Measuring up

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Researchers deploy two autonomous marine acoustic recorders to measure sound levels produced by whale watching vessels and other small boats.

Who should read this paper?

Those with an interest in anthropogenic impacts of underwater noise, specifically as it pertains to commercial and recreational small vessels. This includes scientists, commercial captains, recreational boaters, and law-makers.

Why is it important?

As marine traffic increases, so does associated noise which can have negative impacts on marine life. However, this can be mitigated by certain actions. The results from this study quantify small vessel noise emissions and reveal how speed, vessel, and propulsion type can affect sound levels. This can help inform commercial and recreational boaters as well as law-makers on how to minimize noise underwater. This systematic study of assessing noise emissions of whale watching and other small vessels is the largest known to date for small commercial and recreational vessels. The protocols were designed based on the ANSI standards for measurement of underwater sound from ships. The results can be incorporated into acoustic models to predict sound levels received by marine life and help form wildlife viewing guidelines. This in turn can help reduce underwater sound levels and associated disturbances on animals.

About the authors

Dr. Jennifer Wladichuk completed a B.Sc. in marine biology at the University of British Columbia in 2000. Following that she studied gray whales along the central coast of B.C. where she became curious about how whales navigated without the apparent use of echolocation. This led her to start a PhD on underwater soundscapes. After completing her doctorate at the University of Bath, UK, in 2010, she returned to B.C. and started working at a local environmental acoustics company, JASCO Applied Sciences, where she investigates impacts of underwater anthropogenic noise. Dr. Wladichuk has recently started a postdoctoral fellowship at the University of Victoria in collaboration with Fisheries and Oceans Canada to study the effects of noise on the echolocation of the endangered Southern Resident killer whales.

David Hannay, M.Sc., is Chief Science Officer at JASCO Applied Sciences. His research focus is the application of physical acoustics methods to assessing effects of anthropogenic noise on marine fauna. A large component of his work involves quantifying noise emissions of a variety of marine sources, including shipping, sonars, pile driving, and geophysical survey sources.

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Zizheng Li

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SYSTEMATIC SOURCE LEVEL MEASUREMENTS OF WHALE WATCHING VESSELS AND OTHER SMALL BOATS

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ABSTRACT

Marine mammals rely heavily on sound for foraging, communicating, and navigating. As noise in the ocean increases, their ability to perform these important life functions can be affected. In the past decade, numerous studies have expanded our awareness of the effects of anthropogenic noise on marine life. Improving our knowledge of how sound impacts marine mammals is particularly important in coastal waters where the spatial distributions of vessels and marine mammals overlap, as exemplified by the critical habitat for the endangered Southern Resident killer whale (*Orcinus orca*). The impacts of small vessel traffic (including the commercial and recreational whale watching that is directed on this population) has been difficult to assess as there is a data gap for small vessel noise emissions. In this study, two autonomous marine acoustic recorders were deployed in transboundary Haro Strait (British Columbia, Canada, and Washington State, USA) from July to October 2017 to measure sound levels produced by whale watching vessels and other small boats. During this period, 20 different volunteer vessels were assessed operating at a range of speeds – nominally 5 knots, 9 knots, and cruising speed (generally 20-30 knots) to represent whale watching, approach, and transit speeds, respectively. The vessels were categorized into six types: rigid-hulled inflatable boats (RHIBs), monohulls, catamarans, sailboats, landing crafts, and a small boat with a 9.9 horsepower outboard engine. Acoustic data were analyzed according to the ANSI S12.64 (2009) standard for measuring ship noise using JASCO Applied Sciences' PortListen® software system, which automatically calculates source levels from calibrated hydrophone data and vessel position logs. For all vessels, we observed positive correlations between source levels and speed; however, the rate of increase of source levels with speed were not as strong as those measured previously for large commercial vessel speed trends. Mean source levels (SLs) were computed for each vessel type in the broadband frequency range (0.05-64 kHz), the Southern Resident killer whale (SRKW) communication band (0.5-15 kHz), and the SRKW echolocation band (15-64 kHz) for each of the speed groups. In general, landing crafts produced the highest source levels (overall mean = 166 ± 5 dB re 1 μPa m), followed by catamarans (160 ± 10 dB re 1 μPa m), then RHIBs (158 ± 11 dB re 1 μPa m), monohulls (157 ± 12 dB re 1 μPa m), sailboats (153 ± 9 dB re 1 μPa m), and the small vessel with a 9.9 HP outboard engine was the quietest across speeds and frequency bands measured (150 ± 10 dB re 1 μPa m). However, it should be taken into account that the sailboats and the vessel with the 9.9 HP outboard engine did not perform any high speed passes. A comparison of the 1/3 octave band levels for six of the vessels that had inboard diesel engines suggests that Arneson drive propulsion (a surface-piercing propeller) produces lower sound levels than traditional propellers. However, this is based on a small sample size and more research into acoustic emissions from different propulsion types (e.g., jet, electric, Arneson drive) is needed. Finally, depth sounders were observed to create a peak in acoustic energy at approximately 50 kHz, which is well within the most sensitive hearing range of killer whales [Branstetter et al., 2017]. Therefore, it is recommended that sounders are turned off when not needed in proximity to killer whales and other cetaceans that use high-frequency sound (e.g., harbour porpoises, *Phocoena phocoena*, Dall's porpoises, *Phocoenoides dalli*, Pacific white-sided dolphins, *Lagenorhynchus obliquidens*).

KEYWORDS

Southern Resident killer whale; Underwater noise; Vessel noise emission; Source level; Marine mammal

INTRODUCTION

Many animals use sound for important life functions, particularly in the ocean since sound travels extremely well underwater while light is strongly attenuated. Marine mammals have evolved acute hearing capabilities and rely heavily on sound for foraging, communicating, and navigating. There are subtle differences in the natural underwater soundscape which animals likely utilize [Radford et al., 2008; 2010; Wladichuk, 2010; Putland et al., 2017]; however, as the oceans become increasingly busy with vessel traffic, they are also becoming progressively noisier due to cumulative levels of ship sounds [Ross, 2005; McDonald et al., 2006; Hildebrand, 2009; Frisk, 2012; Williams et al., 2015; McWhinnie et al., 2017]. Other sources of anthropogenic noise, such as military sonars and depth sounders, pile driving, oil and gas surveys, dredging and other construction activities, all contribute to elevated underwater noise levels [Hildebrand, 2009; Tougaard et al., 2009; Slabbekoorn et al., 2010; Quick et al., 2017; Southall et al., 2019]. Anthropogenic noise can mask important sounds on which animals depend, such as environmental cues and vocalizations including echolocation. Furthermore, noise has the potential to disturb the prey of marine mammals, as well as cause physiological effects in the animals. Hence, anthropogenic noise can directly affect an animal's health and ability to survive [Weilgart, 2007; Graham and Cooke, 2008; Hatch et al., 2008; Clark et al., 2009; Holt et al., 2009; Ford et al., 2010; Kight and Swaddle, 2011; Williams et al., 2014; Dunlop, 2016; Erbe et al., 2016b]. Vessel presence alone has been shown to have both physical and behavioural effects on marine mammals. For example, Buckstaff [2004] found that bottlenose dolphins increased their call rate when vessels were approaching. This was suggested to be due to potentially heightened arousal or communication regarding group movements, or was an effective way to compensate for masking. Holt et al. [2009] found that killer whales (*Orcinus orca*) increased their call amplitude by one decibel for every decibel increase in background noise levels, also suggesting a response to masking. Foote et al. [2004] found killer whales increased their call duration when a certain background noise threshold was reached. There are other observations of disturbances of marine mammals due to vessels, such as prolonged intervals between surfacings, increasing swim speed, congregating into groups, and reducing foraging activity [Blane and Jaakson, 1994; Lusseau, 2006; Williams et al., 2006; Pirotta et al., 2015]. All of these behaviours can have an energetic cost to the animals and represent negative impacts.

Underwater noise levels produced by vessels can vary with vessel speed, size, and distance; hence, detailed information on various vessel source levels (SLs) is required to evaluate the potential impacts on marine life and ecosystems [Blane and Jaakson, 1994; Erbe, 2002]. Integrating vessel SLs, together with vessel movement data (e.g., Automatic Information System, AIS), in underwater acoustic models is an efficient and effective approach to predict noise levels. Such models can be used for the mitigation and management of vessel-noise effect on marine mammals [Blane and Jaakson, 1994; Erbe, 2002; Hatch et al., 2008; Erbe et al., 2012; Erbe et al., 2014; Merchant et al., 2014; New et al., 2015; Cholewiak et al., 2018; Cominelli et al., 2018]. However, there is still an information gap for some vessel sources.

Recent studies involving big datasets have been conducted on large commercial ship noise emissions [Simard et al., 2016; Veirs et al., 2016; MacGillivray et al., 2019]; however, there is a limited number of measurements for small vessels [Au and Green, 2000; Erbe, 2002; Buckstaff, 2004; Rudd et al., 2015; Erbe et al., 2016a]. A systematic evaluation of small vessel noise emissions, and particularly the relation of noise to vessel speed, is warranted.

The major shipping corridors to the metropolitan cities of Victoria, Vancouver, and Seattle bisect the critical habitat of endangered SRKWs. This area is also popular for recreational boating and whale watching activities, resulting in daily averages between 10 and 22 boats within a half-statute mile to SRKWs in Haro Strait between May and September [Shedd, 2018]. This population of whales is at risk of extinction, with currently only 73 individuals and declining numbers since 1995 [CWR, 2019]. Three main threats jeopardize their recovery: environmental contaminants, reductions in availability or quality of prey, and both physical and acoustic disturbances [COSEWIC, 2009]. As mentioned previously, acoustic disturbances due to vessel noise can mask important sound signals, impact animal and prey movements, induce chronic stress, and cause other physiological effects. But with limited data on sound emissions from small vessels, it is difficult to set meaningful guidelines for boating activities such as whale watching and to generally mitigate effects. Thus, the aim of this study was to fill this gap by quantifying SLs from a variety of whale watching and recreational vessels and to investigate how source levels correlate with vessel type, speed, and propulsion system. SLs from 20

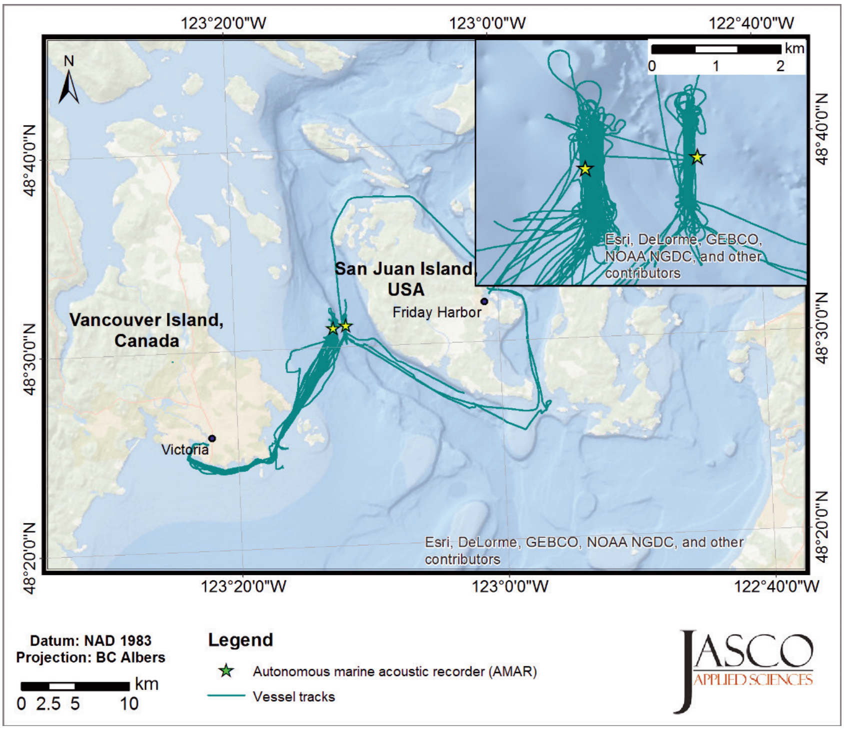

Figure 1: Autonomous marine acoustic recorder (AMAR) locations (stars) and participant vessel tracks in Haro Strait.

dedicated small vessels were computed for three frequency bands recently identified by an expert working group convened by the Coastal Ocean Research Institute as being best suited for assessing the acoustical quality of SRKW habitat [Heise et al., 2017], including broadband (0.05-64 kHz), SRKW communication band (0.5-15 kHz), and SRKW echolocation band (15-64 kHz).

MATERIALS AND METHODS

Data Acquisition

Two autonomous marine acoustic recorders (AMARs) were deployed in approximately 200 m of water adjacent to the traffic lanes in Haro Strait (Figure 1) for a parallel study led by the Vancouver Fraser Port Authority's ECHO Program investigating acoustic emissions of large commercial vessels [MacGillivray et al., 2019]. The AMARs recorded continuously from July 6 through October 26, 2017, and were set to measure at a higher sample rate (128 Kilosamples per second) from 06:00-09:00 PDT to capture the higher frequency noise from small vessels, which overlaps with the echolocation range of SRKW. All measurements were collected with a 24-bit resolution.

The volunteer participant vessels (Table 1) performed at least two transits past one of the AMARs at each of the predetermined speeds (5 knots, 9 knots, and cruising speed – generally 20-30 knots). These speeds are representative of whale watching, approach, and transit operations, respectively. The vessels started at approximately 500 m north or south of the AMAR and transited at a constant engine revolutions per minute (RPM) past a waypoint approximately 110 m adjacent to the AMAR and then continued in a relative straight line 500 m farther (Figure 2). The vessel then turned and maintained the same RPM on a return pass.

Accurate vessel positioning data was collected on either a handheld GPS or the vessel's

Vessel ID	Length (m)	Vessel type	Engine specifications	Propulsion type	Number of accepted measurements
V01	15.5	Monohull	2 x 625 HP inboard diesel	Arneson*	8
V02	17.4	Catamaran	2 x 435 HP inboard diesel	Propeller	9
V03	11.5	Catamaran	2 x 300 HP outboard (4-stroke) gas	Propeller	8
V04	11.5	Monohull	2 x 250 HP + 1 x 300 HP outboard (4-stroke) gas	Propeller	9
V05	11.5	Monohull	3 x 300 HP outboard (4-stroke) gas	Propeller	10
V06	6.8	RHIB	2 x 350 HP V8 outboard (4-stroke) gas	Propeller	6
V07	5.2	RHIB	1 x 150 HP outboard (4-stroke) gas	Propeller	6
V08	9.4	Monohull	1 x 370 HP inboard diesel	Propeller	6
V09	6.4	Landing craft	2 x 90 HP outboard (4-stroke) gas	Propeller	5
V10	9	Sailboat	1 x 30 HP inboard (4-stroke) gas	Propeller	7
V11	12.8	Sailboat	1 x 44 HP inboard (4-stroke) diesel	Propeller	5
V12	16.8	Monohull	1 x 650 HP inboard diesel	Propeller	5
V13	8.2	RHIB	2 x 225 HP outboard (4-stroke) gas	Propeller	5
V14	17	Monohull	2 x 770 HP inboard diesel	Propeller	4
V15	9	Monohull	1 x 350 HP outboard (4-stroke) gas	Propeller	6
V16	7.6	RHIB	2 x 200 HP outboard (2-stroke) gas	Propeller	8
V17	17	Monohull	2 x 850 HP inboard (4-stroke) diesel	Arneson*	6
V18	9.1	Monohull	2 x 225 HP outboard (4-stroke) gas	Propeller	5
V19	8.2	Monohull	2 x 150 HP outboard (4-stroke) gas	Propeller	6
V20	8.2	Small outboard	1 x 9.9 HP outboard (4-stroke) gas	Propeller	4
				Total	**128**

*surface-piercing propeller

Table 1: Participant vessel specifications and number of accepted measurements. Identities of participating vessels have been anonymized.

chartplotter system for correlating with the acoustic data during analysis.

Autonomous Marine Acoustic Recorders (AMARs)

The Haro Strait acoustic recorders consisted of two calibrated AMAR G3 (Autonomous Multichannel Acoustic Recorders-Generation 3) units from JASCO Applied Sciences deployed on subsea moorings next to northbound and southbound traffic lanes. Each AMAR used an M36 omnidirectional hydrophone (GeoSpectrum Technologies Inc., −165 ± 3 dB re 1 V/μPa nominal sensitivity) for measuring underwater sound pressure. The frequency-dependent laboratory calibration of each AMAR and hydrophone was verified before and after deployment at 250 Hz using a Pistonphone Type 42AC precision sound source (G.R.A.S. Sound & Vibration A/S) to ensure the sensitivity of the hydrophones did not change over the deployment period.

After the moorings were deployed, their precise on-bottom locations were calculated using a surface-based transducer that measured the distance to the acoustic releases. Ranging was performed at four GPS waypoints in a square pattern surrounding the moorings. The estimated accuracy of the surveyed coordinates was ±4 m.

The transit area was designed to position vessels approximately in conformance with the Grade-C geometry of the ANSI vessel noise measurement standard [ANSI 12.64-2009 R2014], and to minimize acceleration and turning during the measurement.

ShipSound Analysis

Acoustic data were analyzed using the ShipSound module of JASCO's PortListen® underwater noise measurement software system. The software monitors sound level measurements and uses the vessel location data to automatically extract the corresponding

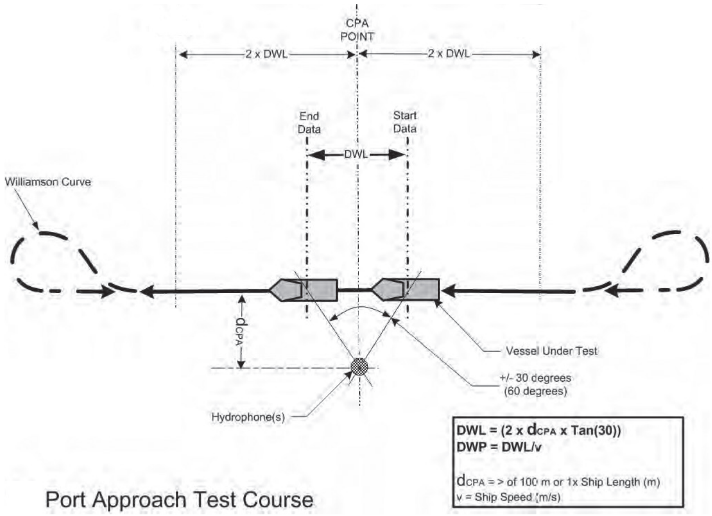

Figure 2: Schematic of the vessel transit protocol for a port approach of the acoustic recorder. The vessel would maintain a constant engine RPM between three waypoints along the transit line for a minimum of two transits past the autonomous marine acoustic recorder (AMAR) at each of the three predetermined speeds. CPA represents the closest point of approach, DWL is data window length, DWP is data window period, and dCPA is distance to CPA. Figure extracted from ANSI/ASA S12.64/Part 1.2009.

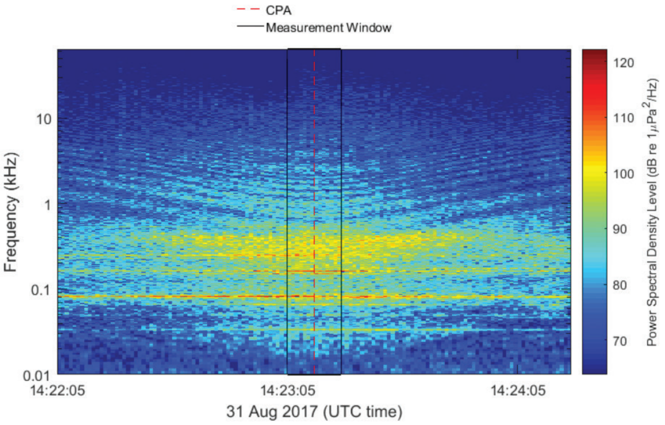

Figure 3: Spectrogram of a single vessel measurement from ShipSound, showing the closest point of approach (CPA) time (red dashed line) and the measurement window (black box) used for calculating vessel source levels. The spectrogram shows the spectrum of the underwater sound pressure recorded on the AMAR hydrophone versus time and frequency.

acoustic data for analysis. It uses the vessel's speed together with a cepstral analysis of the Lloyd mirror pattern to determine the timing and location of closest point of approach (CPA) of the vessel's acoustic centre (Figure 3).

The ANSI/ASA S12.64 data window is defined by the period over which the acoustic centre is within ±30° of the CPA. Spectrum measurements are calculated using 1-second fast Fourier transforms, shaded using a power-normalized Hanning window.

ShipSound calculates two kinds of vessel source levels from the data window: monopole source level (MSL) and radiated noise level (RNL). MSL is equal to the measured sound pressure level scaled according to a numerical acoustic transmission loss model. RNL is equal to the measured sound pressure level, back-propagated according to the distance between a source and the hydrophone. The software determines instantaneous vessel range (R) in metres from the measurement hydrophone for each 1-second step within the data window and applies a back-propagation method of 20 x $\log_{10}(R)$ plus seawater absorption to calculate RNL. Only RNL source levels are presented here.

Data Analysis

Vessel noise measurements were analyzed in the following frequency bands due to their particular relevance to the acoustic quality of SRKW habitat [Heise et al., 2017]:

- Broadband noise (0.05-64 kHz), for evaluating effects of noise on behavioural disturbance
- Communication masking (0.5-15 kHz), for evaluating effects of noise on communication space
- Echolocation masking (15-64 kHz), for evaluating effects of noise on foraging space

Due to high flow noise contamination at frequencies <50 Hz and the relatively low source levels of small vessels at those frequencies, the lower frequency of the broadband SLs was 0.05 kHz instead of 0.01 kHz as listed in Heise et al. [2017]. The upper frequency limit of the broadband and echolocation ranges was 64 kHz instead of 100 kHz [Heise et al., 2017] due to the AMAR sampling rate.

Trends of source level versus speed were analyzed for speed through water, since this accounts for the effect of ocean currents on vessel movements. Trend analysis was performed using Ross's classical power law model [Ross, 1976], which relates change in SL to relative changes in speed:

$$\mathrm{SL} - \mathrm{SL}_{\mathbf{ref}} = C_v \times 10\log_{10}\left(\frac{v}{v_{\mathrm{ref}}}\right) \qquad (1)$$

In this equation, SL is the source level at speed through water v, $\mathrm{SL}_{\mathrm{ref}}$ is the source level at some reference speed v_{ref}, and C_v is a coefficient corresponding to the slope of the curve.

RESULTS

A total of 152 vessel noise measurements (individual passes) collected from 20 different whale watching and recreational boats were analyzed. Of these measurements, 128 were accepted (i.e., passed a manual quality review) and 24 were rejected, primarily due to low signal-to-noise ratio. Passes were also rejected if there was noise contamination from another vessel. These occurrences were minimized during the fieldwork by stopping vessel transits if there was a vessel within 2 nautical miles.

All vessels performed at least two passes at minimum three speeds (5 knots, 9 knots, and cruising speed – generally 20-30 knots). Even though the sailboats were under power during the measurements, they were unable to operate at the higher speeds; therefore, those two vessels made passes at 2 knots, 5 knots, and their maximum speed (6-7 knots). A 9.9 HP outboard engine was also measured on a charter fishing vessel (8.2 m monohull) since it is typically used instead of the larger outboard engines for running at slow speeds, such as when trolling for fish. Only four of its passes were accepted due to low signal-to-noise ratio. The accepted passes were performed at approximately 3, 3.5, 4, and 4.5 knots.

Overall Source Levels

The mean (decibel-average) RNL source levels for each vessel type in each frequency band at slow, medium, and fast vessel speeds are listed in Table 2. Figure 4 presents the corresponding box-and-whisker plots. Generally, landing crafts produced the highest source levels (overall mean = 166 ± 5 dB re 1 µPa m), followed by catamarans (160 ± 10 dB re 1 µPa m), then RHIBs (158 ± 11 dB re 1 µPa m), monohulls (157 ± 12 dB re 1 µPa m), and sailboats (153 ± 9 dB re 1 µPa m), and the small vessel with a 9.9 HP outboard

Speed	Frequency band	RNL SL (dB re 1 µPa m)					
		RHIB (n = 4)	Monohull (n = 10)	Catamaran (n = 2)	Landing Craft (n = 1)	Sailboat (n = 2)	9.9 HP outboard (n = 1)
Slow (<7 knots)	Broadband*	160.9 ± 2.6	164.0 ± 2.8	163.4 ± 3.2	169.7 ± 0	162.0 ± 6.3	162.1 ± 2.1
	Communication**	152.7 ± 2.6	148.6 ± 6.5	161.1 ± 2.8	158.4 ± 0	156.6 ± 5.3	152.0 ± 1.6
	Echolocation***	136.7 ± 5.7	132.9 ± 12	140.3 ± 3.2	167.2 ± 0	141.6 ± 5.9	137.5 ± 2.6
Medium (7-15 knots)	Broadband	167.0 ± 3.5	165.1 ± 4.6	167.2 ± 2.7	171.9 ± 2.8	--	--
	Communication	159.6 ± 2.6	160.0 ± 4.0	161.8 ± 2.5	158.1 ± 0.2	--	--
	Echolocation	143.5 ± 4.9	145.2 ± 7.7	147.2 ± 1.8	167.8 ± 4.9	--	--
Fast (>15 knots)	Broadband	172.0 ± 2.3	172.0 ± 5.4	174.4 ± 3.4	171.8 ± 1.3	--	--
	Communication	170.2 ± 2.6	167.6 ± 5.8	168.6 ± 2.8	167.7 ± 0.4	--	--
	Echolocation	159.5 ± 3.9	155.4 ± 9.7	157.7 ± 5.3	162.0 ± 5.4	--	--

* Broadband frequency range (0.05-64 kHz)
** SRKW communication band (0.5-15 kHz)
*** SRKW echolocation band (15-64 kHz)
-- no vessel passes at this speed

Table 2: Mean and standard deviation (dB-average) source levels (RNL) for each vessel type in the three frequency bands for slow, medium, and fast speeds through water.

engine was the quietest across speeds and frequency bands (mean SL 150 ± 10 dB re 1 µPa m). However, the sailboats and the vessel with a 9.9 HP outboard engine did not perform any high-speed passes. At slow speeds (<7 knots) in the broadband range (0.05-64 kHz), RHIBs had the lowest SL (mean and standard deviation 160.9 ± 2.6 dB re 1 µPa m) of the participating vessels. Sailboats and the 9.9 HP outboard engine were about 1 dB higher (162.0 ± 6.3 dB re 1 µPa m and 162.1 ± 2.1 dB re 1 µPa m, respectively). The landing craft had the highest mean SL (169.7 dB re 1 µPa m). At medium speeds (7-15 knots), monohulls had the lowest mean SLs (165.1 ± 4.6 dB re 1 µPa m) and at high speeds (>15 knots), RHIBs, monohulls, and the landing craft had the lowest SLs and were within 0.2 dB of each other. The sailboats and 9.9 HP outboard engine did not perform any passes at those speeds.

At slow speeds (<7 knots) in the SRKW communication band (0.5-15 kHz), monohulls had the lowest SL (148.6 ± 6.5 dB re 1 µPa m), followed closely by RHIBs (152.7 ± 2.6 dB re 1 µPa m) and the 9.9 HP outboard engine (152.0 ± 1.6 dB re 1 µPa m). The catamarans had the highest mean SL (161.1 ± 2.8 dB re 1 µPa m). At medium and high speeds, monohulls, RHIBs, catamarans, and the landing craft had mean SLs within 5 dB of each other.

At slow speeds (<7 knots) in the SRKW echolocation band (15-64 kHz), the monohulls had the lowest mean SL (132.9 ± 12 dB re 1 µPa m). The mean SLs for RHIBs, catamarans, sailboats, and the 9.9 HP outboard engine were within 5 dB of each other, and on average 6 dB above the mean SL for the monohulls. The landing craft had the highest mean SL (167.2 dB re 1 µPa m). At medium speeds (7-15 knots), the RHIBs, monohulls, and catamarans had mean SLs within 5 dB of each other while the landing craft had a mean SL approximately 20 dB higher (167.8 ± 4.9 dB re 1 µPa m). At high speeds (>15 knots), the four vessel types had mean SLs ranging from 155.4-162.0 dB re 1 µPa m, with monohulls having the lowest value and the landing craft with the highest SL.

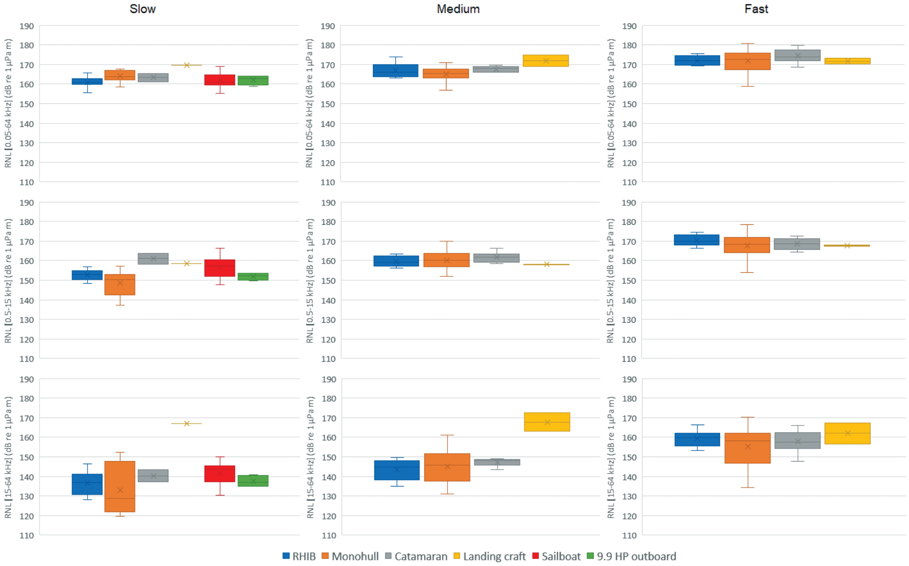

Figure 4: Box-and-whisker plots presenting radiated noise level in the broadband range (0.05-64 kHz; top), SRKW communication band (0.5-15 kHz; middle), and echolocation band (15-64 kHz; bottom) for slow (<7 knots; left), medium (7-15 knots; middle), and fast (>15 knots; right) speed passes for each vessel type. The median is shown as a line within the box, the mean is a cross, the upper and lower ends of the box are the upper and lower quartile, respectively, with the highest and lowest data points at the end of the whiskers.

Within the monohulls themselves, there are a variety of vessel lengths, engine sizes, and propeller types; therefore, large ranges of SLs were observed.

Effects of Speed on Source Levels

A trend analysis was performed for each vessel in each of the frequency bands (broadband, SRKW communication, and SRKW echolocation) for SL versus speed through water for all accepted measurements. The resulting plots are shown in Figures 5-7. Overall, there was a clear positive trend of SL with vessel speed for all frequency bands, but generally the slopes were more gradual for the broadband range and steepest for the echolocation band, i.e., greater rate of increase in SL with speed. In the broadband range, the landing craft had the lowest best-fit trend coefficients (C_v), meaning the lowest increase in SL with increase in speed, followed by RHIBs and the 9.9 HP outboard engine. RHIBs had fairly consistent coefficients while the other vessel types (with more than one vessel) had relatively wide ranges of values. In the SRKW communication band, the catamarans had the lowest C_v, followed closely by the landing craft. However, a few of the monohulls as well as one of the sailboats had comparable coefficients. With respect to the SRKW echolocation band, the landing craft had the lowest C_v, which was negative, meaning the sound level in that frequency band decreased with increasing speed. However, this is based on only one vessel. The 9.9 HP outboard had the next lowest C_v value. Table 3 lists the mean C_v values and standard deviation for each vessel type in each of the frequency bands.

Effects of Propeller Type on Source Levels

Of the 20 vessels measured, six motor boats had inboard diesel engines and two of which had Arneson drives (surface-piercing propellers) (V01, V02, V08, V12, V14, and V17 in Table 1). Since propeller cavitation is

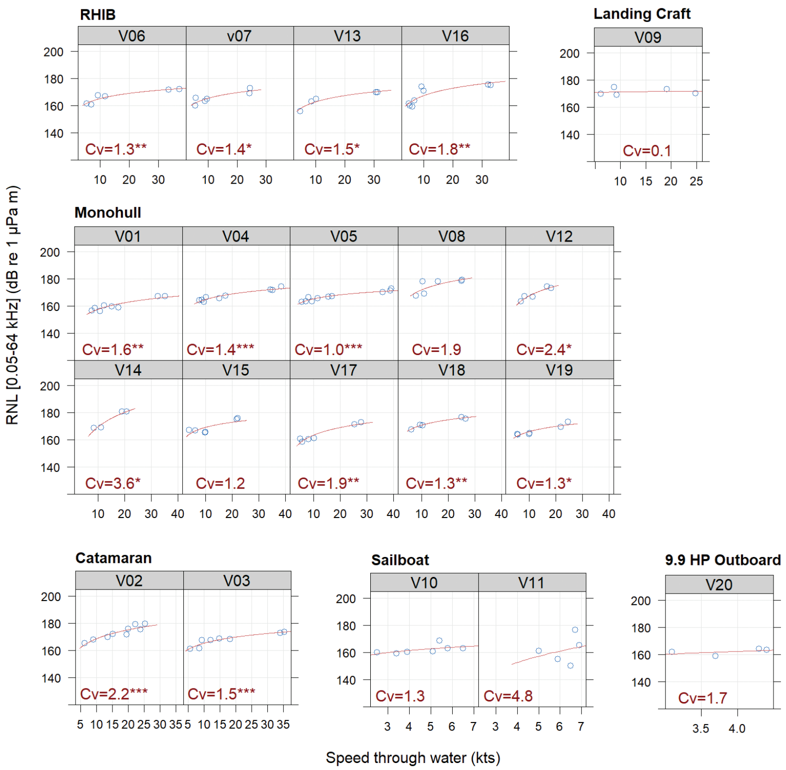

Figure 5: Radiated noise level (RNL) in the broadband range versus speed for each vessel separated by type (accepted measurements only). The red line is the best-fit trendline, based on Equation 1. The annotation indicates the best-fit coefficient (Cv). The asterisks indicate the statistical significance of the trend (* = p < 0.05, ** = p < 0.01, *** = p < 0.001).

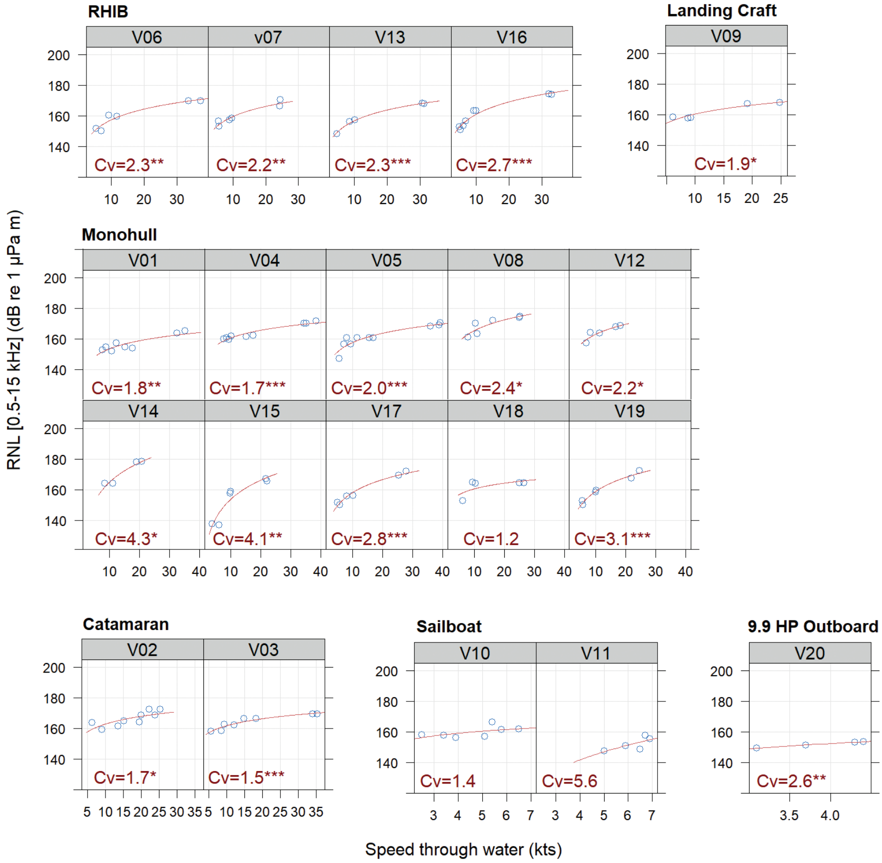

Figure 6: Radiated noise level (RNL) in the SRKW communication band versus speed for each vessel separated by type (accepted measurements only). The red line is the best-fit trendline, based on Equation 1. The annotation indicates the best-fit coefficient (Cv). The asterisks indicate the statistical significance of the trend (* = p < 0.05, ** = p < 0.01, *** = p < 0.001).

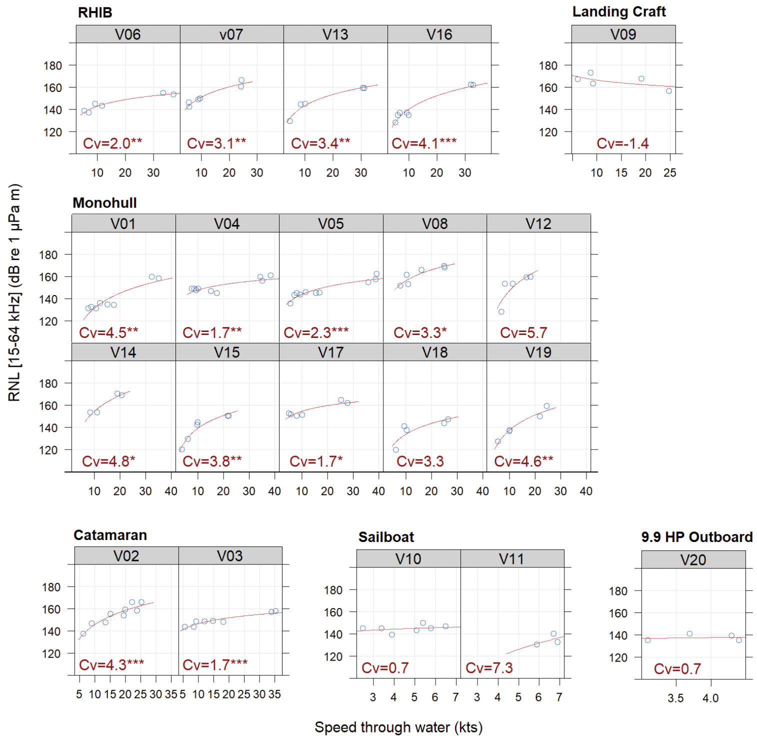

Figure 7: Radiated noise level (RNL) in the SRKW echolocation band versus speed for each vessel separated by type (accepted measurements only). The red line is the best-fit trendline, based on Equation 1. The annotation indicates the best-fit coefficient (Cv). The asterisks indicate the statistical significance of the trend (* = p < 0.05, ** = p < 0.01, *** = p < 0.001).

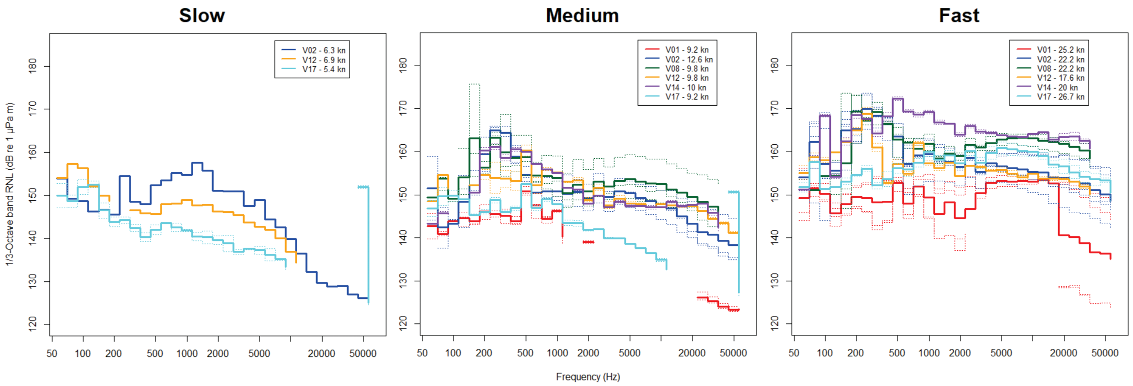

Figure 8: 1/3 octave band levels for all accepted passes of the diesel vessels for slow (<7 knots; left), medium (7-15 knots; middle), and fast (>15 knots; right) speed passes. Dashed lines are individual passes and means of each vessel are bold lines. Gaps in the plots signify that the received level was within 3 dB of the ambient levels and therefore a SL was not computed. Vessels V01 (red lines) and V17 (cyan lines) had Arneson propulsion (surface-piercing propeller), while the other vessels had traditional propellers. No slow speed passes were observed or accepted for vessels V01, V08, and V14. The spike at 50 kHz for the slow and medium passes for vessel V17 was from an onboard echo sounder.

the main source of vessel noise [Ross, 1976], we examined the mean 1/3 octave band levels for each of those six vessels for the three speed ranges (Figure 8) to investigate how the propeller type of similarly sized vessels with comparable engine horsepower might affect SLs.

The plots presented in Figure 8 show that the vessels with Arneson drives (vessels V01 and V17) appear to have lower SLs at the same general speeds. For slow- and medium-speed passes, SLs were predominantly lower for the Arneson drive vessels above approximately 200 Hz. For the high-speed passes, levels

Vessel type	**Mean *Cv* ± standard deviation**		
	Broadband	Communication	Echolocation
RHIB	1.5 ± 0.2	2.4 ± 0.2	3.2 ± 0.9
Monohull	1.8 ± 0.8	2.6 ± 1.0	3.6 ± 1.4
Catamaran	1.9 ± 0.5	1.6 ± 0.1	3 ± 1.8
Landing craft	0.1 ± 0	1.9 ± 0	-1.4 ± 0
Sailboat	3.1 ± 2.5	3.5 ± 3.0	3.9 ± 4.5
9.9 HP outboard	1.7 ± 0	2.6 ± 0	0.6 ± 0

Table 3: Mean C_V values for each vessel type in the three frequency bands.

between approximately 100-500 Hz were substantially lower even though the average speeds of the Arneson vessels were greater. However, this is based on a very small sample size so caution must be made when drawing conclusions. More research is required.

CONCLUSION

As anthropogenic noise – both in-air and underwater – increases, there is need to monitor and mitigate it since various animals, particularly marine mammals, heavily rely on the use of sound for important life functions. There is ongoing research to quantify more sound sources so that they can be incorporated into acoustic models which are used to help predict potential biological effects [Erbe et al., 2012; 2014; Farcas et al., 2016]. Improving our knowledge of how sound impacts marine mammals is particularly important in coastal waters where the spatial distributions of vessels and marine mammals overlap, as demonstrated by the critical habitat of endangered SRKW. The impacts of small vessel traffic (including the commercial and recreational whale watching) has been difficult to assess as there is a data gap for small vessel noise emissions. This study aims to address that issue. Source levels from 20 different volunteer whale watching vessels and other small boats were computed in three frequency bands which were recently identified by an expert working group as being best suited for assessing the acoustical quality of SRKW habitat [Heise et al., 2017]: the broadband frequency range (0.05-64 kHz), the SRKW communication band (0.5-15 kHz), and the SRKW echolocation band (15-64 kHz). The vessel passes were performed at a range of speeds to investigate how source levels vary with speed, as well as vessel and propulsion type.

In general, the landing crafts produced the highest source levels (overall mean = 166 ± 5 dB re 1 μPa m), followed by catamarans (160 ± 10 dB re 1 μPa m), then RHIBs (158 ± 11 dB re 1 μPa m), monohulls (157 ± 12 dB re 1 μPa m), sailboats (153 ± 9 dB re 1 μPa m), and the small vessel with a 9.9 HP outboard engine was the quietest across speeds and frequency bands (150 ± 10 dB re 1 μPa m). However, the sailboats and the vessel with the 9.9 HP outboard engine did not perform any high speed passes. In the broadband frequency range (0.05-64 kHz), mean SLs ranged from 161-174 dB re 1 μPa m across all vessel types, in the communication range (0.5-15 kHz) SLs were between 149-170 dB re 1 μPa m, and in the echolocation range they were between 132-168 dB re 1 μPa m. The source levels (SLs) presented here match well with those from other studies, e.g., communication band SLs with Erbe [2002] and max SL of inboard diesel traditional propeller vessels with that reported in Au and Green [2000].

Clear positive correlations between SLs and vessel speed were observed for all three frequency bands; however, they were stronger in the echolocation band than the broadband and communication band. Overall, the mean C_v value (slope of the curve) in the broadband frequency range for all vessels was 1.8 ± 1.0, which is lower than that derived from a trend analysis of RNL versus speed for large commercial vessels (3.75 ± 0.5) reported in MacGillivray et al. [2019]. Additionally, comparing the spectral shape of the SLs of smaller vessel with that of the larger commercial ships reveals that there is relatively more high-frequency content in the smaller vessel noise emissions. Identifying these differences is important when investigating effects on marine mammal species with different hearing sensitivities.

Comparing 1/3 octave band levels for six of the vessels with inboard diesel engines suggests that Arneson drive propulsion (surface-piercing propeller) could produce lower sound levels across most frequencies than traditional propellers for similarly sized vessels with comparable engine horsepower. We speculate that source levels may have been lower for Arneson drive vessels because radiated noise from their shallow propellers would be more strongly attenuated by the free surface effect. However, this is based on a small sample size, so caution must be made when drawing generalized conclusions. More research is warranted on this topic.

Another key finding was that radiated noise for the slow and medium passes for vessel V17 was dominated by a tonal source at 50 kHz. This peak in acoustic energy was attributed to the onboard depth sounder (50 kHz is a typical depth sounder frequency), and is within the most sensitive hearing range of SRKW [Branstetter et al., 2017]. Many dual frequency depth sounders are available on the market; consideration should be given to the potential impacts to cetaceans and a general practice of turning off or switching depth sounders to higher frequencies (above 100 kHz) is recommended when not needed in proximity to killer whales and other marine mammals that use high-frequency sounds (e.g., harbour porpoises, *Phocoena phocoena*, Dall's porpoises, *Phocoenoides dalli*, Pacific white-sided dolphins, *Lagenorhynchus obliquidens*).

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