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Implications of wind and vessel noise on the sound fields experienced by southern resident killer whales *Orcinus orca* in the Salish Sea

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ABSTRACT: The soundscape of critical habitat for southern resident killer whale (SRKW) *Orcinus orca* in the Salish Sea, the waters around southern British Columbia, Canada, and northern Washington State, USA, is shaped by wind and wave noise as well as heavy commercial and recreational vessel traffic loads. First, we used recordings from 6 passive acoustic moorings to characterize the acoustic landscape experienced by SRKW in this region, focusing on the frequencies used for communication and echolocation. Mid-frequency wind noise was prevalent in winter sound fields, whereas higher-frequency noise levels associated with increased numbers of recreational vessels increased during summer. Commercial vessel presence was consistent, with acoustic inputs prevalent in the western part of the study area. The potential implications of these additions on SRKW acoustics use were then explored for the frequency band 1–40 kHz to represent communication calls and at 50 kHz to consider echolocation. The inputs of wind were extrapolated from modelled hourly wind speed measures and commercial shipping noise. The noise impact was expressed as a proportional reduction of communication and echolocation extent compared to maximum acoustic ranges at 'minimum ambient' levels, void of vessel and abiotic noise. The reductions calculated were substantial, with the presence and impact of vessel noise greater than wind-derived additions and the greatest impacts around shipping lanes. Impacts were found for SRKW foraging areas, with implications for group cohesion and feeding success. This interpretation of the influence of natural and vessel noise more clearly demonstrates the potential implications of altered soundscapes for SRKW.

KEY WORDS: Southern resident killer whales · Soundscape characterization · Vessel noise · Communication range reduction · Echolocation range reduction · Wind noise · Foraging ecology · Salish Sea

1. INTRODUCTION

Elevated underwater noise levels in the North East Pacific in recent decades have been attributed to an increase in both vessel number and capacity (Richardson et al. 1995, Hildebrand 2009). Although focused along shipping routes, increases have also been noted near coastal cities and major ports, with a corresponding increase in tourist-based and recreational traffic (Andrew et al. 2002, Frisk 2012, New et al. 2015). This increase in anthropogenic activity also adds to a trend of increasing storm events and wind-wave heights in the North East Pacific (e.g. Allan & Komar 2000, Gulev & Grigorieva 2004).

The Salish Sea, the waters around the southwest coast of Vancouver Island, northern Washington State, the Gulf of Georgia and San Juan Island, is a productive foraging area for several species, including the endangered southern resident killer whale (SRKW) *Orcinus orca*. This area, however, has the

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highest ambient noise levels for waters along the British Columbia coast (Erbe et al. 2012), which are directly attributable to commercial traffic transiting to and from ports in Vancouver, Victoria, and Nanaimo, Canada, and Port Angeles, Tacoma, and Seattle, USA. Whales are frequently sighted on Swiftsure Bank, in Juan de Fuca Strait, Haro Strait, Boundary Pass, and around the Southern Gulf Islands in the Salish Sea, which are designated critical habitat for SRKWs (Olson et al. 2018, DFO 2017a, 2021), yet international shipping lanes also intersect these areas (Cominelli et al. 2018). A highly acoustic odontocete species, SRKWs rely on the use of communicative calls, including whistles and burst-pulse sounds, as social signals, and echolocation in ultrasonic frequencies for foraging and navigation (Ford 1987, 1989, 1991, Riesch et al. 2006). Yet increases in abiotic and anthropogenic noise overlap with frequencies used by whales for these signals, potentially hindering their ability to echolocate or communicate with conspecifics (Holt et al. 2009, 2011), and shortening their effective communication (Clark et al. 2009) or echolocation range (Au et al. 2004). Both acoustic ranges are defined by the signal emitted, the sound field it is projected into and, in the case of echolocation range, the echo strength of the target.

Here, we used 2 yr of passive acoustic data to describe the spatiotemporal patterns in abiotic and anthropogenic inputs to the soundscape of the Salish Sea with a focus on additions to SRKW communication and echolocation frequencies. Then, wind speed and shipping noise models allowed us to interpolate between mooring locations, and examine the variation of noise through the water column. We then considered the implications of these sound inputs on the acoustic ranges of SRKWs, considering how different noise scenarios may reduce communication or echolocation ranges. This work forms part of a baseline evaluation of the acoustic environmental quality of the Salish Sea for SRKWs, as well as a stimulus for further discussions on the potential level of acoustic disturbance and reduced efficacy in calling or signaling they may experience. By taking this whale-centric perspective, we examine the potential for human impacts on this endangered whale population more directly and lay the foundations for future modelling and experimental work.

2. MATERIALS AND METHODS

2.1. Passive acoustic moorings

Calibrated autonomous multichannel acoustic recorders (AMAR, JASCO Applied Sciences, G4, equipped with GeoSpectrum Technologies M36-100 hydrophones) were deployed in 6 locations throughout the study area. Deployment depths varied between 73 and 235 m (Fig. 1, Table 1). Two years of continuous recordings (February 1, 2018–March 28, 2020) at a sample rate of 256 kHz with 24-bit resolution were made and stored on internal SD memory

Fig. 1. Network of 6 passive acoustic recorders in the Salish Sea (black circles) and weather buoys at Cape Flattery and New Dungeness (black triangles) that provided wind reports. Locations of the international shipping lanes also shown (dotted lines)

Table 1. Hydrophone mooring locations in the Salish Sea from February 1, 2018, to March 28, 2020. Each hydrophone was located 2 m above the sea floor

Mooring name	Latitude (N)	Longitude (W)	Water depth (m)
Swiftsure Bank	48° 30.924′	124° 56.156′	75
Port Renfrew	48° 30.274′	124° 31.016′	170
Jordan River	48° 23.793′	124° 07.976′	120
Sooke	48° 17.365′	123° 39.137′	165
Haro Strait	48° 29.750′	123° 11.567′	235
Boundary Pass	48° 44.014′	123° 08.741′	180

cards as wav files. These files were post-processed using custom Python scripts, modified from those used by Merchant et al. (2015), using 1 s Hanning window and 50% overlap and Welch's averaging. This generated 1 min power spectra in 1 Hz bands in the frequency domain for the full dataset. Data averaged to hour, day, lunar month, and season were used for further analysis, whereby diurnal periods were defined by nautical sunrise and sunset times, and seasons were distinguished using daylight savings dates. Spatiotemporal patterns of the sound levels from the recordings were examined for frequencies in ranges representing SRKW communication and echolocation (500–15 kHz and 15–100 kHz, respectively; Heise et al. 2017), adding to descriptions of the spatiotemporal patterns in soundscape levels by Burnham et al. (2021). For communication calls we used the frequency range of 1–40 kHz. This range was selected based on the sensitivity of hearing in audiogram curves for killer whales described by Szymanski et al. (1999) and Branstetter et al. (2017) and the frequency range of discrete SRKW calls recorded on axis by Holt et al. (2009). This range encompasses SRKW whistles (2–17 kHz; Ford 1989, Thomsen et al. 2001) and pulsed calls (1–15 kHz; Riesch et al. 2006) and their modulated higher and lower frequency components (Miller & Bain 2000). Throughout the calculations a flat frequency response over this range was presumed, and variation in sensitivity in hearing over the range as demonstrated in audiogram data (Szymanski et al. 1999, Branstetter et al. 2017) was not accounted for. This allowed us to take a more cautious approach in our interpretation of the possible acoustic disturbance and showed the maximum reduced ranges by presuming a 'worst case' scenario. For echolocation a single candidate frequency of 50 kHz was used. This analysis was representative of the center of the frequency distribution of SRKW bimodal echolocation clicks and is consistent with previous work by Au et al. (2004). The significance of changes in median hourly sound pressure levels (SPLs) and distribution of sound levels in the recordings over time and between locations were established through the use of non-parametric tests and comparisons in mean values made using Student *t*-tests (IBM SPSS Statistics 27). The recordings were used to validate the models described and annotate the findings.

2.2. Noise surfaces

2.2.1. Wind noise surfaces

Broad scale wind patterns were mapped from hourly wind data from the Environment and Climate Change Canada (ECCC) model reported at a 10 m height (available through the SalishSeaCast model; Soontiens et al. 2016, Soontiens & Allen 2017), downloaded at a spatial resolution of approximately 440 by 500 m, and visualized for the study area. These wind speed measures were converted to wind-generated noise through a relationship at 8 kHz (Vagle et al. 1990), estimated using:

$$\mathrm{SSL}\,(8\,\mathrm{kHz}) = 20 \cdot (s \cdot U10 + b) \text{ in dB re 1 µPa} \quad (1)$$

where $U10$ is the reported wind speed in m s^{-1}, s = 52.87 and b = −80.94. This pressure level at 8 kHz was then extrapolated to frequencies in the 1–40 kHz range and 50 kHz using the assumption that the SPL drops with increasing frequency at a rate of 19 dB per decade (Wenz 1962). This formed a first order estimate of wind-derived sound levels in the communication and echolocation ranges of SRKW.

2.2.2. Vessel noise surfaces

A shipping noise model based on the range-dependent acoustic model (RAM) established by Collins (1993) and refined by Aulanier et al. (2017) was used to further characterize commercial-vessel inputs and interpolate between moorings.The model used the Pade split-stepping method to solve the range-dependent parabolic equation for sound propagation in a cylindrical coordinate system over 120 equally distributed vertical planes and achieve 360-degree coverage around each transiting vessel as a noise source. Model inputs also included bathymetry (~300 m resolution; Haugerud 1999), predictions of sound propagation through unconsolidated sediment (Hamilton 1980, Jensen et al. 2011), salinity and temperature profiles collected during mooring servicing

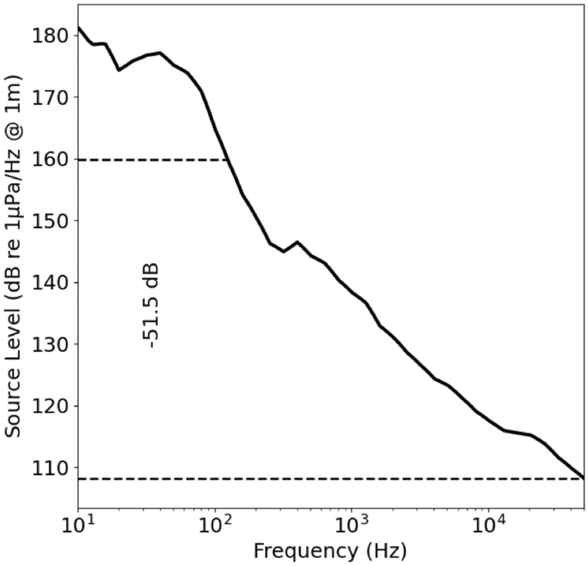

Fig. 2. Average monopole source level of bulk carriers transiting the Salish Sea taken from multiple transits. Figure derived from data from MacGillvray & Li (2018). Correctional factor (–51.5 dB) used for 50 kHz analysis extracted from modelled 125 Hz signals is shown (dashed lines)

(using Seabird Scientific SBE-25 CTD) augmented with hourly data obtained from the SalishSeaCast hydrodynamic model (Soontiens et al. 2016, Soontiens & Allen 2017), sound speed profiles derived from water density fields described by McDougall & Barker (2011) and frequency dependent absorption for a pH value of 8 (Francois & Garrison 1982), and source levels of vessels by type (MacGillivray & Li 2018) adjusted to transit speed using a linear relationship (Veirs et al. 2016). The source level (SL) of bulk carriers, the dominant commercial vessel type in the Salish Sea, was derived using the average signature of numerous vessels with various travel speeds (Fig. 2). This averaging went some way to capture the variance in acoustic signatures between vessels, which is also dependent on vessel speed, cavitation, and maintenance. However, this variation could not be fully captured in the model. The shipping noise model was run using Automatic Identification System (AIS) Class-A vessel information for the period between April 1, 2018, and March 31, 2019. Raw AIS data expressed vessel location, identity and destination every 2–10 s. These data were cleaned and binned into 5 min periods and then used to determine continuous vessel tracks of sequential 5 min data points for each vessel. The data distinguished between deep-sea vessels captured by AIS Class-A transceivers, which included bulk carriers, container ships, tankers and vehicle carriers, from vessels carrying Class-B AIS voluntarily, which are typically recreational or small commercial vessels. The shipping noise model output was a generated noise level (NL) at 125 Hz $\mathrm{NL}(125\,\mathrm{Hz},i,j,d))$ every 30 min at each grid point, at latitude i and longitude j, at up to 120 depths, d, for the year considered.

The NL output by the model at 125 Hz was used to estimate to the NL in SRKW frequencies using the bulk carrier frequency dependent SL curve (Fig. 2). Noise levels at frequencies of interest in SRKW communication and echolocation ranges were calculated using the relative correction needed ($d\mathrm{SL}(125\,\mathrm{Hz}-f)$) between SL at 125 Hz and the SL at the frequency of interest, f (Fig. 2). For the communication range, this correction was applied across each 1 Hz frequency band between 1 and 40 kHz. The relative reduction needed for the 50 kHz echolocation candidate frequency ($d\mathrm{SL}(125\,\mathrm{Hz}-50\,\mathrm{kHz})$) was –51.5 dB (Fig. 2). However, when extrapolating modelled vessel noise received levels (RL) to acoustic frequencies other than those used in the actual model run, the use of the relative SL obtained from the curve (Fig. 2) only is insufficient. A significant additional frequency dependent loss associated with range dependent absorption, $\alpha(f)$, in the water column is also needed. To incorporate frequency and range-dependent water absorption into the modeled received NLs, we assumed that the modelled noise predominantly comes from vessels transiting in the shipping lanes, and incorporated water absorption coefficients calculated for each grid point (i,j) in the model domain as functions of the nearest distances to the shipping lane, R_{SL}. Therefore, the modelled noise level at a given frequency, f and depth d, at any model grid point, $\mathrm{NL}(f,i,j,d)$ was calculated as:

$$\begin{aligned}\mathrm{NL}(f,i,j,d) = \mathrm{NL}(125\,\mathrm{Hz},i,j,d) - \\ d\mathrm{SL}(125\,\mathrm{Hz}-f) - \alpha(f)\cdot R_{\mathrm{SL}}(i,j)\end{aligned} \quad (2)$$

The prevalence of vessel noise over and above the natural abiotic influence of wind was considered by subtracting the wind noise map values from those calculated for shipping noise for each grid square in the model (i,j) for matching time periods. The implications of the excess on communication and echolocation ranges were also considered.

2.2.3. Minimum ambient noise levels

Noise levels from abiotic or anthropogenic sound sources add to the ambient noise level to form the overall soundscape of an area. The 'minimum ambient' noise level was derived for the study area from

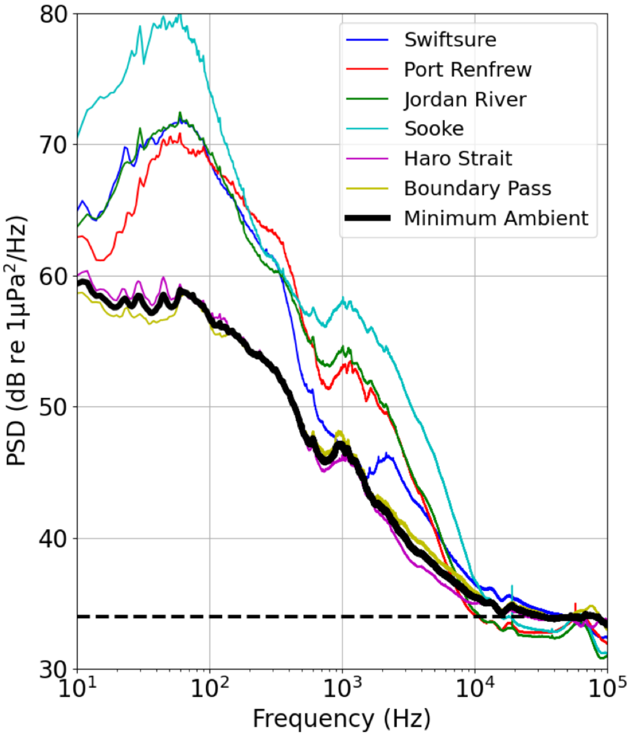

Fig. 3. Power Spectral Density (PSD) for L_{99} noise exceedance levels from recordings of the 6 mooring locations, May–September 2018–2020, with the 'minimum ambient' noise level (black line) formed from an aggregate of Haro Strait and Boundary Pass. Horizontal dashed line indicates the level at 50 kHz (34 dB) used in the present analysis. For locations see Fig. 1

the L_{99} exceedance levels from May to October of the 2 yr of recordings (Fig. 3). Here we use the L_{99} to represent the sound levels that were exceeded 99% of the time of the recordings, and so could be described as the background ambient noise level, when Beaufort Sea State was zero, and wind or vessel noise was absent, $\mathrm{NL}_0(f)$. Summer values were used as ambient noise levels, and the environmental influences on them were typically reduced in these months (Burnham et al. 2021). We chose to use one value that represented the absolute minimum possible for the study area and apply it globally throughout, rather than vary by location. Differences between sites in the range 1–40 kHz were negligible and minimal at 50 kHz (Fig. 3). Also, recordings from Juan de Fuca Strait and on Swiftsure Bank demonstrated a chronic input of commercial vessel noise into the lower frequencies and so were not used; only sites whose vessel passage patterns and topography allowed the exclusion of these noise inputs were therefore included in the minimum ambient curve used in this study (Fig. 3). The modeled noise field used in this study, NL′ can therefore be described as:

$$\begin{aligned} \mathrm{NL}'(f,i,j,d) &= \mathrm{NL}(f,i,j,d) \quad \text{for } \mathrm{NL}(f,i,j,d) \geq \mathrm{NL}_0(f) \\ \mathrm{NL}'(f,i,j,d) &= \mathrm{NL}_0(f) \quad \text{for } \mathrm{NL}(f,i,j,d) < \mathrm{NL}_0(f) \end{aligned} \tag{3}$$

2.3. Acoustic range calculations

2.3.1. Communication range at 1–40 kHz

The communication signals are 1-way signals between a calling animal and conspecifics in surrounding waters. The sonar equation was used to define these calls, whereby a received signal within the frequency band Δf = 1–40 kHz, at R distance away calling whale emitted with source level, $\mathrm{SL}(\Delta f)$, at a depth, d, and near grid point i,j, can be written as:

$$\mathrm{RL}(\Delta f,i,j,d,R) = \mathrm{SL}(\Delta f) - K\log(R) - \alpha(\Delta f)R \tag{4}$$

where K is a spreading loss coefficient and $\alpha(\Delta f)$ is the frequency dependent absorption coefficient at frequencies in the 1–40 kHz range. We assumed that a call is detectable only if RL exceeds the local noise level NL′ from Eq. (3) integrated over Δf. Therefore, the maximum distance over which a communication signal could be detected when emitted at location i,j, and depth d, in the presence of background noise, $R_{\max}(i,j,d)$, would be calculated using:

$$\begin{gathered} \mathrm{SL}(\Delta f) - K\log(R_{\max}(i,j,d)) - \\ \alpha(\Delta f)R_{\max}(i,j,d) - \mathrm{NL}'(\Delta f,i,j,d) = 0 \end{gathered} \tag{5}$$

Spreading loss, K was assumed to be $K = 20$, representing spherical spreading. An SL of $\mathrm{SL}(\Delta f)$ = 174 dB re µPa at 1 m was used, representing the maximum SL reported by Holt et al. (2009) for SRKW-stereotyped calls in the 1–40 kHz range, and consistent with later works by Holt et al. (2011; 135.0–175.7 dB re µPa at 1 m). We assumed that the SL was frequency independent over this frequency range to allow for integration of Eq. (5).

2.3.2. Echolocation range at 50 kHz

The available echolocation range for SRKW is the maximum distance an echolocation click can be transmitted by the whale to a target, and the returning signal can be identified and interpreted by the whale in the presence of noise. The returning signal must exceed background noise levels, and have a signal to noise ratio (SNR) greater than 1. Estimates of range were made using source levels (195–224 dB re µPa at 1 m) and directionality for a 50 kHz signal to a target prey item as outlined by Au et al. (2004).

The target strength of the average Chinook salmon *Oncorhynchus tshawytscha* prey was characterized using a Kirchhoff-ray mode backscatter model (Clay & Horne 1994). The body was defined as fluid-filled cylinders surrounding air-filled cylinders to represent the swim bladder, using dimensions of a Chinook salmon of 0.78 m in length and weighing between 3.7 and 8.1 kg (Au et al. 2004). The relative angle between the whale and its fish target was also important, and therefore it was necessary to define the relative depth between animal and prey when calculating the available echolocation range. In all ranges calculated the whale was kept at 10 m depth, and the fish target varied to 7.5 m, 50 m, and 100 m. The depth of 7.5 m in the upper water column represents SRKW typical traveling depth, 50 m represents the typical Chinook swimming depth (43.4 m; Wright et al. 2017) and a maximum repeatable foraging dive depth is represented by the use of 100 m.

2.3.3. Range reduction calculations

Maximum available communication and echolocation ranges were calculated using the methods outlined above for conditions considered to be 'minimum ambient' noise levels. The estimated communication and echolocation ranges under wind or vessel noise scenarios were then expressed as a proportional reduction of the maximum range. The absolute maximum communication range is when NL' = NL in Eq. (5) and was estimated to be approximately 8050 m. The maximum range for echolocation signals of 50 kHz was calculated with the whale and Chinook prey at the same depth, and using minimum ambient conditions (34 dB, Fig. 3) and was estimated to be approximately 420 m. For both communication and echolocation, range reduction as a result of noise inputs was then calculated as the ratio of calculated range estimates under the noise scenarios to these maximum range estimates. The reductions in range for the abiotic and anthropogenic noise scenarios were considered over time and space. The vessel noise model allowed the examination of changes due to commercial vessel additions in both horizontal and vertical space. Again, taking the whale-perspective, an upper (7.5 m) and mid-water column (50 m) depth was used to represent typical SRKW diving depths, with 100 m used to represent a maximum repeated foraging dive depth (Baird 2000, 2005, Tennessen et al. 2019a,b). The 100 m maximum also represents the distance over which Au et al. (2004) described SRKWs capable of detecting Chinook salmon in quiet conditions.

3. RESULTS

3.1. Spatial and temporal variation of sound in SRKW frequency ranges

The greatest variability in SPL levels for the SRKW communication and echolocation ranges was found at Boundary Pass, where both the highest maximum and lowest minimum SLs were recorded. This was one of the 2 sites averaged to derive the minimum ambient NL (Fig. 3). Significant increases were found from the beginning to the end of the study period in mean hourly SPL for recordings made in Juan de Fuca Strait. For the communication frequencies a rise of 3 dB on average, at Swiftsure Bank (2018 to 2020: $t(911273.626) = -9.134$, $p < 0.001$), and 1.5 dB at Port Renfrew and Jordan River (2018 to 2020: $t(4236.628) = -13.434$, $p < 0.001$ and $t(15797.304) = -7.578$, $p < 0.001$, respectively) was noted. Similar increases were also recorded for SRKW echolocation frequencies (~2 dB from 2018 to 2020, Port Renfrew $t(3551.257) = -14.437$, $p < 0.001$; Jordan River $t(2945.672) = -13.018$, $p < 0.001$).

3.2. Wind noise

Wind noise showed strong seasonal patterning. Offshore influences funneling wind into Juan de Fuca Strait resulted in elevated sound levels in the communication range on Swiftsure Bank and east to Jordan River from October and into the spring (Fig. 4). At the eastern end of the Strait, more localized wind noise increases in the spring and summer (Fig. 4, April to June) dissipated in the winter, with abiotic additions limited to the area around Sooke (Fig. 4) and the recordings made there. In the higher frequency representing the echolocation range only the area around Swiftsure Bank indicated significant reductions during the winter months (Fig. 4).

3.3. Vessel noise

Increases in SPLs in SRKW frequencies in the summer in the recordings were coincident with increases in small vessels observed in the Class-B AIS records. Commercial vessels were consistent over time; however, recreational vessels voluntarily transmitting Class-B AIS signals increased during the summer from June to a peak in August in the coastal waters directly around the moorings. Sound levels at 50 kHz increased at all sites during the summer, likely attrib-

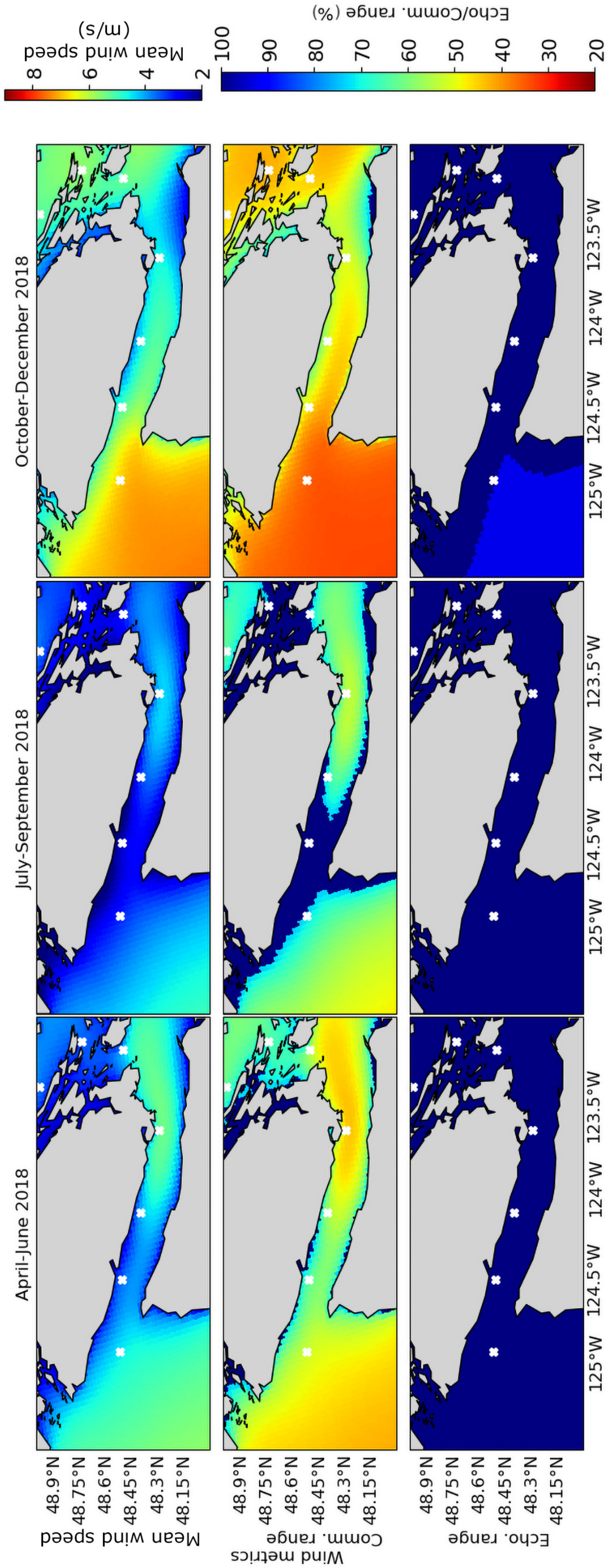

Fig. 4. Average wind speed (top row) and reductions seen for 1–40 kHz (Comm.) and 50 kHz (Echo.) signals resulting from wind noise. Results are unweighted to southern resident killer whale hearing sensitivities and so represent the worst-case scenario. January to March showed identical results to October to December and so are not depicted in a separate panel. Mooring locations indicated as white crosses

utable to higher frequency cavitation of smaller propellers' faster rotation on smaller vessels as well as echosounders or fish finders (Joy et al. 2019, Burnham et al. 2021). Haro Strait and Boundary Pass recordings, used to derive the minimum ambient sound level, showed shorter-term vessel impacts on the soundscape in comparison to the western Strait and Swiftsure Bank, where vessel noise was more consistent.

The low-frequency commercial noise output from the shipping noise model showed that elevated noise levels were focused around the shipping lanes and turning locations and in shallower waters (median vessel noise levels, Fig. 5). Increases in shipping noise were also present throughout the Gulf Islands between April and June due to a seasonal increase in ferry traffic (Fig. 5). Elevated vessel noise was more widespread towards the end of the year and was at its greatest from January to March, with noise levels greatest at this time in the mid-water column (50 m, Fig. 5).

The comparison of vessel and wind noise in the communication band of 1–40 kHz and echolocation candidate frequency of 50 kHz showed that even at the highest wind speeds, and at times and/or places where wind noise would be elevated, the influence of abiotic noise would be less than that from commercial vessels at median levels (Fig. 6). A scenario considering median vessel noise and wind noise derived from average wind speeds showed vessel noise to dominate throughout Juan de Fuca Strait and into the Gulf Islands, especially during summer at 1–40 kHz. At 50 kHz, the dominance of vessel noise was constrained to the shipping lanes only. Otherwise, wind noise was the prevalent soundscape feature (Fig. 6). Varying the contribution of vessel noise with the same average wind speed noise showed that the elevated wind noise in the eastern portion of Juan de Fuca Strait around Sooke (Fig. 4) was only apparent when vessel noise contributions were reduced to L_{25} or lower, suggesting that, even when elevated, wind noise dominated over anthropogenic noise in these areas 25% or less of the time at 1–40 kHz, and the shipping lanes through this area were still highlighted for vessel noise at this level for 50 kHz (Fig. 7).

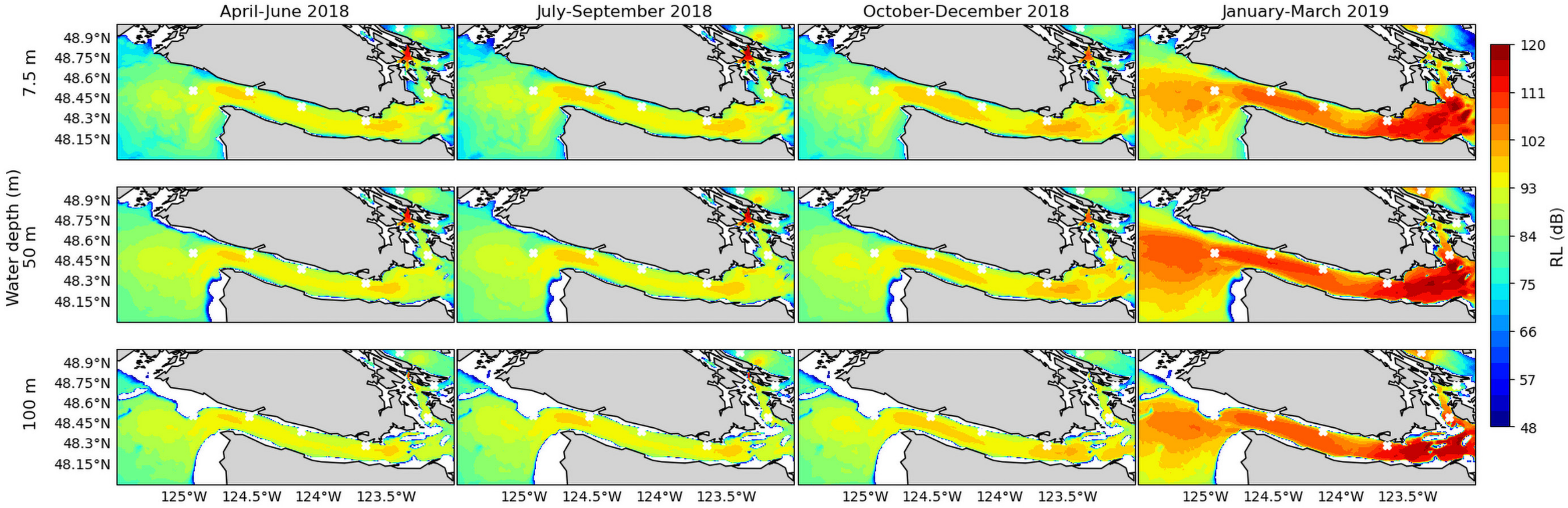

Fig. 5. Vessel noise additions at 125 Hz for commercial Class A vessels transiting the study area as obtained from the shipping noise model. Comparisons were made for median noise levels (L_{50}) for 3 mo periods and for water depths 7.5, 50, 100 m. RL: vessel noise received levels. Mooring locations indicated as white crosses

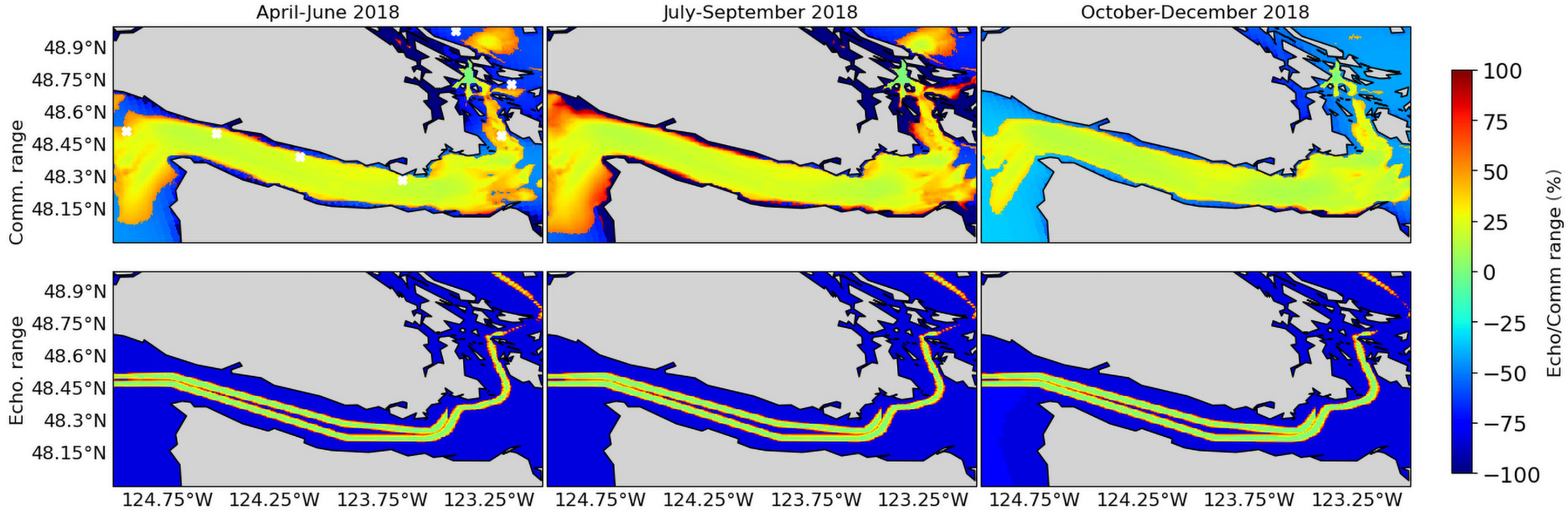

Fig. 6. Communication (Comm.) and echolocation (Echo.) range reductions as a result of median vessel noise (positive percentage values/red-orange tones) and average wind speeds (negative percentage values/blue tones) to indicate where and when each of the 2 noise sources dominate. Mooring locations indicated as white crosses

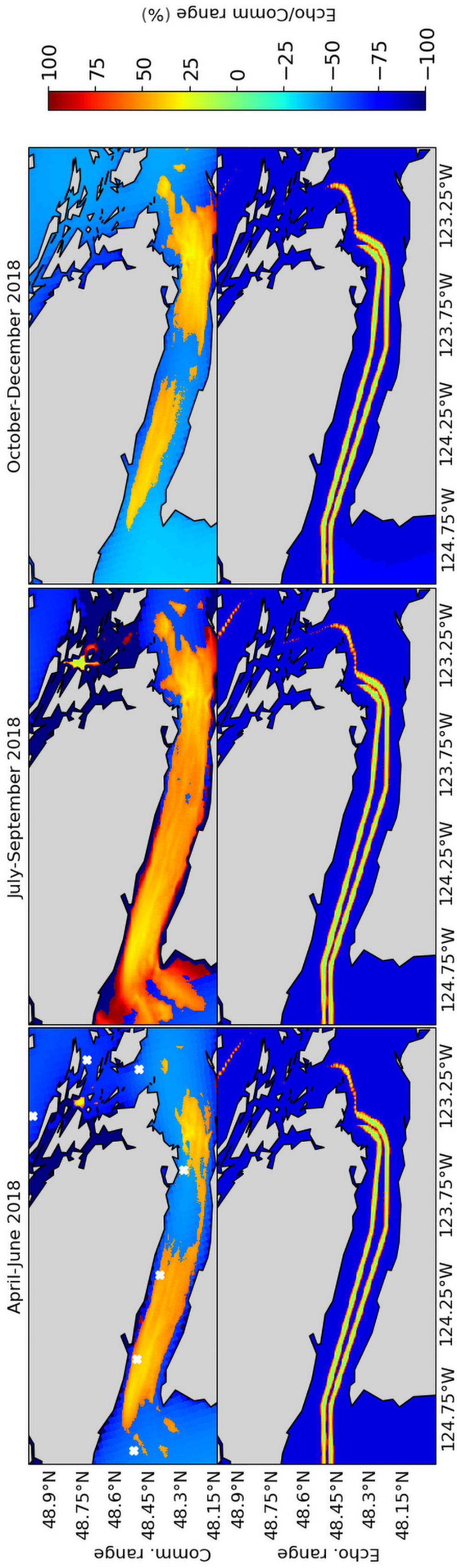

Fig. 7. Communication (Comm.) and echolocation (Echo.) range reductions as a result of L_{25} vessel noise (positive percentage values/red-orange tones) and average wind speeds (negative percentage values/blue tones) to indicate where and when each of the 2 noise sources dominates L_{25} here is the quietest 25% of all vessel noise recordings. Mooring locations indicated as white crosses

3.4. Communication and echolocation range variability

Greater, more spatially extensive, acoustic range reductions were seen in the 1–40 kHz analysis compared to the 50 kHz analysis for both the abiotic and anthropogenic noise scenarios. These both represent a 'worst case' scenario for the potential for masking to occur and does not take into account the variation in hearing sensitivity based on frequency as described by Szymanski et al. (1999) and Branstetter et al. (2017). Greater variation through time and space was also observed for the communication frequency range, with little difference seen between the 3 mo periods for echolocation range reductions (Figs. 4, 8 & 9).

Acoustic range reductions from elevated abiotic noise were greater in the 1–40 kHz analysis compared to the 50 kHz. Spatially, the decreases in range were greatest at the western entrance of Juan de Fuca Strait, around the Port Renfrew mooring and at the entrance to Haro Strait (Fig. 4). Temporally, in these regions the greater range reductions were found from October to March (Fig. 4). The influence of wind noise was notable in the offshore waters of Swiftsure Bank from October and into the spring, and the wind funneling effect was greatest around Sooke in the early summer (April–June, Fig. 4). At times when range reductions were at their greatest (October to March), whales would be expected to experience reduced ranges of 40–60% in almost all regions of the study area from wind noise (Fig. 4). The impacts on echolocation signals at 50 kHz were most strongly found during the fall and winter months from offshore wind increases (Fig. 4).

The shipping noise model also emphasized the decreases in the 1–40 kHz range, greatest at the western entrance of Juan de Fuca Strait, around Port Renfrew, and at times extending as far as the Jordan River mooring. Reductions were also highlighted at the entrance to Haro Strait around the Sooke mooring (Fig. 8). During the cooler months of October to March the extent of these reductions, of up to 90% range reduction, encompassed Juan de Fuca Strait, with the spatial extent of impact the greatest, and communication range most reduced, in December to March at 50 m water depth (Fig. 8). The model suggests at this time, signals at 1–40 kHz between whales may not exceed background noise levels at both western and eastern extents of Juan de Fuca Strait when taking a cautious approach in interpretation (Fig. 8).

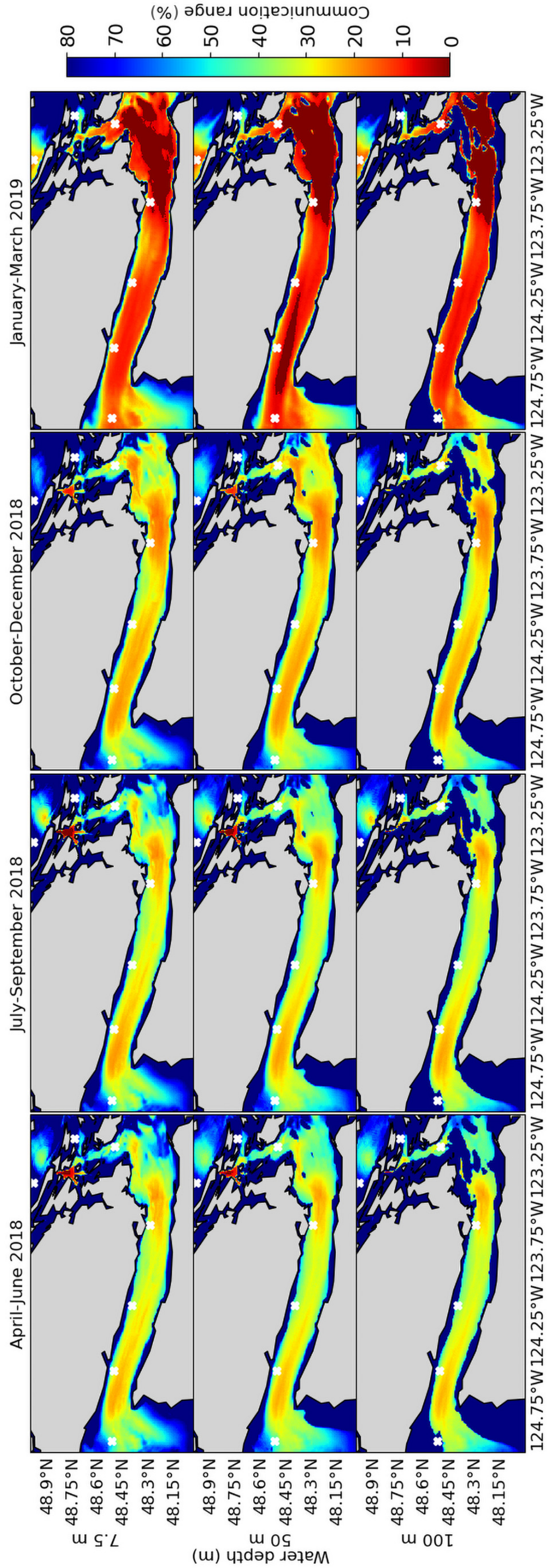

Fig. 8. Proportional reduction of 1–40 kHz band signal range from 'minimum ambient' conditions representing communication call use by southern resident killer whales (SRKWs). Results are unweighted to SRKW hearing sensitivities and so represent the worst-case scenario. Comparisons were made for 3 mo periods, at water depths 7.5, 50, 100 m. Mooring locations indicated as white crosses

Reductions resulting from shipping noise at 50 kHz traced the shipping lanes (Fig. 9). The spatial extent of the higher frequency noise inputs was restricted, but reductions in 50 kHz signal use were greatest between January and March at the 3 depths (Fig. 9). At all times considered, SRKWs swimming in the upper water column at 10 m echolocating to depth would be most impacted the closer to the shipping lanes they were, with these higher frequency additions lost quickly over horizontal space but consistently through the water column (Fig. 9). A 'worst case' scenario of the model suggests that in the shipping lanes themselves echolocation signal returns at 50 kHz would not exceed ambient noise levels, impacting whales transiting and foraging in Juan de Fuca and through the Gulf Islands (Fig. 9).

4. DISCUSSION

Soundscapes are dynamic composites of natural and anthropogenic noise, creating distinct acoustic environments over time and space. In the study area, vessel noise was dominant over average wind noise in the mid-frequencies for SRKW communication calls (1–40 kHz) and echolocation at 50 kHz, in particular near the shipping lanes. In visualizing the spatiotemporal patterns in wind and vessel noise for 1–40 and 50 kHz (Figs. 4 & 5), we did not presume that the anthropogenic and abiotic noise additions would be purely additive in terms of soundscape impact or the perception by SRKWs, and so they were purely compared. When comparing the effects on communication and echolocation ranges from vessel and wind noise, vessel noise dominated the soundscape even when the wind-generated components were present in the same frequency, duration, and amplitude (Figs. 6 & 7). The 1–40 kHz analysis for communication calls was more sensitive to variations in wind noise, yet seasonal increases in wind noise were only perceptible over shipping noise for 25% or less of the time (Figs. 6 & 7).

Range reductions were found most noticeably in the 1–40 kHz analysis compared to the 50 kHz analysis (Figs. 4, 8 & 9). Offshore wind influences were relevant to both the frequency range and higher frequency candidate frequency in the winter months, extending as far as Jordan River (Fig. 4). However, wind noise increases in the

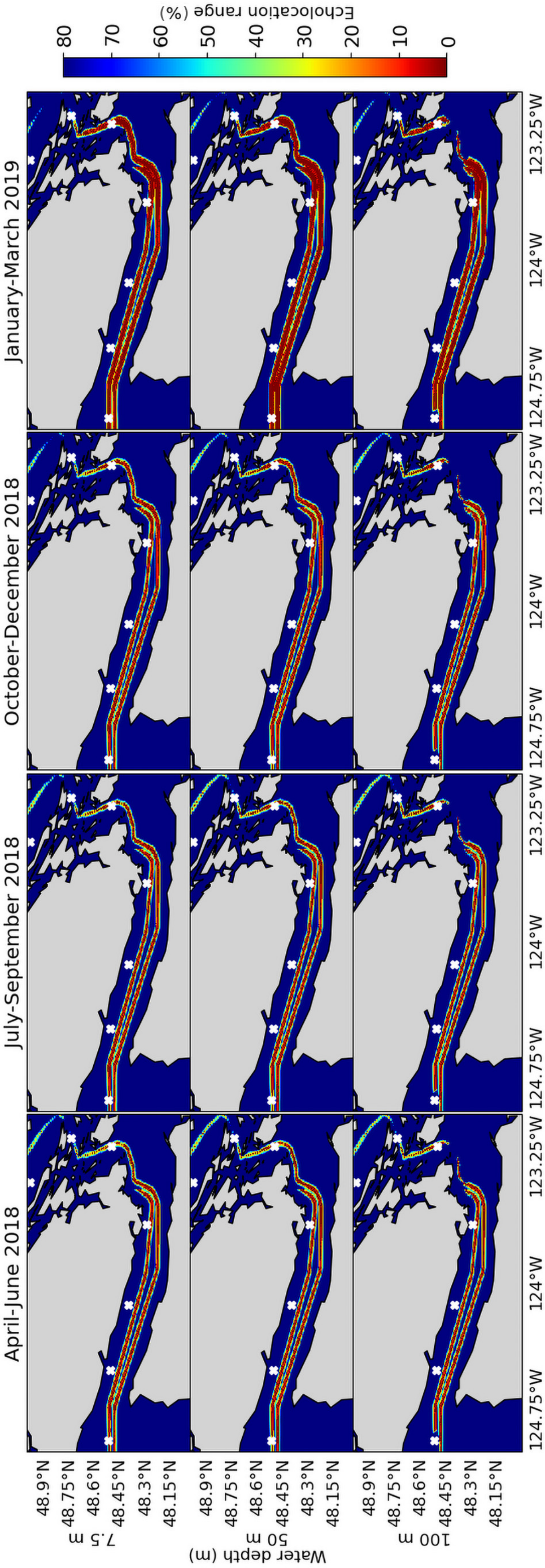

Fig. 9. Proportional reduction of 50 kHz signal range from ‘minimum ambient’ conditions representing echolocation use by southern resident killer whales (SRKWs). Results are unweighted to SRKW hearing sensitivities and so represent the worst-case scenario. Comparisons were made for 3 mo periods, with the whale at 10 m echolocating on Chinook salmon prey at depths of 7.5, 50, 100 m. Mooring locations indicated as white crosses

summer, when SRKWs most frequently utilize the Salish Sea, reduced the active range of communication signals in the 1–40 kHz range dramatically (Fig. 4). The areas most impacted, on Swiftsure Bank and at the entrance to Haro Strait, are where foraging behaviours have been most observed (Fig. 4; Olson et al. 2018, DFO 2021). Observational and anecdotal data suggest that wind noise could impact the way SRKWs use the study area. When wind speeds begin to increase on Swiftsure Bank, whales are more frequently located in inside waters, particularly around Haro Strait, having spent the previous months, when winds are lesser, foraging in the western portion of Juan de Fuca Strait. In the area around Sooke, fewer acoustic encounters and shorter encounter lengths have also been noted in comparison to those in western Juan de Fuca Strait, with visual observations suggesting SRKW behaviour is predominantly travel, rather than foraging, in this area (DFO 2021). Although this and previous analyses (Au et al. 2004) have noted the capacity of natural, non-biological noise to reduce effective acoustic ranges for SRKWs, it is also possible that whales use these types of sound from their surroundings as cues (e.g. Allen 2013) and have evolved to adapt to variations in natural noise (Dunlop et al. 2014, Fournet et al. 2018). Indeed, Au et al. (2004) determined that echolocation signal amplitudes would be great enough for SRKWs to detect prey even in high wind and wave conditions, and our analysis showed that the wind noise influence on echolocation efficacy would be limited to offshore waters during the winter for 50 kHz signals (Fig. 4).

Shipping lanes were the foci of the vessel noise for both the 1–40 and 50 kHz analyses at median exceedance levels (Figs. 8 & 9). In the lower frequency range, the additions traced the shipping lanes in October to December; noise levels were also elevated in shallower waters and in areas of turning or maneuvering for vessels, reducing available communication range between conspecifics (Fig. 8). In the 1–40 kHz analysis, areas noted as foraging regions for SRKWs, including Swiftsure Bank, the Strait of Juan de Fuca, and waters around Salmon Bank in Haro Strait were consistently emphasized for vessel noise impacts (Fig. 8). The model did not show considerable variability of noise effects with depth; however, mid-water depths of 50 m showed the most accentuated effect in the fall and winter (Fig. 8). This represents an increased impact at depths where SRKW might first encounter salmon prey. If a whale were using areas directly in the vicinity of the shipping lanes, the echolocation range of a SRKW at a typical swimming depth (<10 m; Baird et al. 2003, 2005, Tennessen et al. 2019a) to Chinook average swimming depth could be reduced by more than 50 % in these areas at all times due to commercial traffic noise (Fig. 9). Considered together, these results suggest that vessel noise could negatively impact a whale's ability to search for and pursue prey at each step of foraging by foreshortening distances over which conspecifics can coordinate feeding behaviours, shortening the distances SRKWs can effectively send and receive echolocation signals to find and capture fish, and then limiting social signal extent that may initiate prey sharing post-kill (Ford & Ellis 2014, Wright et al. 2016). This could result in significant implications for the health and success of both individuals and the population.

Consistency in the AIS Class-A data, and, therefore, inputs of commercial vessels into the shipping noise model, contrasted with the seasonal changes apparent in the mooring recordings. This further emphasizes the impact on the soundscape of Class-B and recreation vessels that are not currently captured by the model. It is not clear if small vessel contributions would surpass those of commercial vessels, but the mooring data suggest that these vessels may have the power to shape the sound fields in SRKW-relevant frequencies at times and on localized scales, despite them being underrepresented in analyses such as this (Hermannsen et al. 2019, Serra-Sogas et al. 2021). Observations in the study area have shown it is not uncommon to see at least 50 smaller vessels in proximity to whales, especially over summer weekends or holidays (Koski et al. 2006, Holt et al. 2009), and so this may be a considerable factor in SRKW acoustic use and perception, particularly in the higher frequencies. The seasonality in the commercial vessel noise seen in the model outputs (Figs. 6, 8 & 9) may result from reduced propagation losses in the water column (Vagle et al. 2021), as well as the effect of the bottom sediment boundary and the bathymetric features in areas around Swiftsure Bank, Sooke, and the entrance to Haro Strait. Throughout the winter, transmission losses are reduced with depth. This may increase the impact of vessel noise as whales dive and swim at depth and decrease the range over which calling or echolocation might be effective (SNR > 0, Figs. 6, 7 & 9; Vagle et al. 2021).

The reduced ability to send and receive signals, discern a signal from background noise, or accurately interpret signal content could be a critical factor in SRKW survival and has been acknowledged as a particular risk for acoustically sensitive species like killer whales (Simmonds et al. 2004, Weilgart 2007). In the present analysis, the impacts of noise were expressed as a proportional rather than absolute loss to determine the areas in the Salish Sea that might be highly implicated for abiotic or human-derived noise additions. The calculations did not take into account the hearing sensitivity of the whales from audiograms, other than helping define the frequency range considered to describe communication calls. Noise levels in all wind and shipping noise scenarios exceeded hearing threshold for the frequencies used for both conspecific calling and echolocation. An estimation of the SRKW hearing sensitivity at each frequency modeled (1–40 and 50 kHz) could be used to correct the absolute range estimations made under minimum ambient and noise conditions. Inclusion of weighting based on the audiogram (Branstetter et al. 2017) may reduce the extent of noise impacts in the lower frequencies for the communication calls, despite this possibly being an important component of pulsed calls (Miller & Bain 2000). Changes in effect may be seen if detection thresholds considered both background noise level and critical ratios (Fletcher 1940, Jensen et al. 2012, Branstetter et al. 2021) at each frequency to again better represent hearing ability, but here we used a consistent signal to noise ratio for both the 1–40 and 50 kHz analyses, which was in line with the definitions used by Au et al. (2004) in previous work on echolocation range. The inclusions of the critical ratio in this case may be a more pertinent factor for the frequency range used to define communication calls rather than the single candidate frequency used for echolocation (Lemonds et al. 2011, von Benda-Beckmann et al. 2021). The results presented in our analysis may, therefore, overemphasize the potential masking effect at some frequencies. By leaving the results unweighted, the potential maximum effect of noise impacts on SRKW acoustics use is demonstrated. This is in line with taking a more cautious approach when applying results like these to evidence-based management actions designed to lessen acoustic disturbance.

Our findings represent a worst-case scenario, both indicating the highest level of acoustic habitat degradation SRKWs may experience currently and acting as a forewarning of the potential impacts if vessel noise increases further. It is a first approximation of potential effect and represents an initial attempt to quantify the comparative impact of sound additions over space and time. The model does not capture the dynamics or adaptability of SRKW calling or nuances of behaviour, with the work presented here a prologue to future work examining SRKW echolocation source levels and call transmission loss in this area. Results by Leu et al. (2022) suggest how the received echolocating signal might be altered in frequency based on the distance and angle between the animal emitting the 'clicks' and its target from comparisons to the signal characteristics described by Au et al. (2004), and so this may need to be considered in future model iterations. Plasticity in call parameters and calling behaviours such as altered inter-pulse intervals (Lammers et al. 2004, Madsen et al. 2005, Morisaka et al. 2011) or Lombard-effect type compensatory measures in call amplitude, duration or frequency (Foote et al. 2004, Holt et al. 2009, 2011, 2015) was not included. Also, spatial, temporal or co-modulation masking release mechanisms (Erbe et al. 2016) were not considered in this first iteration. The noise source emissions were presumed to be omnidirectional, as was SRKW calling/echolocating and sound reception. To comprehensively calculate the potential reprieve through spatial release, consideration must be given to all possible computations of whale (outgoing signal and hearing direction) and noise source directionality, as well as fish target directionality and orientation for echolocation, and not just angle between the whale and its prey (Au et al. 2004, 2010). Weighting was also not given to areas where whales have been most frequently seen (Olson et al. 2018, DFO 2021). Summer habitat use of the Salish Sea by SRKWs has varied in recent years (Hanson et al. 2021), though sightings are typically greater between April and September, when whales follow the 'in-migration' of Chinook salmon through these waters to spawning grounds (Waples et al. 2004, Hanson et al. 2010). Knowledge of their distribution in the winter is, however, still relatively poor. For those whales using the study area at this time, it is thought that their movements correlate with chum salmon *Oncorhynchus keta* runs (Osborne 1999, Vélez-Espino et al. 2014), which are typically found at shallower water depths (22.0 m; Wright et al. 2017). In not making assumptions regarding habitat use or sensitivity of sound reception, which varies between individuals, we represent the unbiased, most acute noise conditions for whales using the study area. Spatially, the model does not account for variability in the whale location in relation to vessels, nor does it fully represent the transitory nature of vessel noise. The vessel presence is best characterized as a chronic problem, as observed in the Swiftsure Bank recordings, rather than a series of transient acute events, as seen for Haro Strait and Boundary Pass. The results, therefore, represent the most severe scenario of vessel noise additions. Although the shipping noise model allows us to examine the changes with water depth, calculations are still limited to a 2D range rather than a 3D agent-modeled communication or echolocation space or area.

We recognize that by not including these additional variables the work presented here takes a relatively simplistic approach, and refinement of the model and its assumptions, and both vessel noise and SRKW acoustic signaling variables, are required to fully measure the implications of vessels on SRKWs as they use the Salish Sea. Currently the shipping model only represents a portion of the vessel load of this region by modeling only the commercial traffic component, with the expectation that this will increase in the near-term (NEB 2016), along with recreational vessel numbers. That said, having a reference of current vessel loads and ambient noise levels and a mechanism for describing the potential impact will support estimates of the implications of these increases and the design of future management and mitigation plans. The mooring recordings already indicate an increasing trend in sound levels in the SRKW-relevant frequencies; should this continue or be intensified, it could have population-level ramifications.

Behavioural responses in calling, altered dive patterns, and cessation of feeding leading to lost foraging opportunities have been described for SRKW as a result of vessel presence (Foote et al. 2004, Williams et al. 2006, 2009, 2014, Holt et al. 2009, 2011, 2015, 2021, Lusseau et al. 2009, Noren et al. 2009). A level of noise that results in the reduced use or abandonment of foraging areas that could be applicable to SRKW in the Salish Sea, where the level of acoustic disturbance outweighs the biological demands to feed, is yet to be determined. However, this analysis suggests that considerable acoustic stress may be experienced by SRKWs in the study area. Considered in a cumulative framework with other threats, including vessel-strike risk, prey depletion (Shields et al. 2018, Nelson et al. 2019), and habitat contamination (DFO 2017a,b, 2018, Lacy et al. 2017, Raverty et al. 2020), suggests that there are substantial challenges for the SRKW population (Murray et al. 2021). We have focused our interpretation of the acoustic analysis on foraging, but changes in efficacy of echolocation could have implications for travel and navigation, and reduced conspecific call success may have implications for finding a mate, maintaining group cohesion, or structuring social groups and their extent of dispersal (Janik 2000, Jensen et al. 2012). The changes in communication and echolocation ranges we present here could be used by managers as a proxy for foraging ease or success. Quantification of proportional reductions represents a more biologically relevant way to express the impact of increased ambient noise. Considering soundscape changes using a species-specific noise metric supports a more whale-centric approach that will substantially improve our estimation of the implications of noise on an endangered species, even with the limitations of the model. Further model refinement and more accurate inclusion of vessel presence, and their acoustic additions, will increase our knowledge of factors that are impeding SRKW recovery and provide a better foundation of evidence for future mitigation actions.

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