Modelling whale-vessel encounters: the role of speed in mitigating collisions with humpback whales (*Megaptera novaeangliae*)

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ABSTRACT

Increasing whale populations and vessel traffic worldwide has led to an increase in reported whale-vessel collisions. This paper reports on factors that affect the rate of whale-vessel collisions in the four-island region of Maui, Hawai'i. More specifically, it aims at quantifying the probability of a whale-vessel collision with varying vessel speeds using encounter distances as a proxy. A change point model was used to identify a speed threshold of 12.5kts (6.4m/s), which showed a significant change in the relationship between speed and mean sighting distance. A 3.4-fold decrease in close encounters with humpback whales was observed when vessels travelled at speeds of 12.5kts (6.4m/s) or less. Furthermore, results indicate that lone adult whales and calves are the most likely to be involved in a collision. A speed limit of 12.5kts (6.4m/s) is warranted in areas and/or during seasons where a high density of whales occurs. This limit aligns with a reduction in lethal vessel strikes with speed from previous studies which found a significant increase in the likelihood of mortality when vessel speed exceeds 12kts.

KEYWORDS: MODELLING; SHIP STRIKES; HUMPBACK WHALE; PACIFIC OCEAN; SURVEY–VESSEL; CONSERVATION

INTRODUCTION

Vessel collisions with cetacean species are a growing concern worldwide (IWC, 2011; Douglas *et al*., 2008; Laist *et al*., 2001; Van Waerebeek *et al*., 2007). Although a wide range of cetacean species are struck by vessels, collisions are a key mortality factor for larger whale species, including those found on the endangered species list (Laist *et al*., 2001; Redfern *et al*., 2013). Large whales, including humpback whales (*Megaptera novaeangliae*) are more susceptible to collisions in areas where their habitat overlaps with heavy vessel traffic. This risk is increased when whales are resting or moving slowly at the surface (Constantine *et al*., 2015; Laist *et al*., 2001; Vanderlaan and Taggart, 2007).

The increased rate of whale-vessel collisions over the past few decades constitutes an important conservation issue (IWC, 2011; Douglas *et al*., 2008; Laist *et al*., 2001; Silber *et al*., 2010), as they can often be lethal to the animal. Collisions which seriously injure or kill large whales are an important factor threatening the viability of certain populations or sub-populations (Knowlton and Kraus, 2001; Panigada *et al*., 2009).

Increased vessel traffic globally, as well as an increase in size and speed of vessels, has contributed to the rise in whale-vessel collisions (Dolman *et al*., 2009; Jensen and Silber, 2004; Vanderlaan *et al*., 2009). Vessels of all types and sizes are known to be involved in collisions with cetaceans, but larger and faster vessels account for higher instances of lethal collisions (Laist *et al*., 2001; Panigada *et al*., 2006; Silber *et al*., 2010; Vanderlaan and Taggart, 2007). At a speed of 12kts (6.2m/s), 45–60% of collisions between a vessel with mass significantly exceeding that of the whale are lethal; at speeds ≥ 19kts (9.8m/s) 100% of collisions are lethal (Vanderlaan and Taggart, 2007).

While various models provide insight into the survivability of vessel strikes among large whales, our understanding of the true frequency of strikes and the factors that lead to them is limited. Published figures for the frequency of vessel strikes are likely to be underestimates, owing to under reporting, whether intentional or unintentional (Van Waerebeek *et al*., 2007; Neilson *et al*., 2012). In addition, population level effects of collision mortality are also not well understood for most whale species (van der Hoop *et al*., 2013).

Hawai'i is an area where humpback whale habitat and high human use overlap. Over 8.1 million people visited Hawai'i in 2014 (DBEDT, 2015), with vessel-based activities being a major source of revenue for the tourism sector (Lammers *et al*., 2013) owing to the thousands of humpback whales that migrate to Hawai'i each winter to breed and calve. More than half, 53.6%, of the North Pacific humpback whale population migrates to Hawai'i each year (Calambokidis *et al*., 2008) with the population growing by 5.5–7.0% annually (Calambokidis and Barlow, 2004; Mobley *et al*., 2001). As humpback whale numbers continue to grow, so too does the concern about potential increases in whale-vessel collisions.

The majority of whale-vessel collisions reported in Hawai'ian waters by NOAA occur between the islands of Maui, Moloka'i, Kaho'olawe, and Lana'i, collectively referred to as the four-island region of Maui (Laist *et al*., 2001; Lammers *et al*., 2013). From 2013 to 2015, 17 vessel collisions were reported to NOAA, of which 82% (n = 14) were recorded in the four-island region of Maui (Ed Lyman, NOAA/HIHWNMS, pers. comm., 2015). The high percentage of whale vessel strikes within the Hawai'ian Islands Humpback Whale National Marine Sanctuary (HIHWNMS) is not surprising, given that the greatest density of humpback whales occurs within this region (Mobley *et al*., 2001); which is in conjunction with over half of the Hawai'ian whalewatching operations (O'Connor *et al*., 2009) and a multitude of other commercial and non-commercial vessels (Appendix Figs 1 and 2).

Increasing reports of whale-vessel collisions in Hawai'i are likely to be caused in part by an increasing number of humpback whales and increased monitoring efforts over the last 20 years (Lammers *et al*., 2013). However, the incidence of reported collisions is increasing more than would be expected for these reasons alone. Other potential factors include an increase in registered vessels between 7.9 and 19.8m, the size class which is responsible for more than two thirds of strikes in Hawai'i (Lammers *et al*., 2013).

Although mostly limited to vessels that have the ability to avoid collisions, to date very few studies have attempted to quantify the risk of collisions by taking into account not only distance to whale (Gende *et al*., 2008) but also vessel speed at the time of initial sighting. A better understanding of specific factors that influence the incidence of collisions, particularly in the seconds prior to contact, is crucial to reduce this threat. This paper looks at data collected from a dedicated research platform that recorded distances to first sightings of humpback whales travelling at different speeds. These data were then used to assess the frequency and proximity of encounters between small vessels (<10m) and humpback whales in relation to vessel speed and to identify a speed guideline for the Hawai'i regions or similar areas. To our knowledge, this is the first systematic study aimed at better understanding how speed influences the encounter distance between humpback whales and small vessels, utilising an *in situ* approach to developing a whale-vessel collision model for management purposes.

METHODS

Study area

The study region covered an area of 798.0km^2 located within the four-island region of Maui, Hawai'i, and was chosen to cover a large section of the HIHWNMS (Fig. 1). The area experiences high levels of vessel traffic during the whalewatching season from December to April each year (DBEDT, 2015).

Data collection

Surveys were conducted from an 8m *Power Cat* research vessel equipped with two 150 horsepower outboard engines. Data were collected using systematic line transect methodologies (Buckland *et al*., 2004) during the winter months from 2013 to 2016. Observations were undertaken by two experienced observers and the boat operator using a continuous scanning methodology by naked-eye or reticle binoculars (Bushnell 7x50), while a fourth person acted as a data recorder. Only whales sighted within 300m or less, forward and abeam of the vessel, were recorded to represent whales at risk of collision. Within this distance, encounters were further classified into surprise encounters (SE) and near misses (NM) defined as sighting within 80–300m and 0–80m respectively, as outlined in Stack *et al*. (2013). In the context of this paper and throughout the remaining text, SE and NM will be collectively referred to as 'encounters' and refers to whales sighted within 0–300m forward and abeam of the

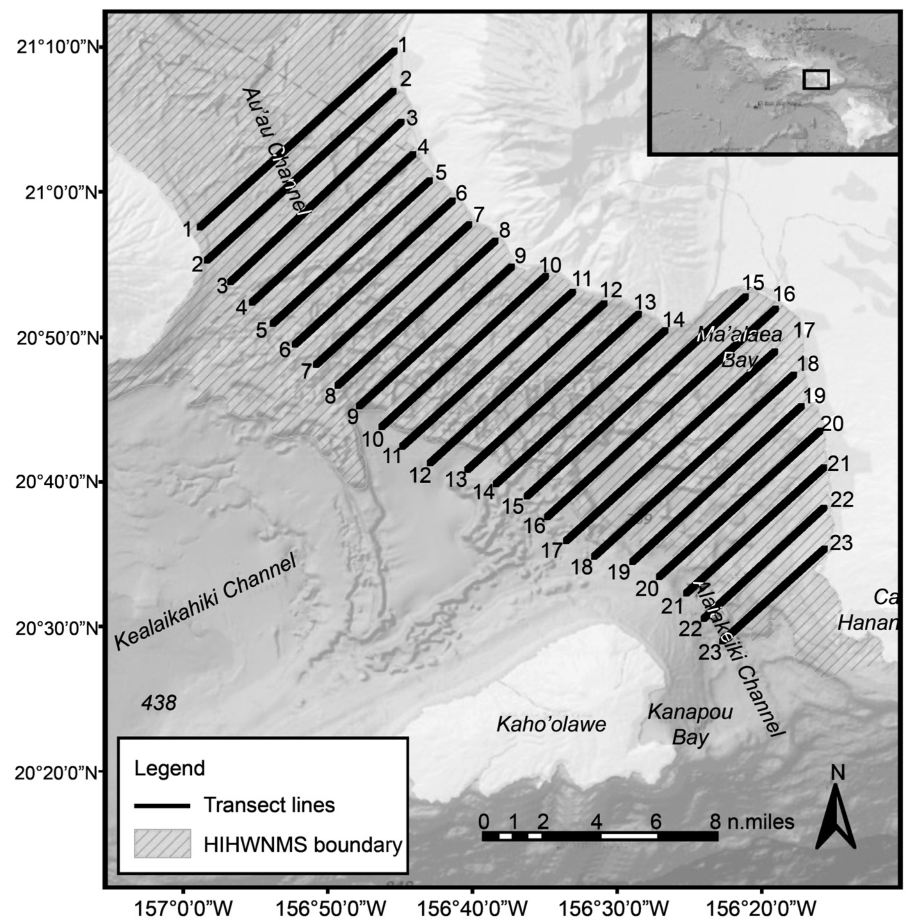

Fig. 1. Transect lines depicting survey area in the four-island region of Maui, Hawai'i, between 2 February 2013 and 31 March 2016 including the Hawai'ian Islands Humpback Whale National Marine Sanctuary (HIHWNMS) boundary.

vessel. The division of encounters into SE and NM allowed for subsequent analysis to determine if specific age classes were more susceptible to NM and/or SE. In addition, the following data were also recorded: time and location (latitude and longitude) of sighting, vessel speed, age-class of whale, number of whales in the pod, angle to pod (measured in magnetic degrees), and direction of travel by the whale. Additional environmental variables including Beaufort Sea state (BSS) as a measure of wind speed and Douglas Sea state (DSS) as a measure of wave height, were recorded at the start of each transect line, and updated as they changed throughout the survey.

To quantify rate encounters with varying vessel speed, a total of seven different speeds were randomly selected for the start of each transect, and speed was increased at 5kt (1.3m/s) increments every 15 minutes until the transect was completed. Depending on the length of the transect line, between two and three speed intervals were completed for each transect. Speeds used were 5.0, 7.5, 10, 12.5, 15, 17.5 and 20.0kts (2.6–10.3m/s) and this range was chosen to best represent the most frequently travelled vessel speeds in the study area.

Analysis

Analyses performed were: (1) assess the composition of SE and NM with varying age class and group composition; (2) change-point modelling to determine a threshold speed at which a change in mean distance at initial sighting of the whale occurred for all encounters; (3) quantification and distribution of encounters above and below identified threshold speed; (4) probabilities of encounters with varying vessel speed.

Change-point modelling

To determine if there was a threshold speed which caused a change in the mean encounter distance a change-point analysis was completed (Gende *et al.*, 2011) using the 'changepoint' package in R (Killick and Eckley, 2014). Encounter data from 2013–2016 were binned into 2.5 knot speed increments, which were summarised by the mean sighting distance derived from a minimum of 30 observations. Encounter data for each set of changes were then checked for normality and independence to ensure adherence to change-point distribution assumptions. As the goal of the analysis was to identify a speed threshold and assess the frequency of encounters above and below this threshold, the At-Most-One-Change method was considered most appropriate for the change-point model fit with a normal distribution:

$$En_i \sim (\beta_j, \sigma^2)$$

Where En_i are the encounters (i) including a speed (kts) and distance (m) with mean (β_j) and variance (σ^2), and j is the mean distance of sighting above and below the identified change point.

Distribution of encounters above and below the threshold speed

To determine the location and frequency of encounters, all on effort sighting and GPS track data collected from February 2013 to April 2016 were combined. Data were then subdivided into two groups: encounters above and below the threshold speed identified using the change-point model. To determine the density of encounters, the study area was divided into 184 grid cells measuring 1.5x1.5km, each with an area of 2.25km^2. Each grid cell was summarised by the count of encounters occurring in that cell and the total on effort distance travelled in that cell. Density of encounters was calculated by dividing the total number of encounters by the on effort distance per grid cell. Only grid cells that had a total on effort distance of ≥ 5km were included in final density estimates. Maps and grid were created using ArcGIS 10.1 (ESRI, 2011).

Probability of encounters with varying vessel speed and month

A General Linear Model (GLM) with a binomial error distribution and logit link function was used to model the relationship between encounters and vessel speed:

$$P_{SE} = e^{\beta_0 + \beta_{sp}} + \varepsilon$$

where P_{SE} is the probability of encounter, β_0 is the intercept, β_{sp} is the speed ranging from 5.0 to 20.0kts (2.6 to 10.3 m/s), and ε is the binomial error.

To account for the variation in number of humpback whales from December to April resulting from a progressive influx in numbers leading to peak season (Baker and Herman, 1981), analysis was divided into five months to represent the primary mating/birthing season in Hawai'i waters: December, January, February, March and April.

Model fit

All computations were completed using the 'stats' package in R (Wood, 2011). Final model selection was based on minimizing the AIC values (Akaike, 1973). To ensure proper model fit and adherence to assumptions, model residuals were graphed and visually checked for violations.

RESULTS

Survey effort

Between 2 February 2013 and 31 March 2016, 143 survey days allowed for sampling of 608 transect lines in the four-island region of Maui. Each transect line was surveyed a minimum of 23 and maximum of 29 times throughout the study period. This corresponded to a total of 4,477.6 nautical miles (n.mi) on effort and 5,009.4 n.mi off effort survey distances.

Composition of SE and NM

A total of 529 SE and 25 NM were recorded during the study period. Calves were present in 23.1% (n = 122) of SE and 48.0% (n = 12) of NM. Of all SE and NM involving calves, 54.5% (n = 73) were mother-calf pairs, 26.1% (n = 35) were mother-calf-escort pods, and 19.4% (n = 26) were lone calves (i.e. mother did not surface). Lone adults accounted for 48.3% (n = 255) of SE and 32.0% (n = 8) of NM, while pods consisting of ≥ 2 adults, accounted for 22.3% (n = 118) of SE and 44.0% (n = 11) of NM.

Change-point modelling

The change point model identified a change in the relationship between speed and mean sighting distance at 12.5kts (6.4m/s) (Fig. 2). The mean sighting distance before and after the change point was 211.2m and 189.4m,

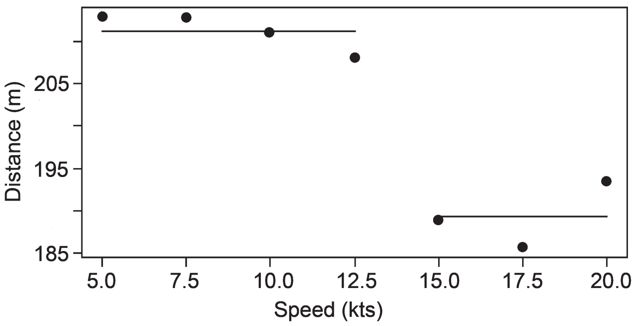

Fig. 2. Mean sighting distance of humpback whales with increasing speed (points) and the identified change point (solid line) recorded within the four-island region of Maui, Hawai'i between 2 February 2013 and 31 March 2016.

respectively. In the field, encounters were reduced 3.4 fold when the vessel travelled at speeds of 12.5kts (6.4m/s) or less. As such, encounters occurred for every 37.0 on effort nautical miles when travelling 12.5kts or less and every 10.9 on effort nautical miles when travelling faster than 12.5kts.

Distribution of encounters above and below the threshold speed

There was no clear trend in distribution of encounters when travelling at speeds below 12.5kts (6.4m/s) (Fig. 3). However, when travelling at speeds greater than 12.5kts (6.4m/s), a higher frequency of encounters was observed in the Au'Au Channel, which is covered by transect lines 1–9.

Probability of encounters with varying vessel speed by month

A significant positive relationship between speed and probability of encounter was identified (p = value: < 0.001, Res.df = 798). When data were further divided by month, three months were found to significantly vary from intercept only models showing a postive relationship between encounters and speed: December (p-value: 0.03, Res.df = 76), February (p-value: 0.006, Res.df = 213), and March (p-value: 0.003, Res.df = 275) (Fig. 4).

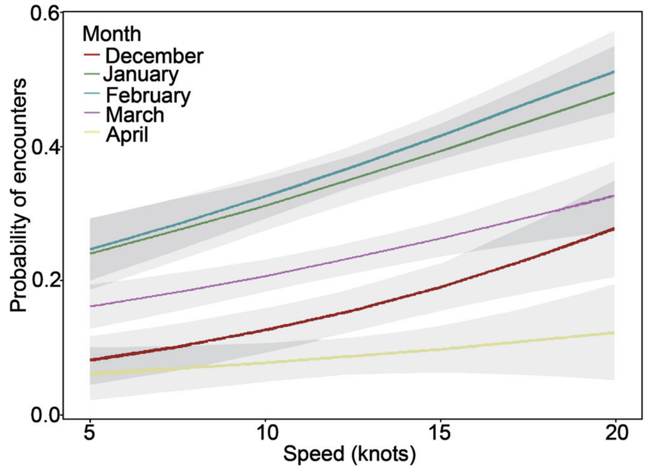

Fig. 4. Probabilities of encounters with humpback whales at varying vessel speeds, where lines represent monthly predictions based on binomial regression and the shaded area represents the 95% confidence interval.

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 close encounters at varying vessel speeds (Richardson *et al.*, 2011). Previous studies have assessed the risk of whale-vessel collisions by establishing co-occurrence of whales within major shipping routes (Redfern *et al.*, 2013). The implications of speed on mortality rate (Vanderlaan *et al.*, 2009) and encounter distance (Gende *et al.*, 2011) has also been investigated. This study aimed at assessing the rate of close encounters (<300m) with humpback whales at varying vessel speeds.

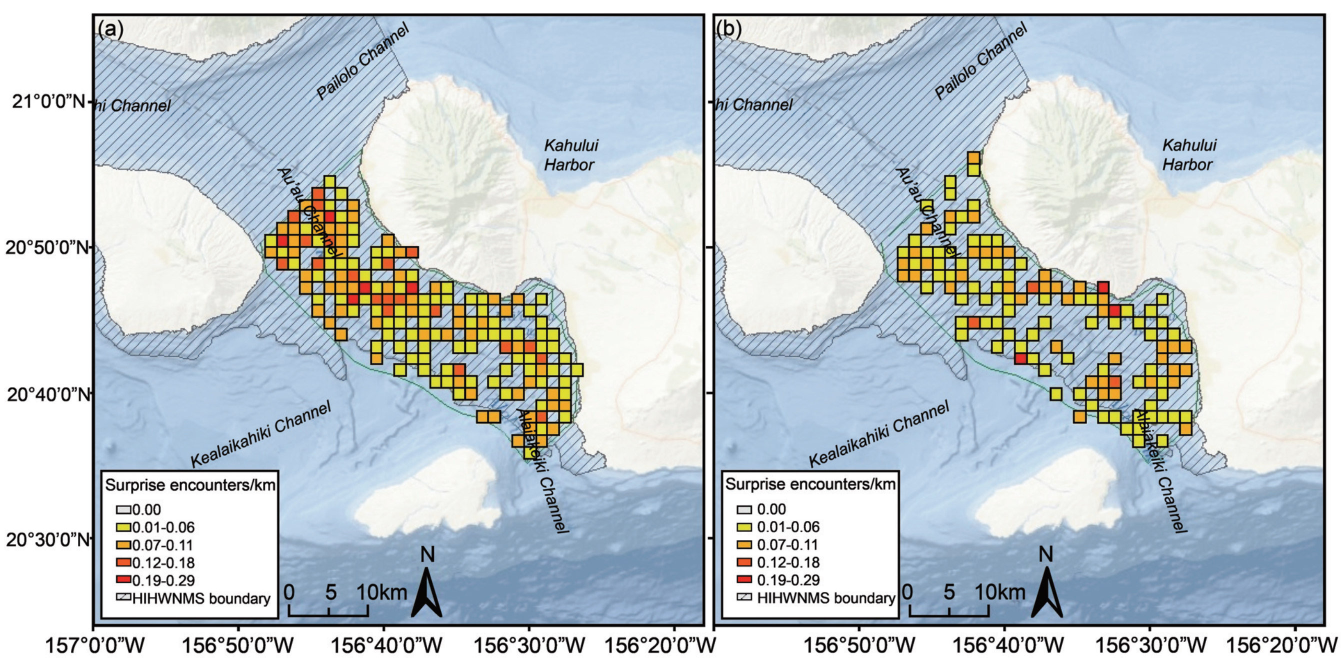

Fig. 3. Encounters per km travelled at speeds (A) above and (B) below the identified 12.5kts (6.4m/s) threshold within the four-island region of Maui, Hawai'i between 2 February 2013 and 31 March 2016.

Change-point modelling

Despite the relatively small change in mean sighting distance identified using the change point model, the speed threshold of 12.5kts (6.4m/s) showed a significant decrease in the frequency of encounters when traveling below this threshold. The small change in mean sighting distance is likely a result of analysing only whales that were sighted within 300m of the vessel. The speed threshold of 12.5kts (6.4m/s) is similar to results presented in Gende *et al*. (2011), which identified a threshold speed of 11.8kts (6.1m/s), despite utilising large cruise ships and including encounter distances up to 1000m. These results suggest that speeds in excess of ~12kts (6.2m/s), regardless of vessel size, will significantly increase the likelihood of whale-vessel collisions.

Distribution of encounters above and below the threshold speed

A reduction in speed may be favorable for preventing whale-vessel collisions over other options, such as reduced or closed traffic areas, as we observed a threefold reduction in encounters when vessel speeds were reduced to 12.5kts (6.4m/s) or less, and noted no clear trends in distribution of encounters for the four-island region. Furthermore, the implementation of a speed limit is much easier and is more likely to become adopted rather than trying to minimise traffic within an area.

Probability of encounters with varying vessel speed by month

The contrast in the monthly rate of encounters suggests that the risk of a whale-vessel collision varies with month and whale abundance. During February, the peak humpback whale season in Hawai'i, the probability of encounter increases from ~35% to 50% when vessel speed is increased from below 12.5kts (6.4m/s) to above. Similarly, a probability analysis modelling the lethality of vessel strikes with speed found a significant increase in the likelihood of lethality when vessel speed exceeds 12kts (6.2m/s) (Vanderlaan and Taggart, 2007). As such, vessel speed restrictions are being used as mitigation measures in various locations (e.g. USA: Gulf of Maine and Glacier Bay, Alaska; New Zealand: Hauraki Gulf, Auckland) to reduce the occurrence and/or severity of whale-vessel collisions with large whale species (Constantine *et al*., 2015; Gende *et al*., 2011; Vanderlaan *et al*., 2009).

Combining information on the rate of near collisions with the severity (Vanderlaan *et al*., 2009) of whale vessel collisions based on differing vessel speeds provides insight into the efficacy of speed restrictions as a management tool. Reduced speed will not only allow whales more time to manoeuvre, but also increases reaction time for a vessel to stop or change course if they are able (Stack *et al*., 2013). Consequently, this could reduce the incidence of collisions. The average speed of whale-vessel collisions reported from 1979–2011 in Maui was 14.7kts (7.6m/s) and, of these collisions, 52.9% were at speeds ≥ 15kts (7.7m/s) (Lammers *et al.*, 2013). Current results suggest implementation of a speed guideline in the four-island region of Maui would be most effective during peak whale season (February–March).

The defining of SE and NM at distances of 300m and 80m respectively (Stack *et al*., 2013) differs from the term near miss defined in IWC (2011) as 100m. The IWC-ACCOBAMS workshop on ship strikes noted that there could be many interpretations of a near miss and a clear definition is required (IWC, 2011). The terms as outlined in this study were designed to quantify the risk of vessel strikes by using close encounters (<300m) as proxies for whale-vessel collisions. Results from this study relating speed to probability of encounters, in conjunction with other studies relating speeds to encounter distance and lethality (Gende *et al*., 2011; Vanderlaan and Taggart, 2007), all point to similar speed thresholds of 11–13kts (5.7–6.7m/s).

Age-class and susceptibility to whale-vessel collisions

SE occurred across all age-classes. However, lone adults were more likely to be involved in a SE than other compositions recorded. This differs from other findings which show a significantly greater proportion of calves and sub-adults involved in SE than the general population (e.g. Richardson *et al*., 2011). The number of lone adult SE increased from 2014 to 2015, suggesting that there are yearly variations in the population, as shown by Tonachella *et al*. (2012). If some years are peak years for calving, there will be more young whales present and therefore an increased susceptibility of that age class to a collision. If, however, there are lulls in the calving rate, the opposite will be true and more SE with adult whales would be expected.

The age-class composition of NM revealed that 48.0% of all NM involved a calf, and yet calves comprise only 7.0–9.0% of the Hawai'ian population of humpback whales (Mobley *et al.*, 2001). This supports earlier research findings indicating that calves and juveniles are highly vulnerable to vessel strikes (Laist *et al*., 2001; Lammers *et al*., 2013). This is likely due to a combination of calf related traits such as: more time spent at the surface to breathe than adults, surfacing often without the mother if the pod is stationary, being less visible than adults, and being relatively naive to interactions with vessels (Laist *et al.*, 2001; Lammers *et al*., 2013). In Hawai'ian waters, 63.5% of the 52 collisions with humpback whales between 1975–2011, in which age-class was specified, involved either a calf or juvenile (Lammers *et al.*, 2013).

Recommendations

Although data were collected within the four-island region, results from previous literature (Constantine *et al*., 2015; Currie *et al*., 2014; Guzman *et al*., 2013; Laist *et al*., 2014; Lammers *et al*., 2013; Richardson *et al*., 2011; Stack *et al.*, 2013; van der Hoop *et al*., 2014; Vanderlaan and Taggart, 2007) suggest implementation of a 12–13kts (6.2–6.7m/s) speed limit is warranted in areas and/or in seasons with high densities of humpback whales. Furthermore, speed restrictions have been proven a successful mitigation measure (Gende *et al*., 2011; Vanderlaan *et al.,* 2009). Instances of whale-vessel collisions still occur at speeds below this threshold (Laist *et al.,* 2001; Vanderlaan and Taggart, 2007) and adoption of programs such as the 'Be Whale Aware' by Pacific Whale Foundation (PWF, 2015) and 'Ocean Etiquette' by NOAA (NOAA, 2015b) should continue to be implemented to help further mitigate whale-vessel collisions. As both whale and human populations increase, with a concurrent increase in anthropogenic activities in the marine environment, more scientific research leading to sound management strategies will ensure that both humans and animals can safely co-exist.

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REFERENCES

Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. pp.267–81. *In*: B.N. Petrov and F. Csáki (eds.) Proceedings of the 2nd International Symposium on Information Theory, Tsahkadsor, Armenia, USSR, 2–8 September 1971, Budapest: Akadémiai Kiadó.

Baker, C.S. and Herman, L.M. 1981. Migration and local movement of humpback whales (*Megaptera novaeangliae*) through Hawaiian waters. *Can. J. Zool.* 59(3): 460–9.

Buckland, S.T., Anderson, D.R., Burnham, K.P., Laake, J.L., Borchers, D.L. and Thomas, L. 2004. *Advanced Distance Sampling*. Oxford University Press, Oxford. 434pp.

Calambokidis, J., Falcone, E.A., Quinn, T.J., Burdin, A.M., Clapham, P.J., Ford, J.K.B., Gabriele, C.M., LeDuc, R., Mattila, D., Rojas-Bracho, L., Straley, J.M., Taylor, B.L., Urbán, J.R., Weller, D., Witteveen, B.H., Yamaguchi, M., Bendlin, A., Camacho, D., Flynn, K., Havron, A., Huggings, J., Maloney, N., Barlow, J. and Wade, P.R. 2008. SPLASH: Structure of populations, levels of abundance and status of humpback whales in the North Pacific. Report submitted by Cascadia Research Collective to USDOC, Seattle, WA, USA. Contract AB133F-03-RP-0078 (unpublished). [Available from the author – JC].

Calambokidis, J. and Barlow, J. 2004. Abundance of blue and humpback whales in the eastern North Pacific estimated by capture-recapture and line-transect methods. *Mar. Mamm. Sci.* 20(1):63–85.

Constantine, R., Johnson, M., Riekkola, L., Jervis, S., Kozmian-Ledward, L., Dennis, T., Torres, L.G. and Aguilar de Soto, N. 2015. Mitigation of vessel-strike mortality of endangered Bryde's whales in the Hauraki Gulf, New Zealand. *Biol. Conserv.* 186:149–57.

Currie, J.J., Stack, S.H., Davidson, E., Kaufman, G.D., Martinez, E. 2014. Results from two years of line transect surveys utilizing surprise encounters and near-misses as proxies of vessels collisions with humpback whales (*Megaptera novaeangliae*) in the four-island region of Maui, Hawai'i, USA. Paper SC/65b/HIM01 presented to the IWC Scientific Committee, 12–24 May 2014, Bled, Slovenia (unpublished). 21pp. [Available from the Office of this Journal].

Department of Business, Economic Development and Tourism (DBEDT). 2015. Research Economics and Analysis. Accessed May 2015. [Available at: *http://hawaii.gov/dbedt/info/economic/databook/*].

Dolman, S.J., Weir, C.R. and Jasny, M. 2009. Comparative review of marine mammal guidance implemented during naval exercises. *Mar. Poll. Bull.* 58:465–77.

Douglas, A.B., Calambokidis, J., Raverty, S., Jeffries, S.J., Lambourn, D.M. and Norman, S.A. 2008. Incidence of ship strikes of large whales in Washington State. *J. Mar. Biol. Ass. U.K.* 88(06): 1,121–32.

ESRI. 2011. ArcGIS Desktop: Release 10.: Environmental Systems Research Institute, Redlands, CA. [Available from: *https://www.esri.com*]

Gende, S.M., Hendrix, A.N., Harris, K.R., Eichenlaub, B., Nielson, J. and Pyare S. 2011. A Bayesian approach for understanding the role of ship speed in whale-ship encounters. *Ecol. Appl.* 21:2,232–40.

Guzman, H.M., Gomez, C.G., Guevara, C.A. and Kleivane, L. 2013. Potential vessel collisions with southern hemisphere humpback whales wintering off Pacific Panama. *Mar. Mamm. Sci.* 29(4):629–42. [Available at: *http://bit.ly/2lTfaec*].

International Whaling Commission. 2011. Report of the Joint IWC-ACCOBAMS Workshop on Reducing Risk of Collisions between Vessels and Cetaceans, 21–24 September 2010, Beaulieu-Sur-Mer, France. Paper IWC/63/CC8 presented to the IWC Conservation Committee, July 2011, Jersey, Channel Islands, UK. 41pp. [Paper available from the Office of this Journal]

Jensen, A.S. and Silber, G.K. 2004. Large whale ship strike database. US Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) Technical Memorandum NMFS-OPR-25. 37pp. [Available from: *http//www.nmfs.noaa.gov*].

Killick, R. and Eckley, I.A. 2014. changepoint: An R Package for Changepoint Analysis. *J. Stat. Softw.* 58(3):1–19.

Knowlton, A.R. and Kraus, S.D. 2001. Mortality and serious injury of northern right whales (*Eubalaena glacialis*) in the western North Atlantic Ocean. *J. Cetacean Res. Manage.* 2:193–208.

Laist, D.W., Knowlton, A.R., Mead, J.G., Collet, A.S. and Podesta, M. 2001. Collisions between ships and whales. *Mar. Mamm. Sci.* 17(1):35–75.

Laist, D.W., Knowlton, A.R. and Pendelton, D. 2014. Effectiveness of mandatory vessel speed limits for protecting North Atlantic right whales. *Endanger. Species Res.* 23:133–147.

Lammers, M.O., Pack, A.A., Lyman, E.G. and Espiritu, L. 2013. Trends in collisions between vessels and North Pacific humpback whales (*Megaptera novaeangliae*) in Hawaiian waters (1975–2011). *J. Cetacean Res. Manage.* 13(1):73–80.

Mobley, J.M., Spitz, S., Grotefendt, R., Forestell, P., Frankel, A. and Bauer, G. 2001. Abundance of humpback whales in Hawaiian waters: Results of 1993–2000 aerial surveys. Report to the Hawaiian Islands Humpback Whale National Marine Sanctuary. 9pp.

Neilson, J.L., Gabriele, C.M., Jensen, A.S., Jackson, K. and Straley, J.M. 2012. Summary of reported whale-vessel collisions in Alaskan waters. *J. Mar. Biol.* 2012:1–18.

NOAA. 2015. Ocean Etiquette. [Available at: *http://oceanservice.noaa.gov/facts/ocean-etiquette.html* Accessed on 15 April 2015.]

O'Connor, S., Campbell, R., Cortez, H. and Knowles, T. 2009. Whale Watching Worldwide: tourism numbers, expenditures and expanding economic benefits. Special report from the International Fund for Animal Welfare. Yarmouth, International Fund for Animal Welfare, Yarmouth, MA, USA.

Pacific Whale Foundation. Be Whale Aware. Accessed on 15 October 2015. 295pp. [Available at: *https://www.pacificwhale.org/be-whale-aware*, accessed 15 October 2015]

Panigada, S., Pesante, G., Zanardelli, M., Capoulade, F., Gannier, A. and Weinrich, M.T. 2006. Mediterranean fin whales at risk from fatal ship strikes. *Mar. Poll. Bull.* 52(10): 1,287–98.

Panigada, S., Leaper, R. and Arcerdillo, A. 2009. Ship strikes in the Mediterranean Sea: Assessment and identification of mitigation measures. Paper SC/61/BC2 presented to the IWC Scientific Committee, 22–25 June 2009, Madeira, Portugal (unpublished). 5pp. [Available from the Office of this Journal].

Redfern, J.V., McKenna, M.F., Moore, T.J., Calambokidis, J., Deangelis, M.L., Becker, E. A., Barlow, J., Forney, K.A., Fiedler, P.C. and Chivers, S.J. 2013. Assessing the risk of ships striking large whales in marine spatial planning. *Conserv. Biol.* 27(2):292–302.

Richardson, D.T., Silva, I.F., Macie, A., Rankin, R.W., Maldini, D. and Kaufman, G.D. 2011. Whale surprise encounters and near misses: proxies of vessel strikes in Maui County waters. Document SC/63/BC2 presented to the IWC Scientific Committee, Tromso, Norway (unpublished). 19pp. [Available from the Office of this Journal]

Silber, G.K., Slutsky, J. and Bettridge, S. 2010. Hydrodynamics of a ship/whale collision. *J. Exp. Mar. Biol. Ecol.* 391:10–19.

Smultea, M.A. 1994. Segregation by humpback whale (*Megaptera novaeangliae*) cows with a calf in coastal habitat near the island of Hawaii. *Can. J. Zool.* 72(5):805–11.

Stack, S.H., Currie, J.J., Davidson, E.H., Frey, D., Maldini, D., Martinez, E. and Kaufman, G.D. 2013. 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, Hawaii, USA. Paper SC/65a/WW04 presented to the IWC Scientific Committee, 3–15 June 2013, Jeju, Korea (unpublished). 20pp. [Available from the Office of this Journal]

Tonachella, N., Nastasi, A., Kaufman, G., Maldini, D. and Rankin, R. W. 2012. Predicting trends in humpback whale (*Megaptera novaeangliae*) abundance using citizen science. *Pac. Conserv. Biol.* 18(4):297–309.

Van der Hoop, J.M., Moore, M.J. and Barco, S.G., Colde, T.V.N., Daoust, P-Y., Henry, A., McAlpine, D.F., McLellan, W.A., Winner, T. and Solow, A.R. 2013. Assessment of management to mitigate anthropogenic effects on large whales. *Conserv. Biol.* 27:121–133.

Van Waerebeek, K., Baker, A.N., Félix, F., Gedamke, J., Iñiguez, M., Sanino, G.P., Secchi, E., Sutaria, D., Van Helden, A. and Wang, Y. 2007. Vessel collisions with small cetaceans worldwide and with large whales in the Southern Hemisphere, an initial assessment. *Latin Am. J. Aquat. Mamm.* 6:43–69.

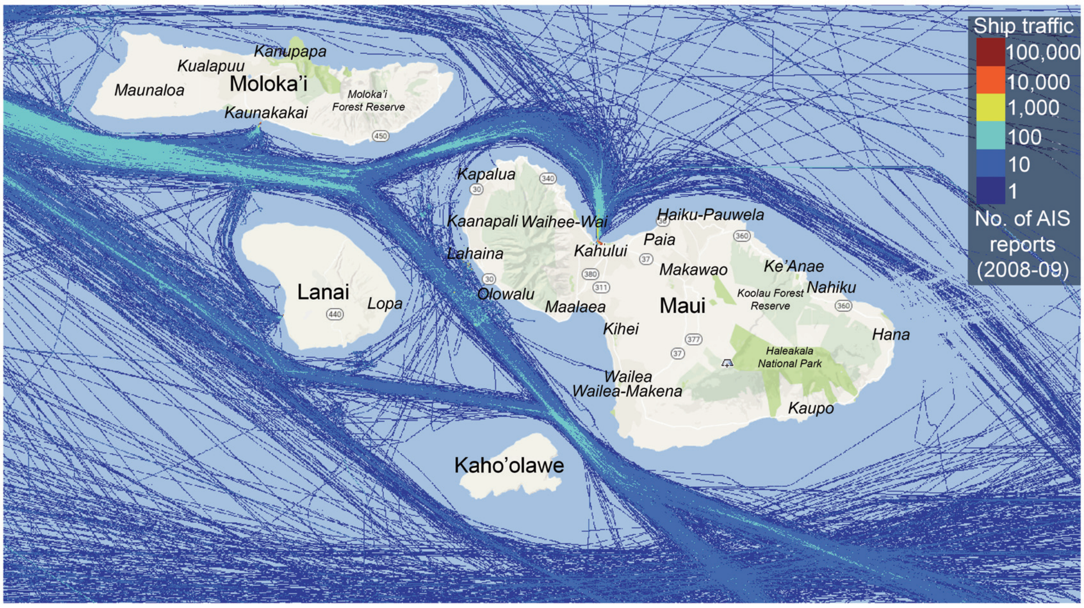
Vanderlaan, A.S.M., and Taggart, C.T. 2007. Vessel collisions with whales: the probability of lethal injury based on vessel speed. *Mar. Mamm. Sci.* 23(1):144–156.

Vanderlaan, A.S., Corbett, J.J., Green, S.L., Callahan, J.A., Wang, C., Kenney, R.D., Taggart, C.T. and Firestone, J. 2009. Probability and mitigation of vessel encounters with North Atlantic right whales. *Endanger. Species Res.* 6(3):273–285.

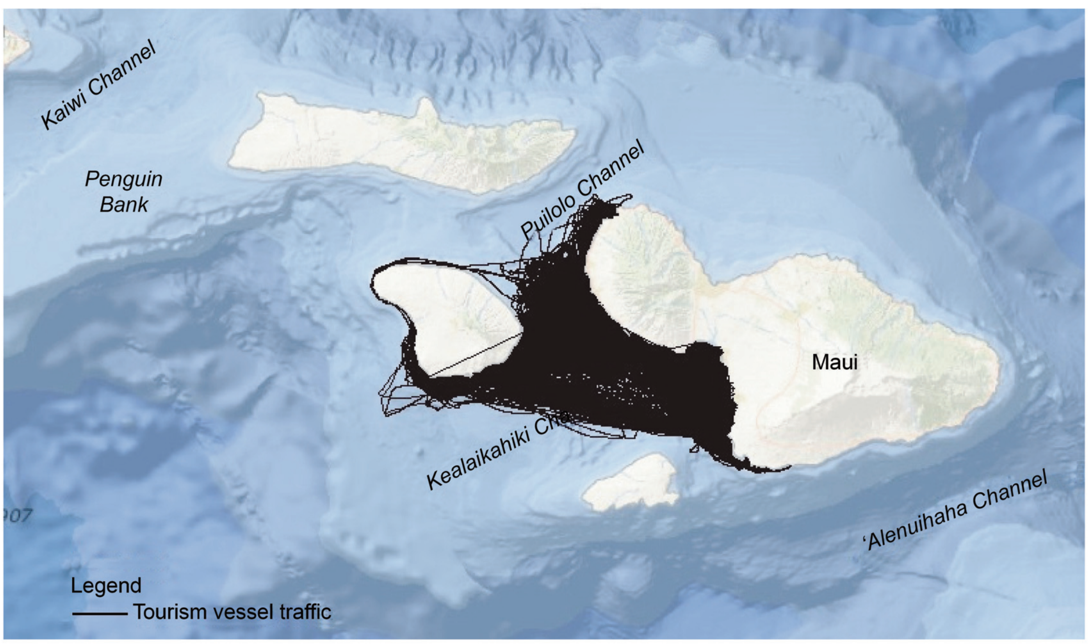
Weinrich, M., Pekarcik, C. and Tackaberry, J. 2010. The effectiveness of dedicated observers in reducing risks of marine mammal collisions with ferries: A test of the technique. *Mar. Mamm. Sci.* 26(2):460–70.

Wood, S.N. 2006. *Generalized Additive Models: An Introduction with R*. Taylor and Francis, UK. 384pp.

APPENDIX 1



Appendix Fig. 1. Map depicting ship traffic densities of vessels equipped with AIS transceivers in the four-island region of Maui, Hawai'i over a one year period. Source: Data for map provided by PacIOOS (*http://www.pacioos.org*), which is a part of the US Integrated Ocean Observing System (IOOS), funded in part by National Oceanic and Atmospheric Administration (NOAA) Awards, NA11NOS0120039 and NA16NOS0120024.



Appendix Fig. 2. Map depicting tourism vessel traffic densities of eight vessels in the four-island region of Maui, Hawai'i over a one year period.