The relationship between vessel traffic and noise levels received by killer whales and an evaluation of compliance with vessel regulations

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Abstract

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Whale watching has become increasingly popular as an ecotourism activity around the globe and is beneficial for environmental education and local economies. Southern Resident killer whales (*Orcinus orca*) comprise an endangered population that is frequently observed by a large whale watching fleet in the inland waters of Washington state and British Columbia. One of the factors identified as a risk to recovery for the population is the effect of vessels and associated noise. Federal regulations limit the approach distance of vessels to 200 m and voluntary guidelines suggest a maximum vessel speed of 7 knots within 400 m of the whales. An examination of the effects of vessels and associated noise on whale behavior utilized novel equipment to address limitations of previous studies. Digital acoustic recording tags measured the noise levels the tagged whales received while laser positioning systems allowed collection of

geo-referenced data for tagged whales and all vessels within 1000 m. The objectives of the current study were 1) to compare vessel data and DTAG recordings to relate vessel traffic to the ambient noise tagged whales receive and 2) to utilize the vessel data to examine vessel behavior during whale watching and assess trends in vessel behavior over time. Vessel attributes found to be significant predictors of noise levels in the likelihood model, using all intervals of vessel and noise data, were length (inverse relationship), number of propellers, and vessel speed (however, $R^2 = 0.15$). When intervals that only recorded the research vessel were excluded, the only significant predictor of noise levels in the likelihood model was vessel speed ($R^2 = 0.42$). Average vessel speed and number of propellers per interval were the only significant correlates with noise levels using simple linear regression (i.e. ignoring other concurrent characteristics). Research, commercial whale watching, and private whale watching vessels increased their distance from observed whales over time. The occurrence of research and commercial whale watching vessels within 100 m of a tagged whale also significantly decreased over time. However, vessel speed (excluding research vessels) significantly increased over time for vessels at distances of 200 m and 400 m from whales. Compliance with the distance regulation has improved, even though distance was not a significant correlate with noise levels received by whales. Increases in vessel speed are a cause for concern since speed was the most important predictor of noise levels received by whales in this study. The information presented here may be useful to managers in assessing the effectiveness of current recovery efforts.

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PREFACE

Both chapters of this thesis are formatted with the intent of eventual submission for publication in appropriate peer-reviewed journals. A substantial amount of the introductory material for both chapters is repetitious, so that each chapter can effectively stand-alone. Data collection for both chapters occurred concurrently, resulting in additional repetition in some of the methods and figures.

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PROLOGUE

Southern Resident killer whales (*Orcinus orca*; hereafter SRKW) are an endangered, yet heavily whale watched population in the Salish Sea. Previous research on the population has shown that vessel traffic leads to behavior modification (Williams et al. 2002a, Williams et al. 2002b, Williams et al. 2009, Lusseau et al. 2009, Noren et al. 2009). Vessels closely approaching SRKW elicited surface-active behaviors, such as breeching (launching body out of the water) and tail-slapping (Noren et al. 2009), possibly responses to perceived risk (Frid & Dill 2002). Such behaviors may be energetically costly. SRKW have also been shown to compensate vocally for increased ambient noise in the general vicinity by increasing the amplitude (Holt et al. 2009, Holt et al. 2011) and duration (Foote et al. 2004, Wieland et al. 2010) of their calls. Such compensations are examples of the Lombard effect, a well-known phenomenon of increasing vocal effort in noisy environments (Lombard 1911, Lane & Tranel 1971). Vocal responses to increased noise may lead to increases in energy expenditure (Noren et al. 2013). The body of research described has led to the implementation of whale watching regulations in U.S. waters. Vessels are prohibited from approaching whales within 200 yd/m overall or within 400 yd/m of a whale's path (NOAA 2011).

In previous studies relating ambient noise to SRKW responses, stationary hydrophones were used to measure ambient noise in the environment. Stationary hydrophones cannot encompass the full auditory environment an individual SRKW experiences as it dives and travels (Holt 2008). Previous studies recorded vessel traffic as the number of vessels at a certain distance while other vessel characteristics were not measured. To address the limitations of previous research, digital acoustic recording tags (DTAGs; Figure 1.4) and laser positioning systems were implemented in a large collaborative study between NOAA/Northwest Fisheries Science Center (NWFSC), D. Giles, and Cascadia Research Collective (CRC). DTAGs have been used on many cetacean species to examine vocal/movement behavior and responses to anthropogenic noise (Johnson & Tyack 2003, Johnson et al. 2009). The laser positioning system (with built-in data collector) allows for an accurate measure of vessel presence by determining the precise position of the tagged whale and any vessel within 1000 meters, while additionally recording vessel characteristics (e.g., size, type) and operational state (e.g., orientation, speed). The overall SRKW DTAG study aims to assess the effects of vessels and associated noise on SRKW behavior. The objectives of the larger project are to 1) quantify the noise levels received by SRKW as they dive, 2) quantify the relationship between vessels and received noise levels, 3) investigate SRKW acoustic behavior during different activities, especially those indicative of foraging, and 4) quantify foraging effort from such data and determine potential effects of vessel traffic and associated noise levels.

The following thesis was the first phase of the larger SRKW DTAG study. The research described here had two overall objectives: 1) to compare vessel data and DTAG recordings to relate vessel traffic to the ambient noise a tagged SRKW individual receives and 2) to utilize the vessel data to examine vessel behavior during whale watching and assess trends in vessel behavior over time.

CHAPTER 1

The relationship between vessel traffic and noise levels received by killer whales

INTRODUCTION

Top predators are key components of ecosystems around the globe. Their removal, and the consequent loss of ecological interactions they facilitate, may be detrimental to natural ecosystems (Janzen 1974, Estes et al. 2011). The large spatial range required by many top predators leads to competition with humans for space and resources, leaving many in danger of negative anthropogenic interactions (Linnell et al. 2001). A variety of human interactions, such as harvest, habitat degradation, and pollution, are known to have negative effects on wildlife populations. Non-lethal human disturbance, such as wildlife viewing, is perceived by observed animals as a predation risk with associated energy costs and effects on survival and reproduction (Frid & Dill 2002). Therefore, it is important to fully comprehend the extent of human use of the environment before negative consequences on animal populations can be assessed and mitigated.

The potential impacts of human interactions with animals in the marine environment are sometimes difficult to evaluate, because of our inability to visually perceive effects on underwater communities. Increases in maritime activity and vessel traffic lead to harmful impacts such as vessel collision and habitat degradation due to noise pollution. Marine mammals, particularly cetaceans, are especially vulnerable to these impacts due to their large size, requisite surface-oriented behaviors relating to respiration, and life history strategies (e.g., long-lived, delayed reproduction in many cases; Evans 1996). Visible light is attenuated rapidly with depth, while sound travels much farther with depth at sea. It is not surprising that hearing is an important sensory modality for marine mammals. Noise pollution is likely harmful for toothed whales, which utilize echolocation and their acoustic habitat for vital activities, such as communication, foraging, and predator detection (Richardson et al. 1995, Hoelzel 2002). Sound exposure can affect auditory function or lead to behavioral modifications or stress responses. Effects on auditory function include simultaneous effects or masking (i.e. when one sound reduces the audibility of another sound) and residual effects such as temporary or permanent hearing loss if the source exceeds certain levels. Common behavioral responses to sound exposure are displacement (i.e. when an area is avoided due to sound) and vocal response (i.e. when an animal modifies vocal amplitude, duration, or frequency to compensate for the sound). Several populations of toothed whales concurrently play important respective ecological roles in marine ecosystems and are listed as endangered or threatened due in large part to interactions with humans.

Southern Resident killer whales (*Orcinus orca*; hereafter SRKW) are potentially vulnerable to negative anthropogenic impacts from vessel traffic and ambient noise (NOAA 2008). SRKW range from central California to southeast Alaska and frequently utilize inland waters (NOAA 2008). The population was substantially reduced as a result of removals for the aquarium trade in the mid-20th century (NOAA 2008), and then began a slow recovery to 98 individuals by 1995. However, from 1996 to 2001, the population declined by almost 20% for unknown reasons (Figure 1.1; Center for Whale Research unpublished data, NOAA 2008). SRKW were listed as endangered under the U.S. Endangered Species Act in 2005 and a Recovery Plan was developed to determine potential causes for the population decline (NOAA 2008). Major threats to SRKW recovery were identified as availability and quality of prey, pollution, and disturbance from vessels and anthropogenic noise. In this study, the potential impact of vessels on the acoustic environment of SRKW was examined.

It is important to preserve the acoustic environment of animals that utilize sound for key life history strategies. SRKW utilize calls, clicks, and whistles for navigation, communication, and foraging (Ford 1989, Barrett-Lennard et al. 1996). Each pod (family group) has a distinctive call repertoire and therefore SRKW likely use these vocalizations for group and individual identification (Ford 1991, Foote et al. 2008). Acoustic communication among SRKW individuals is important for group cohesion, cooperative foraging, and social behavior that may involve reproduction (Ford 1989, Barrett-Lennard et al. 1996). All of these processes have consequences for the survival and fitness of the population. Echolocation is a biological form of sonar involving production of sounds and use of the resulting echo returns to perceive the environment. Echolocation is the primary foraging tool for SRKW (Barrett-Lennard et al. 1996). SRKW specialize on many depleted stocks of salmonid species (Hanson et al. 2010, Williams et al. 2011), so any anthropogenic factor that may limit foraging efficiency could negatively impact the SRKW population.

SRKW in the Salish Sea (i.e., the inland waters of Washington State and British Columbia; Figure 1.2) were the focus of this project due to the increased likelihood of negative anthropogenic impacts coinciding with human and SRKW use of the area. The Salish Sea includes core summer habitat of SRKW (Hauser et al. 2007) and is particularly relevant to the impact of vessel traffic as vessel presence has increased dramatically from whale watching (commercial and recreational), fishing (commercial and recreational), and shipping (NOAA 2008). SRKW are the primary focus of a whale watching fleet in the Salish Sea that increased from very few commercial companies in the 1980s to roughly 80 boats servicing half a million customers per year by 1998 (Osborne et al. 2002, NOAA 2008), and has remained at this level in recent years (Figure 1.3; Koski 2009, Giles et al. 2010, Giles & Koski 2012). Therefore SRKW are not only valued for their ecological role and iconic cultural status in the Pacific Northwest, but also add over $70 million annually to the economy in Washington State and British Columbia (Hoyt 2001, O'Connor et al. 2009, S. Russell, NOAA Northwest Fisheries Science Center, pers. comm.), increasing incentives to manage the population to recovery. SRKW in the Salish Sea provide a unique opportunity to study interactions between direct human use of the marine environment and top predators with significant implications for endangered species management.

The potential impact of vessels on SRKW behavior has been examined but without detailed measures of vessel traffic characteristics or the acoustic environment the whales experience as they move through the water. SRKW are known to alter their behavioral states in the presence of vessels and as vessel traffic and proxies for anthropogenic noise increase (Williams et al. 2002a, Williams et al. 2002b, Williams et al. 2009, Lusseau et al. 2009, Noren et al. 2009). Increased environmental noise also leads to vocal modification by SRKW (Foote et al. 2004, Holt et al. 2009, Wieland et al. 2010, Holt et al. 2011). None of the previous studies have measured the ambient noise that individual killer whales actually receive nor precisely measured the vessel traffic characteristics surrounding the whales. To address this limitation, digital acoustic recording tags (DTAGs; Figure 1.4) and laser positioning systems were utilized concurrently in a large, collaborative project. The larger project aims to understand the effects of vessels and associated noise on SRKW behavior, and the current study is the first phase toward this goal. DTAGs have been used on a variety of cetacean species to examine vocal and movement behavior (Johnson & Tyack 2003, Johnson et al. 2009), but few have utilized ambient noise recordings for inferences regarding the changes in the acoustic environment a whale experiences. The laser positioning system allows for a more accurate measure of vessel presence by determining the precise position of the tagged whale and any vessel within 1000 meters and recording vessel characteristics (e.g., size, type) and operational state (e.g., orientation, speed). This study seeks to compare these two datasets to relate vessel traffic to the ambient noise a tagged SRKW individual receives.

Guidelines for whale watching have existed in the Salish Sea since 2002, and changes have been made since then to reflect research updates on the effects of whale watching on SRKW (Giles & Koski 2012). Initially, voluntary guidelines restricted vessels from approaching whales within 100 m/yd. In May 2011, federal regulations prohibited vessels from approaching whales within 200 yd of whales, or positioning themselves within 400 yd of the path of a whale (NOAA 2011). Research vessels operating under permit are exempt from federal regulations. An additional guideline recommends that vessels do not travel at speeds faster than 7 knots within 400 yd of a whale (http://www.bewhalewise.org/). The federal regulations apply in U. S. waters, but in Canada whale watching is only subjected to the less stringent voluntary guidelines (i.e. 100 m/yd minimum approach distance).

The objectives of this study were to 1) quantify vessel traffic characteristics and activities, 2) utilize a maximum likelihood approach and linear regression to assess the relationship between the quantified vessel characteristics and noise levels received by tagged whales, and 3) assess the relationship between the number of vessels within specific radii of tagged whales and received noise levels. Prior to collecting and analyzing the data, I expected that noise levels would be correlated with vessel characteristics as follows: more noise will be produced by larger vessels with more propellers, traveling at faster speeds and at close distances, where the vessels are parallel to or facing away from the whale. In addition, I predicted a positive correlation of received noise levels and the numbers of vessels in close proximity to tagged whales.

METHODS

Data Collection

Data for the larger project to assess the effects of vessels and associated noise on SRKW behavior were collected for a total of four field seasons. However, only three field seasons of data were analyzed for this study (September 2010, June 2011, September 2012). Data were collected in the semi-enclosed marine waters of the San Juan Archipelago (Figure 1.2). The protected inland waters provide valuable opportunities to access SRKW throughout their core summer habitat while they are also being exposed to high levels of vessel traffic. For each deployment, a DTAG (Johnson & Tyack 2003) was attached via four suction cups to an individual killer whale with a 7 m carbon fiber pole by an experienced operator on a research vessel. The research vessel was a 6.7 m outboard-motored rigid-hull inflatable with two propellers and a bow pulpit added for data collection and tagging. The tags remained on subject whales for an average of 3.6 hours (range: 0.75–7.5 hours) depending on placement of the tag, whale behavior, and the user-defined release time. Twenty-three tags were deployed opportunistically on 22 individual killer whales of varying sex, age, and pod classifications for a total of 82 hours of acoustic data.

The DTAG is an archival tag with two hydrophones that record sound including ambient noise dynamics (Johnson & Tyack 2003). Depth information is also recorded on the tag using a pressure sensor that is corrected for temperature with a temperature sensor (Johnson & Tyack 2003). In 2010 and 2011, “version 2” DTAGs were used and in 2012, “version 3” DTAGs were used, but their functionality relative to this study remained consistent (Figure 1.4). The audio channels of the "version 2" DTAGs had a sampling rate of 192 kHz and the pressure and temperature data were sampled at 50 Hz, but later down-sampled to 5 Hz. The audio channels of the "version 3" DTAGs had a sampling rate of 240 kHz and the pressure and temperature data were sampled at 200 Hz, but later down-sampled to 5 Hz. Tags were retrieved using a VHF radio signal.

After tags were attached, individual tagged whales were followed from the research boat to record vessel traffic characteristics in the vicinity of the tagged whales. Surface-based data collection was possible for 20 of the tag deployments (Figure 1.2). Two laser positioning systems combine a global positioning system (GPS) with built-in data collector to record attribute data (e.g., vessel characteristics), a laser range finder to determine distance, and a compass for bearing to generate geo-referenced (latitude/longitude) data for the tagged whale and vessels (Giles & Cendak 2009, Giles 2014). Data were collected for tagged whales at each surfacing. The research vessel commonly travelled parallel to or behind individual tagged whales at close distances in order to 1) obtain accurate and frequent GPS data on subject whales, 2) photo-document the tag's position on each tagged whale for data calibration purposes, and 3) collect samples (i.e. fecal, prey) opportunistically for objectives of the larger study of SRKW behavioral effects of vessels and associated noise. The following vessel data were recorded: geo-referenced latitude/longitude location, vessel class (commercial and private whale watching, monitoring, enforcement, research, shipping, ferry, military), vessel type (inflatable, small, medium or large hard bottom), vessel position relative to whale (parallel, bow-in perpendicular, bow-out perpendicular), location relative to whales (in front, to the side, behind), and vessel speed (stationary, slow 0-2 knots, medium 3-4 knots, fast 5-6 knots, and very fast ≥7 knots). For commercial whale watching, research, monitoring, and enforcement vessels, the vessel name was recorded, and later used to identify additional characteristics including the number of propellers, propulsion system (inboard, outboard, Arneson surface drive, jet drive, electric hybrid), and length (m). Ideally, data for all vessels within at least 1000 m were collected within 5 minutes, however occasionally data were not recorded for all vessels due to weather conditions, high traffic, or time constraints. In post-processing, custom software was used to calculate the distance between each individual vessel and the surfacing location of the tagged individual whale that was closest in time to the recorded vessel location (Giles 2014).

Data Transformation

Data from the DTAGs were offloaded and unpacked using custom software provided by Woods Hole Oceanographic Institution (WHOI). Data were then calibrated and post-processed using the DTAG toolbox (developed by WHOI) and custom-written routines in Matlab (v. 7.10 and higher). Noise levels from the DTAG audio recordings were measured using criteria similar to those previously published (e.g., Parks et al. 2011). The key criterion invoked here was exclusion of recording segments that contained whale vocalizations or noise from water flow over the DTAG during whale movements. Noise levels based on root-mean-square pressure (in dB re 1 μPa) were integrated over a frequency range of 1-40 kHz (consistent with previous studies because it is the relevant range for killer whale communicative signals and best hearing sensitivity that overlaps with vessel noise; Szymanski et al. 1999, Holt et al. 2009, Holt et al. 2011). Noise levels were averaged in 1-second segments. Data for the depth of the whale from the DTAG recordings were averaged for each 1-second segment of relevant noise level data.

The noise level and vessel traffic datasets were collected on varying temporal and spatial scales due to the differing capabilities of the DTAG computer and human observer to record data, but the datasets were spatiotemporally matched as well as possible. When a suitable noise level was available (i.e. absent of whale vocalizations and flow noise), the time of whale surfacing just prior to, but no more than 5 minutes before, was used as the start of a data interval. All vessel data and 1-second noise level segments recorded within 5 minutes after the identified whale surfacing were included in the data interval. If multiple 1-second noise level segments were available, one average noise level was calculated for the 5-minute interval. If multiple location and behavior attributes were recorded for the same vessel, only the one that occurred closest in time to the relevant whale surfacing event was included.

Numerical vessel characteristics included length, number of propellers, and distance of the individual vessels to tagged whales. A modification was made to the distance measure in order to account for the depth of the whale at the time the noise level was recorded. The average depth of the whale was calculated for each interval and used to calculate the distance from the vessel to the whale at depth with the Pythagorean theorem.

Categorical vessel characteristics were ordered according to best estimates of their relationship to noise levels (Table 1.1). Based on previous research, it was assumed that vessels of relatively large sizes and those traveling at relatively high speeds would be louder (Ross 1976, Erbe 2002, Trevorrow et al. 2008, Hildebrand 2009, Allen et al. 2012, McKenna et al. 2013). Vessel orientation was quantified based on two categories of vessel position relative to individual tagged whales (Table 1.1). Properties of sound propagation are such that the highest received noise levels occur when the vessel motor (i.e. sound source) is facing the receiver (i.e. tagged whale) while the lowest noise levels occur when the vessel motor is directed away from the whale. These classifications should not be confused with descriptions of vessel orientation based on the bow of the vessel. Other studies have shown that vessel noise is louder when the motor faces the receiver than when the motor faces away from the receiver (Trevorrow et al.

2008, Allen et al. 2012, McKenna et al. 2012). Hildebrand et al. (2006) found that commercial whale watch vessels varied in the noise levels produced based on their propulsion system. Inboard motors were the loudest, followed by outboard motors and then jet drives (Hildebrand et al. 2006). Additional information on electric motors and Arneson surface drives from their manufacturers indicated where on this quantification spectrum they likely fall. Electric motors were expected to be comparable to jet drives, being quieter than outboard motors while Arneson surface drives were expected to be comparable to outboard motors, being quieter than inboard motors but louder than jet drives (Table 1.1).

Only intervals that included data for all characteristics of all the vessels within at least 1000 m of individual tagged whales were included in analyses. Intervals with private whale watching vessels were eliminated from analysis since specific information on their length, number of propellers, and propulsion system was not recorded or available. The remaining intervals also included only whale-oriented vessels with complete data (thereby excluding shipping, ferry, and military vessels). There were 57 intervals of vessel and noise level data. Many intervals included more than one vessel such that there was a total of 112 vessels in the interval dataset, but representing only 35 unique vessels. Our research vessel was present in every interval, and therefore, some vessels were counted repeatedly. However, the specific groupings of vessels present had characteristics (speed, orientation, distance, etc.) that varied from interval to interval.

The research vessel was the only vessel within 1000 m of the tagged whale in 27 out of the 57 total intervals. The research vessel did not vary in its number of propellers, propulsion system, length, or type, and was most frequently the closest vessel to the whale. As a result, it was possible that including intervals that only represented the research vessel in the statistical analysis could skew the results. Therefore, a separate analysis was conducted excluding any intervals that only included the research vessel. This analysis served to relate noise levels to vessel traffic on a broader scale (e.g. the whale watching fleet), instead of relating noise levels to the characteristics and behavior of the research vessel. There were 30 intervals of vessel and noise level data after research vessel-only intervals were excluded (i.e. when there was at least one other vessel present in addition to the research vessel).

Modeling Approach

A multiple regression model was developed with the assumption that noise levels in dB relate to each vessel characteristic with a linear relationship. One exception to linearity was the measure of distance between relevant vessels and individual tagged whales. It is estimated that sound propagates in the Salish Sea with transmission loss characterized by spherical spreading (Urick 1983, Richardson et al. 1995, Jones & Wolfson 2006). This led to the assumption that received noise levels would be related to 20 $\log_{10}$(distance). In terms of vessel speed, although in theory vessel power should be proportional to the cube of speed (Urick 1983), in practice, marine vessel source levels are proportional to speed on a linear scale (McKenna et al. 2013).

Using a maximum likelihood approach, I predicted the noise for each vessel separately with each of the characteristics as predictors. I then summed the predicted noise levels for all the vessels in a given interval to compare to the observed noise level. The equation for the noise level (NL) prediction for all vessels (*V*) of a given interval was:

$$\hat{N}L_i = 20\log_{10}\sum_{v=1}^{V}10^{\frac{\beta_1+\beta_2(\text{length})+\beta_3(\#\text{ propellers})+\beta_4(\text{speed})+\beta_5(\text{orientation})+\beta_6(20\log_{10}(\text{distance})+\beta_7(\text{propulsion system})+\beta_8(\text{type})}{20}}.$$

For all models, the set of parameters that minimized the negative log likelihood (after omitting constant terms) was found by assuming that error and observed noise levels were normally distributed:

$$-\ln L(NL \mid \hat{\theta}) = -\ln L = \sum_{i=1}^{n} \frac{(N\hat{L} - NL)^2}{2\hat{\sigma}^2} + \ln \hat{\sigma}\,.$$

Parameters were estimated by nonlinear function minimization using Solver in Microsoft Excel. I began with the full model and followed a backward stepwise approach using Akaike's Information Criterion with small-sample correction (AICc; Burnham & Anderson 2002) to determine which variable removal most affected the model's likelihood. I ranked the resulting candidate models according to AICc and used Akaike weights (*w*) to determine relative support for each model (Burnham & Anderson 2002). The value of *w* for any model *i* is:

$$w_i = \frac{\exp(-0.5\Delta_i)}{\sum_{r=1}^{R} \exp(-0.5\Delta_r)}\,,$$

where Δ_i is the difference in AICc between model *i* and the best model (i.e. lowest AICc) among *R* candidates.

I used model averaging to derive the relationship between vessel traffic and noise levels that was not conditional on any particular model (Burnham & Anderson 2002). This method also serves to ameliorate potential effects of uninformative parameters (Arnold 2010). I used Akaike weights to weight the parameters from each model to determine model-averaged parameter estimates:

$$\hat{\bar{\beta}} = \sum_{r=1}^{R} w_i \hat{\beta}_i\,.$$

This allowed me to develop a predictive model of noise levels given vessel traffic data for use in other studies. I also used the AICc weights to calculate model-averaged noise level predictions. I compared these predicted values to the observed noise levels to assess model fit. This entire process was repeated for the set of data that did not include research vessel-only intervals.

Individual Characteristic Analysis

I examined the relationship between received noise levels and the number of vessels within specific radii from the tagged whale without regard to variation in other vessel characteristics. Specific radii included 200 m (minimum distance law in the US enacted in 2011; NOAA 2011), 400 m (minimum distance law for within the path of the whale) and 1000 m. Information for all characteristics of all vessels within a 5-minute interval was not necessary to determine the number of vessels present. Thus, there were 125 intervals available for these analyses. Linear regression was used to compare noise levels to the count of vessels within each radii. Generalized linear models were also used with a Poisson distribution.

I assessed the relationship between received noise levels and each vessel characteristic individually. For this analysis, each vessel characteristic was averaged for all the vessels of a given interval, using only the 57 intervals of complete data for all vessels present. Linear regression was used to compare noise levels to the following variables separately: vessel length, the number of propellers, vessel speed, vessel orientation, distance of the vessel to the whale, vessel type, and propulsion system. Linear regression was also used to examine the correlation between each of the vessel characteristics. Statistical tests were conducted in the R programming environment (R Core Team 2013). Statistical significance was determined using an assigned alpha level of 0.05.

RESULTS

Negative log likelihood model including all intervals

The model that best predicted noise levels given the observed data (for all complete intervals, including research vessel-only intervals, n=57) included vessel length (inverse relationship), number of propellers, and vessel speed (Table 1.2). This model had an AICc weight of 0.38 indicating a 38% chance that these three characteristics are necessary to predict noise levels. Models with fewer parameters had very little weight and substantially high ΔAICc values. A high ΔAICc value indicates that the removed parameter is significant (i.e. its removal greatly impacted the model's ability to predict noise levels given the data; Burnham & Anderson 2002). Therefore vessel length (inverse relationship), number of propellers, and vessel speed are significant predictors of received noise levels. Models with more parameters than the best model also had an adequate amount of weight. The additional parameters included distance with an inverse relationship and propulsion system with a positive relationship as expected. The parameter estimates for vessel orientation and type were inversely proportional to noise levels, which was not expected based on their classification. Due to the nature of AICc the additional parameters could be classified as uninformative (Arnold 2010), so model averaging was used to ameliorate the effects.

Model-averaged predicted noise levels explained approximately 15% of the variation in observed noise levels (Figure 1.5). Model-averaged parameter estimates indicate that the relationship between noise levels and vessel characteristics can be expressed as:

$$NL = 20\log_{10}\sum_{v=1}^{V} 10^{\frac{76.66 - 3.34(\text{length}) + 20.10(\#\text{ propellers}) + 3.07(\text{speed}) - 1.66(\text{orientation}) - 0.07(20\log_{10}(\text{distance}) + 2.47(\text{propulsion system}) - 0.31(\text{type})}{20}}$$

Negative log likelihood model excluding research vessel-only intervals

The model that best predicted noise levels given the observed data when excluding research vessel-only intervals (n=30) included only vessel speed as a predictor (Table 1.2). This model had an AICc weight of 0.45 (i.e. there is a 45% chance that only speed is necessary to predict noise levels). The null model had very little weight and a high ΔAICc value; therefore speed is a significant predictor of noise levels in this model (Burnham & Anderson 2002).

Models with more parameters than the best model also had an adequate amount of weight. The additional parameters included distance with an inverse relationship and number of propellers, length, and orientation with a positive relationship as expected. The parameter estimates for vessel type and propulsion system were inversely proportional to noise levels, which was not expected based on their classification.

Model-averaged predicted noise levels when research vessel-only intervals were excluded explained approximately 42% of the variation in observed noise levels (Figure 1.6). Model-averaged parameter estimates indicate that the relationship between noise levels and vessel characteristics can be expressed as:

$$NL = 20\log_{10}\sum_{v=1}^{V} 10^{\frac{78.04+0.006(\text{length})+3.73(\#\text{ propellers})+4.46(\text{speed})+0.004(\text{orientation})-0.06(20\log_{10}(\text{distance})-0.003(\text{propulsion system})-0.15(\text{type})}{20}}$$

Individual Characteristic Analysis

Results of the individual linear regression analyses indicated that received noise levels were not correlated with the number of vessels within 200 m ($F_{1, 123} = 0.44$, $p = 0.51$), 400 m ($F_{1, 123} = 0.28$, $p = 0.60$), or 1000 m ($F_{1, 123} < 0.01$, $p = 0.99$). Results of the generalized linear regression with Poisson distribution also indicated that received noise levels were not correlated with the number of vessels within 200 m ($Z = 0.40$, $p = 0.69$), 400 m ($Z = 0.32$, $p = 0.75$), or 1000 m ($Z < 0.01$, $p = 0.995$).

There was no significant relationship between received noise levels and average vessel length (Figure 1.7), average distance of vessels to tagged whales (Figure 1.8), average vessel orientation (Figure 1.9), average vessel type (Figure 1.10), or average vessel propulsion system (Figure 1.11) per interval. Variation in average vessel length was skewed toward the smaller vessels (Figure 1.7). Variation in average vessel distance was slightly skewed toward closer distances (Figure 1.8). There was little variation in the average orientation of vessels with most vessels maintaining a parallel orientation while some had motors facing away from individual tagged whales. There were no intervals where on average the vessels had motors facing toward tagged whales (Figure 1.9). Variation in average vessel type was heavily skewed toward inflatables and no intervals where vessels were on average in the medium or large hard bottom category (Figure 1.10). Variation in average vessel propulsion system was quite small with outboard motors present on most vessels per interval (Figure 1.11).

Two vessel characteristics, considered separately, were significantly correlated with noise levels even when other variables were not incorporated into the statistical model. Received noise levels increased significantly with the average vessel speed per interval (Figure 1.12; $F_{1, 55} = 6.704$, $p = 0.012$). There was substantial variation in vessel speed per interval, although no intervals had on average a vessel speed of “Very Fast 7+ knots”. Received noise levels also increased significantly with the average number of propellers on the vessels per interval (Figure 1.13; $F_{1, 55} = 5.476$, $p = 0.023$). This was true even though there was a lack of variation in the number of propellers among vessels, as most vessels had two propellers. There were occasionally vessels with one or three propellers, but not enough of them to calculate a meaningful average number of vessels of one or three (Figure 1.13).

A few vessel characteristics, when averaged within an interval, were correlated with each other. Vessel distance was highly positively correlated with vessel length ($F_{1, 55} = 30.62$, $p<0.001$; Figure 1.14) and type ($F_{1, 55} = 27.77$, $p<0.001$; Figure 1.15). The research vessel is clearly visible in the plots as a large number of data points of an inflatable of short length and at close distances to tagged whales. Vessel length was also highly correlated with vessel type ($F_{1, 55} = 67.47$, $p<0.001$; Figure 1.16). This is an inherent aspect of the characteristics since both are quantifying vessel size in some way. The number of propellers was marginally significantly correlated with vessel speed ($F_{1, 55} = 3.385$, $p = 0.071$; Figure 1.17).

DISCUSSION

The significant predictors of noise levels in the likelihood model (including research vessel-only intervals, n=57) were length (inverse relationship), number of propellers, and vessel speed. While most studies have shown that larger vessels contribute to higher noise levels (Ross 1976, Hildebrand 2009), occasionally within a vessel class, length can be inversely proportional to vessel noise for unknown reasons (Allen et al. 2012). In this study, it is likely that length was inversely proportional to noise levels because of the highly significant positive correlation between length and distance of relevant vessels to tagged whales (i.e. smaller vessels were more likely to be closer to tagged whales). This might increase the importance of vessel distance as a predictor of noise levels even though it acted as an uninformative parameter in the multi-model inference (Burnham & Anderson 2002, Arnold 2010). The parameter estimate for vessel type was inversely proportional to noise levels, which also may be due to the high correlation between vessel type and the distance of vessels to tagged whales. Unexpectedly, the parameter estimate for vessel orientation was inversely proportional to noise levels, which bears more investigation. Model-averaging provided parameter estimates for all vessel characteristics which can be used to predict noise levels in future studies, although it should be noted that relatively little (15%) of the variation in noise levels was explained by the multi-model inference.

The only significant predictor of noise levels in the likelihood model when research vessel-only intervals were excluded (n=30) was vessel speed. This corroborates the importance of vessel speed as a predictor of noise levels since both models indicated that it was a significant predictor. The parameter estimates for vessel type and propulsion system were inversely proportional to noise levels in this model, although these were not significant predictors. Model-averaging provided parameter estimates for all vessel characteristics which can also be used to predict noise levels in future studies, and in this case 45% of the variation in noise levels was explained by the multi-model inference. However, observed noise levels had larger variation than predicted noise levels (observed range: 89.2-116.3 dB; predicted range: 95.9-109.7 dB), so interpretation is limited in accurately predicting the lowest and highest noise levels received by individual tagged whales. I suggest that future studies utilize the model-averaged parameters of this model (n=30) as it removes the potential bias of repeatedly sampling the research vessel, which would have led to a lack of substantial variation in each of the characteristics and inflated the importance of some variables due to the research vessel presence alone. The multi-model inference from this analysis also explains considerably more of the variation in observed noise levels. However, further analysis with a larger sample size should be conducted to confirm these findings.

Received noise levels were not correlated with the number of vessels within 200 m, 400 m, or 1000 m when other vessel characteristics were disregarded. This is inconsistent with previous research that illustrates that ambient/environmental noise levels (i.e. not those received by tagged whales but measured when the whales were within 400 m) significantly increase with the number of vessels within 1000 m (Holt et al. 2009). In the current study, data were collected during periods when vessel traffic was relatively low (the maximum number of vessels was 11), unlike in previous studies (Holt et al. 2009) where high volumes of commercial whale watching traffic allowed for greater inference from analyses. Analysis of individual characteristics without concurrent regard to other characteristics revealed that received noise levels significantly increased with only two characteristics, the average number of propellers and vessel speed per interval. This further illustrates the importance of the number of propellers as a predictor of noise levels since this characteristic was also a significant predictor of noise levels in the multi-model inference including research vessel-only intervals. Vessel speed is identified as the most important predictor of noise levels as it was a significant predictor in linear regression, in the multi-model inference including research vessel-only intervals, and in the multi-model inference excluding research vessel-only intervals.

The statistical models used in this study were limited in their predictive power due to small sample size. There was a lack of data collected on private whale watching vessels (i.e. vessel length, number of propellers, and propulsion system) which, based on model results indicating the importance of some of these variables, made it inappropriate to include any intervals where private whale watchers were present in the analysis. This limited the dataset to a small number of intervals, although other factors also contributed to limitation of sample size. The exclusion of ambient noise levels that included whale vocalizations or flow noise also limited the number of suitable received noise levels used for analysis. Occasional discrepancies in methods of vessel data collection made it difficult to spatiotemporally match vessel and noise level data and also reduced the number of intervals in which all vessels within 1000 m were recorded within 5 minutes.

Predictive power in the statistical methods was also limited by the presence of the research vessel. Repeated measures of the research vessel's characteristics, which did not vary (i.e. length, number of propellers, propulsion system, and type) or varied infrequently (e.g. orientation and distance), heavily skewed the variation in the characteristics. The research vessel was a small, outboard-motored inflatable with two propellers that frequently travelled parallel to or behind tagged whales (i.e. motor facing away from the whale) at close distances. The lack of variation in these characteristics may explain the inability of the statistical methods to identify significant correlations with received noise levels. Certain vessel characteristics were also highly correlated with each other (i.e. vessel type and length, vessel type and distance, vessel length and distance), decreasing the ability of the statistical methods to separate the effects of different characteristics. Such co-variations are also potential explanations for the observation that inverse vessel length was a significant predictor of noise levels (in the model including research vessel-only intervals), since the model cannot distinguish the contribution of individual variables if correlation is high.

There are likely additional factors of vessel traffic that contribute to noise levels received by killer whales that were not included in the dataset. Although the number of propellers was included in the study, not all propellers are equivalent in their characteristics. Cavitation is thought to be the most important component of vessel-radiated noise, but the machinery noise and hydrodynamic noise are also important components (Urick 1983). Increasing the horsepower of an engine increases the vessel noise source level (Young & Miller 1960, Erbe 2002). The age or quality of the motor will also affect the machinery noise propagated from a vessel (Urick 1983). Additional sources of noise include the vibration of cavities and propeller-induced hull vibrations (Urick 1983). Therefore vessels of varying hull configurations (e.g. monohull or catamaran) or varying hull materials (e.g. fiberglass, aluminum, rubber) may also differ in their noise source levels. Small-scale vessel behavior changes such as turning maneuvers increase noise levels, even after there is a correction for source directionality and speed (Trevorrow et al. 2008). Vessels in the dataset frequently turned and maneuvered since the whale watch setting is highly dynamic, which may contribute to noise level variation not explained by the data collected. It is also likely that anthropogenic sources of sound beyond 1000 m contributed to received noise levels as sound travels farther and faster in water than it does in air. On occasion, large ships were seen and noted in the dataset and it is known that their noise source levels are substantial within the frequency range examined (Hermannsen et al. 2014). Such intervals were not included in analysis, but there could be intervals in which a sound source was audible under water even if it was not visible or audible to observers on the research vessel.

There are additional abiotic factors that contribute to noise levels received by killer whales that were not included in this dataset. Noise levels are known to vary substantially under varying weather (e.g. precipitation, wind) and sea state conditions within the frequency range analyzed in this study (Wenz 1962). However, collection of data in the field could be done only when conditions of weather and sea were relatively mild. Therefore, environmental factors capable of generating significant sound energy were relatively consistent during data collection periods throughout the study (i.e. no rain and low wind: Beaufort scale ranged from 0-3 on most days; no vessel data were collected when white caps were present). Although sound speed varies with temperature and salinity (Urick 1983), waters around the San Juan Islands are fairly deep and well mixed. Data were recorded at varying times of the year (i.e. September in 2010 and 2012, June in 2011), but the potential seasonal impact on water temperature and salinity in the Salish Sea is limited except for locations near the mouths of rivers. Different bathymetric characteristics, including substrate type and depth of the seafloor will influence sound reflection and absorption, also influencing the levels of noise actually received by a subject whale. Different areas in which data were collected differed in bathymetric characteristics but, for simplicity, relevant data were not collected or included in the analysis.

Including additional vessel characteristics and abiotic factors may have improved the predictive power of the statistical methods and models, but the model was still a purposeful representation of the observed data (Starfield 1997). Noise predictions are complicated and often have substantial shortcomings (Heitmeyer et al. 2003). However, from this study, it is apparent that vessel speed is one of the most important contributors of noise levels received by killer whales. Other studies have also determined that speed is correlated with vessel noise levels (Ross 1976, Erbe 2002, Trevorrow et al. 2008, Hildebrand 2009, Allen et al. 2012, McKenna et al. 2013). The current management regulations only limit the distance of approach of vessels to endangered SRKW (NOAA 2011), although there is a voluntary guideline to limit vessel speed to less than 7 knots (http://www.bewhalewise.org/). Results from this study will allow managers to assess the effectiveness of current regulations and determine if additional characteristics (e.g. vessel speed) should be formally restricted.

Future studies could address the limitations of the current methodology and apply results to other datasets. For example, substantial data exist on vessel traffic characteristics without concurrent noise level data. Results from the models developed here can be applied to predict the noise levels that Southern Resident killer whales experienced at other times (e.g. during the period of rapid population declined from 1996-2001). Findings could also be applied to other species and study areas where vessel activity may be recorded but access to received noise levels is not possible.

While many studies have examined the effect of vessel characteristics on noise source levels, this is the first study to examine the relationship between vessel characteristics and noise levels received by an endangered whale species or population. Southern Resident killer whales alter their behavior in the presence of vessels and associated noise (Williams et al. 2002a, Williams et al. 2002b, Foote et al. 2004, Williams et al. 2009, Lusseau et al. 2009, Noren et al. 2009, Holt et al. 2009, Wieland et al. 2010, Holt et al. 2011). In these previous studies, the link between vessel traffic characteristics and noise levels actually received by proximate whales is assumed but not explicit. Findings from this study illuminate this relationship and allow for more direct comparisons between vessels and received noise. DTAGs have been used extensively to examine vocal and movement behavior of marine mammals (Johnson et al. 2009). This study illustrates a new use of the DTAG technology, which can be applied to other studies where human use of the environment is measured concurrently with animal behavior.

Table 1.1. Quantification of vessel characteristics based on categorical qualities collected in the field. For vessel orientation, two field-based categorical qualities were used in conjunction to determine the relevant orientation of the vessel motor relative to the whale.

Vessel Charac-teristic	Category	Category 2	Relevance	Quantity
Type	Inflatable	N/A	N/A	1
	Small Hard Bottom	N/A	N/A	2
	Small-Medium Hard Bottom	N/A	N/A	3
	Medium Hard Bottom	N/A	N/A	4
	Large Hard Bottom	N/A	N/A	5
Speed	Stationary	N/A	N/A	1
	Slow 0-2 knots	N/A	N/A	2
	Medium 3-4 knots	N/A	N/A	3
	Fast 5-6 knots	N/A	N/A	4
	Very Fast 7+ knots	N/A	N/A	5
Orientation	Bow-In perpendicular	Behind whales	Motor away from whale	1
	Bow-In perpendicular	Side of whales	Motor away from whale	1
	Bow-In perpendicular	Front of whales	Motor away from whale	1
	Parallel	Behind whales	Motor away from whale	1
	Parallel	Side of whales	Motor parallel	2
	Parallel	Front of whales	Motor facing whale	3
	Bow-Out perpendicular	Behind whales	Motor facing whale	3
	Bow-Out perpendicular	Side of whales	Motor facing whale	3
	Bow-Out perpendicular	Front of whales	Motor facing whale	3
Propulsion system	Jet drive	N/A	N/A	1
	Electric	N/A	N/A	1
	Outboard	N/A	N/A	2
	Arneson surface drive	N/A	N/A	2
	Inboard	N/A	N/A	3

Table 1.2. Results of the negative log likelihood model (for all complete intervals, including research vessel-only intervals, n=57). Model parameters are the vessel characteristics that contribute to received noise. The model that best fit the data was model 3. However, models with additional parameters also had an adequate amount of weight but due to the nature of AICc, could represent uninformative parameters.

Mod-el	cons-tant β_1	length β_2	# pro-pellers β_3	speed β_4	orien-tation β_5	dist-ance β_6	prop system β_7	type β_8	σ^2	k	ΔAICc	*w*
Null	98.59	-	-	-	-	-	-	-	7.69	2	**24.05**	<0.01
1	118.15	-2.60	-	-	-	-	-	-	7.09	3	**17.08**	<0.01
2	90.44	-6.87	28.94	-	-	-	-	-	6.36	4	**6.99**	0.01
3	79.63	-4.18	20.84	3.14	-	-	-	-	5.86	5	0	**0.38**
4	80.91	-3.28	19.26	3.12	-2.45	-	-	-	5.75	6	0.39	0.31
5	85.35	-2.35	18.60	3.13	-2.95	-0.21	-	-	5.68	7	1.61	0.17
6	60.04	-2.32	19.83	2.99	-3.30	-0.27	13.14	-	5.63	8	3.27	0.07
7	18.70	-1.49	23.34	2.92	-2.99	-0.25	30.13	-6.24	5.53	9	4.08	0.05

Table 1.3. Results of the negative log likelihood model (excluding research vessel-only intervals, n=30). Model parameters are the vessel characteristics that contribute to received noise. The model that best fit the data was model 2. However, models with additional parameters also had an adequate amount of weight but due to the nature of AICc, could represent uninformative parameters.

Mod-el	cons-tant β_1	speed β_4	# pro-pellers β_3	dist-ance β_6	type β_8	length β_2	orien-tation β_5	prop system β_7	σ^2	k	ΔAICc	*w*
Null	93.92	-	-	-	-	-	-	-	6.63	2	**8.61**	<0.01
1	81.38	4.69	-	-	-	-	-	-	5.53	3	0	**0.45**
2	71.62	4.33	5.74	-	-	-	-	-	5.38	4	0.67	0.32
3	79.83	4.14	7.73	-0.24	-	-	-	-	5.32	5	2.38	0.14
4	80.45	4.50	10.52	-0.33	-1.66	-	-	-	5.24	6	3.99	0.06
5	81.52	4.58	8.10	-0.29	-1.98	0.23	-	-	5.23	7	6.50	0.02
6	80.75	4.63	8.01	-0.30	-2.32	0.31	0.70	-	5.23	8	9.16	<0.01
7	85.69	5.05	4.81	-0.21	-2.85	0.60	0.65	-2.74	5.23	9	11.98	<0.01

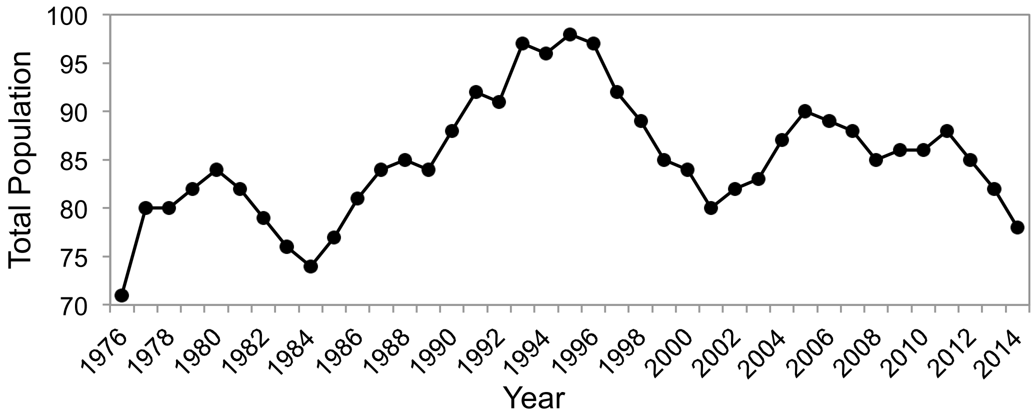

Figure 1.1. Population of SRKW from 1976-2014, showing lack of population recovery following captures for the aquarium trade prior to 1976 and a steep population decline 1996-2001 for unknown reasons (Center for Whale Research unpublished data).

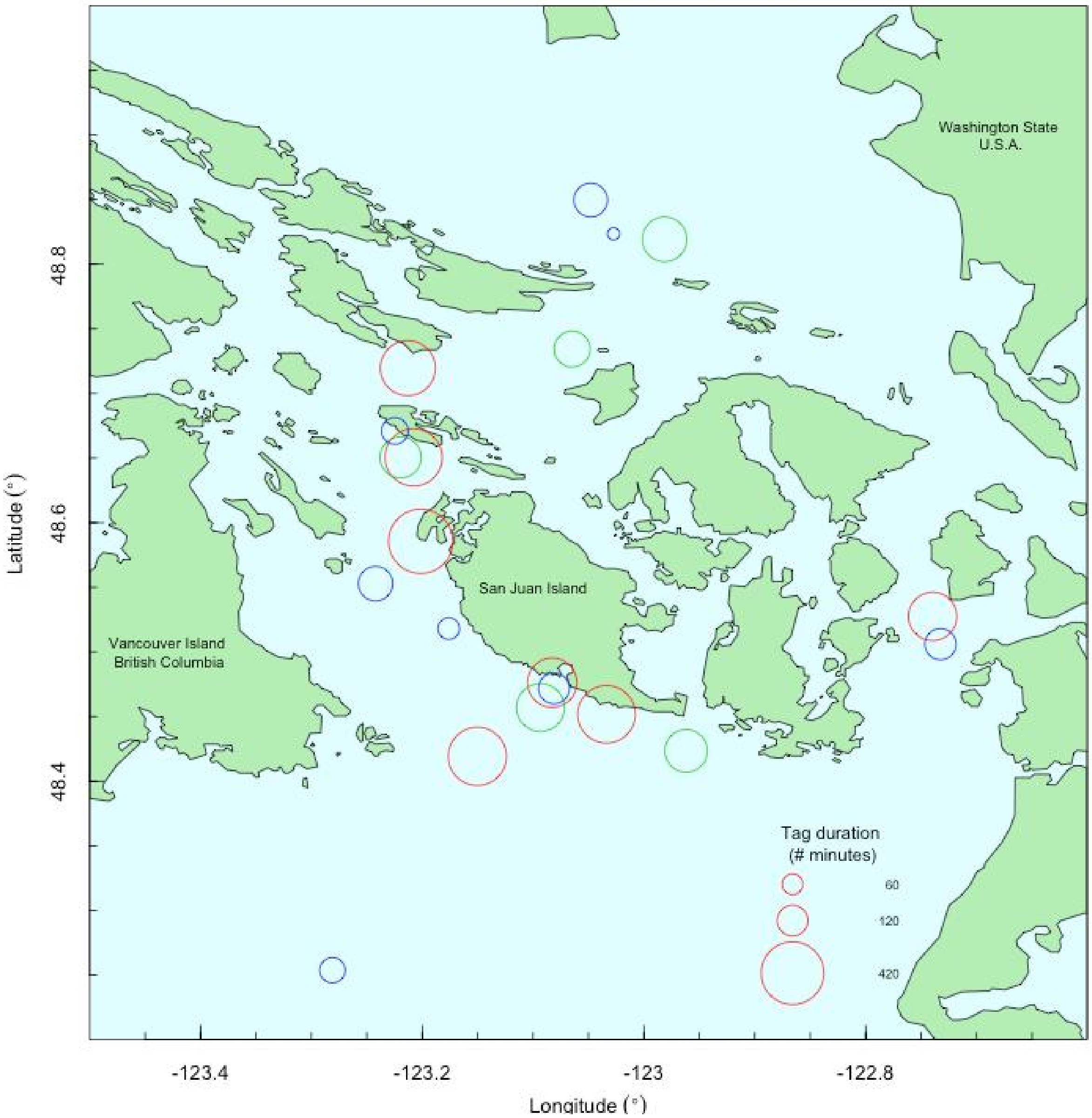

Figure 1.2. Locations of tag deployments during which vessel data were collected concurrently (n=20). The color of the marker corresponds to the year as follows: 2010 – red, 2011 – green, 2012 – blue. The size of the marker depicts the duration of the tag deployment in minutes. The tagged whale travelled beyond the extent of the marker throughout the deployment period.

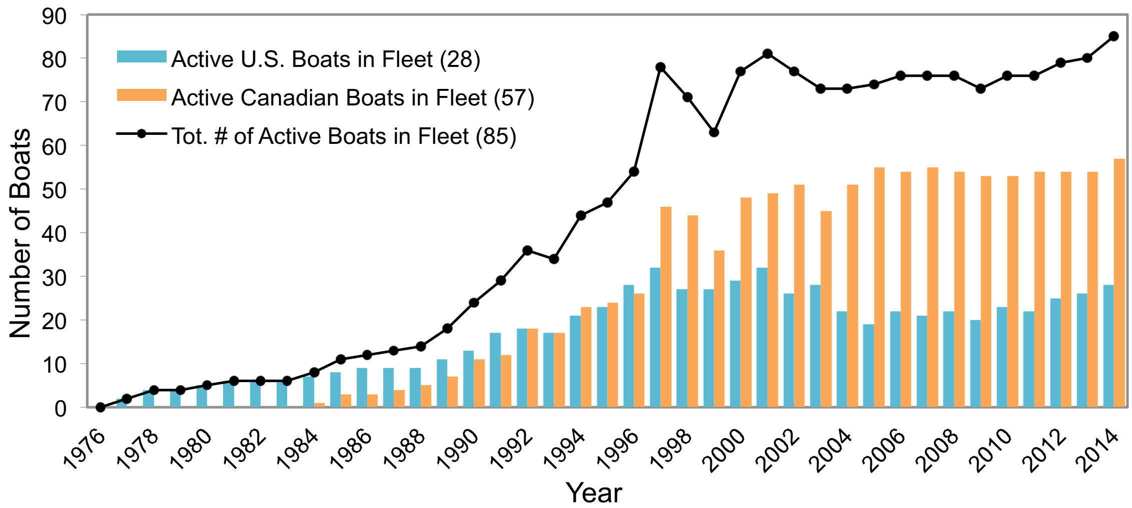

Figure 1.3. Number of commercial whale watching boats in the Salish Sea over time (© Soundwatch/The Whale Museum 2014).

Figure 1.4. Version 2 DTAG on SRKW 9/22/2010 (left) and version 3 DTAG on SRKW 9/17/2012. © NOAA NWFSC, taken under research permit.

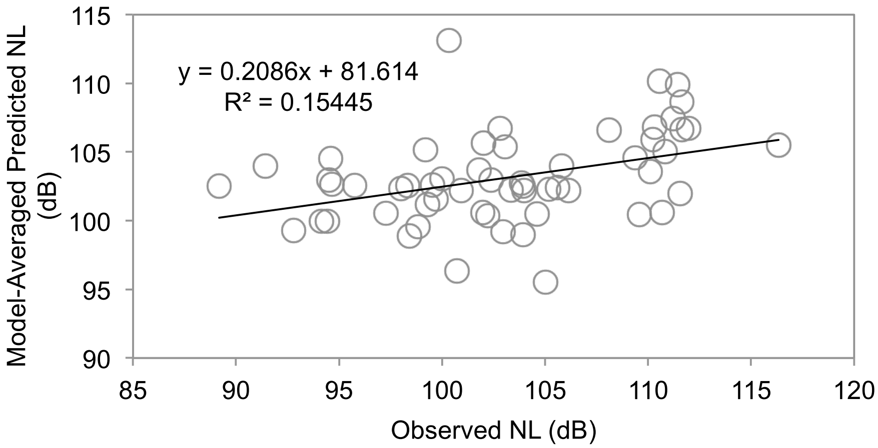

Figure 1.5. Model-averaged predicted noise levels compared to observed noise levels (for all complete intervals, including research vessel-only intervals, n=57). About 15% of the variation in observed noise levels was explained by the multi-model inference.

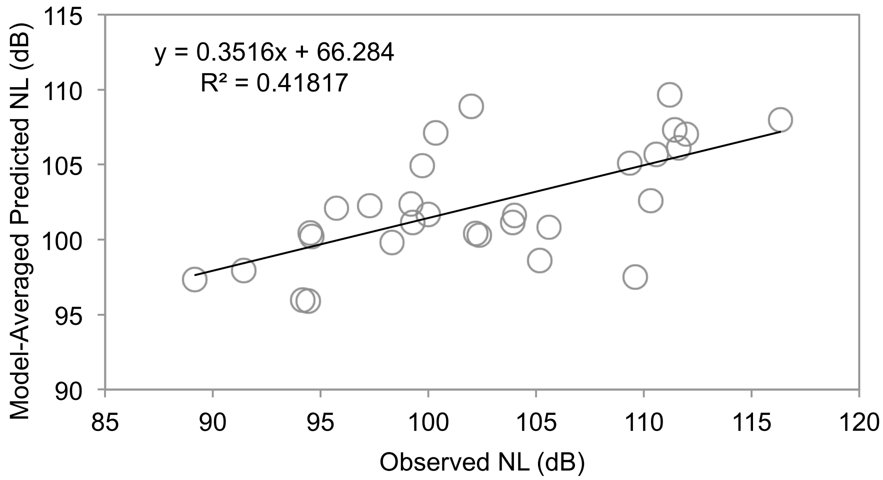

Figure 1.6 Model-averaged predicted noise levels compared to observed noise levels (excluding research vessel-only intervals, n=30). About 42% of the variation in observed noise levels was explained by the multi-model inference.

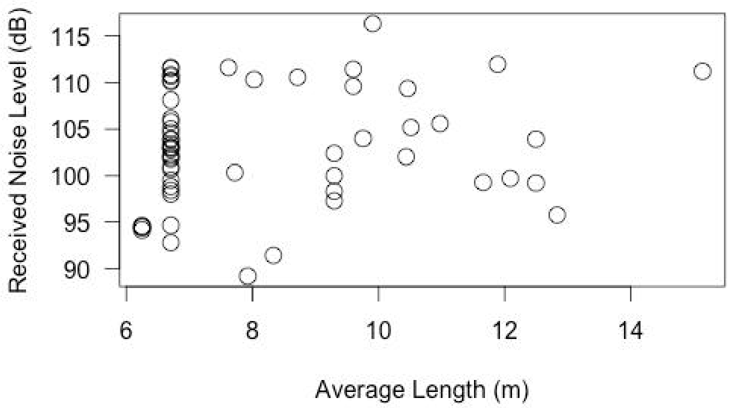

Figure 1.7. There was no significant relationship between received noise levels (dB re 1 μPa) and average vessel length (m) per interval. Variation in average vessel length was skewed toward the smaller vessels.

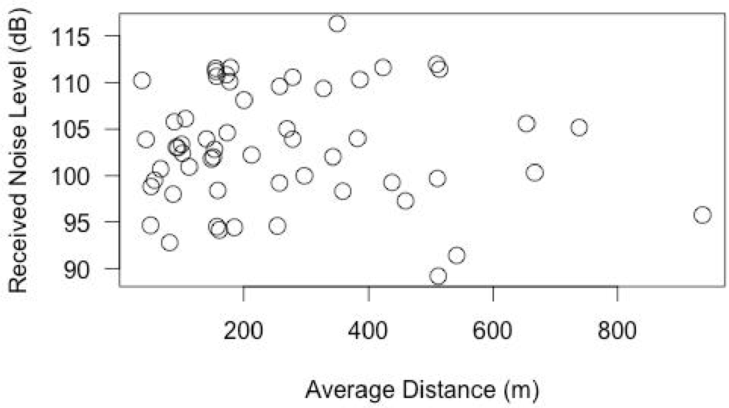

Figure 1.8. There was no significant relationship between received noise levels (dB re 1 μPa) and the average distance of vessels to tagged whales (m) per interval. Variation in average vessel distance was slightly skewed toward closer distances.

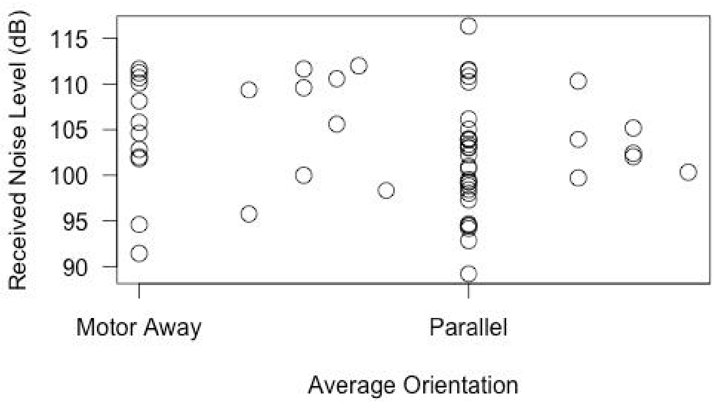

Figure 1.9. There was no significant relationship between received noise levels (dB re 1 μPa) and the average vessel orientation per interval. Orientation descriptions are relating the motor's relationship to the whale (i.e. motor away indicates the motor is facing away from the whale, see Table 1.1). There was little variation in the average orientation of vessels with most vessels maintaining a parallel orientation while some had motors facing away from the whale. There were no intervals where on average the vessels had motors facing toward the whale.

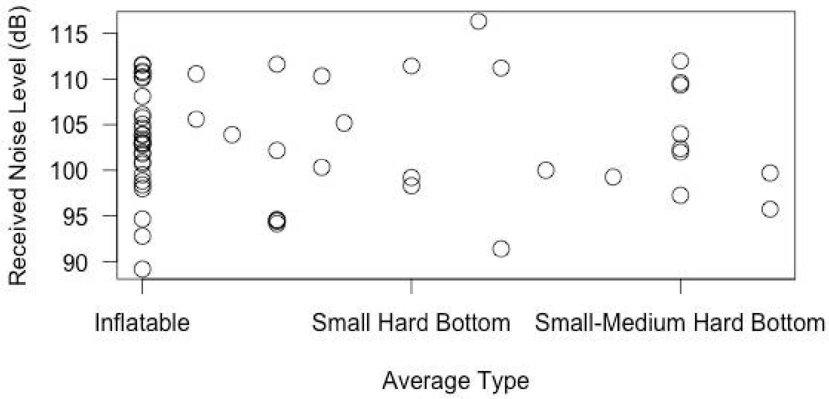

Figure 1.10. There was no significant relationship between received noise levels (dB re 1 μPa) and the average vessel type per interval. Variation in average vessel type was heavily skewed toward inflatables and no intervals where vessels were on average of the medium or large hard bottom distinction.

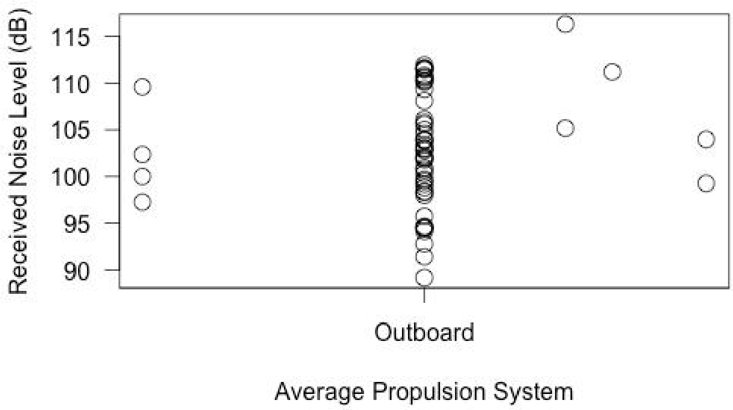

Figure 1.11. There was no significant relationship between received noise levels (dB re 1 μPa) and the average vessel propulsion system per interval. Variation in average vessel propulsion system was very poor with outboard motors present on most vessels per interval.

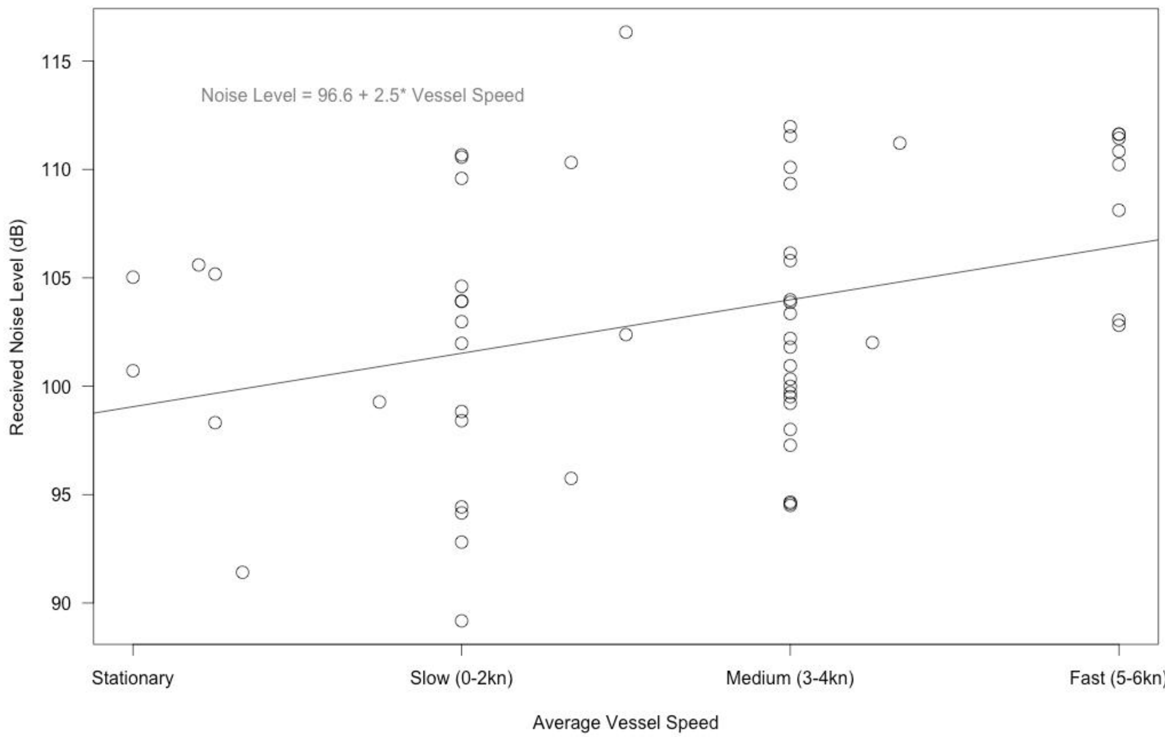

Figure 1.12. Received noise levels (dB re 1 μPa) increased significantly with the average vessel speed per interval ($F_{1, 55} = 6.704$, $p = 0.012$). There was substantial variation in vessel speed per interval, although no intervals had on average a vessel speed of "Very Fast 7+ knots".

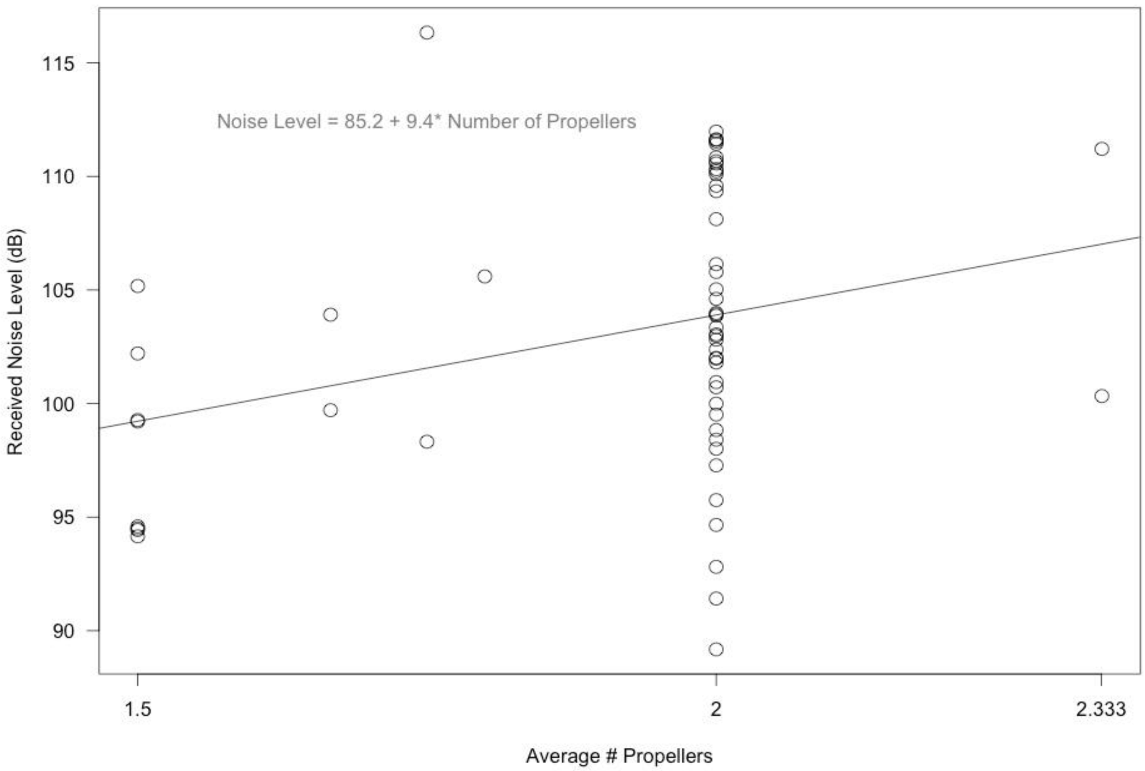

Figure 1.13. Received noise levels (dB re 1 μPa) increased significantly with the average number of propellers on the vessels per interval ($F_{1, 55} = 5.476$, $p = 0.023$). There was a lack of variation in the number of propellers among vessels, as most vessels had two propellers. There were occasionally vessels with one or three propellers, but not enough of them to calculate a meaningful average number of vessels of one or three.

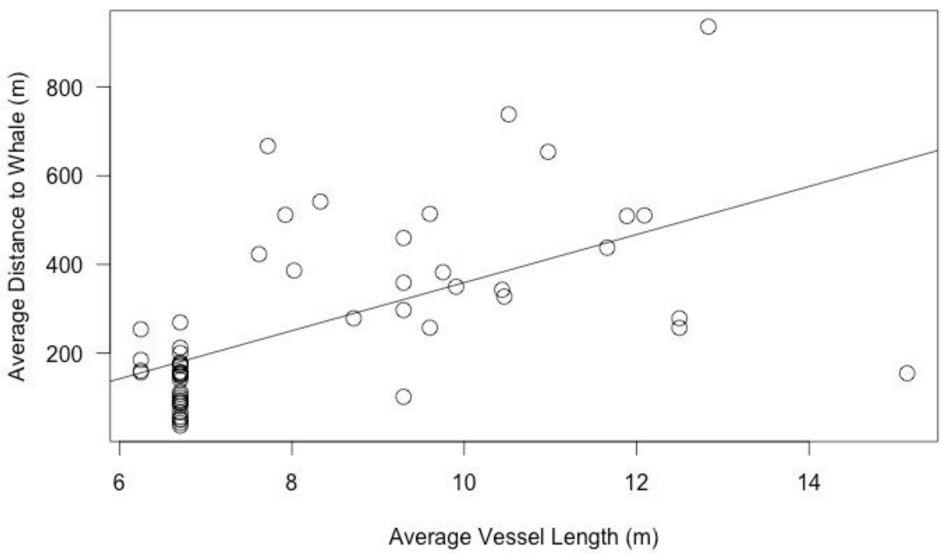

Figure 1.14. The average distance (m) of vessels to tagged whales had a highly significant correlation with average vessel length (m) per interval ($F_{1, 55} = 30.62$, $p<0.001$).

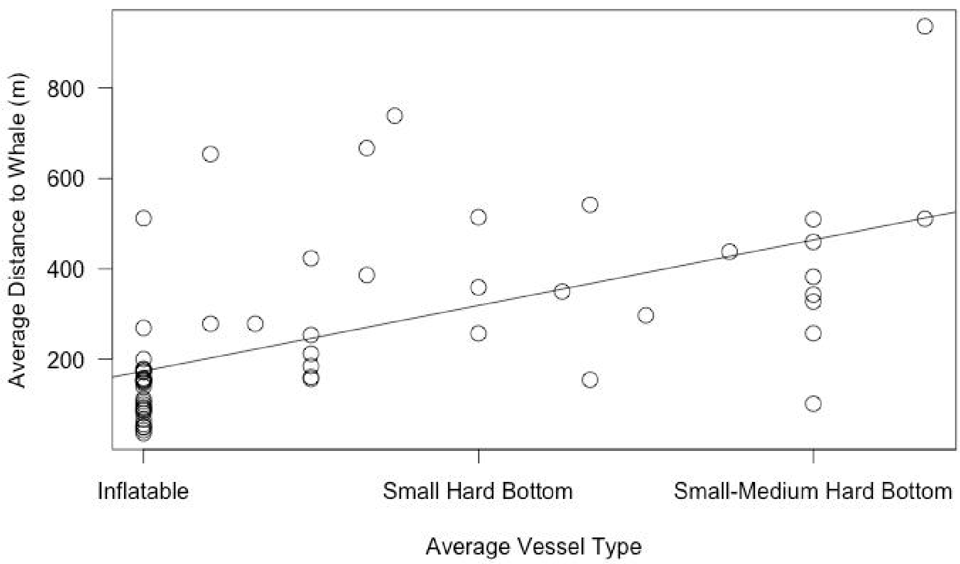

Figure 1.15. The average distance (m) of vessels to tagged whales had a highly significant correlation with average vessel type per interval ($F_{1, 55} = 27.77$, $p<0.001$).

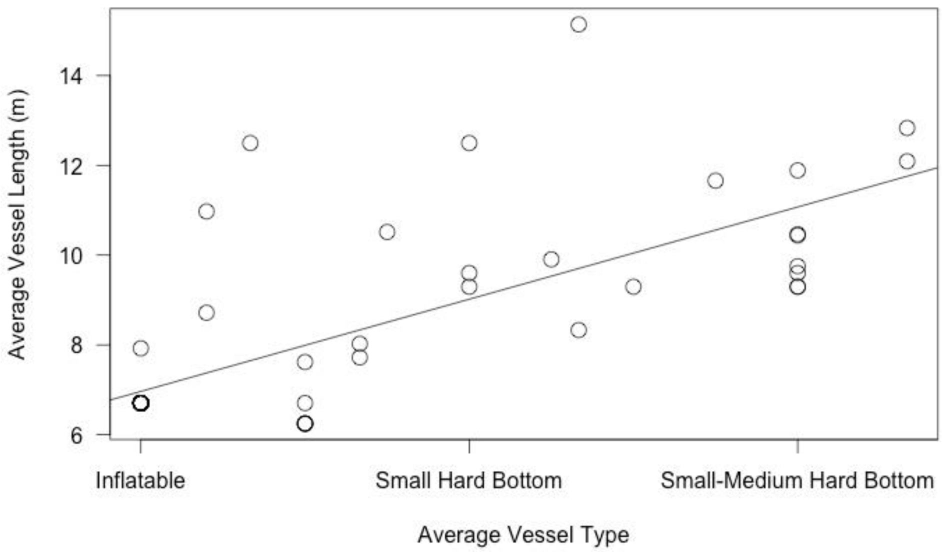

Figure 1.16. The average vessel length (m) had a highly significant correlation with average vessel type per interval ($F_{1, 55} = 67.47$, $p<0.001$).

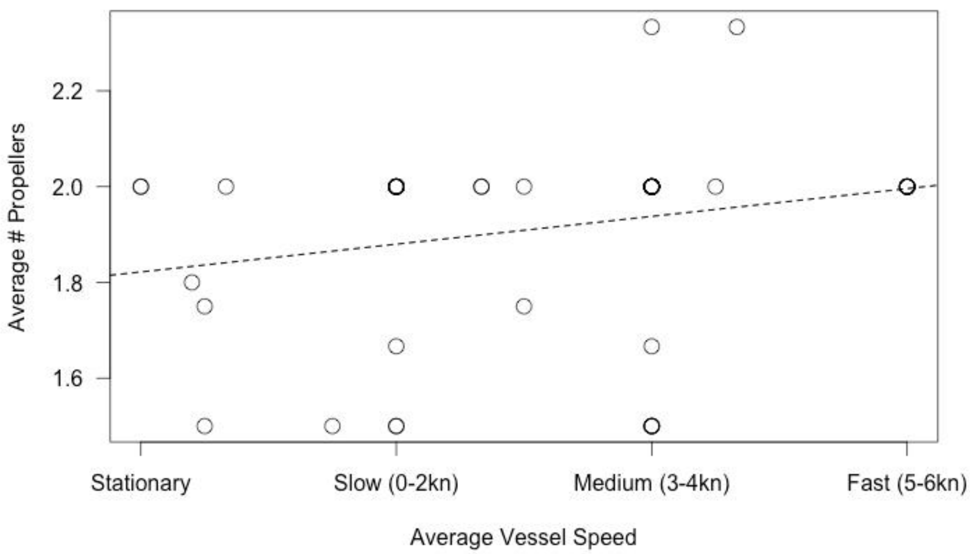

Figure 1.17. The average number of propellers had a marginally significant correlation with average vessel speed per interval ($F_{1, 55} = 3.385$, $p = 0.071$).

CHAPTER 2

An evaluation of vessel compliance with whale watch regulations

INTRODUCTION

Commercial whale watching is considered by many to be a more sustainable use of whales than commercial whaling (Orams 2001, Hoyt and Hvenegaard 2002, O'Connor et al. 2009, Cisneros-Montemayor et al. 2010). There are substantial economic benefits to societies that utilize whale watching (Hoyt 2001, O'Connor et al. 2009, Cisneros-Montemayor & Sumaila 2010). There are also less direct benefits of whale watching, such as enhanced education opportunities and increases in public support for conservation (Wilson & Tisdell 2003, Andersen & Miller 2006, Zeppel 2008).

However, some studies have shown that there are potentially negative effects of whale watching on the subject animals. The presence and proximity of motorized vessels have been shown to affect cetacean behavior, distribution, and population dynamics (Nowacek et al. 2001, Constantine et al. 2004, Bejder et al. 2006a, Bejder et al. 2006b). The noise levels created by vessel activity may also impact cetacean species negatively (Richardson and Wursig 1997). Guidelines and regulations are usually developed to limit the potentially harmful effects of whale watching.

Southern Resident killer whales (*Orcinus orca*; hereafter SRKW) are an endangered but heavily whale watched population in the Salish Sea. The effects of vessels and associated noise are identified as a risk factor to the population's recovery (NOAA 2008). Previous research has shown that SRKW change their behavior in response to vessels (Williams et al. 2002a, Williams et al. 2002b, Williams et al. 2009, Lusseau et al. 2009, Noren et al. 2009) and associated noise (Foote et al. 2004, Holt et al. 2009, Wieland et al. 2010, Holt et al. 2011). The behavioral changes demonstrated could result in increased energy expenditure (Noren et al. 2013), which is a matter of concern given that prey limitation is also an identified risk factor for SRKW recovery (NOAA 2008).

Numbers of commercial whale watching vessels in the Salish Sea fleet have been stable since the late 1990's (Figure 2.1; Koski 2009, Giles et al. 2010, Giles & Koski 2012) while SRKW population abundance has not recovered from a recent minimum in 2001 (Figure 2.2; NOAA 2008). Previous research regarding the effects of vessels on SRKW has led to increased regulations on whale watching (Giles & Koski 2012). Previously, voluntary guidelines limited the minimum approach distance of vessels to 100 yd/m of whales. In May 2011, federal regulations were implemented in U. S. waters, which prohibited vessels from approaching whales within 200 yd/m or within 400 yd/m of a whale's path (NOAA 2011). A speed guideline was also put in place, suggesting that vessels do not travel faster than 7 knots within 400 yd/m of whales (http://www.bewhalewise.org/). Exemptions from this regulation exist for research vessels operating under permit. In Canadian waters, whale watching vessels are only subjected to the less stringent voluntary guidelines (i.e. 100 yd/m minimum approach distance).

A large collaborative project to assess the effects of vessels and associated noise on SRKW behavior was recently conducted. Digital acoustic recording tags (DTAGs; Figure 2.3; Johnson & Tyack 2003) were attached to individual SRKW and used to measure vessel noise received by tagged whales. DTAGs have been used to examine vocal and movement behavior of several cetacean species (Johnson et al. 2009). Twenty-three tags were deployed opportunistically in the Salish Sea in September 2010, June 2011, and September 2012 (Figure 2.4). Laser positioning systems (Giles & Cendak 2009, Giles 2014) were used to record precise locations of the tagged whale and any vessels within 1000 m. The laser positioning system allows for an accurate measure of vessel position relative to tagged whales. Vessel characteristics (e.g., size, type) and operational state (e.g., orientation, speed) were also recorded for each vessel. The current study seeks to utilize spatial distributional data for observed vessels to examine vessel behavior during whale watching activities and to assess trends in behavior of whale watching vessels over time.

The data in the current study allowed me to evaluate compliance with whale watch guidelines and regulations. This study presented a unique opportunity to document changes in whale watching behavior that result from the implementation of regulations as data were collected before, just after, and over a year after the regulations became effective. The objectives of this study were to 1) evaluate the average distance of vessels (by vessel class) from tagged whales and determine if patterns of distance have changed over time, 2) assess the occurrence of vessels (by vessel class) within specific radii from tagged whales and determine if the proportion of closely approaching vessels has changed over time, and 3) assess the speed of vessels (excluding research vessels) within specific radii from tagged whales and evaluate changes over time. I hypothesized that vessels of all classes would increase in distance from tagged whales (i.e. approach less closely to whales) over time, especially between 2010 (pre-regulation) and 2011/2012 (post-regulation). Further, I predicted that the occurrence of vessels of all classes within close distances to tagged whales would decrease over time. Finally, I hypothesized that vessel speed would not change over time since speed was not formally regulated throughout the course of the study.

METHODS

Data Collection

Data for the large collaborative project, which seeks to assess the behavioral effects of vessels and noise on SRKW, were collected over four field seasons. Three field seasons of data were analyzed for the current study (September 2010, June 2011, September 2012). Data were collected in the semi-enclosed marine waters of the San Juan Archipelago. This area provides a valuable opportunity to access SRKW in their core summer habitat (Hauser et al. 2007, NOAA 2008) while the majority of the whale watching fleet targets them. An experienced operator on the research vessel (i.e. a 6.7 m rigid-hull inflatable) attached archival DTAGs via suction cups to individual killer whales with a 7 m carbon fiber pole. The tags remained on subject whales for an average of 3.6 hours (range: 0.75–7.5 hours). Tag duration depended mostly on whale behavior, but also on the placement of the tag and the user-defined time of release. Twenty-three tags were deployed opportunistically on 22 individual killer whales of varying sex, age, and pod classifications. However, surface-based data collection only occurred for 20 of the deployments (Figure 2.4).

After a tag was attached, the research vessel followed the tagged whale to record data from the surface. Two laser positioning systems combine a global positioning system (GPS) with built-in data collector to record attribute data (e.g., vessel characteristics), a laser range finder to determine distance, and a compass for bearing to generate geo-referenced (latitude/longitude) data for the tagged whale (at each surfacing) and all vessels within 1000 m (Giles & Cendak 2009, Giles 2014). The research vessel commonly travelled parallel to or behind tagged whales at close distances in order to obtain accurate and frequent GPS data on the whales. The following vessel data categories were recorded: geo-referenced latitude/longitude location, vessel class (commercial and private whale watching, monitoring, enforcement, research, shipping, ferry, military), vessel type (inflatable, small, medium or large hard bottom), vessel position relative to tagged whales (parallel, bow-in perpendicular, bow-out perpendicular), location relative to tagged whales (in front, to the side, behind), and vessel speed (stationary, slow 0-2 knots, medium 3-4 knots, fast 5-6 knots, and very fast 7+ knots). Ideally, data for all vessels within 1000 m were collected within 5 minutes of an observed surfacing by a tagged whale. However, occasionally data could not be recorded according to this framework due to weather conditions, high traffic, or time constraints.

Data Analysis

Statistical approach

Statistical tests were conducted in the R programming environment (R Core Team 2013). Statistical significance was determined using an assigned alpha level of 0.05.

Average distance by class

Custom software was used to calculate the distance between each vessel and the tagged whale surfacing that was closest in time to the recorded vessel location (Giles 2014). Distances were truncated to 1000 m to include only vessels that were likely actively whale watching. Average distances (within 1000 m) were calculated for each vessel class for all years combined and for each year separately. A linear regression was used to evaluate the difference in distance between private and commercial whale watching vessels for all years combined. Linear regression was also used to evaluate the change in distance over time for each vessel class. Post-hoc pairwise comparisons were conducted on significant changes in distance over time using the Tukey Honest Significant Differences test with adjusted p-values.

Vessel occurrence at distance

Distances (d) were truncated to three measures to include all data for vessels located at between 0 m and 100 m, 200 m ($0 \leq d \leq 200$ m), or 400 m ($0 \leq d \leq 400$ m) from a tagged whale. The number of vessels within each distance measure was determined. The proportion of vessels was calculated as the number of vessels within a given distance measure as compared to the total number of vessels within 1000 m. All data were separated by vessel class and by year. Only three vessel classes had substantial data for each distance measure each year and were analyzed for significant changes: research, private whale watching, and commercial whale watching. A χ^2 test was done for each vessel class to evaluate the change in proportion of vessels within each distance measure by year.

Vessel speed at distance

Distances from vessels to subject whales were binned into categories every 100 m from 0-1000 m. Each distance bin was mutually exclusive (e.g., the 200 m bin included distances greater than 100 m but less than or equal to 200 m). All research vessels were excluded from analyses since they were exempt from vessel regulations while operating under permit. The number and proportion of vessels in each speed category in each distance bin were determined for each year. To evaluate changes before and after the vessel regulation was enacted, data from 2011 and 2012 were combined. A χ^2 test was done for each distance bin to evaluate the change in the proportion of vessels in the speed categories pre- and post-regulation.

To evaluate compliance with the speed guideline of 7 knots within 400 yd/m of observed whales, the speed categories were combined into two categories: under 7 knots (i.e. “stationary”, “slow”, “medium”, and “fast”) and over 7 knots (i.e. “very fast”); and the distances were truncated to 400 m (i.e., distances 0-400 m only). A χ^2 test was done to evaluate the change in the proportion of vessels within 400 m that were over or under 7 knots pre- and post-regulation.

RESULTS

Average distance by class

Descriptive statistics and sample sizes of distances to tagged whales by class and year are listed in the respective tables. There were substantial data on research, private whale watching, and commercial whale watching vessels, with lesser sample sizes for the other vessel classes (e.g., see Table 2.1). For the entire time period, 2010-2012, research vessels were on average less than 200 m from tagged whales while private whale watching and commercial whale watching vessels were on average over 400 m away (Table 2.1). Similar patterns existed when looking at 2010, 2011, and 2012 separately (Table 2.2, Table 2.3, and Table 2.4, respectively). Private whale watching vessels seem to have increased in median distance to tagged whales each year while commercial whale watching and research vessels increased in distance from 2010 to 2011 but then decreased from 2011 to 2012 (Figure 2.5). Minimum approach distances for the three vessel classes were closest to tagged whales in 2011 (private whale watching vessels: Table 2.3, Figure 2.5) or 2012 (research vessels: Table 2.4, Figure 2.5, and commercial whale watching vessels: Table 2.4, Figure 2.5). Private whale watching vessels were significantly closer to tagged whales than commercial whale watching vessels for all years combined ($F_{1,1635} = 6.358$, $p = 0.0118$; Table 2.1, Figure 2.5).

There were statistically significant changes in distance of the vessel to tagged whales over time. Research, private whale watching, and commercial whale watching vessels significantly increased in distance from tagged whales (i.e. got farther away) over time (Table

2.5). Pairwise comparisons illustrated that research vessels significantly increased in distance to tagged whales from 2010 to 2011 and from 2010 to 2012, but significantly decreased in distance to tagged whales from 2011 to 2012. Private whale watching vessels had a highly significant increase in distance to tagged whales from 2010 to 2012, but other pairwise comparisons were not significant. Commercial whale watching vessels significantly increased in distance to tagged whales from 2010 to 2011 and from 2010 to 2012, but the change from 2011 to 2012 was not significant.

Vessel occurrence at distance

Trends in the proportion of vessels by class within 100 m, 200 m, and 400 m of tagged whales suggested that occurrence rates within the radii changed over time (Table 2.7, Table 2.8, Table 2.9, respectively). Research vessels significantly decreased the proportion of occurrence within 100 m of tagged whales over time, but there were no significant changes in occurrence within 200 m or 400 m of tagged whales (Table 2.10). Proportions of private whale watching vessels seemed to decrease within each radii of tagged whales over time, but none of the apparent trends were statistically significant (Table 2.11). Proportions of commercial whale watching vessels significantly decreased within 100 m of tagged whales over time, but there were no significant changes in occurrence within 200 m or 400 m of whales (Table 2.12).

Vessel speed at distance

For 2010 and 2012, it seemed that vessels that were farther away from tagged whales more commonly traveled at faster speeds (Figure 2.6 and Figure 2.8, respectively; Table 2.13 and Table 2.15, respectively), but the trend was not apparent in 2011 (Figure 2.7, Table 2.14). The proportion of vessels in each speed category significantly changed pre-/post- regulations for vessels 100-200 m and 300-400 m away from tagged whales (Table 2.16). While χ^2 tests on changes in proportion do not indicate the direction of the change, visual examination suggests that vessels more often occurred at faster speeds post-regulation (compared to pre-regulation) in the 200 m and 400 m distance bins (pre-regulation: Figure 2.6, post-regulation: Figure 2.7 and Figure 2.8). There were no significant differences in the proportion of vessels in each speed category pre-/post- regulations for any other distance bin. While the proportion of vessels traveling greater than 7 knots seemed to increase from pre- to post-regulation, this relationship was not significant (Table 2.17).

DISCUSSION

There was a trend among vessels (of classes with substantial sample sizes) to increase distances to tagged whales (i.e. get farther away on average) over time. Research, private whale watching, and commercial whale watching vessels were significantly farther from whales in 2012 than in 2010, although changes year by year were not as straightforward. There seems to be a greater effect on vessel distance in 2011, just after the regulations became effective. Research and commercial whale watching vessels actually were observed to be closer to tagged whales on average in 2012 compared to 2011 (significantly for research vessels only). Research vessels may have approached tagged whales at closer distances in 2012 in order to facilitate data collection with the laser positioning system. Although average distances increased over time, the minimum approach distances did not change, with private whale watching vessels approaching closer to tagged whales in 2011 and research and commercial whale watching vessels approaching closer in 2012. However, research and commercial whale watching vessels were within 100 m of tagged whales less often over time.

In general, vessels that were closer to tagged whales traveled at slower speeds, but there were also changes in vessel speed at distance over time. Vessels traveled faster over time at the 200 m and 400 m distance bins. This is an interesting finding as both of these distances are included in the new vessel regulations (i.e. minimum approach distance is 200 yd/m, minimum approach distance within the path of the whale is 400 yd/m; NOAA 2011). While the guideline relative to speed recommends that vessels within 400 yd/m travel less than 7 knots, it seems that the proportion of vessels that were noncompliant with this guideline increased over time, although the trend was not significant.

Although the intention in data collection was not to evaluate vessel compliance with regulations, the findings do illustrate some informative temporal trends that may not be otherwise available. There are limitations to interpretation due to the nature of the data collection protocol. Data were collected in both U. S. and Canadian waters and were not separated for analysis. Since the U. S. federal vessel regulation does not apply in foreign waters, whale watch behavior may change based on locations of tagged whales and whale watching vessels relative to the international border. However, the proportion of data collected in Canada in each year did not change, so assessing changes in approach distance over time is justified. Vessel data were recorded for all vessels within 1000 m of tagged whales approximately every 5 minutes. Therefore, there is repeated sampling of vessels within a focal follow or day and results cannot be directly compared to previous studies of vessel compliance, which only included the vessel's point of closest approach (e.g. Noren et al. 2009). The current study also did not take into account the behavior of tagged whales. Whale behavior (e.g. fast, traveling whales vs. slow, resting whales) may change seasonally, from year to year, throughout the day, and by individual among the tag deployments in this study. The potential changes in whale behavior could influence the behavior of whale watching vessels, but such changes were not analyzed in the current study. The data analyzed in the current study are robust and useful as long as the potential limitations are acknowledged.

Findings from this study examined compliance with vessel regulations and therefore have implications for the effectiveness of regulatory management. In terms of approach distance, the behavioral change in whale watching was as intended and the regulations could be deemed successful. Vessels maintained greater distances from whales after implementation of regulations and average distances were well over the minimum distance regulation (i.e. >400 m for whale watching vessels). Distance estimation on the water is often underestimated (Baird & Burkhart 2000), which may explain the greater average distances to whales from whale watching vessels as compared to expectation. Private whale watching vessels approach whales closer than commercial whale watching vessels, indicating a need for better education of private whale watchers. Minimum approach distances of whale watching vessels actually decreased over time. This further justifies the need for boat-based education, monitoring, and enforcement in the Salish Sea, since increasing these programs would most likely result in increased compliance by private and commercial whale watchers alike.

Management tools in action occasionally produce unintended changes in behavior that are not conducive to the desired outcome (Mascia et al. 2003). The unintended changes in vessel speed illustrated here are examples of this phenomenon. Commercial whale watch operators may be adjusting their behavior due to vessel regulations, which could explain the increase in vessel speed observed over time. To comply with the regulations, some operators have described that they now spend more time under power traveling parallel to the whales, rather than past practices which involved driving ahead of the whales and idling or shutting down as the whales pass by, which could result in their vessel occurring within 200 m overall or 400 m of a whale's path (L. Barre, NOAA, Northwest Regional Office, pers. comm.). Since vessel speed is an important predictor of the noise levels received by whales (Houghton, Chapter 1), the apparent behavioral change by whale watching vessels may be detrimental to the recovery of the killer whale population.

In other areas, regulations and guidelines pertaining to whale watching vessels have had moderate levels of success (e.g. Duprey et al. 2008). In coastal marine waters off the northeast region of the U. S., voluntary guidelines are not effective as there is a high level of noncompliance (Wiley et al. 2008). In west Scotland, the effectiveness of the government-produced guideline is limited, but the majority of whale watch operators apparently conduct themselves under locally or operator-produced guidelines (Parsons & Woods-Ballard 2010). The Salish Sea is described as being one of the most successful regions in terms of compliance with whale watch guidelines (Garrod & Fennell 2004). Similar to the current study, Noren et al. (2009) observed an increase in approach distance after changes were made to the Salish Sea guidelines. Overall, whale watching guidelines and regulations seem to have a high level of compliance in the Salish Sea, but all observed changes in vessel behavior (whether intentional or unintentional) need to be assessed in terms of their potential effect on the whale population.

Table 2.1. Average and sample size of distance to tagged whales (m) by class for 2010-2012. Distances truncated to 1000m.

	Res-earch	Priv. WW	Com. WW	En-force-ment	Moni-toring	Fish Com.	Ferry	Ship-ping	Mil-itary
Average	178.9	463.9	495.1	487.8	597.6	599.3	717.9	644.6	N/A
Sample size	1104	577	1060	17	13	5	13	11	0

Table 2.2. Descriptive statistics for distance to tagged whales (m) by class for 2010.

	Res-earch	Priv. WW	Com. WW	En-force-ment	Moni-toring	Fish Com.	Ferry	Ship-ping
Average	141.1	416.6	471.8	355.0	538.7	N/A	699.7	617.2
Minimum	10.2	31.8	17.2	355.0	238.6	N/A	232.8	333.7
Maximum	965.8	972.1	994.9	355.0	785.0	N/A	993.5	909.4
Sample size	272	241	490	1	8	0	11	8

Table 2.3. Descriptive statistics for distance to tagged whales (m) by class for 2011.

	Res-earch	Priv. WW	Com. WW	En-force-ment	Moni-toring	Fish Com.	Ferry	Ship-ping
Average	210.28	470.33	527.61	508.30	691.79	785.24	818.24	717.49
Minimum	19.79	22.79	42.15	233.30	400.23	785.24	793.99	472.69
Maximum	980.64	999.73	974.64	739.11	949.38	785.24	842.68	889.19
Sample size	350	72	131	6	5	1	2	3

Table 2.4. Descriptive statistics for distance to tagged whales (m) by class for 2012.

	Res-earch	Priv. WW	Com. WW	En-force-ment	Moni-toring	Fish Com.	Ferry	Ship-ping
Average	177.34	505.26	511.28	488.79	N/A	552.85	N/A	N/A
Minimum	8.22	55.45	4.48	192.29	N/A	281.66	N/A	N/A
Maximum	948.45	995.73	988.09	822.17	N/A	929.11	N/A	N/A
Sample size	482	264	439	10	0	4	0	0

Table 2.5. Regression results for change in distance over time by vessel class. Research, private whale watching, and commercial whale watching vessels significantly increased in distance to tagged whales over time.

	Res-earch	Priv. WW	Com. WW	En-force ment	Moni-toring	Fish Com.	Ferry	Ship-ping
F-statistic	16.15	8.96	4.572	0.201	1.57	0.5853	0.3264	0.4951
df	2, 1101	2, 574	2, 1057	2, 14	1, 11	1, 3	1, 11	1, 9
p-value	**<0.0001**	**0.0001**	**0.0105**	0.8205	0.2362	0.4999	0.5793	0.4994

Table 2.6. Pairwise comparisons with Tukey HSD analysis for research, private whale watching, and commercial whale watching vessels. Research vessels significantly increased in distance to tagged whales from 2010 to 2011 and from 2010 to 2012, but significantly decreased in distance to tagged whales from 2011 to 2012. Private whale watching vessels had a highly significant increase in distance to tagged whales from 2010 to 2012, but other pairwise comparisons were not significant. Commercial whale watching vessels significantly increased in distance to tagged whales from 2010 to 2011 and from 2010 to 2012, but the change from 2011 to 2012 was not significant.

		Research	Priv. WW	Com. WW
2010-2011	Difference	+	+	+
	Adjusted p-value	**<0.0001**	0.2066	**0.04591**
2011-2012	Difference	**-**	+	-
	Adjusted p-value	**0.0054**	0.5047	0.7705
2010-2012	Difference	+	+	+
	Adjusted p-value	**0.0045**	**<0.0001**	**0.0318**

Table 2.7. Count and proportion of vessels within 100 m by year by vessel class (i.e. proportion out of all vessels of that class w/in 1000 m).

Year		Res-earch	Priv. WW	Com. WW	En-force-ment	Moni-toring	Fish Com.	Ferry	Ship-ping
2010	Count	126	13	25	0	0	0	0	0
	Proportion	0.463	0.054	0.051	0	0	0	0	0
2011	Count	80	4	3	0	0	0	0	0
	Proportion	0.229	0.056	0.023	0	0	0	0	0
2012	Count	135	8	9	0	0	0	0	0
	Proportion	0.280	0.030	0.021	0	0	0	0	0

Table 2.8. Count and proportion of vessels within 200 m (i.e. 0-200 m) by year by vessel class (i.e. proportion out of all vessels of that class w/in 1000 m).

Year		Res-earch	Priv. WW	Com. WW	En-force-ment	Moni-toring	Fish Com.	Ferry	Ship-ping
2010	Count	219	39	74	0	0	0	0	0
	Proportion	0.805	0.162	0.151	0	0	0	0	0
2011	Count	229	11	9	0	0	0	0	0
	Proportion	0.654	0.153	0.069	0	0	0	0	0
2012	Count	359	37	51	1	0	0	0	0
	Proportion	0.745	0.140	0.116	0.100	0	0	0	0

Table 2.9. Count and proportion of vessels within 400 m (i.e. 0-400 m) by year by vessel class (i.e. proportion out of all vessels of that class w/in 1000 m).

Year		Res-earch	Priv. WW	Com. WW	En-force-ment	Moni-toring	Fish Com.	Ferry	Ship-ping
2010	Count	260	122	209	1	3	0	2	1
	Proportion	0.956	0.506	0.427	1.000	0.375	0	0.182	0.125
2011	Count	309	33	40	2	0	0	0	0
	Proportion	0.883	0.458	0.305	0.333	0	0	0	0
2012	Count	447	101	167	4	0	1	0	0
	Proportion	0.927	0.383	0.380	0.400	0	0.000	0	0

Table 2.10. Results of χ^2 tests to evaluate changes in proportion of research vessels within distance measure (out of all research vessels within 1000 m) by year. Research vessels significantly decreased the proportion of occurrence within 100 m of the whale over time.

	Distance to whale		
	0-100 m	0-200 m	0-400 m
χ^2	21.2981	2.9087	0.4881
df	2	2	2
p-value	**>0.0001**	0.2336	0.7834

Table 2.11. Results of χ^2 tests to evaluate changes in proportion of private whale watching vessels within distance measure (out of all PWW vessels within 1000 m) by year. There were no significant changes in the proportion of PWW vessels within specific radii of the whale over time.

	Distance to whale		
	0-100 m	0-200 m	0-400 m
χ^2	1.8332	0.343	3.0415
df	2	2	2
p-value	0.3999	0.8424	0.2185

Table 2.12. Results of χ^2 tests to evaluate changes in proportion of commercial whale watching vessels within distance measure (out of all CWW vessels within 1000 m) by year. Commercial whale watching vessels significantly decreased the proportion of occurrence within 100 m of the whale over time.

	Distance to whale		
	0-100 m	0-200 m	0-400 m
χ^2	6.5543	5.5948	3.0743
df	2	2	2
p-value	**0.03773**	0.06097	0.215

Table 2.13. Count of vessels (excluding research vessels) in each speed category by distance in 2010.

Speed class	Distance bins (m)									
	100	200	300	400	500	600	700	800	900	1000
Stationary	20	41	41	43	38	41	30	20	12	10
Slow	9	23	37	28	20	26	19	18	11	5
Medium	1	4	21	27	18	16	21	8	8	4
Fast	0	1	6	8	12	8	17	11	8	4
Very fast	1	0	1	2	3	6	7	2	3	2

Table 2.14. Count of vessels (excluding research vessels) in each speed category by distance in 2011.

Speed class	Distance bins (m)								
	100	200	300	400	500	600	700	800	900	1000
Stationary	3	4	5	7	5	4	6	9	0	5
Slow	1	4	10	5	10	12	9	10	8	1
Medium	1	0	4	3	9	4	5	2	2	1
Fast	1	4	7	6	3	6	11	5	5	3
Very fast	1	1	4	4	2	1	2	2	3	0

Table 2.15. Count of vessels (excluding research vessels) in each speed category by distance in 2012.

Speed class	Distance bins (m)								
	100	200	300	400	500	600	700	800	900	1000
Stationary	11	29	25	43	33	27	40	40	30	15
Slow	4	29	35	42	28	29	28	20	20	15
Medium	2	9	13	10	21	13	9	20	11	3
Fast	0	4	3	7	5	5	5	1	6	2
Very fast	0	0	1	2	3	2	5	2	2	1

Table 2.16. Results of χ^2 tests to evaluate changes in speed (categories = stationary, slow, medium, fast, very fast) pre-/post- regulations (pre-regulation = 2010; post-regulation = 2011-2012) by distance bin. Speed significantly changed pre-/post- regulations for vessels 100-200 m away from the whale and 300-400 m away from the whale.

	Distance bins (m)									
	100	200	300	400	500	600	700	800	900	1000
χ^2	3.3653	9.6402	6.5679	11.662	6.2642	6.0766	7.5368	8.774	1.8115	3.6475
df	4	4	4	4	4	4	4	4	4	4
p-value	0.4987	**0.047**	0.1606	**0.0201**	0.1803	0.1935	0.1101	0.067	0.7704	0.4558

Table 2.17. Evaluation of compliance with the guideline of 7 knots within 400 m.

Count of vessels	Speed under 7 knots	Speed over 7 knots	Proportion 7 knots + out of total
Pre-regulation	310	4	0.0127
Post-regulation	331	13	0.0378
Pearson's χ^2 with Yates' continuity correction			
$\chi^2 = 3.1586$	df = 1	p-value = 0.07553	

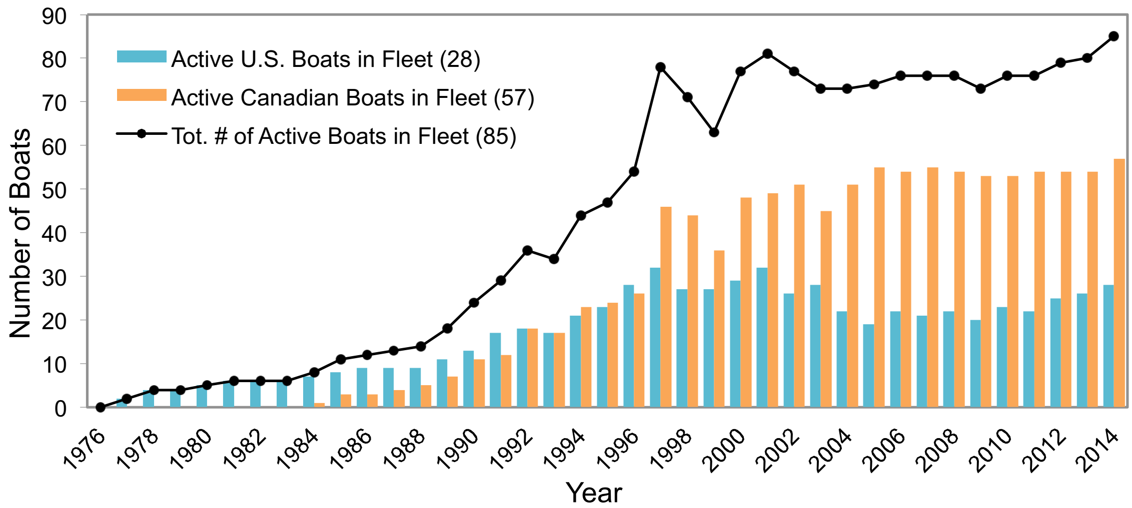

Figure 2.1. Number of commercial whale watching boats in the Salish Sea over time (© Soundwatch/The Whale Museum 2014).

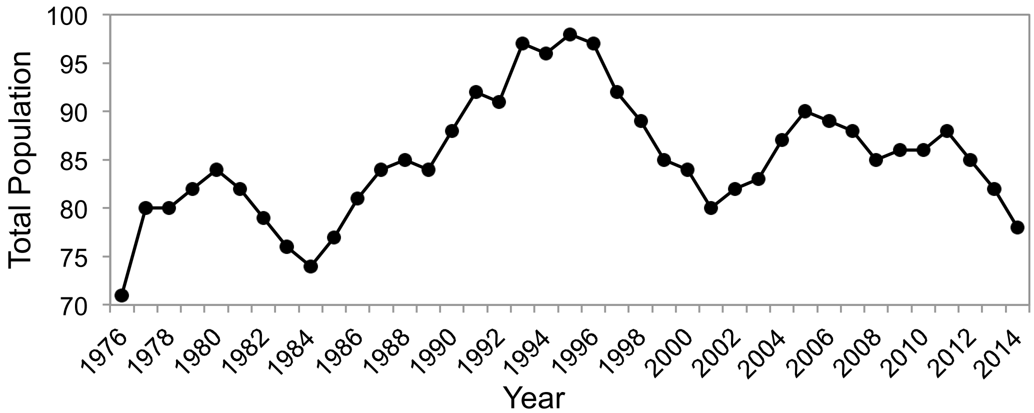

Figure 2.2. Population of SRKW from 1976-2014, showing lack of population recovery following captures for the aquarium trade prior to 1976 and a steep population decline 1996-2001 for unknown reasons (Center for Whale Research unpublished data).

Figure 2.3. Version 2 DTAG on SRKW 9/22/2010 (left) and version 3 DTAG on SRKW 9/17/2012. © NOAA NWFSC, taken under research permit.

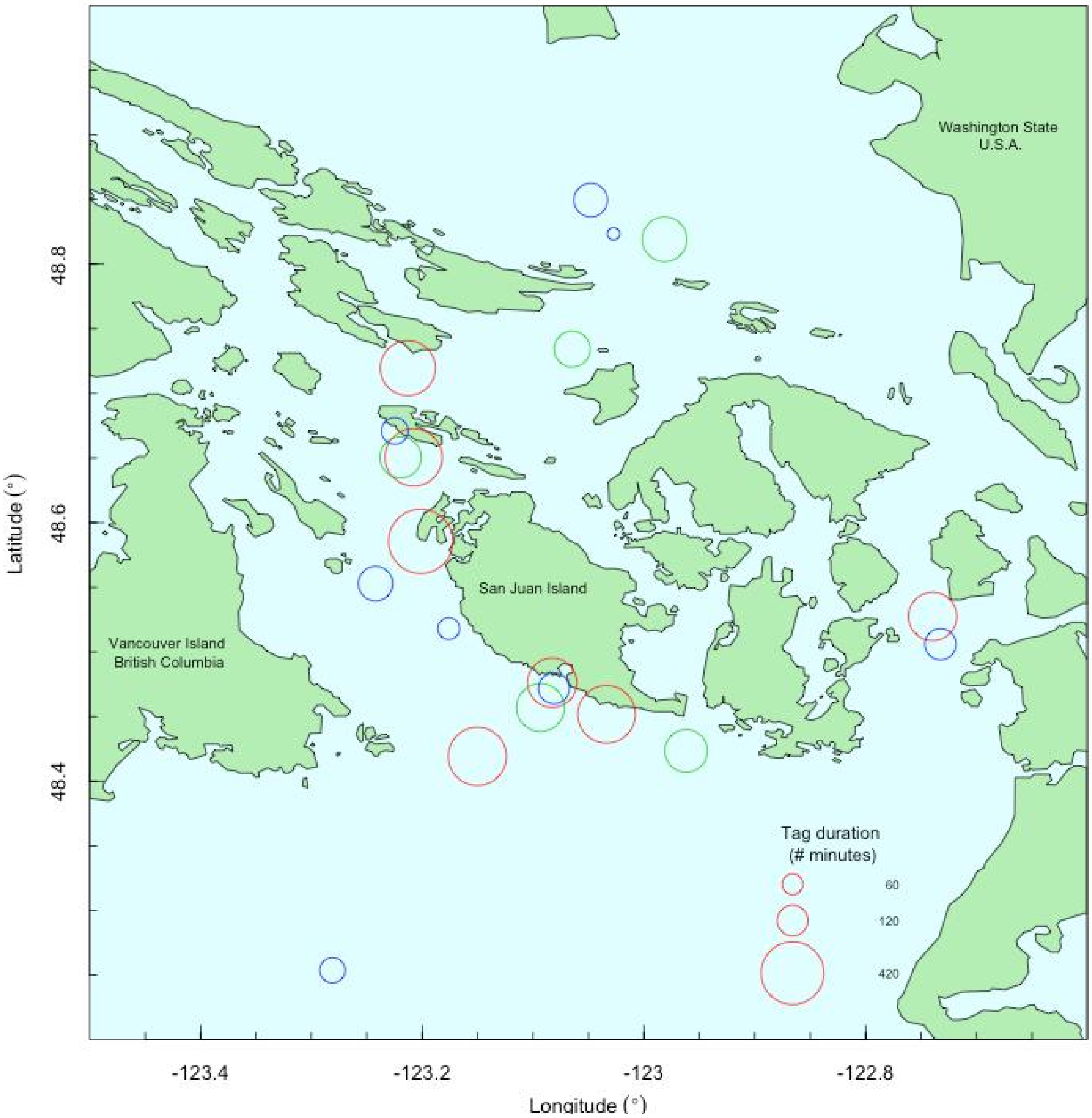

Figure 2.4. Locations of tag deployments during which vessel data were collected concurrently (n=20). The color of the marker corresponds to the year as follows: 2010 – red, 2011 – green, 2012 – blue. The size of the marker depicts the duration of the tag deployment in minutes. The tagged whale travelled beyond the extent of the marker throughout the deployment period.

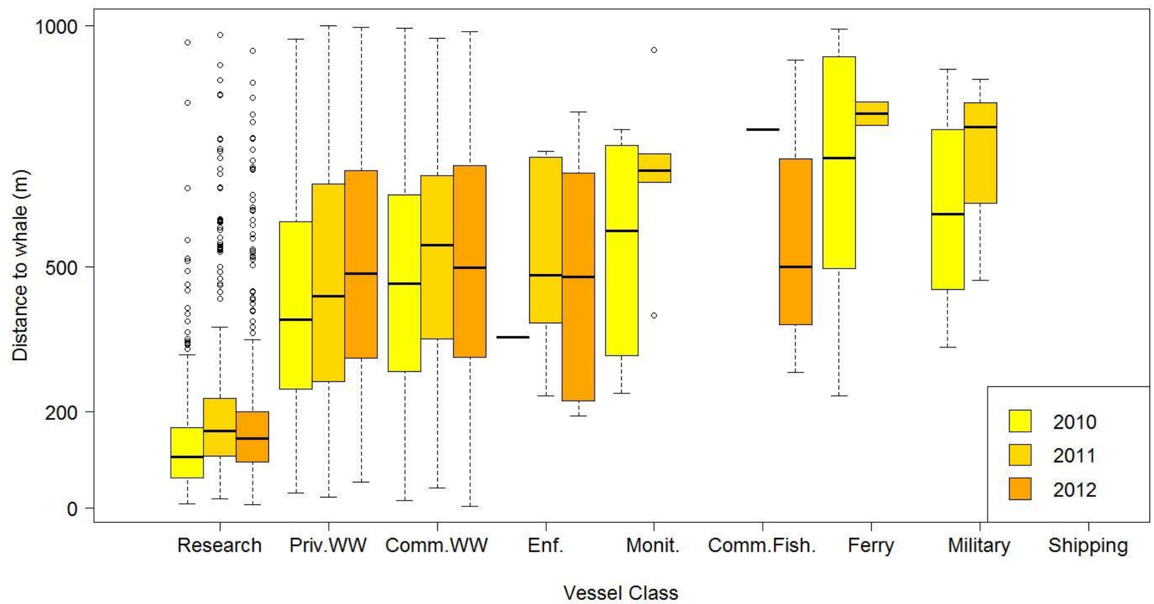

Figure 2.5. Distance of vessels to tagged whales (m) by vessel class and year. Thick black bars represent the median distance. Boxes encompass the inner quartile range (IQR). Whiskers extend to the minimum and maximum observations, except when an outlier (a value beyond 1.5xIQR) is plotted as a dot. Only research, private whale watching, and commercial whale watching vessels have substantial data for comparisons over time. Private whale watching vessels seem to have increased in distance to tagged whales each year while commercial whale watching and research vessels increased in distance from 2010 to 2011 but then decreased from 2011 to 2012.

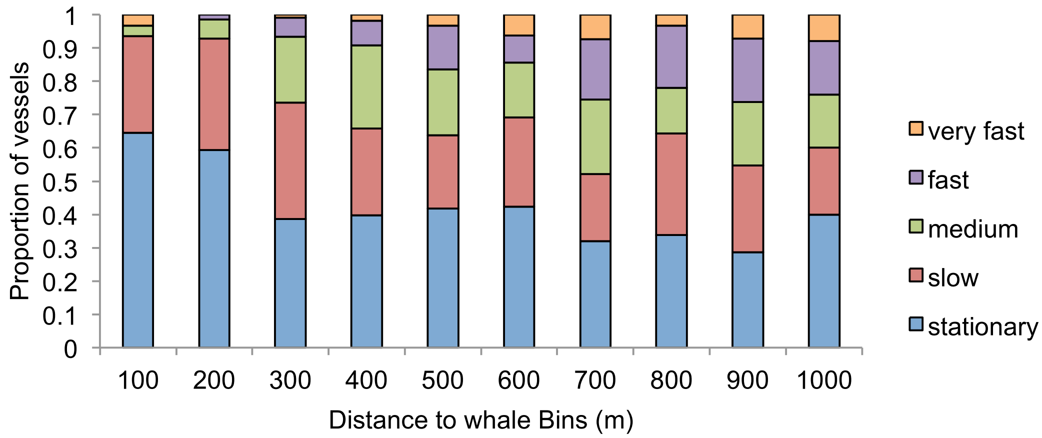

Figure 2.6. Proportion of vessels in speed categories by distance in 2010, excluding research vessels. Distance bins are 0-100 m labeled as 100; >100 m and ≤200 m labeled as 200; >200 and ≤300 m labeled as 300, etc. Speed categories were estimated with the following criteria: stationary = 0 knots; slow = 0-2 knots; medium = 3-4 knots; fast = 5-6 knots; very fast = 7+ knots.

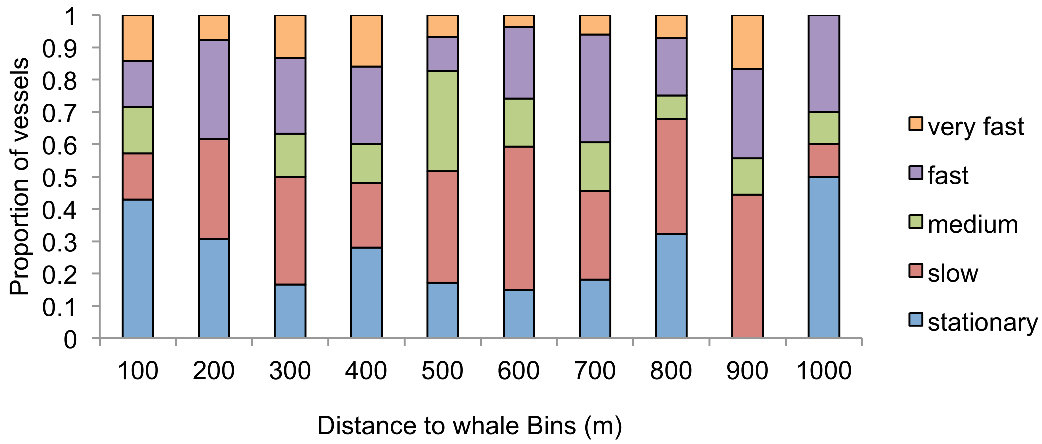

Figure 2.7. Proportion of vessels in speed categories by distance in 2011, excluding research vessels. Distance bins are 0-100 m labeled as 100; >100 m and ≤200 m labeled as 200; >200 and ≤300 m labeled as 300, etc. Speed categories were estimated with the following criteria: stationary = 0 knots; slow = 0-2 knots; medium = 3-4 knots; fast = 5-6 knots; very fast = 7+ knots.

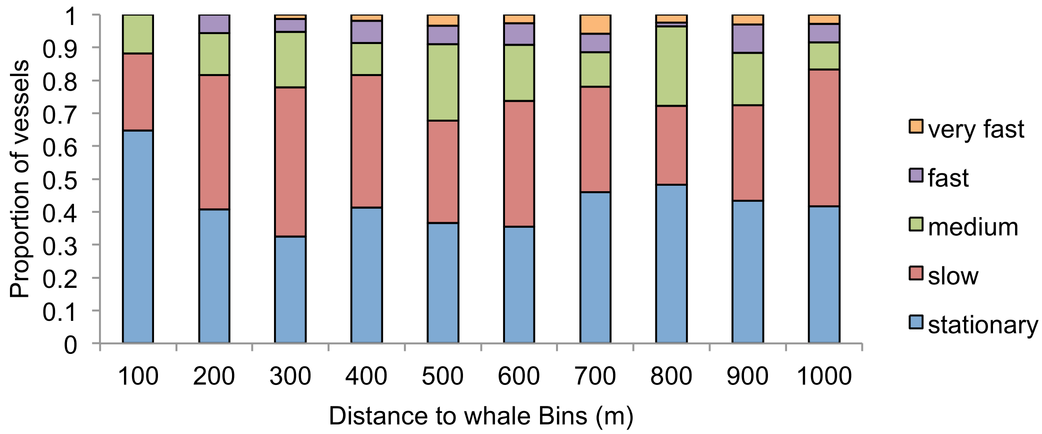

Figure 2.8. Proportion of vessels in speed categories by distance in 2012, excluding research vessels. Distance bins are 0-100 m labeled as 100; >100 m and ≤200 m labeled as 200; >200 and ≤300 m labeled as 300, etc. Speed categories were estimated with the following criteria: stationary = 0 knots; slow = 0-2 knots; medium = 3-4 knots; fast = 5-6 knots; very fast = 7+ knots.

CONCLUSION

In this study, the relationship between vessel traffic and noise levels received by endangered killer whales was described. This was a previously missing, but assumed link, and results can aid in further studies of the effects of vessels and associated noise on killer whales. This study also evaluated the compliance of whale watch operators with regulations and guidelines and assessed how vessel compliance has changed over time (2010-2012).

To compare the noise levels received by the whale to specific characteristics of vessel traffic, the data were spatiotemporally matched in five-minute intervals. Using the data for all intervals (n = 57), the likelihood model identified three vessel characteristics as significant predictors of noise levels: length (inverse relationship), vessel speed, and number of propellers. However, relatively little predictive power was present in the multi-model inference ($R^2 = 0.15$). When intervals that only recorded the research vessel were excluded (n = 30), the likelihood model identified only vessel speed as a significant predictor of noise levels ($R^2 = 0.42$). Average vessel speed and the average number of propellers for all vessels per interval were each significantly correlated with noise levels using simple linear regression. These findings suggest that the relationship between vessel traffic and received noise levels is complicated, but vessel speed is the most important vessel characteristic in its contribution to received noise.

All of the vessel data collected for this study was utilized to evaluate compliance with vessel regulations. Research, commercial whale watching, and private whale watching vessels increased in distance to tagged whales significantly over time. Moreover, research and commercial whale watching vessels less frequently approached tagged whales within 100 m over time. Excluding research vessels, vessel speed increased over time when vessels were 200 m and 400 m away from tagged whales. Other trends in vessel behavior over time were not significant.

The 200 m distance regulation went into effect in 2011 and compliance regarding distance has improved since then. The change in vessel speed was an unintended change in behavior, possibly due to the vessel regulation, and should be examined further.

The distance of vessels to tagged whales was not a significant predictor of the noise levels received by whales, but whale watch operator compliance with distance-based regulations did increase. Vessel speed was the most significant vessel characteristic that contributes to noise levels received by tagged whales. The observed change in vessel behavior of increasing vessel speed over time is therefore cause for concern as it likely has led to increasing noise levels received by the whale. The results presented here will allow managers to assess the effectiveness of current regulations in mitigating a risk factor to meet recovery goals.

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