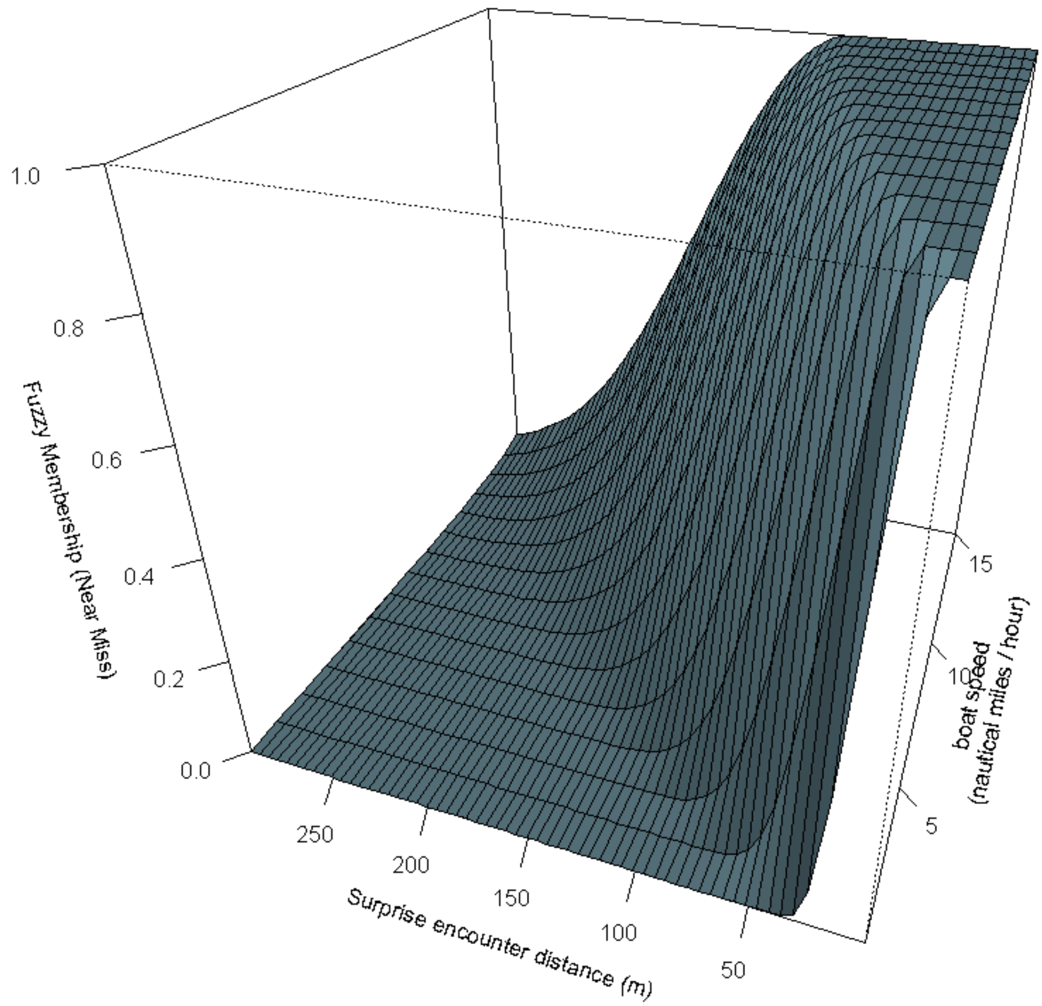

Figure 5 - Fuzzy classification of a surprise encounter becoming a hit or "near miss", varying by distance to surprise encounter and traveling velocity of the whale-watching vessels.