A study to estimate the effect of noise from whale watch boats and commercial vessels and on killer whales

The Enhancing Cetacean Habitat and Observation (ECHO) Program commissioned a study to better understand the effects of the noise from whale watch boats and commercial vessels on Southern Resident Killer Whales (SRKW) in the Salish Sea.

This summary document was prepared to describe why the study was conducted, its key findings and conclusions, and how the results are planned to be used by the ECHO Program to help better understand and manage the impact of shipping activities on at-risk whales throughout the southern coast of British Columbia (B.C.).

What question was the study trying to answer?

Shipping noise has been identified as a concern for cetacean species in B.C. because of its potential to mask their vocalizations or disrupt their behaviour. The Endangered SRKW population is the focus of the local whale watching industry in the Salish Sea. Like commercial vessel noise, whale watch boat noise can also affect SRKW. Whale watch boats have a different sound signature than larger commercial vessels and they tend to spend longer periods of time in proximity to the whales. A previous study has attempted to quantify the effects of vessel noise on SRKW using computer simulation but whale watch boats were not included in the study because, unlike commercial vessels, their locations are generally not tracked and recorded. This study was a preliminary study into the potential noise effects of both whale watch boats and commercial vessels on SRKW in Salish Sea waters. The questions posed in the study were:

- How can whale watch boat locations be simulated and their noise be quantified to determine noise effects on SRKW overtime?
- What is the predicted behavioural response of the whales to the noise from both whale watch boats and commercial vessels overtime?
- How much is the noise of whale watch boats and commercial vessels that overlaps with echolocation clicks affecting the ability of SRKW to detect prey?
- Is there a cumulative effect on the whales from combined whale watch boat and commercial ship noise?

Who conducted the study?

SMRU Consulting North America was selected to undertake this study based on their expertise in underwater noise effects on marine mammals and the availability of an existing tool (model) developed to quantify effects of commercial ships on SRKW. Several other researchers have contributed to the model development or supplied additional data for this study.

What methods were used?

A computer simulation (model) was used to estimate how much whales were exposed to noise from whale watch boats and commercial vessels throughout summer (May to

September period) and to predict the effects of the noise on the whales. The model included the core areas of the critical habitat for SRKW and for whale watching in the Salish Sea. The study first quantified the noise contribution of whale watch boats by estimating 1) the probability that whale watch boats are with SRKW, and if with SRKW, 2) the number of boats present, 3) the noise levels from the boats present, and 4) the proximity of boats to the whales. This was then used to estimate the noise exposure of each whale.

The noise effect of the exposure was determined by repeating model simulations to estimate how often and how long whales show a behavioural response at the predicted noise levels and how often and how long noise levels at high frequencies likely reduce the range at which SRKW can detect prey (with echolocation clicks) throughout the summer. Additional analyses were done to better understand the reliability of the model and the importance of assumptions made.

What were the key findings?

The study found that:

- Whale watch boat noise increased the estimated time when SRKW may not be able to find prey because of changes in behaviour from 3 hours per day that SRKW were present in the study area to 3.2 hours per day (i.e., from 12.5% to 13.4%) when compared to noise from commercial vessels alone. This noise exposure effect was primarily due to commercial vessel noise (up to 93% of this time).
- The potential for noise of reducing prey detection range through masking of echolocation clicks outside this period was negligible for commercial vessels, but for whale watch boats, ranged between 5% and 34%. This is equivalent to whales detecting prey at up to 238m and 165m respectively rather than 250m. Whale watch boats and commercial vessels had a cumulative effect (12-37% range reduction).
- Potential lost foraging time due to click masking resulted in an additional 1.7 to 2.3 hours per day (7-9% of each day whales are present). This noise exposure effect was primarily due to whale watch boat noise (up to 93% of this time).
- Overall, the time for foraging potentially lost due to behavioural responses and click masking totaled 20-23% of each whale day (4.9-5.5 hours), with approximately two thirds of this time due to noise from large commercial vessels and one third due to noise from whale watch boats.
- These results are reflective of the difference in noise intensity (loudness) and frequencies of whale watch and commercial vessels and the difference in vessel number, proximity and behaviour around the whales.
- Confidence in model results was higher for behavioural responses than for echolocation click masking predictions due to limited data to estimate noise levels received by the whales from whale watch boats.

Conclusions and next steps

Study results indicate that noise from whale watch boats and commercial vessels in combination may result in a cumulative loss of time for foraging representing 20% to 23% (4.9-5.5 hours) of each day that SRKW are present in the study area during May to September. The results of this study provide additional insight and support for developing mitigation measures to reduce the effects of commercial vessels and boat noise on SRKW as part of the ECHO Program.

Estimating the effects of noise from commercial vessels and whale watch boats on Southern Resident Killer Whales

Prepared for the ECHO Program of Vancouver Fraser Port Authority

[July, 2017]

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Estimating the effects of noise from commercial vessels and whale watch boats on Southern Resident Killer Whales

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Executive Summary

An increase in underwater noise has the potential to affect marine mammals through behavioural changes, range displacement, communication masking, decreased foraging efficiency, hearing damage, and physiological stress. Underwater noise may be impacting the population recovery of endangered Southern Resident Killer Whales (SRKW). An environmental assessment conducted for a proposed terminal at Roberts Bank, near Vancouver, BC, Canada, considered the potential effects of underwater noise from large commercial vessels (e.g., merchant ships, ferries, tugs, large passenger vessels) on SRKW using an SRKW-noise exposure model (SMRU et al. 2014a). This simulation model used data from a ten year SRKW habitat use synthesis and a commercial vessel noise model to predict

1. the number of noise-related behavioural responses or BRs (using dual SRKW-specific dose-response relationships) and
2. the extent of any residual high frequency echolocation click masking.

The objective of this exploratory study was to also include underwater noise produced by whale watch boats, to better understand their noise contribution to the summer (May-September) soundscape and potential cumulative noise effects on SRKW within the Salish Sea during this period. This study included the core of SRKW's critical habitat and the time period when whale watching activities are strongly focused in the region.

The SRKW-noise exposure model kept some data inputs consistent under all modeling scenarios, including SRKW habitat use and monthly pod occurrence, commercial vessel noise levels, and dose-response/masking relationships. Modeled estimates of additional whale watch boat noise received by SRKW were achieved in a multi-step process by deriving 1) the probability of whale watch boats being with whales, 2) if with whales, how many boats are present, 3) how loud are the boats that are present, and 4) what is the whale-boat proximity. Model simulations were repeated 500 times to generate 95% confidence intervals, and sensitivity analyses were undertaken on key assumptions to provide an indication of model reliability and parameters that most influence the model's outputs.

Large commercial vessel noise in the study area was predicted to trigger 7.1 low severity BRs per day per whale and 3.2 moderate severity BRs per day per whale. Whale watch boat noise increased the overall number of moderate and low severity behavioural responses by 3% and 16% respectively compared to noise from commercial vessels alone. These periods of BR are considered to temporarily disrupt SRKW's ability to forage either via strong masking effects (either of communication calls/whistles or of echolocation clicks) or by switches in behavioural or activity states (e.g., changing from foraging to traveling). Whale watch boat noise increased the estimated 'potential lost foraging time' due to BRs from 12.5% to 13.4% (or from 3 to 3.2 hours per day that SRKW were present in the study area or 'whale

days'). Whale watch boats therefore contributed approximately 7% of this BR-related 'potential lost foraging time' model prediction and commercial vessel noise contributed approximately 93%.

In any time period where no BR was predicted, potential for residual click masking was assessed at 50 kHz. Reduction of echolocation click detection range was negligible for commercial vessels, but for whale watch boats ranged between 5 and 34% depending on whether individuals within each pod were considered 'dispersed' or 'clustered' in a tight group. A cumulative effect (12-37% range reduction) was apparent when commercial vessel and whale watch boat noise was combined.

Using a simple 1:1 distance-time conversion, 'potential lost foraging time' due to residual click masking from both commercial vessels and whale watching boats resulted in an additional 1.7-2.3 hours per day (7-9% of each whale day). Of this, large commercial vessels contributed up to just 7%, with whale watch boats contributing the remainder and thus whale watch boat noise strongly dominated this residual click masking noise exposure effect.

Commercial vessel noise spectra indicate that energy is also emitted above the model's 50 kHz click masking threshold (Veirs et al. 2016), but our findings highlight that when large commercial vessels such as container ships are in close proximity to SRKW (a few hundred metres) moderate severity BR thresholds are frequently triggered, with the chance of low severity BRs beyond a few kilometers, and so for these instances, click masking is subsequently not calculated further in the model. As commercial vessels transit away from SRKW, power spectral density levels at 50 kHz are typically reduced, by both transmission loss and high frequency absorption, to values below the 50 kHz click masking threshold. In contrast, whale watch boats are in close proximity to whales for long time periods each day, but when assumed to be moving slowly and mostly at the whale proximity distances of more than 200m, they do not regularly trigger BR thresholds, but instead trigger the 50 kHz click masking threshold.

Overall, SRKW-noise exposure model predictions of 'potential lost foraging time' (i.e., BRs and residual click masking effects combined) totaled 20-23% of each whale day (4.9-5.5 hours), with approximately two thirds of those effects due to noise from large commercial vessels and one third due to whale watching boats. These results highlight that underwater noise mitigation measures should be considered for both commercial vessels and whale watch boats, given that their predicted effects on SRKW were found to be different.

This study provided a starting point to assess the cumulative noise effects of both large commercial vessels and whale watch boats, noting the potential disturbance effects of the physical presence of boats were not included. While occupying their nearshore core areas during summer and fall, resident killer whales spend about 40-67% of their time foraging, and spend significant time resting, socializing and travelling (Ford 2006). Because BRs and masking can also disrupt other activities, our metric termed ‘potential lost foraging time’ might alternatively be described as ‘time associated with behavioural disruption and sound masking’. It is also important to recognise that this study covered a specific area and a specific time of year, which represents approximately 23-33% of where each pod spends their time annually (SMRU et al. 2014a).

Confidence in modelled BR results were considered relatively good, while noting whale watch boat noise level assumptions have most effect (+29% to -9%) on our predictions. In contrast, confidence in click masking predictions are considerably lower, with multiple assumptions having large effects (including vessel speed, vessel type, pod separation and boat proximity assumptions, as well as our focus on 50 kHz frequency and selection of a 250m click detection range). The accuracy of the masking model results could be improved through the use of received noise levels collected from tagged whales and through the development of more sophisticated models (Erbe 2015) that incorporate a range of different frequencies and fine-scale animal and boat movements.

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List of Acronyms

AIS: Automated Identification System
BR: Behavioural Response
dB: Decibel
DTAG: Digital Acoustic Recording Tag
ECHO: Enhancing Cetacean Habitat and Observation
FMA: Focused Model Area
HP: Horse Power
HF: High Frequency
Hz: Hertz
IB: Twin inboard engine
kHz: kilohertz
km: kilometer
m: meter
NOAA: National Oceanic and Atmospheric Administration (US Federal entity)
OB: Twin outboard engine
PCOD: Population Consequences of Disturbance
PMV: Port Metro Vancouver (now operating as Vancouver Fraser Port Authority)
PSD: Power Spectral Density
RBT2: Robert Bank Terminal 2
SRKW: Southern Resident Killer Whale
VTOSS: Vessel Traffic Operations Support System
WW: Whale Watch

1. Introduction

The Fisheries and Oceans Canada Recovery Strategy for Northern and Southern Resident Killer Whale (2011) identifies disturbance and noise pollution (as well as contaminants and reduced prey availability) as one of the key current threats to both of these small populations. Killer whales use sound to navigate, communicate, and locate prey. The recovery strategy suggests that increased vessel traffic is responsible for the increase in ambient noise levels detected over the last 100 years. Endangered Southern Resident Killer Whales (SRKW, *Orcinus orca*) frequently utilize the waters of the Salish Sea in summer, using echolocation to forage mainly for salmon. This region has high levels of vessel activity, including shipping lanes into the busy ports of Vancouver and Seattle, multiple ferry routes, a significant whale watch industry, as well as fishing and recreational vessel activity. An increase in underwater noise has the potential to affect marine mammals through behavioural changes, range displacement, communication interference, decreased foraging efficiency, hearing damage, and physiological stress (Southall et al. 2007, Rolland et al. 2012). Vessel noise is known to disrupt behaviour and potentially mask sounds required for navigation, communication and detecting prey (Aguilar Soto et al. 2006, Erbe 2002, Lusseau et al. 2009, Williams et al. 2014). Source level intensities and frequency spectrum vary across vessel types (Veirs et al. 2016) and to date no published study has attempted to assess the cumulative noise effects of different vessel and boat types on SRKW.

The environmental assessment conducted for a proposed terminal near Roberts Bank, Vancouver, BC, Canada, considered the potential effects of underwater noise from large 'commercial vessels' on SRKW using a fine-scale SRKW-noise exposure model (SMRU 2014a). This noise exposure model sampled data from a ten year SRKW density synthesis (Hemmera 2014) and a commercial vessel noise model (JASCO 2014) to predict both the number of noise-related behavioural responses (using a SRKW-specific dose-response relationship, SMRU 2014b) and the degree of any residual masking of high frequency (HF) clicks that are produced by SRKW to locate their prey through echolocation (SMRU 2014a). The results from this SRKW-noise exposure model were then used in a Population Consequences of Disturbance (PCOD) model, by estimating 'potential lost foraging time' (or the time associated with behavioural disruption and sound masking) of SRKW due to vessel noise, and applying this relative 'cost' metric to salmon availability to investigate the potential population level effects on SRKW for different traffic volume scenarios (SMRU 2014c, see Figure 1). Commercial vessel movements were based on data from Vessel Traffic Operations and Support System (VTOSS) data. These data include vessel positions obtained from vessels that have Automatic Identification System (AIS) receivers (i.e., primarily commercial vessels (>500 deadweight tonnes or >60' length), therefore referred to as 'commercial vessels' hereafter). These include merchant ships, ferries, tugs, cruise ships, government vessels, large recreational/passenger vessels, but does <u>not</u> capture smaller boats, including the majority of the whale watch fleet, which numbered 79 in 2012. For example, Canadian boats in the whale watch fleet account for 68% of the total and are mostly smaller rigid hull inflatable style of vessels (Eisenhardt 2012). These boats spend most of the daylight hours on the water searching for or with whales during the whale watching season (mostly May to September). Private recreational boats also strongly contribute (29%) to the mix of vessels (up to 50) observed near whales (Eisenhardt 2012) and are also considered in this noise-exposure comparative study.

The objective of this study was to include in the SRKW-noise exposure model, noise produced by small whale watch boats to better understand the noise contribution of this vessel type and the potential cumulative noise effects (both whale watch boats and large commercial vessels) on SRKW during summer (May-September) in the Salish Sea. The study included the core of SRKW's critical habitat in summer which is where and when whale watching activities are strongly focused in the region. The study was commissioned by the Enhancing Cetacean Habitat and Observation (ECHO) Program, a program led by the Vancouver Fraser Port Authority and aimed at mitigating the effects of commercial shipping on whales. This data gap is of interest because whale watch boats spend more time in proximity to SRKW and have different noise frequency spectral contents compared to 'commercial vessels' (e.g., Jensen et al. 2009), and therefore, have potentially different (and cumulative) noise effects on the whales.

To quantify the noise exposure contribution from whale watch boats, it was first necessary to make model input predictions on 1) how often whale watch boats are with whales, 2) how many boats are interacting with whales, 3) the noise levels associated with those boats and 4) how close are these boats to individual whales to estimate received noise levels. This study should be considered a starting point to understanding cumulative noise effects on SRKW. A sensitivity analysis was conducted to assess model reliability and to identify key data gaps for future research.

2. Methods

This study adapted an SRKW-noise exposure model (SMRU 2014a) to estimate the relative contribution of commercial vessels and whale watch boats to cumulative vessel noise effects on SRKW, as well as to estimate their contribution to noise effects in isolation (Figure 1). Data inputs for SRKW habitat use and monthly pod occurrence, commercial vessel noise levels, as well as dose-response/masking relationships were kept consistent in all scenarios. Received noise levels due to whale watch boats were estimated for this study using a multi-step process (red boxes annotated a-e in Figure 1), followed by a sensitivity analysis to assess the importance of key whale watch boat noise model assumptions.

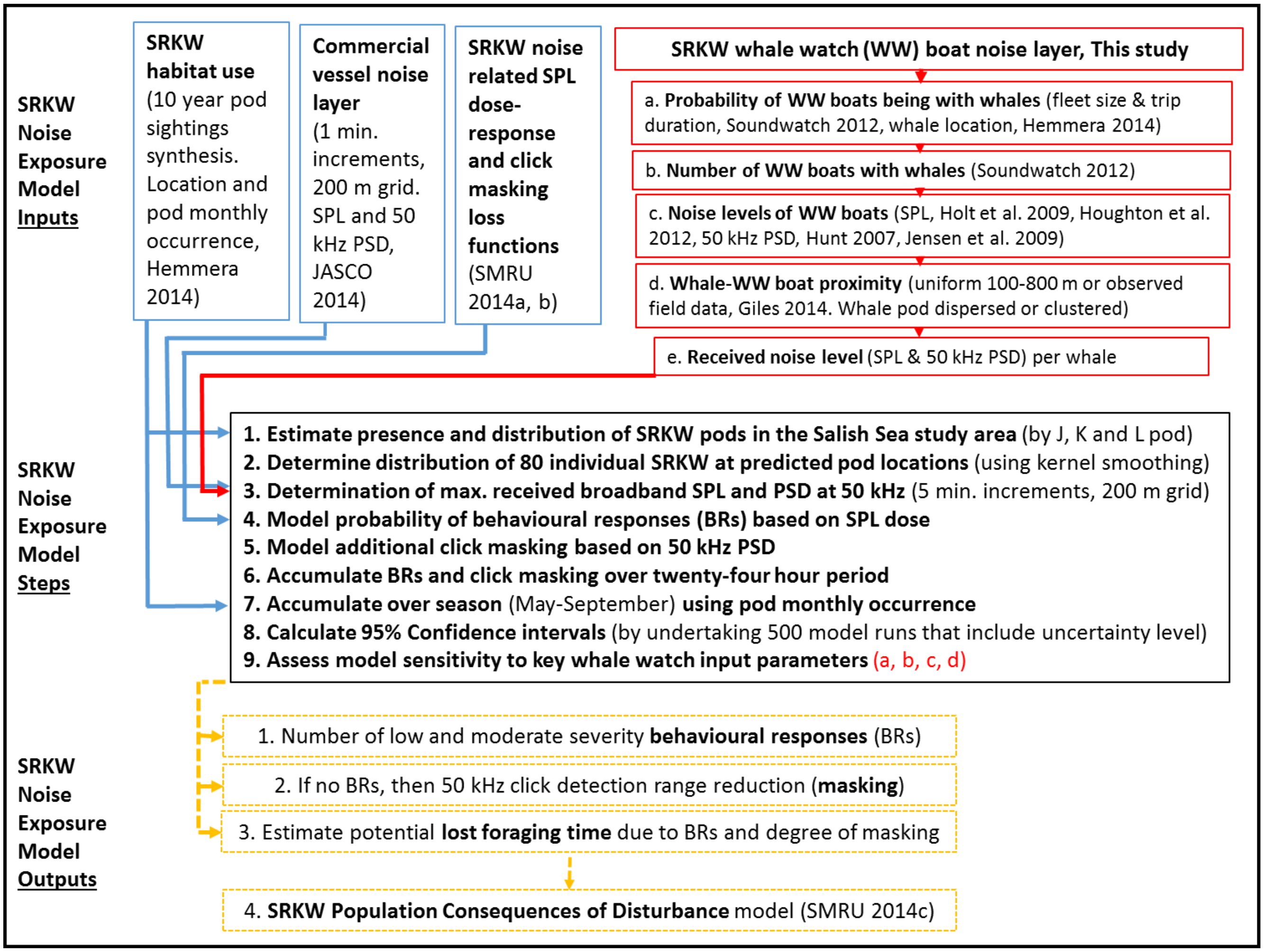

Figure 1. SRKW-noise exposure model framework outlining model inputs, main model steps and range of model outputs. SPL = Sound pressure level, PSD = Power spectral density. New model inputs developed for this study for estimating the whale watch boat noise layer have been marked in red.

2.1 Study area

The study area for this analysis is shown in Figure 2 was the same as the 'focused study area' used in the previous modelling conducted in support of the environmental assessment for the proposed terminal at Roberts Bank (JASCO 2014, SMRU 2014a). The study area contains the core areas of SRKW critical habitat and for whale watching in the Salish Sea.

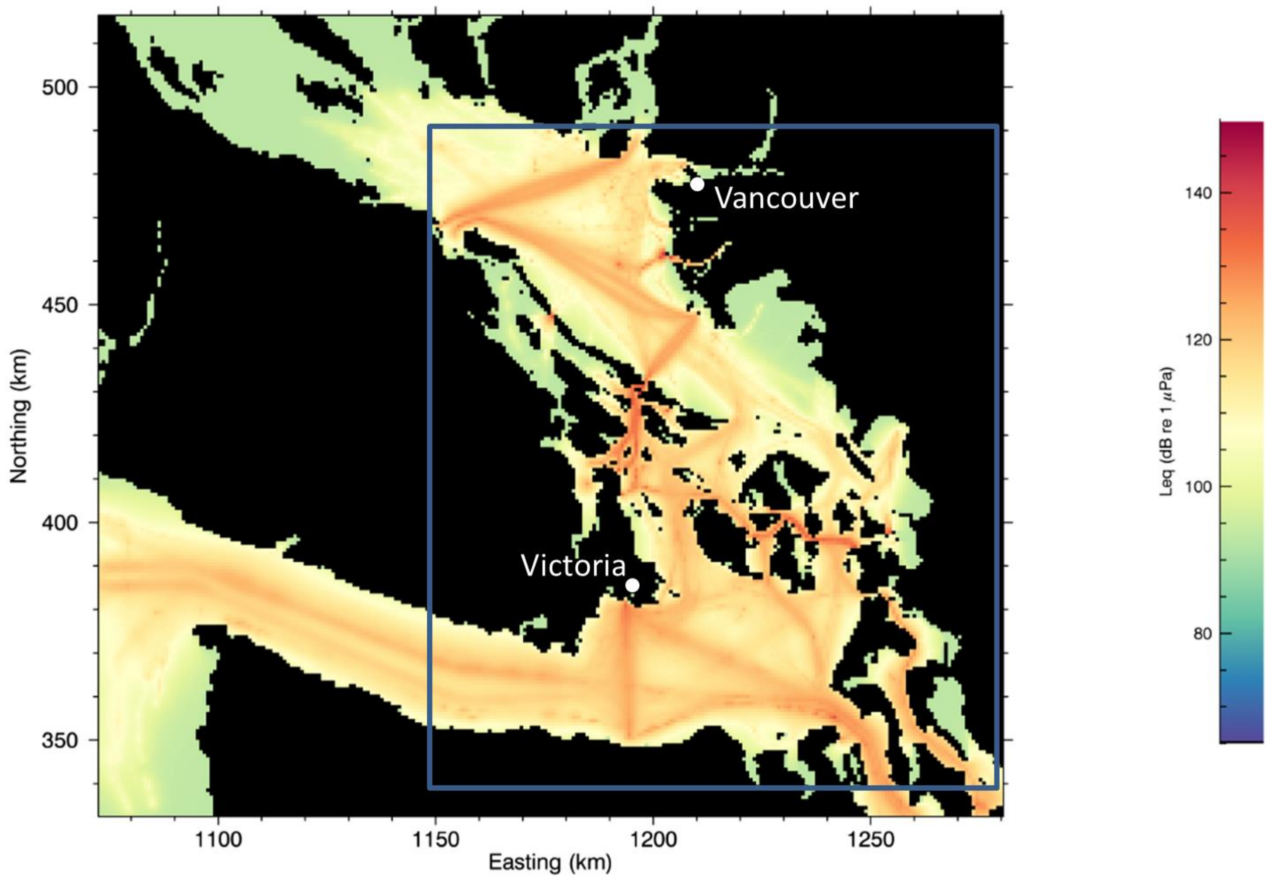

Figure 2 Extent of study area (blue rectangle) with regional monthly mean commercial vessel sound pressure level (Leq) for July as estimated by Jasco Applied Sciences (JASCO 2014).

2.2 Summary of underlying SRKW-noise exposure model

The SRKW-noise exposure model was first developed to capture the large variability in noise levels received by whales as large commercial vessel are transiting through the Salish Sea. This requires fine-scale information on SRKW presence and noise levels. Baseline data used for the commercial vessel noise layer were from one-minute time increments across 200m sized grid cells for a relatively high vessel volume day in mid-summer 2012. Detailed model methodology and key assumptions are detailed in Appendix 1, but are summarised in the following nine steps;

1. **Estimate presence and distribution of SRKW pods in the study area**. Each of the three pods (J, K and L) was determined present or absent in the study area, and the 80 individuals from the population (based on 2013 population estimates from the Center for Whale Research) were distributed as per the relative density predictions by pod and monthly probability of occurrence from Hemmera (2014). The duration of this study encompassed 153 days, with SRKW estimated to be present within the study area on 97.5 "whale days" on average (J pod = 121 days, K pod = 84 days, L pod = 89 days).

2. **Determine distribution of individual SRKW at predicted pod locations.** Individual whales in each pod were distributed over multiple 200 m cells using a kernel smoothing approach.
3. **Determination of received SPL and PSD at 50 kHz.** This step uses fine-scale (200 m grid) data from a 2012 commercial vessel noise model developed by Jasco Applied Sciences (JASCO 2014) to estimate maxima within 5-minute increments, the broadband (20 Hz – 96 kHz) received sound pressure levels (SPLs) and Power Spectrum Density (PSDs) at 50 kHz. Methodological details used in this study to specifically estimate whale watch boat noise are provided in the following sections (and conceptually illustrated in Figure 1).
4. **Model behavioural responses based on SPL dose.** It should be noted that triggering a BR has been assumed to temporarily inhibit a killer whales' ability to forage (e.g., changing from foraging to traveling, Lusseau et al. 2009), and that this response to broadband noise includes the equivalent of complete masking (either of communication calls and whistles or of echolocation clicks). The number of low and moderate severity behavioural responses (BR) were predicted based on SRKW-specific dose-response relationships, with median (50th percentile) broadband (20 Hz – 96 kHz) received noise level threshold values of 129 and 137 dB re 1 μPa for low and moderate severity respectively (SMRU 2014b). Relationships were developed using resident killer whale data from three sources; digital acoustic recording tags (DTAG), a theodolite whale-vessel tracking study (Williams et al. 2014) and a passive acoustic monitoring study (SMRU 2014a). A low severity response (e.g., minor changes in respiration rates, locomotion speed, direction or deviation) was estimated (using analysis of DTAG data) to result in 5 minutes of lost foraging time. A moderate severity response (e.g., moderate to extensive changes in locomotion speed, direction and/or dive profile, moderate or prolonged cessation of vocal activity, potential avoidance of area) was estimated to result in 25 minutes of lost foraging time (SMRU et al. 2014c). High severity scores were not reported during vessel interactions in the three data sources used and therefore were not predicted in this study. The potential effects from vessel proximity (i.e., physical disturbance rather than BR to noise) were not explicitly included in the noise exposure model.
5. **Model high frequency click masking based on 50 kHz PSD.** Foraging related echolocation clicks have a peak in intensity centered at 50 kHz (Au et al. 2004). At lower broadband noise levels, when no behavioural response was predicted, the model estimated the degree of additional or residual high frequency masking using a precautionary maximum click detection range (threshold) of 250 m and calculating a median proportional reduction in click detection range due to 50 kHz noise levels. Both 1-dimensional (distance; 1-D) and related 3-dimensional (volume; 3-D) loss functions were additionally used to simply translate this proportional loss into proportion of minutes within each 5-minute increment affected.
6. **Accumulate BRs and click masking over a twenty-four-hour period**. The above process was repeated 288 times, for each 5-minute increment of the day and the number of low and moderate severity behavioural responses and degree of masking were accumulated for each

individual whale. The original model also used a winter's day noise layer (JASCO 2014) to develop overall annual estimates.

7. **Accumulate BRs and click masking over entire season (May through September).** The above process was repeated for the 153 days of summer (May-September), but integrating monthly variability in pod occurrence (Hemmera 2014, Appendix 1).
8. **Calculate 95% confidence intervals.** The entire model simulation was run 500 times to generate the 95% quantiles or confidence intervals (CIs).
9. **Assess model sensitivity to key whale watch boat noise assumptions.** See Figure 1 and Section 2.3 for details of model sensitivity analyses. The original model assessed changes from baseline due to future (increased) commercial traffic volume predictions.

2.3 New whale watch boat inputs to the SRKW-noise exposure model

To estimate the number of low and moderate behavioural responses and the degree of masking due to whale watch boats, noise levels caused by motorised whale watch boats near whales need to be systematically incorporated into the SRKW-noise exposure model. Noise levels are significantly related to the number of boats with whales (Holt et al. 2009), which in turn is driven by when and where the whales are sighted. Therefore, information from several different data sources was incorporated to estimate boat noise levels. The steps taken to quantify noise levels (i.e., input parameters required for the model) can be summarized under the following sequential questions: 1) are whale watch boats with whales, 2) if so, how many boats are present, 3) how loud are those boats that are present, and 4) what is the whale-boat proximity?

2.3.1 Data sources

For whale watch boat temporal counts, we used data recorded by the Whale Museum's Soundwatch Boater Education Program (Eisenhardt 2012). Vessel proximity data were taken from Giles (2014). For underwater noise levels in the vicinity of whale watching boats, we used empirical data from Dr. Marla Holt (NOAA) from her published study (Holt et al. 2009), as well as SRKW DTAG acoustic datasets collected by NOAA and University of Washington and presented by Houghton et al. (2012), whale watch boat acoustic data provided by Dr. Scott Veirs and Tim Hunt (Beam Reach Marine Science and Sustainability School, Hunt 2007), and additional vessel noise data from Jensen et al. (2009). Holt et al. (2009) and Eisenhardt (2012) both provided data relating to all boats engaged in active whale watching – both commercial and recreational. We would like to acknowledge the support of each of these groups, as these data were critical to undertaking this study.

2.3.2 Are whale watch boats with whales?

In the noise exposure model previously developed, Hemmera and SMRU Consulting used effort-corrected voluntary sightings data of SRKW to estimate relative SRKW density within the study area (Hemmera 2014). As part of effort correcting (a method originally developed by the Vancouver

Aquarium), an estimate of the relative effort of the commercial whale watch fleet was developed, based on the boat's home port, average travel distances and the daily number of whale watch trips from each home port (Hemmera 2014). These were calculated in ArcGIS and matched the 200m grid cell resolution of the JASCO commercial vessel noise model (JASCO 2014) for the study area. Dr. Anna Hall, a cetacean scientist with multi-year experience as a commercial whale watch skipper operating out of Victoria (the main whale watching port in the area), provided further advice on commercial whale watch activities. To estimate the probability of whale watch boats being with whales in each 200m grid cell, the relative summer SRKW density was multiplied by the relative whale watch effort and then normalized to have values between 0 and 1 (i.e., by subtracting the overall minimum value from the value of a given grid cell and dividing by the range).

Whale watching effort is known to peak in July and varies across the five months considered as 'summer' in this study (May – September); therefore, monthly modifiers were derived to down-weight the spatial relative probability of whale watch boats being with whales compared to July values. Monthly modifiers were derived using the average number of boats counted within 805m (½ mile) of whales as reported by Soundwatch in 2012 (Eisenhardt 2012) for each of these five months. Each monthly average was divided by the July average to calculate this modifier. Thus, each month had its own spatial relative probability of whale watch boats being with whales. To estimate the time (number of 5-minute increments) the first whale watch boat took to find each pod in the study area, we generated a geometrically-distributed random number where the length of time was related to the spatial relative probability of whale watch boats being with whales. This effort correction enabled the model to incorporate the assumption that some whale locations take longer for the whale watch fleet to find. Once the pod had been located on a given day, it was assumed to be located for the remainder of the day, but numbers of whale watch boats with the pod were determined as per Section 2.3.3. Without empirical information on whale watch effort it is difficult to further ground-truth these relative probabilities. We therefore conducted a sensitivity analysis to determine the potential effect of varying this parameter. As a reasonable starting point for our sensitivity analyses, we both halved and doubled this measure of relative probability rates (termed low and high probability scenarios; see Table 1 and Appendix 2 for details on all sensitivity analyses).

2.3.3 How many boats are with whales?

If the noise exposure model determined that whale watch boats were with whales, we determined how many boats were present with the whales in a pod based on Soundwatch 2012 boat count data (Eisenhardt 2012). When Soundwatch staff are on the water near a pod of whales, they count the number of boats within 805m (½ mile) of whales every half an hour. These data show that boats are typically with whales between the hours of 9:00 and 19:00 and peak in numbers in July. Those data were extracted by hour and by month to generate monthly distributions from which the model could randomly select the number of boats with whales at each hour of the day. We tested a "low boat" sensitivity in our model by dividing the Soundwatch 2012 boat count data by the number of unique pod locations in the study area (Table 1, Appendix 2). This “low boat” scenario assumed that Soundwatch boat numbers with whales represented counts of all active whale watch boats in the study area, rather than a count of the boats seen by the Soundwatch team at one pod location. A “high boat” scenario was considered unnecessary.

2.3.4 How loud are the boats with whales?

The next step to incorporating whale watch boat noise into the exposure model required a conversion from the number of boats with whales to the noise levels they generate (both broadband received levels and Power Spectral Density (PSD) levels at 50 kHz. Data sources used in this step were Holt et al. (2009) and Hunt (2007), supplemented by data from Jensen et al. (2009).

2.3.4.1 Broadband noise levels

Holt et al. (2009) collected received levels of noise when different numbers of whale watching boats were in the immediate vicinity (< 1km) of the stationary research vessel and found a significant relationship between the number of whale watch boats and the resulting noise levels. For these simulations, we have assumed that the variance in noise levels Holt et al. (2009) observed at the research vessel captured the variability in received noise levels experienced by whales due to the effects of variable boat speed, type, distance, orientation and variable environmental conditions affecting noise propagation over short ranges. Holt et al. (2009) background noise levels were calculated in the frequency range of 1 – 40 kHz, while our behavioural response of SRKW to commercial vessel noise exposure estimates are based on broader band noise estimates (20 Hz – 96 kHz) (SMRU et al. 2014a). A conversion factor was therefore needed to augment the narrower frequency band noise data from Holt et al. (2009) to the broadband noise level estimates used in the original model (SMRU 2014a).

To develop the conversion factor, the study used noise levels of a number of different slow motoring (6 – 8 knots) commercial whale watch boats (Hunt 2007). The PSDs for three boats with reliable data were used, including a twin outboard 150 horse power (HP) boat (with a planing hull, 8 m length), a twin inboard 400 HP biodiesel (>20m), and a twin inboard diesel (both with displacement hulls, 14m). These data spanned the frequency range from 20 Hz – 96 kHz, the same as used in our SRKW-noise exposure model (SMRU 2014a). The conversion factor from number of boats to noise was calculated by integrating the Hunt (2007) power spectral density data across both 1 – 40 kHz and 20 Hz – 96 kHz frequency ranges, and by calculating the mean difference in decibel (dB) between these two noise measurements. The Holt et al. (2009) regression relationship between the log number of boats present and background noise levels was then recalculated using the mean converted noise levels. To test model sensitivity to broadband noise levels, we used a “high SPL noise” value based on the maximum dB conversion factor, and selected the “low SPL noise” value based on received values recorded directly from acoustic tags (DTAG) attached with a suction cup on SRKW individuals (Houghton et al. 2012) and the mean conversion factor (See Table 1, Appendix 2).

2.3.4.2 High frequency noise levels

Estimates of power spectral density levels at 50 kHz used in the model to assess click masking were considerably more challenging to derive, as they required a back-calculation based on boat number, speed, and whale-boat proximity, for which there was a sparsity of empirical data. The 50 kHz frequency represents the peak in distribution of the center frequency of killer whale clicks and was the frequency used for modeling in the only published study assessing click masking thresholds in killer whales (Au et al. 2004). Au et al. (2004) reported that, in a quiet environment, an echolocating killer whale would receive echoes that are between 29 and 33 dB above the hearing threshold at a horizontal range of 100m and further noted that these echo levels taper off slowly beyond 100m suggesting the detection range, and therefore masking range, probably extends considerably further. We used the maximum inter click interval recorded at the Lime Kiln hydrophone on San Juan Island to estimate a maximum click detection range of 250m for 50 kHz clicks (SMRU 2014a). In using this maximum range, the masking thresholds developed using the Au et al. (2004) data are extrapolated and consequently might be considered precautionary with regards to this model's quantification of high frequency clicks.

For this part of the study, we used unpublished data from the same three ~8-20m whale watch boats used previously (Hunt 2007) and two smaller 5-6m aluminium hulled whale watch boats with 85-135 HP outboard engines (Jensen et al. 2009). A custom Matlab script was written to estimate 50 kHz PSD levels near whales based on these data. This script assumed spherical spreading and an absorption rate of 15 dB per km in estimates of transmission loss. Boats measured by Hunt (2007) were all slow motoring at 6.0 to 8.0 knots, while those measured by Jensen et al. (2009) were travelling at 2.5 and 5.0 knots. Given the great variety of both commercial and private whale watch boat types and speeds around SRKW, these preliminary estimates should be treated with appropriate caution.

Received noise levels were converted to source levels and a random source level between the minimum and maximum source level was assigned to each boat. Using the assumptions of transmission loss, a combined 50 kHz PSD received level was then calculated for each scenario and iteration. One hundred iterations were run for scenarios with 1 to 50 whale watch boats, the latter being the maximum recorded at a pod location.

2.3.4.3 SRKW-whale watch boat proximity

Soundwatch data were used to estimate the number of boats by hour of day and by month associated with each whale in a pod and the appropriate SPL and PSD data were then drawn from the distributions developed (Figure 3 and Figure 8). PSD Estimates were generated by placing boats uniformly between 100 and 800m from whales, and using empirical data from Giles (2014), a field study that used video and GPS locations to determine boat-whale proximity (Figure 3). We then applied a spherical spreading and absorption function, and summed the noise of all whale watch boats in log10-space to give a PSD value for a whale watch boat fleet of 1 to 50 boats (Figure 4). Two whale pod distribution scenarios were utilized to determine the effects of assumed pod distribution on the model results: dispersed and clustered. Hourly estimates of boats with whales were distributed around the entire pod with all individuals affected equally (clustered pod scenario, Table 1). This assumes the individuals within a pod are in a tight group. The dispersed pod scenario assumes that as the number of boats increases from a single vessel to greater than nine, an increasing larger proportion (35-80%) of individual whales are affected. The proportions used were based on vessels interacting with an increasing number of matrilineal groups within a pod. This dispersed scenario precludes the unlikely situation where a small number of vessels are interacting with the entire pod.

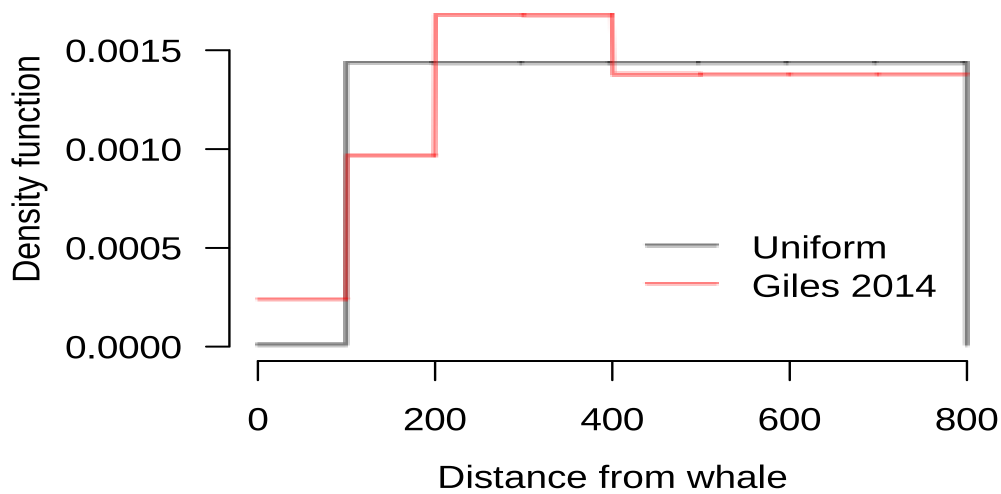

Figure 3 Proximity (distance in m from whale to whale watch boats) distributions based on empirical data collected by Giles (2014), as well as a uniform distribution between 100 and 800 m.

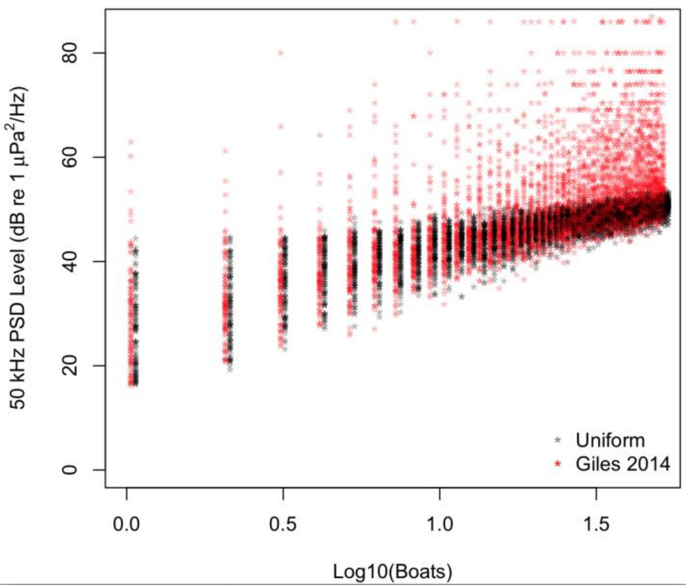

Figure 4 Distribution of 100 simulated PSD values from 1 to 50 boats plotted on a log10 X-axis. Red dots denote Giles (2014) proximity data, while the dark dots represent uniform proximity values.

2.3.5 SRKW-noise exposure model scenarios and sensitivity analyses.

Sensitivity analyses were performed to highlight the effects of our key whale watch boat noise assumptions and guide future research. Base scenarios were modelled for only commercial vessels (AIS Base, scenario 1, Table 1), only whale watch boats (WW Base) and both combined (AIS+WW Base) using Giles (2014) proximity and dispersed pod assumptions (Scenarios 2a and 3a). In addition, we assessed the effect of our pod separation (dispersion) assumption by repeating the whale watch scenario and combined noise scenarios using a clustered pod assumption (scenarios 2b and 3b, Table 1). In the remaining scenarios of the sensitivity analysis (3c-3h), we used precautionary assumptions (uniform proximity and clustered pod) on combined commercial vessels and whale watch boats to test the effect of changing the probability of finding whales (3d – low probability, 3e – high probability), effect of distributing the number of whale watch boats across all pods (3f – low number of boats), rather than at each pod, and the effect of varying received SPL levels (3g – low noise levels, 3h – high noise levels). Scenarios 3d to 3h thus vary just one input parameter to allow direct comparison with scenario 3c (see Appendix 2 for further details).

Table 1 Details of noise exposure base scenarios and sensitivity analysis scenarios undertaken for this study. Appendix 2 provides additional information on whale watching related assumptions included in each sensitivity analysis scenario.

Scenario #	Noise exposure scenario name	Vessel types	Key assumptions included in scenario
1	AIS Base	Commercial vessel only	Not applicable
2a	WW Base (Dispersed)	Whale watch (WW) boats only	Giles 2014 proximity, dispersed pod
3a	AIS + WW Base (Dispersed)	Commercial and WW combined	Giles 2014 proximity, dispersed pod
2b	WW Base (Clustered)	Whale watch (WW) boats only	Giles 2014 proximity, clustered pod
3b	AIS + WW Base (Clustered)	Commercial and WW combined	Giles 2014 proximity, clustered pod
3c	AIS + WW (c)	Commercial and WW combined	Uniform proximity, clustered pod
3d	AIS + WW (d)	Commercial and WW combined	3c with low probability of finding whales
3e	AIS + WW (e)	Commercial and WW combined	3c with high probability of finding whales
3f	AIS + WW (f)	Commercial and WW combined	3c with boats distributed across all pods
3g	AIS + WW (g)	Commercial and WW combined	3c with low SPL noise levels incorporated
3h	AIS + WW (h)	Commercial and WW combined	3c with high SPL noise levels incorporated

3. Results

The results of the multi-step process to determine noise levels from whale watch boats (i.e., the inputs to the SRKW-noise exposure model) are provided in section 3.1, followed by SRKW-noise exposure model results (outputs) in section 3.2.

3.1 Inputs to the SRKW-noise exposure model

3.1.1 Are whale watch boats with whales?

The estimated maximum spatial probability of whale watch boats being with whales occurred in July (detailed in Figure 5). The highest probabilities coincided with areas of greatest whale watching effort and SRKW density. These included Haro Strait and Boundary Pass. The monthly modifier results are provided in Table 2. July had the highest ratio and May the lowest. The probability of whale watch boats being with whales in each 200m grid cell was multiplied by these monthly modifiers to produce a spatial probability of whale watch boats being with whales. Thus, the model used five different monthly spatial estimates of the probability of whale watch boats being with whales, which was translated to monthly estimates of the time it took before a pod of whales was "found" by the whale watch fleet.

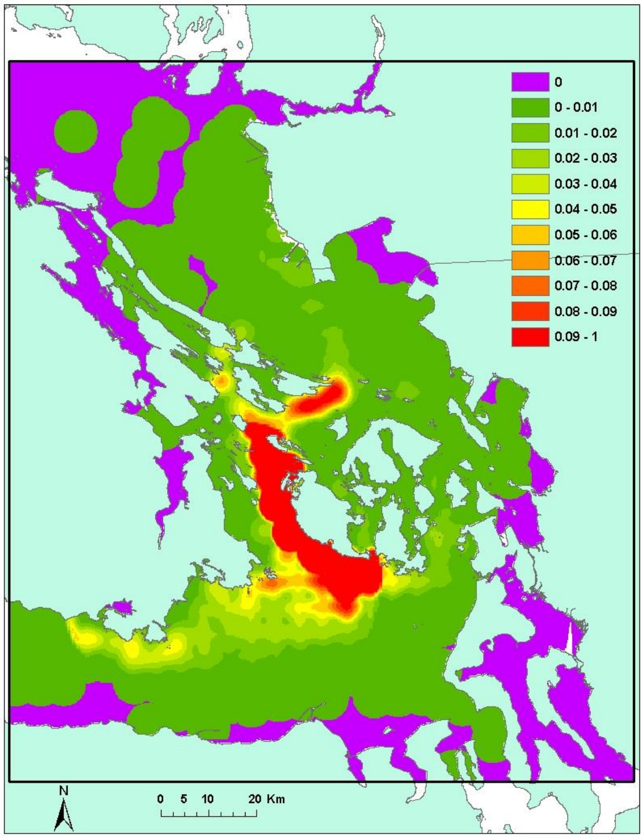

Figure 5 Relative spatial probability of whale watch boats being with whales. Probabilities are scaled from 0 to 1.

Table 2 Monthly modifier used to down-weight the July relative spatial probability of whale watch boats being with whales based on Soundwatch 2012 data (Eisenhardt 2012).

Month	Monthly Modifier
May	0.50
June	0.64
July	1.00
August	0.92
September	0.97

3.1.2 How many boats are with whales?

Based on Soundwatch 2012 data (Eisenhardt 2012), boats were active for a period of 10 hours between 9:00 and 19:00. The highest average number of boats with whales occurred at 15:00 (mean=18.2) and the lowest at 19:00 (mean=5.0) (Figure 6). The model randomly sampled from the empirical distribution by matching a count for a given hour and month to each 5-minute increment and used these counts as inputs.

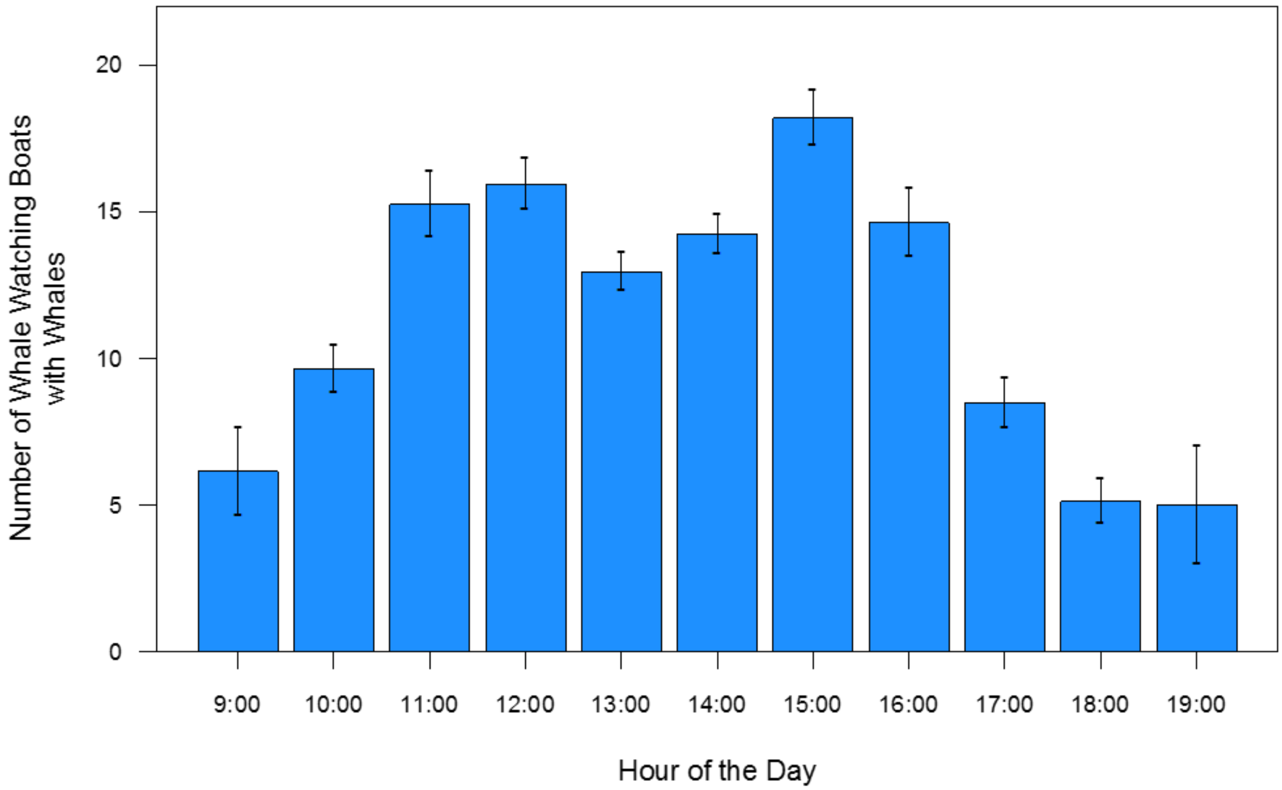

Figure 6 Distribution (mean and standard error) of the number of boats with whales by time of day across May to September based on Soundwatch 2012 data (Eisenhardt 2012).

3.1.3 How loud are the boats with whales?

3.1.3.1 Broadband noise levels

The representative PSD of the three whale watch boats recorded by Hunt (2007) are shown in Figure 7. These data were recorded while 'slow motoring' (i.e., 6 – 8 knots), noting that in the United States the law requires boats to stay below 7 knots when within 400m of SRKW. The mean difference when integrating the PSDs from 1 – 40 kHz and 20 Hz – 96 kHz was 4.6 dB. This difference in sound pressure levels was added to the Holt et al. (2009) noise levels. The modified Holt et al. (2009) SPL relationships are presented in Figure 8. The resulting regression line equation is Noise Level = 108.09 + 6.512 * log10(Vessel Count). This relationship and the data residuals were used to estimate the noise levels from whale watch boats to apply within the model. In other words, we used the Holt et al. (2009) data as the underlying received noise values to represent whale watch boats but have up-weighted the original values using data from slow motoring vessels to account for noise energy at frequencies not originally measured by Holt et al. (2009). To assess sensitivity around SPL assumptions, we used a lower bound low SPL noise scenario (scenario 3g, Table 1) estimate (using a converted relationship developed by Houghton et al. (2012) using DTAG data), where Noise Level = 104.8 + 5 * log10(Vessel Count). For an upper bound high SPL noise scenario (scenario 3h, Table 1) estimate, we added the maximum difference (8.3 dB) when integrating the power spectral densities to the Holt et al. (2009) data (Noise level = 111.79 + 6.512 * log10 (Vessel Count); Appendix 2).

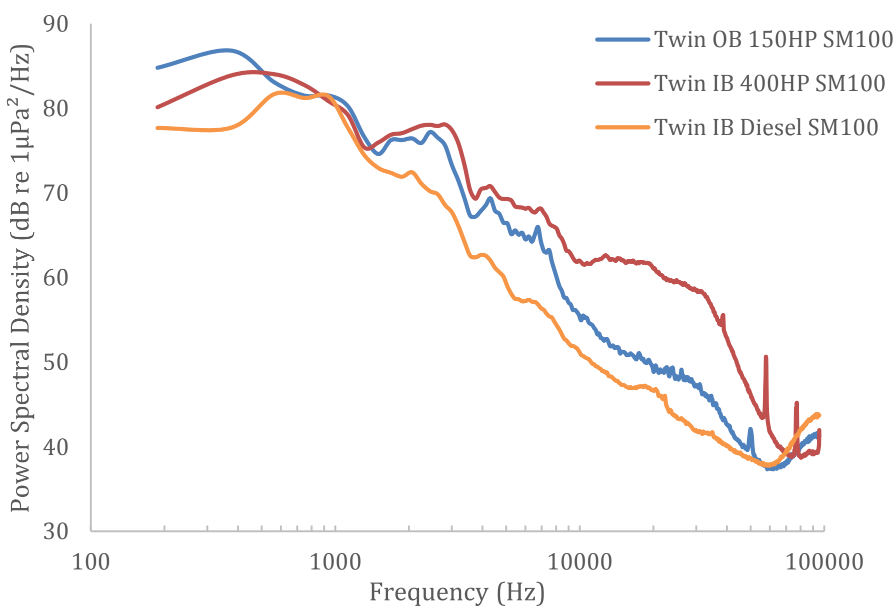

Figure 7 Power spectral density plots of the Hunt (2007) data for three different commercial whale watch boats. OB = outboard motor. IB = inboard motor. HP = horse power. SM = slow motoring (6 – 8 knots). 100 = range in meters between the slow motoring boat and the recording hydrophone.

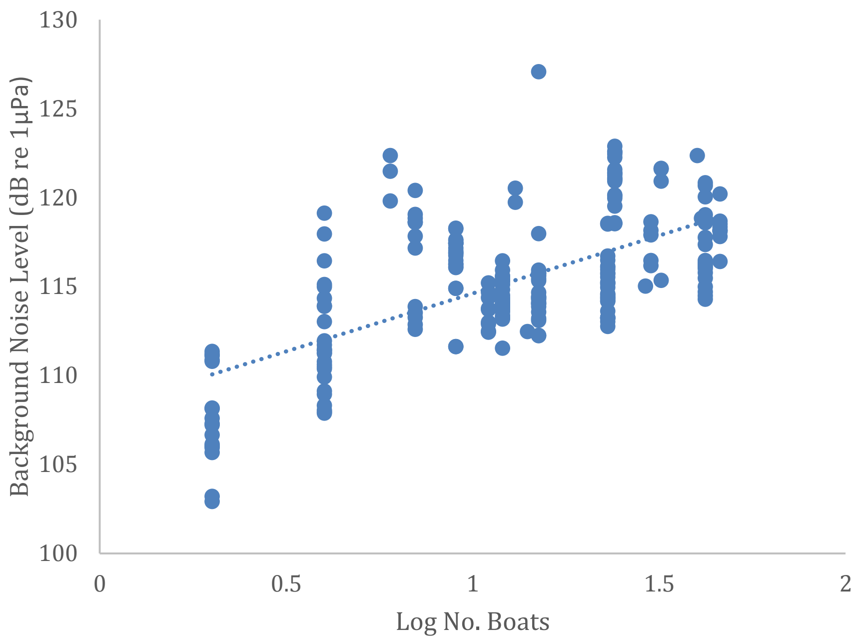

Figure 8 Linear regression of the log number of boats and background noise levels from Holt et al. (2009) with 4.6 dB added to better estimate model compatible noise levels in the frequency range 20 Hz – 96 kHz (see Appendix 2 for further details).

3.1.3.2 High frequency noise levels

Power spectral density at 50 kHz was based on the five slow motoring commercial whale watch boats recorded by Hunt (2007) and Jensen et al. (2009). It is important to note that wide differences in PSD are often apparent between vessels and vessel types travelling at different speeds (e.g., Hildebrand et al. 2006, Jensen et al. 2009), even with relatively small differences in speed. In order to better understand the potential effects of vessel type, speed and whale-boat proximity, as well as the assumption of a maximum range of 250m for echolocation click detection made in our residual click masking analyses, we subsequently undertook a supplementary analysis of data contained within Hildebrand et al. (2006), as well as data used in this study. This supplementary click masking analysis is reported in Appendix 3.

3.2. Outputs of the SRKW-noise exposure model

This section describes the model-predicted Behavioural Responses (BRs) and residual click masking of SRKW for the following three Base noise scenarios:

1) AIS Base: Commercial vessel 2012 baseline noise levels (JASCO 2014) based on large commercial vessels tracked by VTOSS with AIS transmitters only.
2) WW Base: Whale watch (WW) boat noise levels only.
3) AIS + WW Base: Commercial vessel and whale watch boat noise levels combined.

3.2.1 Behavioural Responses

The SRKW-noise exposure model outputs the median number of low and moderate severity BRs per individual whale per day (plus 95% confidence intervals) within the entire study area. Monthly estimates for both dispersed and clustered pods are provided in Figure 9. The number of daily BRs was fewest in May and greatest in July and August reflecting seasonal variation in SRKW monthly occurrence. Numbers of BRs were as expected higher under clustered pod assumptions.

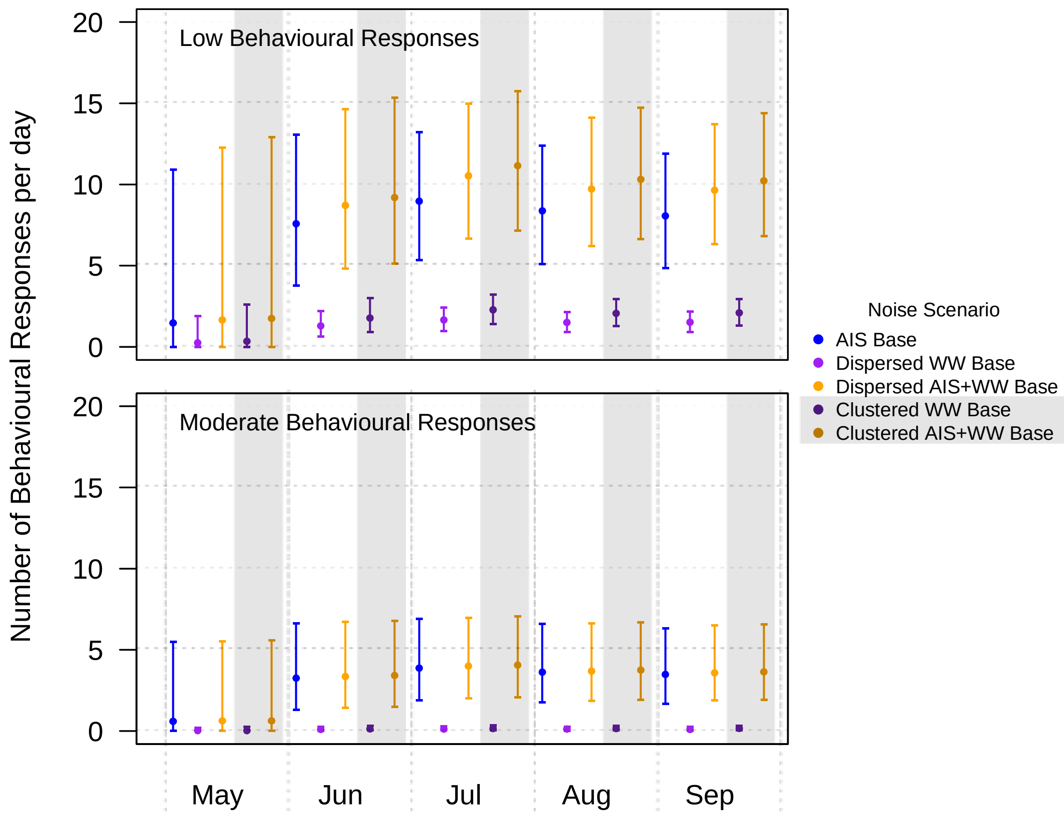

Figure 9 Median numbers of low and moderate severity behavioural responses per individual whale per day (with 95% confidence intervals) across months for three main noise exposure scenarios (with both dispersed and clustered pod assumptions).

Monthly BR data were accumulated for the entire study period (153 days) and also converted into number of BRs per day when SRKW pods were predicted to be in the study area (termed a "whale day"). Overall, whale watch boats alone (WW Base) were predicted to trigger few low severity BRs (median = 194 per whale, or 1.3 per study day) and very few moderate severity BRs (median = 15 per whale or 0.1 per study day) across the May to September study period. The contribution of noise from whale watch boats increased the number of low severity BRs by 16% and moderate severity BRs by 3% over noise generated from only large commercial vessel (AIS Base). When we accumulated the broadband noise from both commercial vessels and whale watch boats (AIS + WW Base), the median number of low severity BRs per whale was 1,261 or 8.2 per day (95% CI total = 961-1818) and for moderate severity BRs was 501 or 3.3 per day (95% CI total = 331-760), with AIS vessels thus contributing 84% and 97% to the total respectively (Table 3). Of these, 58% and 51% occurred respectively in the 10 hr period (9:00 to 19:00) during which whale watch boat presence was modeled. The summed separate totals of AIS Base and WW Base are equal or slightly lower than the combined total (AIS+WW Base) using combined noise layers, highlighting no clear cumulative effect. Estimates of BR per day are systematically 57% higher when apportioned over whale days only (Table 3), reflecting that whales were predicted (averaged across pods) to be in the study area for 97.5 days.

Table 3 Median total number of low (Low BR) and moderate (Mod BR) severity behavioural responses from May to September (plus 95% Confidence Intervals, CI) per SRKW whale for three Base noise exposure scenarios (dispersed pod assumptions). BRs have also been converted into potential lost foraging time metrics (total minutes/hours, hours per day (%) per study day, hours per day (%) per whale day).

Comparative Noise Exposure Metric	AIS Base (Commercial vessels)	WW Base (Only whale watch boats)	AIS + WW Base (Combined)
Low BRs (95% CI)	1083 (800-1580)	194 (144-1283)	1261 (961-1818)
Low BRs per study day (per *whale day*)	7.1 (11.1)	1.3 (2.0)	8.2 (12.9)
Moderate BRs (95% CI)	486 (319-742)	15 (7-26)	501 (331-760)
Moderate BRs per study day (per *whale day*)	3.2 (5.0)	0.1 (0.2)	3.3 (5.1)
Total potential lost foraging minutes (hours) due to low and moderate BRs	17565 (292.75)	1345 (22.42)	18830 (313.83)
Total potential lost foraging hours (percent) due to low and moderate BRs per study day	1.91 (7.96%)	0.15 (0.63%)	2.05 (8.54%)
Total potential lost foraging hours (percent) due to low & moderate BRs per *whale day*	3.00 (12.50%)	0.23 (0.96%)	3.22 (13.42%)

Next, BRs were converted into total potential lost foraging time based on a previous analysis of killer whale DTAG data following a vessel interaction (Section 2.1, SMRU 2014a), which estimated foraging behaviour may be considered impaired for 5 minutes after a low severity BR and 25 minutes after a moderate severity BR. Total hours were converted to percent of day assuming they can feed 24 hours per day (Table 3). BR-related broadband noise levels from whale watch boats increased the commercial vessel base estimates of potential foraging time lost by 7%, with commercial vessels representing up to 93%. This overall estimate of potential foraging time lost is the equivalent of 2.05 hr (8.5%) per study day or 3.22 hr (13.4%) per whale day (Table 3, Figure 9). Overall, two thirds of this potential lost foraging time was as a consequence of moderate severity BRs (as opposed to low BRs), reflecting the five-fold longer estimated residual effect of moderate severity BRs on SRKW.

In our sensitivity analyses, applying a clustered pod scenario (rather than dispersed pod) resulted in a total increase of 72 low severity BRs (37% increase) and 6 moderate severity BRs (40% increase) for whale watch boats, with an increase of 72 (6%) and 14 (3%) for AIS + WW Base combined, the equivalent of increasing potential lost foraging time per whale day from 3.22 hr to 3.38 hr (clustered scenario total=13.9%, see Appendix 2). Sensitivity analyses also highlighted that varying the spatial probability layer of whale watch boats being with whales, or the number of boats assumed to be around each pod had little impact on BRs (1 – 2% and 1% of our AIS + WW Base estimate respectively). In strong contrast, our high whale watch boat noise levels scenario resulted in a 29% increase in potential lost foraging time compared to our Base estimate, while our low whale watch noise levels scenario resulted in a decrease of 9% (see Appendix 2), highlighting underlying whale watch boat noise levels (based on Holt et al. 2009) as the key model assumption.

3.2.2 Residual High Frequency Click Masking

Our 50 kHz (high frequency) click masking threshold is a measure associated with SRKW's ability to hear the echoes of clicks above ambient noise from up to 250m away and was based on an extrapolation of Au et al. (2004). The model firstly outputs the percentage range reduction due to echolocation click masking. For example, a 50% range reduction would mean clicks could be heard up to 125m away. Importantly, predictions of residual click masking were only made if no BRs had occurred within the associated 5 min (for low BRs) or 25 min (for moderate BRs) time increment, as BRs are assumed to also represent periods of complete masking. This results in fewer occasions of residual click masking when BRs occur more often (e.g., in scenarios where commercial vessel noise is included).

Across the whale watch time period 9:00 – 19:00, median percentage range reduction for the WW Base was 5% (95% CI = 0-31%) for dispersed pods and 34% (95% CI = 0-45%) for clustered pods, equivalent to click detectability or masking at 238m and 165m (Figure 9). Range reduction due to commercial vessels over this period was 0% (95% CI = 0-0%), highlighting BRs are instead triggered during higher noise levels associated with transits by these vessel types. For both commercial vessels and whale watch boats combined, range reduction was 12% (95% CI = 0-35%) for dispersed pods and 37% (95% CI = 0-47%) for clustered pods, highlighting a cumulative masking effect of combining the two noise layers and also the importance of our pod separation assumptions (Figure 10). Lower 95% confidence intervals include zero across all scenarios (Figure 10) due to occasions in which the model did not predict SRKW and vessel or boat presence to occur.

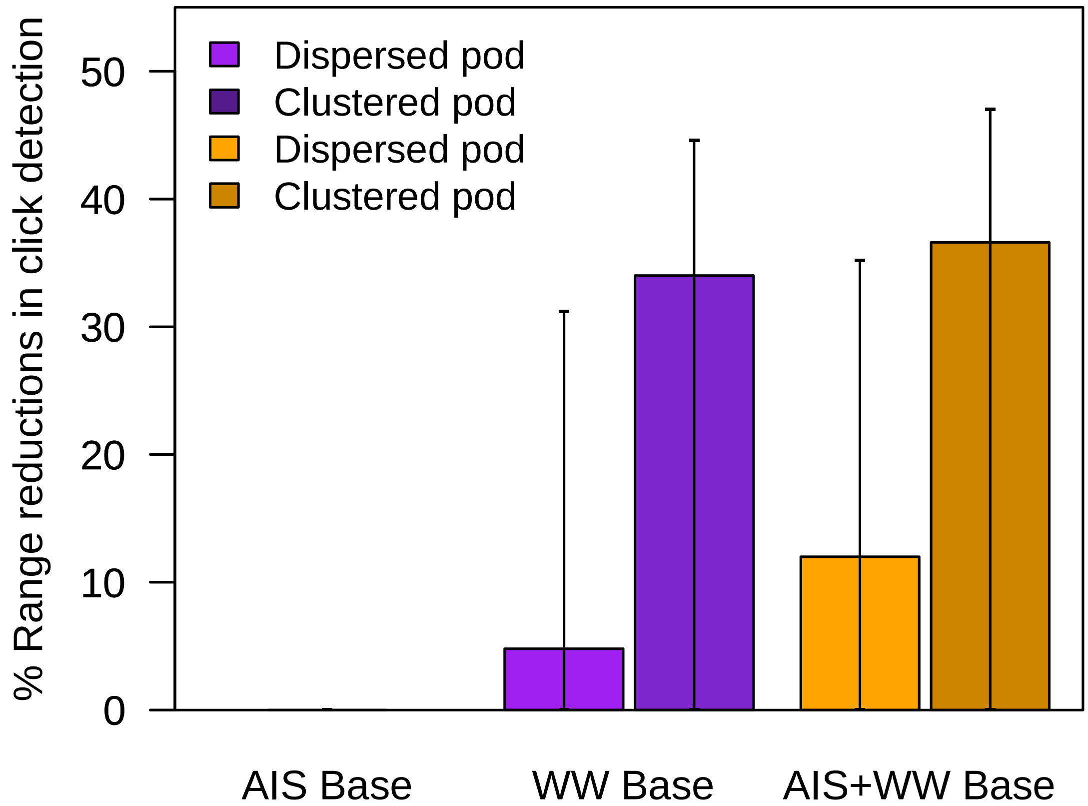

Figure 10 Residual click masking effects for three Base noise exposure scenarios (for both dispersed and clustered pod assumptions) depicting median monthly percent range reduction (95% Confidence Intervals) in click detection (May – September, 9:00 – 19:00).

For the entire 24 hr modelling period, a second comparative metric was calculated to estimate potential lost foraging time each day due to residual click masking and therefore to allow direct comparison with BR-related estimates (Figure 11, Figure 12, Table 4). Median total minutes of residual click masking was derived using 1-D (distance) loss functions, noting that this 1:1 distance translation to potential lost foraging time is relatively simplistic in its assumptions (Appendix 1). A 3-D (volume) loss function was also calculated as per SMRU (2014a, Figure 11, Table 4).

In this study, commercial vessel estimates for residual click masking minutes (1-D) were 0.11 hr per day per whale (equivalent of 0.5% of a whale day, total minutes: 651 (254-1431)). In comparison, whale watch boat only estimates were 1.8 hr per day per whale (7.5% of a whale day, total minutes: 10554 (6527-17130), while all vessels and boats combined estimates were 1.66 hr per day per whale (6.9% of a whale day, total minutes: 9719 (6074-15853)). Clustered pod estimates were 36-38% higher than these dispersed pod values (Figure 11), while use of a 3-D loss function increased residual click masking predictions by 66% (compared to using a 1-D loss function) (Figure 11). The small (8% in the above example) reduction in click masking time when all vessels and boats were combined versus only whale watch boats reflects the fact that residual click masking was not estimated for time periods after a low or moderate severity BR occurred, which occurred more often when commercial vessels were present.

Table 4 Potential lost foraging time (per SRKW) for three Base noise exposure scenarios as a) the median total number of minutes (hours) due to residual click masking effects (1-D and 3-D, dispersed pod assumptions, from May – September, 0.00 – 24:00); b) 1-D masking effects converted to hours and percent per study day and per whale day; c) BRs (Table 3) and 1-D masking effects converted to hours (and percent) per study day and per whale day. Confidence intervals and results using the clustered pod assumption are presented in Figure 11 and Figure 12.

Comparative Noise Exposure Metric	AIS Base (Commercial vessels)	WW Base (Only whale watch boats)	AIS + WW Base (Combined)
Total potential lost foraging minutes (hours) due to 1-D masking	651 (10.9)	10554 (175.9)	9719 (161.9)
Total potential lost foraging minutes (hours) due to 3-D masking	1184 (19.7)	17431 (290.5)	16092 (268.2
Total potential lost foraging hours (percent) due to 1-D masking per study day	0.07 (0.30%)	1.15 (4.79%)	1.06 (4.41%)
Total potential lost foraging hours (percent) due to 1-D masking per *whale day*	0.11 (0.46%)	1.80 (7.52%)	1.66 (6.92%)
Total potential lost foraging hours (percent) due to low & moderate BRs and 1-D masking per study day	1.98 (8.26%)	1.30 (5.42%)	3.11 (12.95%)
Total potential lost foraging hours (percent) due to low & moderate BRs and 1-D masking per *whale day*	3.11 (12.96%)	2.03 (8.48%)	4.88 (20.34%)

When overall potential time lost foraging is accumulated for both BRs and residual click masking (1-D), the model predicts 1.98 hr per study day or 3.11 hr (13%) per whale day for only commercial vessels, 1.30 hr per study day or 2.03hr (8.5%) per whale day for only whale watch boats, and for all vessels and boats combined a total of 3.11 hr per study day or 4.88 hr (20.3%) per whale day. This is an increase of 56.9% above commercial vessel noise effects alone when whale watch boat noise is included (Table 4). In this case, commercial vessels contribute up to 64% (~2/3) of this total potential time lost foraging. Using clustered pod assumptions, the model predicts a higher relative contribution from whale watch boats (11.3% per whale day) resulting in combined vessel and boat total lost foraging time of 22.8% of each whale day. In this case, commercial vessels therefore contribute up to

57% of this total (Figure 12), instead of 64%. Comparative total lost foraging time per whale day for both BRs and 3-D residual click masking are 24.9% (dispersed) and 29.0% (clustered, Figure 11).

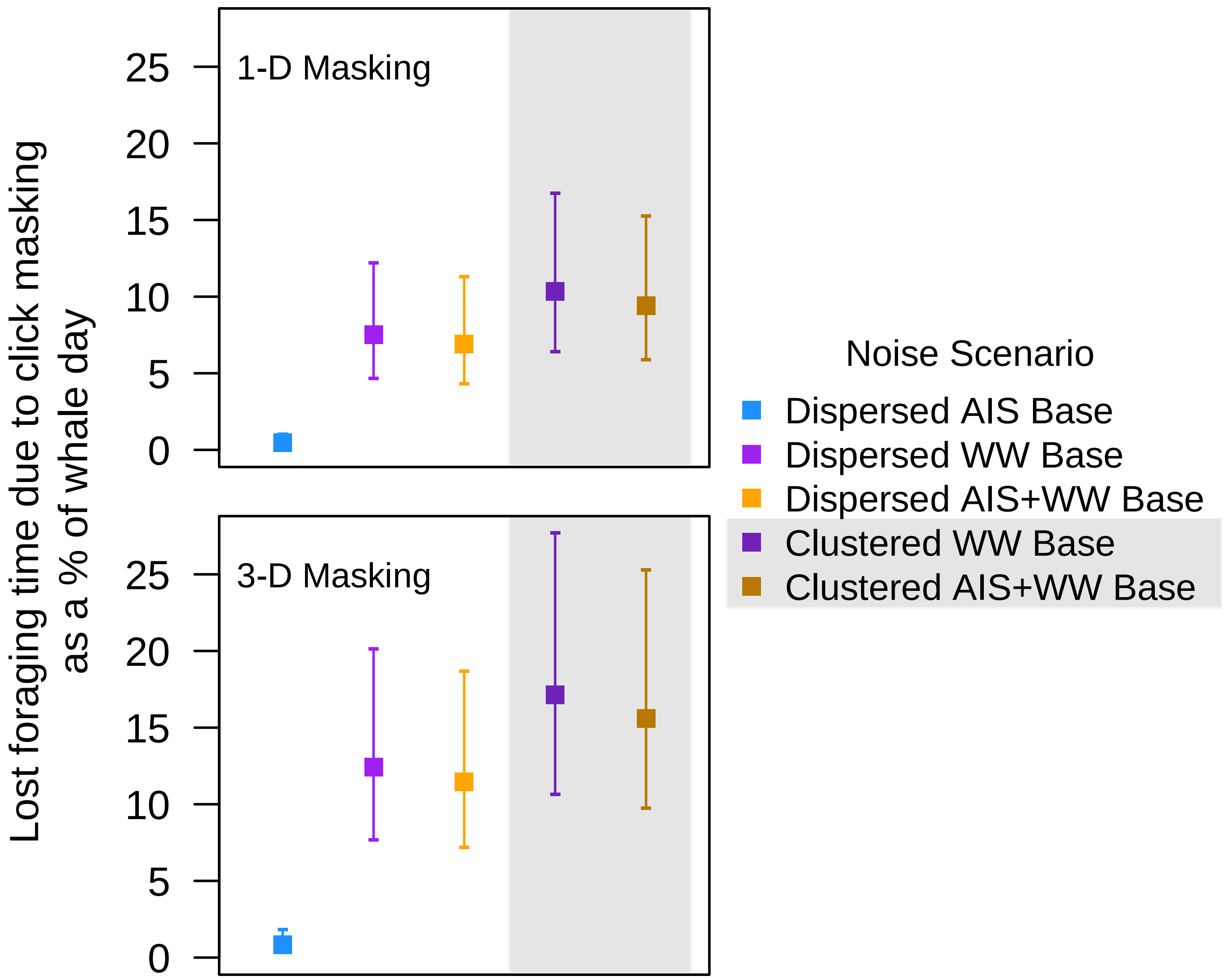

Figure 11 Potential lost foraging time (per SRKW) for three Base noise exposure scenarios as a percent of days (May – September) when SRKW are present (per whale day) due to residual click masking estimated from 1-D and 3-D loss function (with 95% confidence intervals) for both dispersed and clustered pod scenarios (AIS Base – commercial vessel, WW Base – only whale watch boats, AIS + WW Base – combined commercial vessels and whale watch boats).

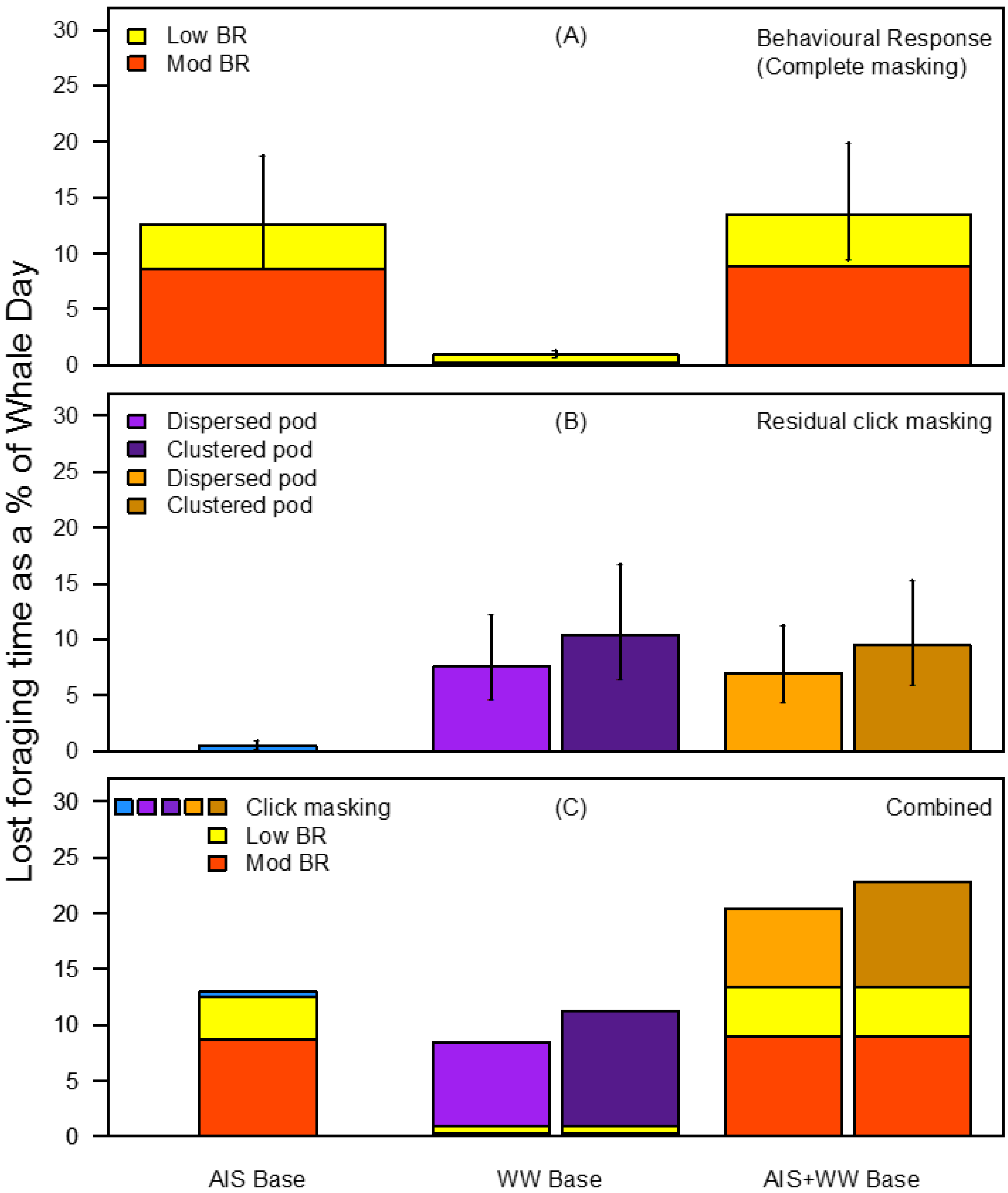

Figure 12 Potential lost foraging time (per SRKW) for three Base noise exposure scenarios as a percent of whale days (May – September, days when SRKW are present) due to (A) only low and moderate severity behavioural responses (BRs) with 95% confidence intervals (B) residual click masking estimated from 1-D loss function with 95% confidence intervals for both dispersed and clustered pod scenarios (C) combined BRs and residual click masking (AIS Base – commercial vessel, WW Base – only whale watch boats, AIS + WW Base – combined commercial vessels and whale watch boats).

4. Summary and conclusions

Underwater noise may be impacting the population recovery of endangered Southern Resident Killer Whales (SRKW). This study used an SRKW-noise exposure model to compare noise effects from large (VTOSS tracked and AIS-enabled) commercial vessels with whale watch boats during summer (May-September) within the core of their critical habitat in the Salish Sea (Figure 2). The study area and time period selected aimed to capture the majority of SRKW whale watching noise effects. Using fine-scale SRKW habitat use and noise layers to predict broadband sound pressure levels and power spectral density (PSD) at 50 kHz, the noise exposure model calculated the number of low and moderate severity BRs using SRKW-specific dose-response relationships and, if no BRs were triggered, the extent of residual echolocation click masking within the high frequency band of 50 kHz. BRs were considered to temporarily inhibit the ability of SRKWs to forage either via strong masking effects (either of communication calls, whistles or echolocation clicks) that prevent effective foraging or by switches in behavioural state (e.g., changing from foraging to travelling, e.g., Lusseau et al. 2009).

Large commercial vessel noise in the study area was predicted to trigger 7.1 low severity BRs per day per whale and 3.2 moderate severity BRs per day per whale. Compared to commercial vessel noise effects, the addition of whale watch boat noise resulted in an overall 16% increase in the number of low severity BRs (from 1083 to 1261 overall) and a 3% increase in the number of moderate severity BRs (from 486 to 501 overall, Table 2). Effects were mainly predicted from June through September, reflecting SRKW monthly pod presence. Broadband noise levels from commercial vessels were therefore estimated to contribute up to 93% of overall BR-related potential lost foraging time, with whale watch boats contributing the remaining 7% (Figure 12, panel (A)) during their mean estimate of 6.1 hr with each whale per day. Lower broadband noise levels of slow moving whale watch boats had low probabilities of exceeding BR thresholds (averaging 2 low and 0.2 moderate severity BRs per whale day or 0.23 hr of potential lost foraging time), while large commercial vessels regularly exceed the BR dose-response thresholds (averaging 11 low and 5 moderate severity BRs per whale day or 3 hr). Overall, combined vessel and boat noise lost foraging time per whale due to BRs alone was estimated as a median 3.2-3.4 hr per day, per whale, when whales were present in the study area (representing the equivalent of 13.4-13.9% of each whale day, Figure 12, panel (C)). Sensitivity analysis of with whale probabilities, boat noise, and boat numbers around BR-related noise effects ranged between approximately +30% to -10%, highlighting good confidence in predictions that large commercial vessel noise dominates the total number of BRs predicted, while also highlighting the need for better whale watch boat noise estimates or ideally 'at whale' received noise level estimates. It is noted that noise from some large commercial whale watch boats are captured within the commercial vessel category (JASCO 2014), though the relevant 'passenger vessel' sub-category contribute a small (2%) proportion of the total regional noise budget (JASCO 2016).

Combined commercial vessel and whale watch boat residual click masking effects resulted in a median 50 kHz click detection range reduction of 12-37% (Figure 10) depending on pod separation assumptions. This resulted in a 1-D model predicted accumulation of an additional 1.7-2.3 hr of potential lost foraging time, which was strongly dominated by high frequency noise predicted from slow moving (2.5-8 knot) whale watch boats (Figure 11 and Figure 12). Median echolocation click detection range reduction was estimated as 0% for commercial vessels alone and 5-34% for whale watch boats alone, highlighting a cumulative masking effect for combined commercial vessel and whale watch boat results.

Commercial vessel noise spectra indicate that energy is also emitted above the model's 50 kHz click masking threshold (Veirs et al. 2016), but our findings highlight that when large commercial vessels such as container ships are in close proximity to SRKW (a few hundred metres depending on source level) moderate severity BR thresholds are frequently triggered, with the chance of low severity BRs beyond a few kilometers, and so for these instances, click masking is subsequently not calculated further in the model. Then, as commercial vessels transit away from SRKW, power spectral density levels at 50 kHz are typically reduced, by both transmission loss and high frequency absorption, to values below the 50 kHz click masking threshold. In contrast, whale watch boats are in close proximity to whales for long time periods each day, but when assumed to be moving slowly (and mostly at the whale proximity distances of more than 200m), they do not regularly trigger BR thresholds, but instead trigger the 50 kHz click masking thresholds.

The estimation of masking effects on SRKW is complex (e.g., Erbe 2015). In order to back-calculate received levels, we made assumptions about whale watch boat type, speed and proximity, how individual whales were separated, and defined a threshold for 50 kHz click detection at 250 m. As a consequence, uncertainty levels should be considered relatively high. The accuracy of the masking model results could be improved through the use of suitable received noise levels collected from tagged whales and through the development of more sophisticated models (Erbe 2015) that incorporate a range of different frequencies and fine-scale animal and boat movements and do not rely on 1:1 loss function translations from effect distance to time affected (see also Appendix 3).

Overall, SRKW-noise exposure model predictions of potential lost foraging time (BRs and residual click masking) totaled 20.3% of each whale day (4.9 hr) for dispersed pods, with up to 64% of this time due to noise from large commercial vessels (Figure 12), highlighting mitigation measures for both commercial vessel and whale watch boats should be considered. Notably, the predicted noise effects on SRKW were different, with larger vessels causing most of the BRs and whale watch boats most of the residual click masking. Comparative values for precautionary clustered pod assumptions were 22.8% of each whale day (5.5 hr), with up to 57% contributed by commercial vessels. Overall, potential lost foraging time distributed across all study days (rather than whale days) was the equivalent of 13-14.5% of each day or 3.1-3.5 hr per day.

This study provided a starting point to assess the cumulative noise effects of both large commercial vessels and whale watch boats, noting the potential disturbance effects of the physical presence of boats were not included. While occupying their nearshore core areas during summer and fall, resident killer whales spend about 40-67% of their time foraging, and spend significant time resting, socializing and travelling (Ford 2006). Because BRs and masking can also disrupt other activities, our metric termed 'potential lost foraging time' might alternatively be described as 'time associated with behavioural disruption and sound masking'.

Finally, in trying to assess the overall effects of underwater noise from vessels and boats, it is important to recognise that this study covered a specific area and a specific time of year, representing approximately 23 – 33% of each pod's time spent annually (SMRU et al. 2014a). This report is therefore not a complete estimate of all noise effects experienced by SRKW, nor the annual contribution of commercial vessel traffic compared to whale watch boats. Nevertheless, this analysis has indicated that together, noise from commercial vessels and whale watch boats has the potential (in different ways) to disrupt SRKW as much as ~5 hours or 20% of each (whale) day that they are found in the study area, most of which is designated as critical habitat in Canada and the United States of America.

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Appendix

Appendix 1: Detailed methodology to obtain number of behavioural responses and degree of masking for commercial vessels

The original SRKW-noise exposure model developed by SMRU et al. (2014a) was designed to evaluate the potential effects of underwater noise from future anticipated increases in commercial vessel traffic on SRKW behaviour over one year. Other vessels such as whale watch boats spend a large proportion of their time in proximity to SRKW and their noise contribution was not included as part of the previous model because they generally do not have AIS receivers and therefore, their exact movements are not known. To assess the effects of the added noise contribution of whale watch boats to SRKW behavioural responses and click masking, this study used a five-month subset of the data used in SMRU (2014a) for May through September and added the predicted underwater noise generated by whale watch boats. The following is a description of how the model was implemented in 5-minute increments for each day across the 153 days included in this noise effects study.

For each five-minute time increment, low and moderate severity behavioural responses were assigned to SRKW within each pod based on SRKW-specific dose-response curves (SMRU 2014b). Potential occurrence of masking of echolocation clicks (when behavioural responses were not predicted) was also estimated using high frequency (50 kHz) noise levels based on a masking model developed by Au et al. (2004). The model was repeated 500 times to incorporate uncertainty around behavioural response to noise. The commercial vessel summer noise exposure estimates were built on one busy 24-hour period of VTOSS-AIS data collected on Friday, July 16, 2010. More details on the underwater noise modelling can be found in JASCO (2014), but small recreational and fishing vessels were not included.

In the original SRKW-noise exposure model, underwater noise level estimates from commercial vessel (JASCO 2014) were combined with 10 years of SRKW relative density data from 2001 through 2011 (Hemmera 2014). This required data inputs on noise levels (broadband SPL and PSD noise levels at 50 kHz), SRKW relative density and predictions linking noise levels with behavioural responses and masking (Table A-1). For this study, the SRKW-noise exposure model was completed for three Base scenarios 1) commercial vessel noise only, 2) whale watch boat noise only and 3) whale watch boat noise in combination with commercial vessel noise.

Table A - 1 Summary of inputs to the SRKW-noise exposure model

Input	Source	Brief Overview
Broadband Noise Levels	Regional Commercial Vessel Traffic Noise Modelling Study (JASCO 2014)	At 5-minute resolution, the maximum predicted broadband sound pressure levels (SPL) was selected from JASCO's 1-minute increment predictions for each of the 200m grid cells. Broadband underwater noise estimates for commercial vessels were obtained for a day in summer with complete coverage over time (1,440 minutes converted to 288 5-minute increments)
50 kHz Noise Levels	Regional Commercial Vessel Traffic Noise Modelling Study (JASCO 2014)	PSD noise levels at 50 kHz in 1-minute increments for each of the 200m grid cells. 50 kHz underwater noise estimates for larger vessels were obtained for a day in summer with complete coverage over time (1,440 minutes converted to 288 5-minute increments).
SRKW Effort Corrected Sightings	Southern Resident Killer Whale Network Sighting Synthesis Study (Hemmera 2014)	Effort corrected SRKW sighting data transformed into probability estimates of relative density. Figure A-1
Behavioural Dose-Response Curves	Determination of Behavioural Effect Noise Thresholds for Southern Resident Killer Whales Study (SMRU 2014b)	Dose-response curves (with 95% CI) that predicted the probability of behavioural responses from SRKW to a given received sound level. Figure A-2
Click Masking thresholds	Potential for HF Masking of Southern Resident Killer Whale Calls and Echolocation Clicks due to Underwater Noise (SMRU 2014a)	An acoustic masking model that predicted when HF masking of SRKW echolocation clicks were likely to occur (in cases where no behavioural response had been predicted) and the duration of the occurrence. Figure A-3

The number of low and moderate severity behavioural responses (BR) were predicted based on SRKW-specific dose-response relationships, with median (50^{th} percentile) broadband (20 Hz – 96 kHz) received noise level threshold values of 129 and 137 dB re 1 μPa for low sand moderate severity respectively (SMRU 2014b) (Figure A-2). Relationships were developed using resident killer whale data from three sources; digital acoustic recording tags (DTAG), a theodolite whale-vessel tracking study (Williams et al. 2014) and a passive acoustic monitoring study. A low severity response (e.g., minor changes in respiration rates, locomotion speed, direction or deviation) was estimated (using analysis of DTAG data) to result in 5 minutes of lost foraging, while a moderate severity response (moderate to extensive changes in locomotion speed, direction and/or dive profile, moderate or prolonged cessation of vocal activity, potential avoidance of area) was estimated to result in 25 minutes of lost foraging. High-severity behavioural responses were not predicted to occur as a result of underwater noise produced by commercial vessel traffic, as SRKW were considered highly unlikely to approach to within a few metres of the vessels' propellers, where received levels may exceed 180 dB re 1 μPa.

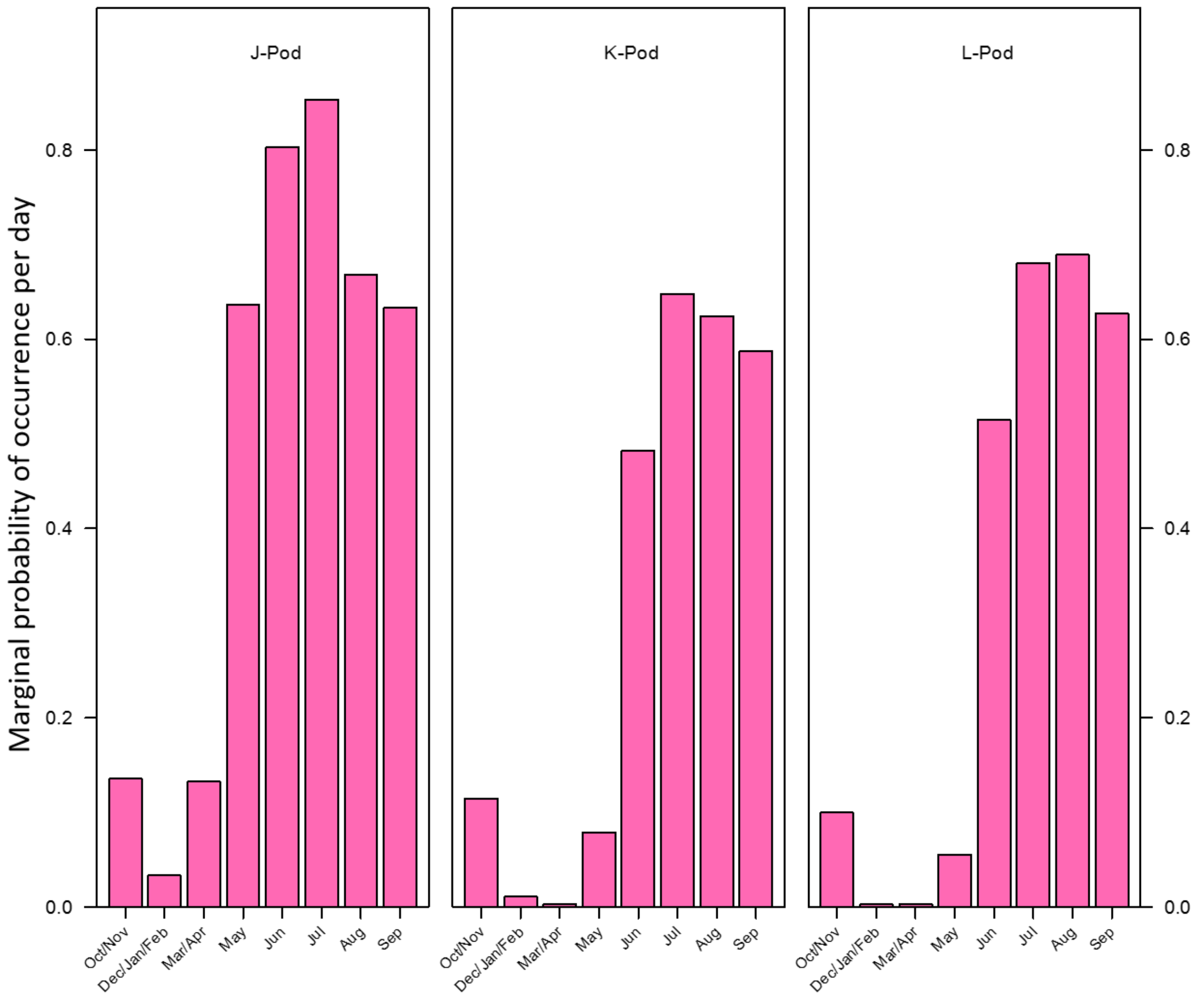


Figure A - 1 Monthly marginal probabilities of occurrence of SRKW pods J, K, and L.

Methods for estimating the masking of echolocation clicks in the current study were developed by Au et al. (2004). This simple model, with masking estimated at a single frequency, was chosen because so much is unknown about masking of echolocation clicks. The 50 kHz frequency was used by Au et al. (2004) for their masking model because it is near the centre of the frequency distribution of often bimodal killer whale echolocation clicks. The masking model took into account the amplitude of killer whale clicks, transmission loss, how much of the click echoes off preferred salmon prey (known as the target strength), and killer whale hearing. The appropriate 1/3 octave band was extracted from JASCO (2014) and converted to 50 kHz PSD levels, and compared to the echo level at successively larger distances from the modelled killer whale location. The distance at which the 50 kHz PSD noise level is no longer less than the echo level is considered the masking distance. Comparable PSD data from Beam Reach were available for three slow motoring whale watch boats.

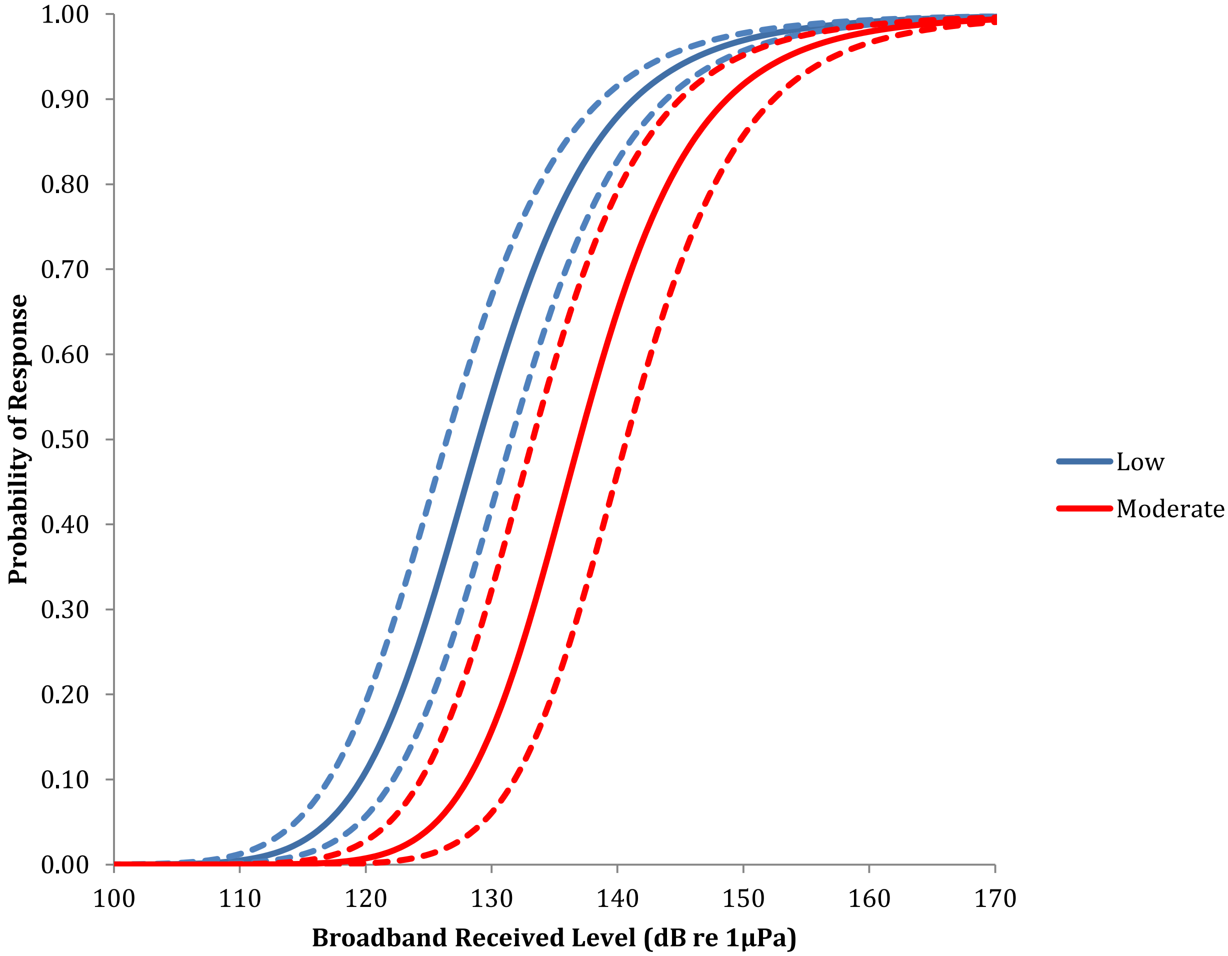


Figure A - 2 Low severity and moderate severity behavioural dose-response curves developed for SRKW with corresponding 95% confidence intervals (dotted lines) from SMRU et al. (2014a)

Since there is uncertainty in whether to measure changes in echolocation by distance, area, or volume, masking was calculated as a proportional loss function in 1, 2, and 3-D listening space. The maximum echo distance was inferred from data collected from a hydrophone located at Lime Kiln State Park, Washington State and was set for 1, 2, and 3-D at a distance of 250 m, area of 7,009 m^2, and volume of 210,885 m^3, respectively. The area and volume were based on the distance of 250 m and a half power beam width angle of 13º (this is the angle at which the echolocation click amplitude drops by 3 dB). This angle was estimated using a formula developed by Au et al. (1999) which uses the diameter of the sound source and its frequency to estimate the beam width angle. An example of proportion of lost foraging time, as a result of masking, using these three metrics is presented in Figure A-3, which provides an example where masking starts at a distance of 150 m. Under this scenario, the estimated percent lost foraging time would be 40, 64, and 78% for 1, 2, and 3-D metrics, respectively.

Residual HF masking was only assumed to occur if an SRKW individual had not already experienced a low severity or moderate severity behavioural response in that 5-minute or 25-minute period respectively, as these behaviour changes were assumed to cause a loss of foraging opportunity (and/or the equivalent to complete masking).

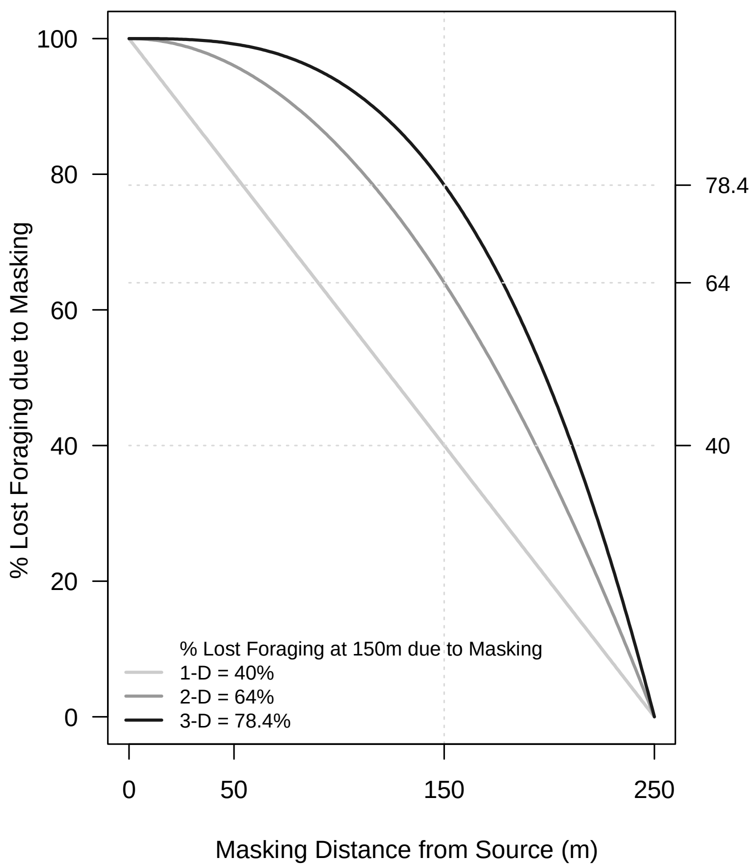


Figure A - 3 Loss function of foraging time (% lost foraging) for residual high frequency (50 kHz) click masking as a function of distance from source (the SRKW individual).

The underlying SRKW-noise exposure model was implemented using the following steps:

Step 1: For a given day, up to three pods totalling up to 80 SRKW were randomly distributed across the study area (SRKW population was estimated at 80 individuals in the original model and this was kept consistent). Pods were selected as present (yes/no) each day based on a Bernoulli trial similar to the flipping of a biased coin where the bias is the probability of occurrence of pod J, K, and L for the month in which that day occurs. If a pod was selected for the given day, the location of the pod 'centroid' was proportional to the relative measure of occurrence derived from the kernel-smoothed SRKW relative density (Hemmera 2014). Occurrence of each pod was assumed independent, but if more than one pod was randomly chosen, the location of the pods was based on the probability of seasonal association. The probability of association between pods was implemented through the use of a copula function that linked the marginal distributions of pods J, K, and L. A copula is a function that joins several outcome variables described by a multivariate distribution to their 1-D marginal distribution functions. Pods were located once for a 24-hour period, so that location was constant over all time windows during the 24-hour period, but noting that over 500 simulations, pods were moved on each simulation.

Step 2: For each of the (up to three) centroid locations, 'killer whales' associated with each pod were spatially distributed in a density-weighted kernel of 4.5 km, which is the same kernel bandwidth used with the sightings data for the kernel-smoothed density. The 4.5 km radius was selected to allow variability in the sound exposure and behavioural response of whales within the same pod, and approximate the potential spatial spread of SRKWs in the wild.

For each day, and for each pod on the surface, the simulation samples from a geometric distribution with probability equal to the pods centroid location (i.e., the product of the relative summer SRKW density and the relative whale watch effort, modified by the monthly index as described in Section 3.1.1). The geometric distribution was chosen as it is a discrete sampling distribution that describes the number of Bernoulli trials required until the first success is observed (or in our model, the number of 5-minute increments until a pod of whales has at least 1 whale watch boat with it). The model assumed each pod is independent with its own probability of being found informed by its location. Once the whales associated with a centroid location have been found, all whales in that pod were assumed to be with at least one whale watch boat.

Step 3: For one 5-minute increment, called time window (t), and each whale present, the model determined the received SL from the broadband and 50 kHz noise datasets. If whale watch boats have not yet found the pod, the simulation continues for subsequent 5-minute increments.

If the model indicated that the whale watch fleet has found the pod, the model then randomly sampled from the empirical distribution of boat numbers described by the 66 days of Soundwatch boat counts, matched to the appropriate day of the year, and time of day. Once the simulated number of boats with the pod is known, we used the modified Holt et al. (2009) regression equation to relate the boat count to received level of noise for each SRKW in the pod. Uncertainty was incorporated by sampling randomly from the residuals and adding this uncertainty to the Holt prediction. This uncertainty was added to incorporate measurement error as well as boat-to-boat variability in this relationship. We then added in the broadband and 50 kHz noise levels from the whale watch boats to the commercial vessel noise levels for the time window (t).

Step 4: For time window (t) and each whale present, the probability of low and moderate severity response to the broadband measure of noise at that location was determined according to the dose response curve. This was calculated with two Bernoulli random variables that were generated with probability of low and moderate behavioural response proportional to the dose-response curve, with uncertainty generated according to the confidence intervals (CI) around those curves (SMRU 2014a; reproduced in Figure A-2). This procedure generated either a 0 (corresponding to no response) or 1 (corresponding to a response) for low and moderate severity responses, and resulted in a record for that time window of whether each whale exhibited a low or moderate behavioural response. If a whale exhibited both a low and moderate response, only the moderate response was counted (to avoid double counting).

Step 5: For time window (t) and each whale present, the 1-, 2-, and 3-D loss functions shown in Figure A-3 were used to determine the horizontal distance at which masking occurs for each whale on the surface. The 1-D proportion of 250 m lost due to masking (% range reduction) was calculated and reported. It was also translated to proportion of minutes lost to foraging for each dimension, with 1-D and 3-D models reported from this study, to capture the upper and lower bounds. For example, if there was a 50% loss in foraging distance, then there was a loss of 2.5 minutes of foraging (i.e., 50% of the 5-minute time increment). If the whale already had a behavioural response in that period, then no masking was calculated (to avoid double counting).

When Steps 4 and 5 are complete, the model provides for that time window (t) and each of (up to) 80 whales as follows:

- 0 (absence) or 1 (presence) of the whale watch community with pod J, K and L
- The number of whale watch boats with the pod
- The broadband and 50 kHz noise levels generated from the whale watch community- 0 or 1 for low severity behavioural response if moderate severity = 0;
- 0 or 1 for moderate severity behavioural response;
- Proportion of time lost due to HF click masking (in 1, 2 and 3-D) if both severity responses = 0; and
- Foraging range reduction due to 1-D HF click masking.

Step 6: Simulation for each 5-minute increment was repeated in all 288 increments for a 24-hour period in summer. At the end of each 'day' the model provides 288 measures of the outputs in step 5, which are summarised for that day and passed to the outcome array as follows:

- Number (and minutes) of low severity behavioural responses per day;
- Number (and minutes) of moderate severity behavioural responses per day;
- Number of any **additional** minutes of foraging time lost due to HF masking (i.e., periods of masking when no behavioural response was predicted to have occurred) over the 24-hour "day".
- Foraging range reduction was summarized for the 120 5-minute time increments that occur between 09:00 and 17:00 when the whale watch fleet is assumed active.

Step 7: The model was repeated for all 153 days in the five summer months. Probability of pod occurrences changed with each 'month' according to Figure A-1

Step 8: The model was repeated for 500 iterations to get a distribution of all simulation outcomes.

The simulation was repeated for the whale watch boats and commercial vessels combined scenario.

Appendix 2. Description of Base model input assumptions and sensitivity scenario assumptions.

Model sensitivity was explored by varying key Base model assumptions for generating whale watch boat noise (see Tables 1 and A-2). A description of 11 different scenarios undertaken is found in Table 1. Behavioural response model sensitivity to broadband noise levels, number of boats with whales, probability of whale watch boats with whales, as well as pod separation and boat proximity assumptions were assessed.

Table A - 2 Description of whale watch related Base assumptions and upper and lower bound assumptions used in subsequent sensitivity analyses.

Model sensitivity descriptor	Base estimate	Lower bound sensitivity estimate	Upper bound sensitivity estimate
Broadband noise levels for BR analyses	Data taken from Holt et al. (2009), and up-weighted 4.6 dB (mean conversion factor value) for broadband compatibility based on Hunt (2007) (see Figure 5: Noise Level = 108.09 + 6.512 * log10 (Vessel Count).	Low noise: Data taken from Houghton et al. (2012) American Cetacean Society SRKW DTAG presentation regression up-weighted 4.6 dB for broadband compatibility based on Hunt (2007) (i.e., Noise Level = 104.8 + 5 * log10 (Vessel Count)). Note lesser slope from data compared to Holt et al. (2009). Regression data accessed from https://julianahoughton.files.wordpress.com/2012/05/houghton_et_al_acsposter_final.pdf	High noise: Data taken from Holt et al. (2009), and up-weighted 8.3 dB (maximum conversion factor value) for broadband compatibility based on Hunt (2007) (i.e., Noise level = 111.79 + 6.512 * log10 (Vessel Count)).
Number of boats with whales	Varied by time of day and month based on Soundwatch (2012) data and independently assigned to each independent pod groupings.	Low boat: Varied by time of day and month based on Soundwatch (2012) data but the number of boats was spread between any pod grouping present in model area.	No estimate produced as best available data were considered a near maximum.
Probability of whale watch boats with whales	Multiplication of relative whale watch effort and relative SRKW density, then normalized from 0 to 1 (See Figure 4). Also modified by monthly modifier (see Table 1).	Low effort (probability): 0.5 times the base estimate.	High effort (probability): 2 times the base estimate.

The SRKW-noise exposure simulation model was run for each scenario 500 times to provide the median number per day (plus 95% confidence intervals) of low and moderate severity BRs across months per individual SRKW (Figure A-4), as well as median total numbers of BRs per SRKW across all five months including 95% confidence intervals (Table A-3). Table A-4 converts these BRs into potential lost foraging time.

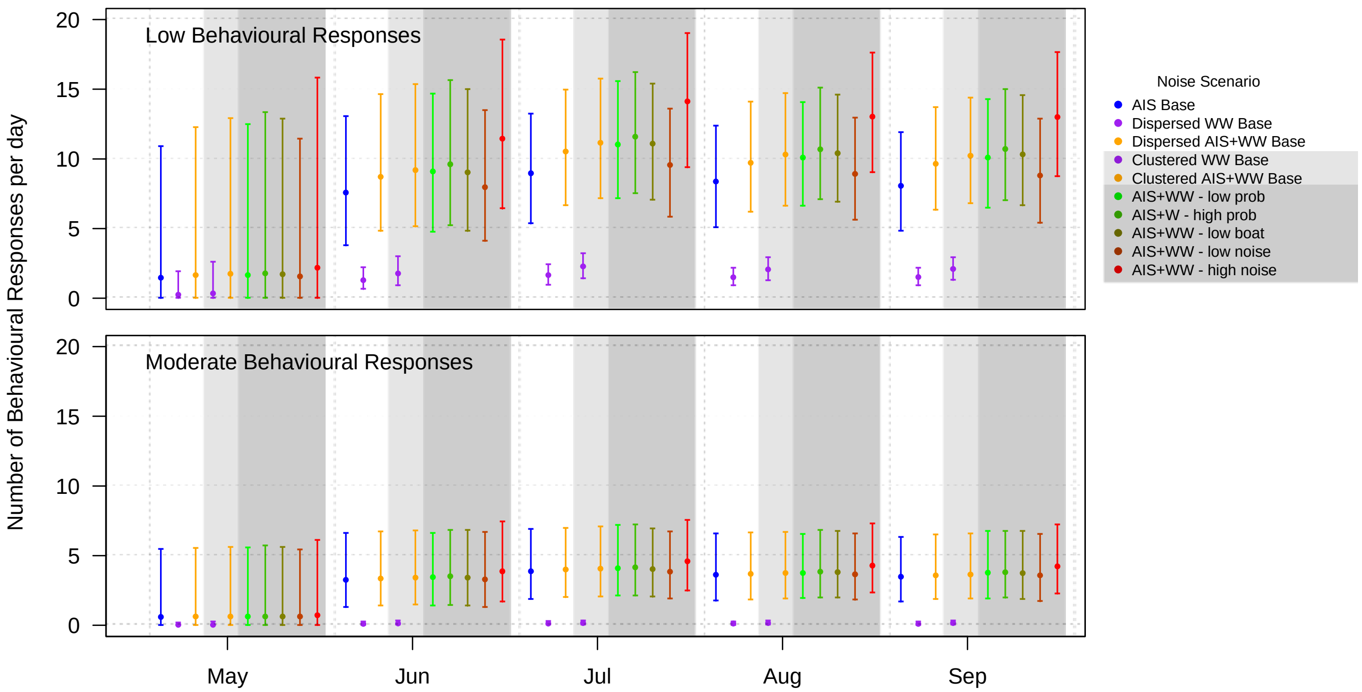


Figure A - 4 Median number of low and moderate severity behavioural responses per day (with 95% confidence intervals) across months per individual SRKW for each noise exposure scenario.

Table A - 3 Median total number of low (Low BRs) and moderate severity behavioural responses (Mod. BRs) for May to September per individual for 11 noise exposure scenario with lower and upper 95% confidence intervals (CI) based on 500 simulations. Scenarios 2a, 3a, 2b and 3b use whale-boat proximity based on Giles (2014), while Scenarios 3c to 3h all use uniform whale boat proximity assumptions. Dispersed and Clustered describe assumptions about the separation of individuals within a pod.

Noise exposure scenario name and #	Number of Low BRs	Lower 95% CI	Upper 95% CI	Number of Mod. BRs	Lower 95% CI	Upper 95% CI
1) AIS Base	1083	800	1580	486	319	743
2a) WW Base (Dispersed)	194	144	283	15	7	26
3a) AIS+WW Base (Dispersed)	1261	961	1818	501	331	760
2b) WW Base (Clustered)	266	201	386	11	21	34
3b) AIS+WW Base (Clustered)	1333	1023	1917	509	337	771
3c) AIS+WW (uniform)	1344	1043	1937	515	346	781
3d) AIS+WW (uniform) – low probability	1302	1005	1886	509	344	776
3e) AIS+WW (uniform) – high probability	1380	1065	2001	520	346	794
3f) AIS+WW (uniform) – low boat	1326	1029	1914	512	344	778
3g) AIS+WW (uniform) – low SPL noise	1154	876	1675	491	326	749
3h) AIS+WW (uniform) – high SPL noise	1667	1320	2388	573	398	859

Table A - 4 Potential lost foraging time due to low and moderate severity behavioural responses (BRs) May to September per whale for 11 noise exposure scenarios. Included is the ratio of each scenario compared to AIS Base and total hours as a percent per day of both total study days (n=153) and whale days (n=97.5). Scenarios 2a, 3a, 2b and 3b use whale-boat proximity based on Giles (2014), while Scenarios 3c to 3h all use uniform whale boat proximity assumptions. Dispersed and Clustered describe assumptions about the separation of individuals within a pod.

Noise exposure scenario name and #	Potential lost foraging minutes due to low BRs	Potential lost foraging minutes due to mod. BRs	Total potential lost foraging hours due to low & mod. BRs	Ratio of potential lost foraging hours compared to AIS Base	Total hours as a percent per day across study days	Total hours as a percent per day across whale days
1) AIS Base	5415	12150	292.8	1.00	1.91	3.07
2a) WW Base (Dispersed)	970	375	22.4	0.08	0.15	0.23
3a) AIS+WW Base (Dispersed)	6305	12525	313.8	1.07	2.05	3.29
2b) WW Base (Clustered)	1330	275	26.8	0.09	0.17	0.28
3b) AIS+WW Base (Clustered)	6665	12725	323.2	1.10	2.11	3.38
3c) AIS+WW (uniform)	6720	12875	326.6	1.12	2.13	3.42
3d) AIS+WW (uniform) – low probability	6510	12725	320.6	1.10	2.10	3.36
3e) AIS+WW (uniform) – high probability	6900	13000	331.7	1.13	2.17	3.47
3f) AIS+WW (uniform) – low boat	6630	12800	323.8	1.11	2.12	3.39
3g) AIS+WW (uniform) – low SPL noise	5770	12275	300.8	1.03	1.97	3.15
3h) AIS+WW (uniform) – high SPL noise	8335	14325	377.7	1.29	2.47	3.95

Appendix 3. Supplementary analysis of vessel and boat noise on click masking

Our masking model follows Au et al. (2004) to estimate the maximum functional range of echolocation clicks used by SRKW. In this supplementary analysis, we compared PSD data from Hunt (2007), Hildebrand et al. (2006) and Jensen et al. (2009). We plotted these data, at various distances between whale and vessel and compared them with our precautionary 250m masking threshold and also the 100m threshold reported by Au et al. (2004). Hildebrand et al. (2006) reported source PSD levels for four whale watch boats cruising at >10 knots and a container ship moving at 21 knots. The 50 kHz PSD levels were estimated from their plots. Jensen et al. (2009) reported 1/3 octave received levels of two whale watch boats at 10m while moving at 2.5, 5 and 10 knots. The highest reported 1/3 octave level was centered at 40 kHz. We converted this to an average PSD level and assumed this would be representative of the PSD levels at 50 kHz, noting that at 10 knots, PSD for both vessels were the same. Assuming spherical spreading and an absorption of 15 dB per km, we then estimated the 50 kHz PSD levels for all vessels and plotted them together next to our echolocation click masking thresholds (Figure A-5 and A-6).

The most evident (and expected) patterns are that the slower the boats are moving and the farther they are from whales, the lower their 50 kHz PSD levels. Boats moving at 2.5 knots, even 100m from a whale, would not have decreased the whale's echolocation click range less than our 250m functional echolocation range threshold. If we had assumed the functional echolocation range of SRKW was 100m, then average PSD levels of boats reported by Hunt (2009) or Jensen et al. (2009) would be above threshold if modelled individually. At a range of 800m between whale and vessel, only the loudest Hildebrand et al. (2006) boat and the single container ship would produce masking using our assumption of 250m functional echolocation range. If we had assumed a 100m functional echolocation range, none of the vessels used in this study would have caused masking and as such, our approach was considered conservative for 50 kHz clicks. However, based on these results, a more detailed assessment of click masking at lower frequencies (e.g., 20 kHz) and using a wider range of boat types and representative speeds is recommended for future work, as well as additional estimates of functional echolocation range (i.e., the actual range at which SRKW can detect salmon).

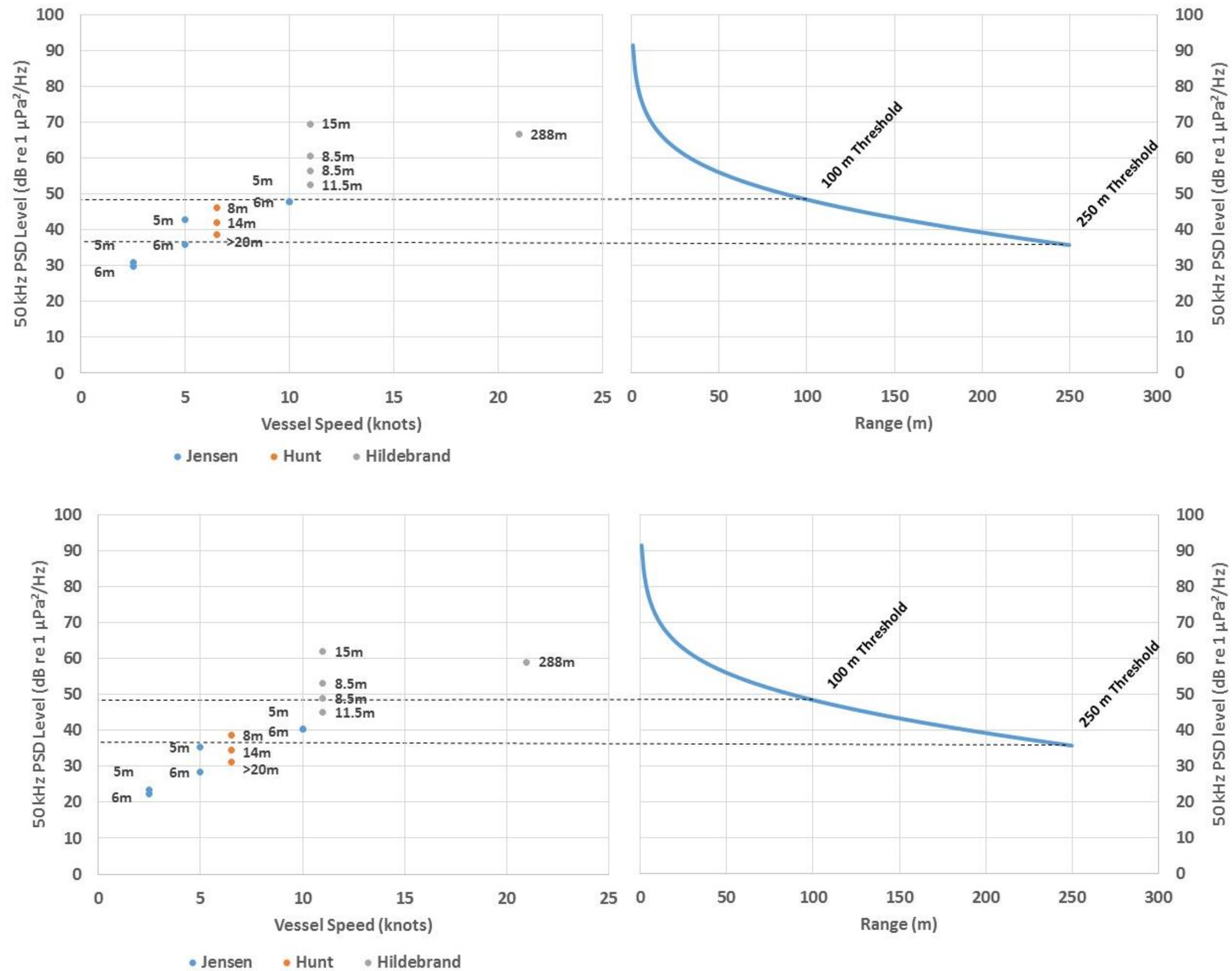
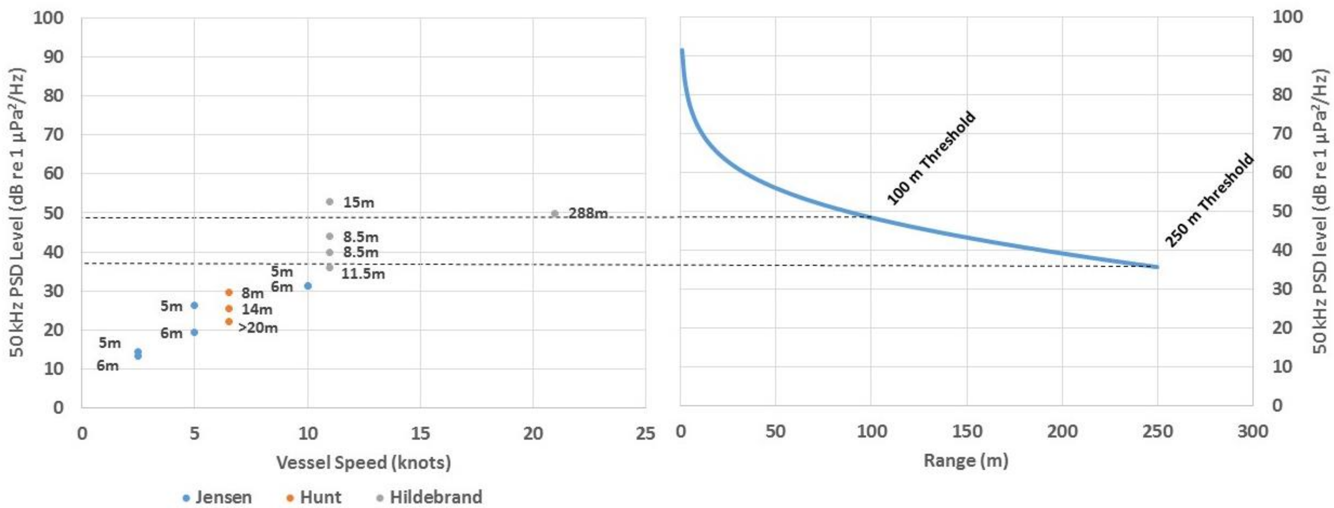


Figure A - 5 A comparison of residual high frequency (50 kHz) echolocation click masking thresholds for various vessel types and speeds using thresholds of 250m (this study) and 100m ranges. Vessels are placed 100m (top) and 200m (bottom) from the whale. Vessel length is provided in the figure with colours relating to the source given below each figure.



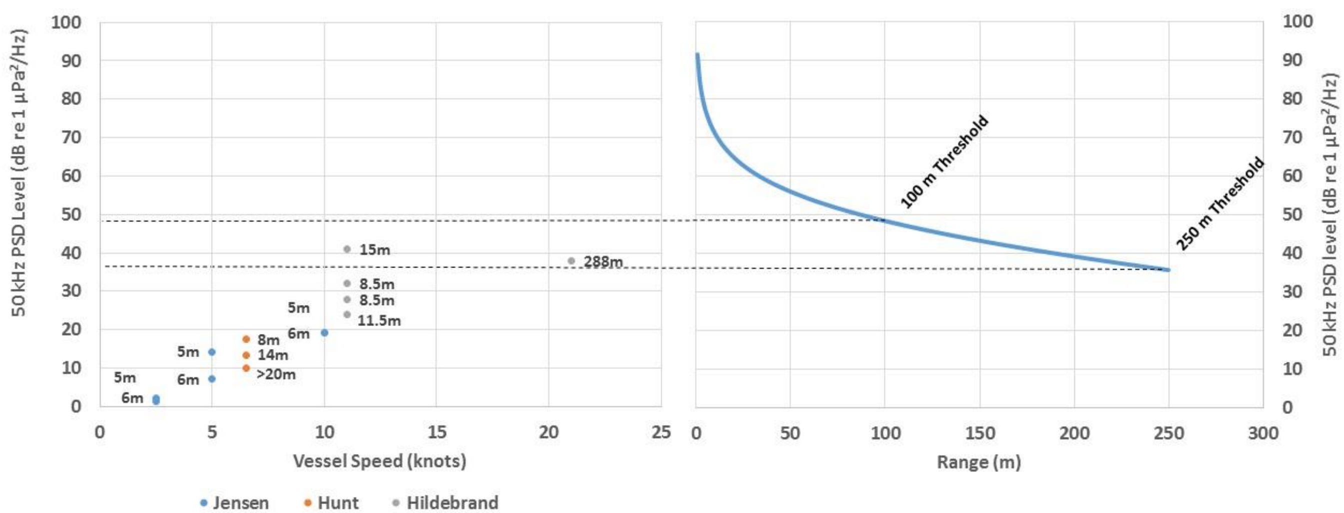


Figure A - 6 A comparison of residual high frequency (50 kHz) echolocation click masking thresholds for various vessel types and speeds using thresholds for 250m (this study) and 100m ranges. Vessels are placed 400m (top) and 800m (bottom) from the whale. Vessel length is provided in the figure with colours relating to the source given below each figure.