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Areas of elevated risk for vessel-related physical and acoustic impacts in Southern Resident Killer Whale (*Orcinus orca*) critical habitat

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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PREFACE

The Southern Resident Killer Whale (SRKW; *Orcinus orca*) population in Canadian Pacific waters is listed as Endangered under the Federal *Species at Risk Act*. Critical habitat (CH) has been identified as portions of the waters on the continental shelf off southwestern Vancouver Island and eastward to include parts of the Salish Sea (Figure 1). The spatial extent of the CH is large and there is a need to focus recovery efforts on areas within the CH that have the greatest potential to provide benefits to the population.

The Southern Resident Killer Whale (SRKW) population consisted of 74 individuals in 2021 (Centre for Whale Research 2021[1]). Areas of coastal and inland waters around Vancouver Island are now legally designated critical habitat (CH) as they are important for life history events that support the survival and recovery of the population.

The Salish Sea encompasses the inland waters around southern Vancouver Island, the Juan de Fuca Strait and the Strait of Georgia in Canada, and the San Juan Islands and Puget Sound in Washington State in the United States, and is bounded to the west by a line from Cape Flattery to Carmanah Point. These waterways will be collectively referred to as the Salish Sea throughout this document. The area of SRKW CH to the west of this line includes La Perouse Bank, Swiftsure Bank, and various canyons and submarine features. For ease of reference, this portion of SRKW CH is referred to as 'the Swiftsure Bank area' throughout this document. The phrase 'the study area' is used in this document to refer to both of these regions.

The co-occurrence analysis presented here brings together the sighting records and behavioural observations that are detailed in Thornton et al. (2022), with the soundscape and vessel presence analysis of Vagle et al. (2021), to highlight areas where SRKW would be most at risk of physical and acoustic disturbance and vessel strike. These analyses focus on whale presence data from May to October, which is referred to throughout the document as 'summer'.

Physical and acoustic disturbance, and vessel strike have been listed as primary threats to SRKW population recovery. Contaminants and reductions in prey availability are also listed as key threats to SRKW, but are outside the scope of this document. It is hoped that a similar co-occurrence analysis will be applied to these factors in the future, adding additional layers of understanding to the risk analysis presented here.

[1] Center for Whale Research. 2020. Southern resident orca community demographics, composition of pods, births and deaths since 1998. Unpubl data. Accessed from Orca Network.

ABSTRACT

Primary threats to the endangered Southern Resident Killer Whale (SRKW) population are reduced prey availability, acoustic and physical disturbance, contaminants, and vessel strike. Successful threat mitigation is contingent on knowledge of spatiotemporal overlap of whale presence with areas of elevated risk.

A co-occurrence framework was used to illustrate areas within the critical habitat where SRKW are at higher risk for physical and acoustic disturbance and strike from vessels from May to October. The SRKW sightings data analyses indicate that the locations with the highest SRKW frequency of occurrence are Swiftsure Bank, Haro Strait, the Fraser River estuary. Individual and group follow data were used to add behavioural context to sightings data and identify Swiftsure Bank and Haro Strait as key foraging locations, while Juan de Fuca Strait is mainly used for travel.

Collision risk was determined using a combination of Automatic Information System (AIS) vessel data to assess presence of large commercial ships, and aerial surveys adding to records of the presence of smaller or recreational vessels.

The acoustic implications of vessel presence were explored by examining the noise additions in frequency ranges used for SRKW communication (500 Hz to 15 kHz) and echolocation (15-100 kHz). A reference level of ‘minimum ambient’ noise was derived from the 1% quietest conditions obtained from acoustic mooring recordings in the study area. The ranges at which calls and clicks could travel in minimum ambient conditions were then calculated. Loss of communication and echolocation ranges were expressed as percent reductions from minimum ambient. Noise from AIS Class A vessels resulted in significant loss of both echolocation and communication range in SRKW critical habitat. Echolocation range loss of greater than 50% was identified in key foraging locations, and range loss increased with foraging depth. Echolocation range loss from small vessels was also observed, with increased impacts occurring on weekends.

These analyses will inform recovery measures to reduce acoustic impacts on SRKW in critical habitat, and provide a framework for future investigations on threats to recovery. Moving forward, inclusion of prey and contaminants data into the co-occurrence analysis will inform our understanding of cumulative effects, and will support management actions for the survival and recovery of the population.

1. INTRODUCTION

The Southern Resident Killer Whale (SRKW) population is the smallest of the four Killer Whale populations found in Canadian Pacific waters and is listed as Endangered under Canada's *Species at Risk Act* (SARA). In 2021, the population consisted of only 74 individuals (Center for Whale Research, 2021[1]). Primary threats to recovery were identified in the Recovery Strategy (Fisheries and Oceans Canada, 2018) and included reductions in prey availability, physical and acoustic disturbance, and contaminants. In 2017, vessel strike was identified as an additional threat to the population (Fisheries and Oceans Canada, 2018; Raverty et al., 2020).

Killer whales associate in maternal groups which usually consist of multiple generations of individuals that are related by matrilineal descent (Bigg et al., 1987). Closely related matrilines are identified as pods, which share stereotyped calls that can be used to acoustically differentiate each pod (Ford, 1991). The SRKW population consists of the J, K and L pod.

Areas of coastal and inland waters around Vancouver Island have been identified as SRKW critical habitat (CH) under the SARA (Figure 1; Ford, 2006; Fisheries and Oceans Canada, 2018; Ford et al., 2017). Identification and designation of CH is designed to protect areas that are necessary for the survival and recovery of the species, and to support key life process such as foraging, socializing, resting, travelling and mating. The SARA protects any part of the SRKW's CH from destruction (Section 58; Appendix I). Destruction of CH would result if part of the habitat was degraded, either permanently or temporarily, such that it would not serve its function when needed by the species. Understanding how different areas support various SRKW life processes (i.e., the 'function' of CH) is an important step in providing effective protection.

Analysis of the relative occurrence of SRKW in the Salish Sea and the Swiftsure Bank area have identified areas of preferred habitat within CH (Thornton et al., 2022). Occurrence data emphasized the importance of areas on and around Swiftsure Bank, as well as confirming the significance of Haro Strait on the west side of San Juan Island to SRKW. Behavioural analyses also identified locations within the areas of high occurrence in which foraging was the predominant behaviour (Thornton et al., 2022). The prevalence of SRKW sightings in these areas, and the location of the foraging hotspots, lends further support to previous inferences that SRKW presence is driven by the seasonal availability of their primary prey, Chinook salmon (*Oncorhynchus tshawytscha*; Baird et al., 2005; Ford et al., 2017; Hanson et al., 2010, 2021).

The acoustic sense is the primary means for SRKW to send and receive information about their surroundings. The three SRKW pods each have their own acoustic dialect that includes 7-17 discrete calls (Ford, 1987, 1991). These include whistles and burst-pulse sounds. Whistles are continuous, narrow-band, continuous wave or frequency-modulated tones in the 2-10 kHz range, and are used as social signals in most odontocete species (Janik and Slater, 1988; Herzing, 2000; Lammers et al., 2003). Burst-pulses are more broadband sounds of rapidly repeating pulses, in the range of 500 Hz to 25 kHz (Ford, 1987, 1989, 1991; Reisch et al., 2006). The use of echolocation clicks informs navigation and prey location. The dominant frequency in these clicks usually reaches the ultrasonic range (>20kHz).

The acoustic 'active space' of a whale represents the area over which acoustic information can be both sent and received (Tyack and Clark, 2000; Clark et al., 2009; Burnham, 2018). Active space considers both a range or two-dimensional extent over which sounds can propagate, as well as some indication of directionality and area over which transmissions would be possible in three dimensions. The extent over which conspecific communication signals can be accurately received and interpreted can be described as the communication range (Clark et al., 2009; Hatch et al., 2012; Burnham, 2018; Stanley et al., 2017). For SRKW, the distance over which a whale can have clear reception of its own echolocation clicks has been used to define its echolocation range (Au et al., 2004). The extent of both communication and echolocation range is determined by the signal from the whale and the sound field into which the signal is projected.

Vagle et al. (2021) considered the abiotic and anthropogenic noise in the soundscape in parts of the Salish Sea and Swiftsure Bank area, and their impacts on the frequencies used for SRKW communication (500 Hz to 15 kHz) and echolocation (15-100 kHz; Heise et al., 2017). Passive acoustic recordings made in the study area and outputs from a vessel noise model indicated considerable additions to the sound field from both natural and vessel noise. For instance, larger commercial vessels, which predominantly emit lower-frequency (< 500 Hz) noise (Richardson et al.,1995; Veirs et al., 2016), added to the sound fields in the frequencies up to at least 50 kHz (Vagle et al., 2021). In early- to mid-summer, wind contributions to the sound field were substantial in the areas around Sooke, and lower in the offshore areas. In September-October, the converse was observed, with the eastern extent of the Strait experiencing lesser wind contributions to the sound field, while Swiftsure Bank and the western extent of Juan de Fuca Strait experienced greater noise impacts from offshore wind. This quantification of noise in the frequency ranges used for communication and echolocation by SRKW demonstrated the potential for masking from vessel noise. Other studies suggest that prey detection and foraging efficacy could be reduced between 38-100% when a killer whale is in close proximity to a vessel (Au et al., 2004; Holt et al., 2013), either through direct masking of acoustic signals or reduced ability to coordinate prey location and capture (Ford and Ellis, 2014), and prey sharing (Ford and Ellis, 2006; Wright et al., 2016). The SRKW population has been characterized as nutritionally stressed, as evidenced by reduced survival and reproduction (Ward et al., 2009; Ford et al., 2010; Wasser et al., 2017), and an observed decline in body condition (Fearnbach et al., 2011, 2018). As SRKW use acoustic signals to locate and pursue prey, degradation of their sonic environment is of paramount concern.

Non-acoustic vessel disturbance also presents a risk to SRKW population recovery, but is challenging to quantify. The physical presence of vessels may result in behavioural changes or create impediments to SRKW movements (Noren et al., 2009; Ferrara et al., 2017). Foraging behaviours can be interrupted in the presence of vessels, where whales were more likely to transition to non-foraging behaviour, potentially increasing energy expenditure and resulting in lost prey capture opportunities (Bain et al., 2006; Lusseau et al., 2009; Williams et al., 2014b., Holt et al., 2021). In bottlenose dolphins, vessel presence has been associated with short term reduction in foraging activity with no relationship to noise level (Pirotta et al., 2015). In the Salish Sea and the Swiftsure Bank area, core SRKW feeding areas are in close proximity to international shipping lanes, as well as sites of frequent use by recreational vessels (Cominelli et al., 2018; Olson et al., 2018; Vagle et al., 2021; Thornton et al., 2022). Incidents involving non-motorized vessels (kayaks, paddleboards) are increasing (Seely et al., 2017) and while the impact may be viewed as minimal, the cumulative effects of changes in whale behaviour away from those which support vital functions have a higher likelihood of impact in an endangered population (Lacy et al., 2017; Murray et al., 2021).

The speed at which a vessel is travelling defines another level of risk to SRKW. While only a small percentage of the cause of SRKW mortality is known, evidence from strandings and non-fatal vessel strikes are sufficient to identify vessel strike risk as an important threat to the population (Raverty et al., 2020). Knowing the speed of vessel travel can help discern the likelihood and severity of the strike (Kelley et al., 2020). As vessel speed increases, so does the risk of a lethal impact to whales; for example, vessels exceeding 18 knots will likely result in mortality if a whale is struck (Vanderlaan and Taggart, 2007; Conn and Silber, 2013). Identifying areas with higher densities of vessels travelling at elevated speeds will facilitate risk assessment for this threat to SRKW recovery.

This paper examined the potential impacts from vessels to SRKW habitat use and discusses the risks to individuals. Focus is given to areas where frequency of SRKW occurrence is high and where observational data has defined their behavioural use. Noise-related reductions in SRKW communication and echolocation ranges are presented as proportional reductions in extent compared to periods when wind and vessel noise is absent. The temporal aspect of potential acoustic impacts of vessel noise in locations where foraging and travelling are predominant are explored by quantifying the proportion of time over a representative week during the core summer months, that the extent of both communication and echolocation ranges may be reduced. Vessel presence and strike risk are also explored by presenting monthly vessel densities at two different speed thresholds in high-occurrence areas, reflecting likelihood of sub-lethal and lethal interactions. These analyses illustrate the power of the co-occurrence framework to assess impacts at varying spatial and temporal scales and highlight areas where vessel presence may impede SRKW survival and recovery. Results from these analyses will provide support for evidence-based conservation measures to mitigate the principal threats for this endangered population.

2. METHODS

The study area for this analysis included waters of the Salish Sea and Swiftsure Bank area that are bounded by 49.0°N, 125.5°W in the northwest, 49.0°N, 123.0°W in the northeast, 48.0°N, 125.5°W in the southwest and 48.0°N, 123.0°W in the southeast (Figure 1). The Swiftsure Bank area exhibits a variety of bathymetric features; locations are identified in Figure 2 and descriptors for these areas are as follows: Swiftsure North (along the coast in the vicinity of Nitinat), Swiftsure Bank (the shallow bank on the continental shelf), and the Swiftsure Foreslope (areas to the east of the bank where the bathymetry indicates a steep slope). The analyses presented here were restricted to the presence of whales between May 1 and October 31 (hereafter referred to as 'summer') with whale data from 2009-2020 informing the occurrence areas, and data from 2018 to 2020 informing the vessel noise and potential collision risk layers.

2.1. SRKW PRESENCE AND HABITAT USE

Areas of SRKW summer occurrence in the study area were estimated using modeled outputs of effort-corrected sightings data to determine probability of occurrence, according to methods outlined by Watson (2020), and presented in Thornton et al. (2022). The number of SRKW sightings per unit search effort at a given location was expressed as intensity of SRKW occurrence with a >0.9 confidence level. Areas of highest intensity of occurrence, which are assumed to be representative of SRKW preferred habitat between May and October, were used in this study and are visually represented by a 90% polygon, with diminishing intensity described by the 80% and 70% polygons (Figure 3).

Areas of forage and travel were defined from DFO's SRKW behavioural surveys (2018-2020) and the National Oceanic and Atmospheric Administration's (NOAA) behavioural observation data for the Salish Sea (2006-2009; see Thornton et al., 2022). These areas are identified here as polygons where there was an >0.7, >0.8 and >0.9 probability that foraging or travelling were the dominant behaviours (Figure 4-5; Thornton et al., 2022).

Six representative sites within these areas (three in foraging-dominated locations and three in travelling-dominated locations) were selected to examine the impacts of noise on SRKW communication and echolocation range, and how that varied with depth (Figures 4-5).

2.2. ACOUSTIC ENVIRONMENT

Soundscape recordings were obtained from six passive acoustic moorings deployed throughout the Salish Sea and on Swiftsure Bank (Figure 1). Each mooring consisted of an Autonomous Multichannel Acoustic Recorder (AMAR, JASCO Applied Sciences, G4) equipped with GeoSpectrum Technologies M36-100 hydrophone, and positioned approximately 2 m from the sea floor. Each system was calibrated by the manufacturer, and then again using a 250 Hz piston phone prior to each deployment. Recordings were made continuously at a sample rate of 256 kHz with 24-bit resolution and stored on internal SD memory cards as .wav files. On recovery, the .wav files were post-processed with custom Python scripts, modified from those used by Merchant et al. (2015). One-minute power spectra were computed using a 1 second Hanning window, with a 50% overlap and Welch's averaging, from which sound pressure level (SPL) metrics were calculated.

Sound speed profiles and sound propagation characteristics for the study area were calculated knowing water depth, substrate type, and water properties (salinity, temperature, depth), using both observational and model data as described in Vagle et al. (2021). Noise additions from both wind and vessels were examined to explore both natural and human-derived additions to the soundscapes. The potential impact to SRKW was determined by examining the noise additions from these sources in frequencies relevant to the SRKW's communication and echolocation ranges. For simplicity in the analysis, single frequencies were used to represent the ranges of SRKW communication and echolocation signals. The communication range of 500 Hz to 15 kHz was represented by 10 kHz, which represents a mid-value of the fundamental frequencies of SRKW whistle production (2-17 kHz; Ford, 1989; Thomsen et al., 2001). The echolocation range of 15-100 kHz was represented by 50 kHz, which is the center of the frequency range over which echolocation clicks are produced and in line with previous studies (Au et al., 2004).

2.2.1. Soundscape description: wind- and vessel-derived noise

Wind noise was estimated by retrieving wind speed data from the SalishSeaCast model (Soontiens et al. 2016) and using the known relationship at 8 kHz described by Vagle et al. (1990). Data were then extrapolated to 10 kHz to reflect potential effects on SRKW communication range, and 50 kHz to reflect effects on their echolocation range as described in Vagle et al. (2021) and following the assumption that the SPL decreases with frequency at a rate of 19 dB/decade (Wenz, 1962). Monthly averages of wind noise values for the period from May to October were used to estimate changes in communication and echolocation range in these frequencies (see methods below).

Vessel noise in the SRKW communication and echolocation frequency ranges was extrapolated from a Range-dependent Acoustic Model (RAM) for shipping noise, developed for the study area (Vagle et al., 2021). The vessel noise model outputs at 125 Hz were extrapolated to give a first-order estimate of noise at the two frequencies selected to reflect communication and echolocation ranges (10 kHz and 50 kHz; Vagle et al., 2021). Ambient noise levels that were exceeded 5% (L_5), 50% (L_{50}) and 95% (L_{95}) of the analysis time as a result of vessel noise were determined for five of the 40 water layers, i.e., at 7.5 m, 20 m, 50 m, 100 m, and 150 m water depths, to quantify vessel noise propagation through the water column, and to evaluate the communication and echolocation range loss at different depths (see methods below).

2.2.2. Communication and echolocation range calculation

2.2.2.1. Communication range

The maximum available communication range for SRKW and range-dependent transmission loss at each of the mooring locations was calculated from data gathered experimentally using a known noise source (engine noise from a research vessel). The Canadian Coast Guard Ship (CCGS) VECTOR is a small coastal oceanographic vessel with an overall length of 39.7 m, beam of 9.5 m, draft of 3.5 m and total displacement of 560 tons. Cruising speed is approximately 10 knots (5.1 m/s) at 1500 RPM from a single three-bladed variable pitch propeller driven by a 600 kW diesel engine (Trevorrow et al., 2008). The VECTOR was equipped with an AIRMAR Technology Corp. CM265LH Chirp-Ready acoustic transducer (100 mm by 164 mm) operating at 50 kHz for naval sonar operations, and a 12 kHz SIMRAD 830-107783 transducer (580 mm diameter) to detect water column depth for scientific operations. The VECTOR ran transect lines directly over and up to a maximum of 10 km away from the moorings, and between mooring locations repeatedly over a 24 h period. Results from transects completed in September-October 2020 were used in this analysis to estimate the frequency-dependent reductions in sound pressure levels (SPL). Water column conductivity, temperature and depth (CTD) profiles were obtained from a Seabird Scientific SBE-25 CTD at two-hour intervals during the transects from which sound speed profiles were calculated using equations from Leroy et al. (2008).

The maximum detection range of SRKW communication calls was estimated using measured sound pressure levels of the VECTOR at points along the transect lines and signal at 10 kHz with a source level of 125 dB re 1µPa at 1 m, which is typical for dolphin whistles (Watkins and Schevill, 1974). This represents a relatively low source level for killer whale calls; however, if this value was extended from the single frequency of 10 kHz to the full frequency range noted for SRKW communication calls, the source level would align with SRKW values observed in previous studies (131-175.7 dB re 1µPa at 1 m see Miller and Tyack, 1998; Miller, 2006; Holt et al., 2009).

2.2.2.2. Echolocation range

A model of signal source levels and directionality, and target strength for Chinook salmon, as described by Au et al. (2004), was used to estimate returning echolocation signal levels (in dB) under different ambient noise conditions in the Salish Sea. The dimensions of the Chinook salmon were modeled on those used by Au et al. (2004), where the fish was 0.78 m in length, placing its theoretical weight within the range of observed preferential fish weight (3.7-8.1 kg; measures from D. Rogers U.W. 2002 and detailed in Au et al. 2004). The Kirchhoff-ray mode backscatter model (Clay and Horne, 1994) was used to represent the target strength of the fish, modelling its body as a fluid-filled cylinder surrounding an air–filled cylinder, representing the swim bladder. The target strength was calculated for echolocation signals projected at 50 kHz with source levels varying from 195 to 224 dB re 1uPa at 1 m. Echolocation distance was defined as the distances over which an echolocation click signal returned with a signal to noise ratio (SNR) greater than 1.

To assess the changes in soundscape and the implications on acoustic range for SRKW, a 'minimum ambient' reference level was defined as corresponding to conditions where abiotic noise was at its minimum and anthropogenic noise was absent (see Vagle et al., 2021). This reference level was derived from acoustic mooring recordings using the L_{99} exceedance levels, i.e., the 1% quietest conditions, from Boundary Pass and Haro Strait recordings aggregated over the six months study period (May to October) and averaged over the three years of study (Vagle et al., 2021). Moorings in these two regions were deemed to be the least affected by chronic and far-ranging vessel noise as a result of their geography, and also represented areas with the least potential for abiotic noise additions given their location in more protected waters. Therefore the ‘minimum ambient’ level applied to this analysis was presumed to reflect absence of vessel noise, and negligible wind-derived noise. A single reference ‘minimum ambient’ value was applied throughout the study area for this analysis.

2.2.3. Communication and echolocation range loss

The loss in both communication and echolocation range was derived by comparing the range over which calls at 10 kHz, and echolocation clicks at 50 kHz, could travel when ‘minimum ambient’ conditions prevailed with conditions obtained from wind- and vessel-derived noise models (Vagle et al., 2021).

Changes in ambient noise due to wind were modeled over the extent of the study area per month (May to October) and year (2018 to 2020) at a 25-m depth. Median SPL values (L_{50} exceedance level) for this component were derived at 10 kHz and 50 kHz, and compared to values obtained at ‘minimum ambient’, and expressed as percent reductions in communication or echolocation range. Trends over early, mid-, and late summer were examined using the 2019 values for May, July and October, respectively.

Changes in vessel noise through the water column across the study area were examined for the upper- (7.5 m) and mid-water column (50 m), and at a maximum representative depth for foraging dives (150 m; Baird et al., 2005; Tennessen et al., 2019). Sound pressure levels that were exceeded at these depths for 5%, 50%, and 95% of the time (L_5, L_{50} and L_{95}, respectively) were examined, again for frequencies representative of communication (10 kHz) and echolocation (50 kHz) ranges. For these calculations, the communication range was calculated with the whale calling at the three depths examined, while for the echolocation range the whale was presumed to be at 10 m depth sending echolocation signals to a target at each of the three depths assessed.

The above-derived changes in ambient noise as a result of wind or vessel noise reflect the worst-case scenario for the study period as they assumed constant and thus chronic presence of winds or vessels without release.

The vessel noise model described above accounts only for AIS Class A vessels. To assess noise additions from smaller vessels, SPL at 50 kHz were derived from each minute of the recordings from the six mooring locations. Range reduction as a result of smaller and recreational vessels was estimated using the same method first employed by Au et al. (2004) and described above. The 50 kHz frequency was selected as it reflects noise generated from small engines, and encompasses the most common echosounder signal frequency used by these small vessels in the study area (Burnham et al., 2021a; Vagle et al., 2021). The minute-wise change in echolocation range from minimum ambient was visualised monthly for each mooring.

2.2.4. Co-occurrence of SRKW and noise

A spatial and temporal comparison between areas of high SRKW frequency of occurrence and noise from wind and vessels was undertaken. Overlaying the model outputs of SRKW intensity of occurrence with the raster layers representing the proportional loss of acoustic range as a result of abiotic (wind-derived) and anthropogenic (vessel-derived) noise facilitated identification of areas of co-occurrence. Frequency of occurrence of SRKW was expressed as the 70%, 80% and 90% exceedance values at a 90% confidence level for each month in the period from May to October.

Two regions used intensively by SRKW were identified for comparison: the Swiftsure Bank area and Haro Strait. To spatially standardize the areas, boundaries were created that limited the frequency of occurrence polygons to those regions. Raster values for proportional echolocation and communication range loss (using the L_{50} exceedance level) were mapped for each month (May to October). This analysis was undertaken at 25 m depth for wind noise, and at two depths for vessel noise: 10 m, and 100 m. The proportional loss in range was then spatially expressed for each of the 70%, 80%, and 90% SRKW frequency of occurrence polygons.

Range loss was also expressed as the percent time during which the environment was degraded at a specific location. To achieve this, the amount of acoustic range that would be available to an individual (binned as 0-25, 25-50, 50-75 and 75-100% of available range) at a given depth over the course of one week was calculated at three foraging locations and three travelling locations, and four different depths (7.5, 20, 50, and 100 m). The week of August 1-7th, 2018 was used as a representative sample of the study period, whereas foraging and travelling locations were those where there was a >0.9 certainty of occurrence of these behaviours and that were located within areas of 90% probability of SRKW occurrence.

2.3. VESSEL PRESENCE AND SPEED

2.3.1. Vessel presence

The presence of vessels in the study area was described using Automatic Identification System (AIS) data collected by Canadian Coast Guard terrestrial receivers. Vessel tracks interpolated to obtain a data point every five minutes were used to assess vessel presence and calculate vessel speed throughout the Salish Sea and Swiftsure Bank area (Vagle et al., 2021). AIS Class A transceivers are mandatory on larger commercial vessels including bulk carriers, container ships, ferries, cruise ships, tankers, and vehicle carriers. The use of AIS is not mandatory for smaller vessels, such as recreational vessels and small commercial vessels (e.g., tugs), and so the presence of these vessels in the data is an underestimate of true vessel presence. These smaller vessels either do not use an AIS transceiver, or are equipped with AIS Class B transceivers, which transmit their signal less frequently, and over shorter distances than Class A transceivers.

Since the AIS data were presumed to under-represent the presence of smaller, and non-commercial vessels, data from Fisheries and Oceans Canada (DFO) Creel aerial surveys were included in the analysis to provide additional data on underrepresented vessel classes (Vagle et al., 2021). Acoustic data from the six passive acoustic moorings (Figure 1) also provided information on small vessels using the methodology described above.

2.3.2. Vessel speed

Variation in vessel presence at different speeds was evaluated to examine the risk of lethality from vessel strike in areas of high SRKW intensity. Speed over ground (SOG) for each vessel was calculated from the distance travelled and time elapsed in the AIS data. AIS Class A and Class B data were filtered using thresholds for minimum speed over ground (SOG). SOG exceeding 1 knot was used to represent all vessels making way, and SOG exceeding 10 knots was used to represent vessels traveling at cruising speed. Monthly layers of AIS vessel presence were generated, as described in Vagle et al. (2021), and expressed as overall average daily vessel-hours per 1 km^2 grid cell, averaged across 2018-2020, for three broad AIS vessel categories. Vessels travelling at cruising speed were assumed to represent a greater risk of strike to SRKW and pose a higher risk of lethality if a strike were to occur.

2.3.3. Co-occurrence of SRKW with vessel presence and speed

Polygons depicting whale presence at the 70% frequency of occurrence were overlaid with the vessel presence raster layers to assess co-occurrence. AIS Class A large commercial vessels, other AIS Class A vessels, and AIS Class B vessels from Vagle et al. (2021) were summed to create a set of monthly raster layers for all vessel presence combined. In the case of non-AIS (i.e. recreational fishing) vessels, the raster layer for underrepresented vessel presence was created based on all DFO Creel surveys.

Additionally, trends in vessel presence across months were examined by speed and vessel type (binned into vessel categories) within the polygons of high SKRW occurrence intensity in Haro Strait and the Swiftsure Bank Area. The size and boundaries of these polygons varied across months, as they were based on the monthly results of the SRKW occurrence model. AIS Class A vessels were binned into six categories: cargo, tug, passenger/ferry, fishing, recreational, and other. The cargo category primarily consisted of bulkers, container ships, tankers and vehicles carriers. The 'other' category included supply, whale-watch, naval, government and research vessels. All AIS Class B vessels were grouped together in a 'Class B' category. For each of these seven categories, vessel presence was calculated per region (Haro Strait and the Swiftsure Bank Area) and month, for vessels making way (SOG >1 knot) and vessels traveling at cruising speed (SOG >10 knots). Vessel presence was calculated as average vessel-hours per day (as described in Vagle et al., 2021), and was then divided by the area of the region (Table 2) to calculate average daily vessel-hours per km^2.

3. RESULTS

3.1. SRKW PRESENCE AND HABITAT USE

The SRKW occurrence model outputs showed areas of consistently high SRKW intensity of occurrence within the Swiftsure Bank area, and a smaller area within Haro Strait along the west side of San Juan Island (Figure 3; Thornton et al., 2022). The behavioural model outputs exhibited a pattern similar to the occurrence model, with a preference for foraging in the Swiftsure North area (coastal waters to the north and extending east into Juan de Fuca to Port Renfrew (Figure 4), the Swiftsure foreslope (eastern wall of Swiftsure Bank) and in Haro Strait on the southwestern tip of San Juan Island (Figure 5, Thornton et al., 2022). In Juan de Fuca, travel was identified as the dominant behaviour to the east of Port Renfrew through to Jordan River, and in the northern extent of Haro Strait through Boundary Pass and in waters surrounding Pender, Maine and Saturna Islands (Figure 5, Thornton et al., 2022).

3.2. IMPACTS TO THE ACOUSTIC ENVIRONMENT

3.2.1. Natural and man-made sounds

Recordings of the CCGS VECTOR from moorings in Juan de Fuca Strait at Port Renfrew, Jordan River, and Sooke and on Swiftsure Bank indicated the maximum detection range under 'minimum ambient' conditions to be approximately 2,500 m for calls in the SRKW communication range (500 Hz -15 kHz), specifically at 10 kHz (Figure 6). Transmission loss was found to be a function of range, following a range to the power of -1.9 best fit transmission loss characteristics. This helped to establish the potential propagation distances of communication calls under the different scenarios of wind and vessel noise tested for the analysis on acoustic extent of SRKW calls.

Wind patterns were strongly seasonal (Burnham et al., 2021a; Vagle et al., 2021; Figure 7). Regions where wind speeds were high included the south-eastern portion of Juan de Fuca

Strait, and Sooke and the Haro Strait in particular during mid-summer, and the western portion of the Juan de Fuca Strait, including west of Washington, as a result of offshore winds during later summer (Figure 7).

Vessel noise increased during the core period considered. Although commercial vessel passage rate was consistent throughout, the numbers of Class B AIS vessels increased from June and peaked in August (Burnham et al., 2021b). The vessel noise model showed the most elevated noise levels to be in the vicinity of the shipping lanes; in areas of turning and vessel maneuvering; and at Swiftsure Bank (Figures 8-9, Vagle et al., 2021). Spatial patterns in AIS vessel-derived noise were consistent between months. Therefore, the data from July 2018 was used as a representative month from which to highlight the impacts of vessel noise on communication and echolocation range at different depths.

The analysis of the soundscape recordings at 50 KHz, a proxy for presence of small vessels, indicated Sooke was an area where the sound levels in this frequency were the most elevated (Figure 10).

3.2.2. Co-occurrence of SRKW and noise

Wind noise added only to the SRKW communication range (Figure 7). The areas most impacted by wind did not significantly overlap with areas of high whale occurrence and so are not discussed further (Figure 12).

Impacts from AIS vessels on the acoustic field were less for communication than echolocation frequencies. The impact changed little with depth for the frequencies that SRKW use to communicate (Figures 8-9). Areas near Sooke and nearer to the international shipping lanes, where AIS-tracked vessels undertake directional maneuvers, were locations where the greatest potential impacts on communication and echolocation ranges were likely to occur. For both communication and echolocation range, the impacts were greater for areas indicated for increased SRKW frequency of occurrence on Swiftsure Bank than of the Haro Strait for all months. For communication range and all depths, reductions of 40% or more (up to 60-80% locally) were estimated in all months, with up to 50% of their high-occurrence areas being strongly ensonified (>40% reduction in range) in September. Similar results were obtained for loss of echolocation range when a whale in surface waters was echolocating in the upper water column (both at 10 m depth). As the distance between the whale and prey target increased, losses were more severe. In these cases, when the whale is echolocating from 10 m to a prey at 100 m depth, the range at which echolocation could be successfully used was reduced to 0 to 20% of that available under minimum ambient conditions when in areas of highest (90%) frequency of occurrence (Figure 13-14). These extreme conditions of nearly complete compromised echolocation range prevailed over more than 40%, and sometimes 75% (September) of these high-use habitats (Figure 14).

Comparing reduction of communication and echolocation range among three foraging and three travelling sites indicates potential range reductions at all six sites (Figures 15-16). Overall, Swiftsure North was the least affected (foraging) location, whereas Swiftsure Foreslope was the most affected (foraging) location. Looking specifically at communication frequencies, the travelling location at Turning Point, as well as the Swiftsure Foreslope foraging site and adjacent travel location (Swiftsure), which are both in close proximity to the international shipping lane, were subject to the largest interference from vessel noise. The range available was < 50% during approximately half of the time, especially at deeper depths (Figure 16). At the quietest site (Swiftsure North), communication range remained affected by vessel noise only when near the surface (7.5 m) where a range less than 75% that of minimum ambient was almost the norm, being prevalent for more than 80% of the time. The travel location in Juan de Fuca showed the least persistence of vessel noise impacts on communication range, having the least time spent in the most reduced range conditions (Figure 15).

The echolocation range was reduced by approximately half for more than 50% of the time at all but one location (Swiftsure North) when whales at 10 m were echolocating to the deepest depths (Figures 15 and 16). Range loss for echolocation calls was generally less variable among the three travel locations when compared to communication range loss. All sites showed similar reductions (~50%+) in range for whales using acoustics to locate prey in the upper water column (Figures 15-16). The range loss increased as the target echolocation depth increased, and was most pronounced at the Turn Point location (Figure 16). At the quietest foraging location, echolocation range was largely unaffected by vessel noise. The echolocation range was at least 75% of the maximum range calculated under minimum ambient conditions for at least 60% of the time. This was true for a whale at 10 m echolocating to each of the three depths considered. At the most ensonified foraging location, on the Swiftsure Foreshore, over 70% of the time was spent with less than half the echolocation range available minimum ambient conditions (Figure 15).

For small vessel presence, greatest losses in echolocation range occurred in areas around Sooke (Figure 10). Similar, but less distinct patterns, were seen for areas near Port Renfrew and Jordan River, particularly in September. The greatest sound levels in the 50 kHz band, and the greatest reductions in echolocation extent were observed for weekend days, during daylight hours from early morning to late afternoon (Figure 11). During these periods, echolocation range in the vicinity of these recorders frequently fell below 25% (Figure 10-11).

3.3. VESSEL PRESENCE AND SPEED

Vessels were present in all areas identified as intensively used by SRKW. They were in greater numbers in Haro Strait than at Swiftsure Bank for all AIS equipped vessel categories and vessel speeds, and each month tested (Figures 17-18). AIS Class B vessels were the predominant vessel category in Haro Strait, especially in July and August, but were typically not travelling at the greatest speeds. Large commercial vessels (i.e., cargo and tug), were consistently present in Haro Strait from May to October, with cargo ships representing the largest proportion of vessels traveling at speeds above 10 knots (Figure 18). Similar patterns in large commercial vessel presence were seen for the Swiftsure Bank area, with cargo being the dominant vessel category travelling at cruising speeds; however, cargo vessels represented a greater proportion of the vessels making way or travelling at cruising speed at Swiftsure Bank than in Haro Strait (Figure 18). Commercial fishing vessels using AIS were more prevalent at Swiftsure Bank, but typically traveled at less than 10 knots (Figure 18).

As expected, given the proximity of SRKW habitat to the shipping lanes, there was a significant overlap between commercial vessel presence and SRKW occurrence for all months (Figure 17). However, the SRKW presence also overlapped substantially with recreational fishing vessels (Figure 19). The co-occurrence of these smaller vessels with SRKW was more important in June to October in areas around Port Renfrew, Sooke, and Victoria based on survey data; however, spatial coverage for aerial surveys was limited in May and October (Vagle et al., 2021). Data from acoustic recorders at Port Renfrew, Sooke and Jordan River demonstrated a pattern of reduction in echolocation range that mirrors the expected pattern of small vessel transits (significant increase on weekends between 6 am and 3 pm) which supports the visual co-occurrence data for SRKW and small vessels (Figures 10-11).

4. DISCUSSION

Effective protection of SRKW and their CH begins with an understanding of spatiotemporal patterns of presence and habitat use. While it is often difficult to separate threats to an individual from those that result in CH destruction, mitigation efforts focused on areas of greatest SRKW occurrence are more likely to reduce impacts to individuals, and therefore have the greatest influence on recovery. The development of the co-occurrence framework presented here identifies areas of high SRKW frequency of occurrence, where threats to individuals or risk of CH destruction may be elevated. These analyses were focused on vessel-related impacts; however, with additional layers describing the extent and distribution of factors related to the threats of prey reduction and contaminants, a more complete evaluation of impacts may be achieved.

Killer whales vocalize and have hearing sensitivity into the low frequencies (< 1 kHz, Miller, 2006; Branstetter et al., 2017), but are presumed to have the most acute hearing capacity in the mid- to high-frequencies. This wide hearing range, from several hundred Hertz in the low frequencies to approximately 115 kHz (Szymanski et al., 1999; Miller, 2002; Branstetter et al., 2017) results in an increased vulnerability to noise additions from a range of sources, especially vessels. Noise-induced stress responses and physiological damage to hearing causing changes in sensitivity have been noted for several species of marine mammals (e.g., Hastie et al., 2003; Southall et al., 2008; Rolland et al., 2012). By assessing noise inputs to the soundscape, and expressing these contributions in terms of communication and echolocation range loss, overlaid on SRKW frequency of occurrence maps, it becomes possible to identify areas of higher risk and adopt a more focused approach for impact mitigation.

Wind Effects

Wind-based noise typically increases ambient noise levels in the frequency range between 500 Hz and 50 kHz (Wenz, 1962; Vagle et al., 1990; Carey et al., 1993), and unsurprisingly, was likely to have a larger influence on SRKW communication range than on their echolocation range. Although the use of monthly averages may not fully capture gusting winds and variability in wind conditions, this study indicates no overlap between areas of high SRKW occurrence and those where high winds and elevated ambient noise prevailed. Indeed, SRKW use of the inner Salish Sea waters peaked later in the summer when wind effects were lower, and winds effects were higher at Swiftsure Bank, where presence is higher earlier in the summer (Center for Whale Research, 2020[1]; Thornton et al., 2022). Cetaceans have evolved adaptation strategies to compensate for variations in natural noise levels (Simmonds et al., 2014); changes in relative occurrence in areas as wind noise varies may be a behavioural adaptation to acoustic habitat quality as well as prey abundance.

Vessel Noise Impacts

The SRKW are exposed to potential physical and acoustic disturbance from commercial vessels that cross Swiftsure Bank and traverse the length of Juan de Fuca Strait to service ports in British Columbia and Washington State. Commercial vessels in the Salish Sea have raised the ambient noise levels, with additions in the frequency ranges that SRKW use for communication and echolocation (Erbe et al, 2012; Veirs et al., 2016). This study provided quantitative evidence for impacts of vessel noise on both the echolocation and communication ranges of SRKW both in surface waters and when diving at or echolocating to depth. Reductions in communication and echolocation range were greater for the Swiftsure Bank area when compared to the Haro Strait location. The variations between sites could be attributed to differing topography and water property profiles, as well as the differing composition in vessel traffic. A parallel study indicates that vessel noise is more sustained through the Swiftsure Bank area, whereas for Haro Strait, there are times of relative quiet between vessel transits (Vagle et al., 2021).

The comparison of noise impacts among foraging and travel locations within the SRKW critical habitat indicated that whales travelling in waters near Turn Point or foraging on the Foreslope of Swiftsure Bank would experience the greatest reductions in communication and echolocation ranges. This likely results from the presence of larger commercial vessel traffic in these areas. At the Turn Point location, manoeuvers and course alterations that occur in this area result in elevated vessel noise contributions to the environment, while the Foreslope of Swiftsure Bank is directly under the confluence of vessel traffic in the inbound and outbound shipping lanes.

The persistence in the documented range loss, often over 50% of the time in both foraging and travelling locations, suggests that SRKW dependence on echolocation could be significantly hindered in high use areas of their critical habitat, especially if using echolocation to locate prey at depth. For instance, all three travelling sites were generally characterized by echolocation ranges that were less than half of those under minimum ambient conditions for more than 50% of the time. A shorter effective signal range while travelling may have repercussions on the whales' navigation capacity.

A loss in echolocation range in foraging areas might also have negative consequences on SRKWs. The surface waters in Swiftsure Foreslope foraging area showed the greatest loss of echolocation range for the greatest proportion of time (i.e., > 70% of the time with less than 50% of the echolocation range available). Much of SRKW prey searching occurs in the upper water column (Baird et al., 2003, 2005; Tennessen et al., 2019), and then pursue fish to depth, necessitating deeper SRKW dives during foraging events (Baird et al., 2003, 2005; Tennessen et al., 2019). This is matched in our analysis of echolocation range with the whale positioned at 10 m water depth, and using clicks to search for prey at various depths. While echolocation range at the Swiftsure Foreslope location was fairly constant with increasing prey depth, the Haro Strait location exhibited a greater range loss as the depth of the prey target increased.

A reduction in range that SRKW can contact conspecifics using communication calls could impact group cohesion, and hinder the coordination of foraging or prey sharing (Ford and Ellis 2014; Wright et al., 2016).

Certain assumptions were made about the impacts of noise on SRKW when implementing and interpreting the AIS Class A vessel noise models, as discussed in Vagle et al. (2021). The models failed to capture the full complexity of both vessel and SRKW behaviour, and of the dynamic nature of their environment within SRKW CH. Acoustic recordings from the study area indicated a quieter environment than the model predictions, demonstrating that the model overestimated the level of noise from AIS Class A vessels (Vagle et al., 2021). As empirical data would include all noise sources, including non-AIS equipped vessels, vessel noise estimations represent a worst-case scenario that could be encountered by SRKW in these areas. The model assumed vessel noise production and reception are omnidirectional, and did not take into account the more dynamic nature of SRKW calling, in terms of directionality, beam width, call strength or inter-pulse-interval modification in the presence of noise sources (Miller, 2006; Lammers et al., 2004; Madsen et al., 2005; Morisaka et al., 2011; Jensen et al., 2018; Wellard et al., 2020). In addition, no compensatory calling or masking release mechanisms were considered, nor were the intensity of noise and animal hearing sensitivity evaluated (Nedwell et al., 2007; Barber et al., 2010; Pine et al., 2018, 2020). The amplitude of noise by frequency was unweighted for hearing sensitivity (Szymanski et al., 1999; Southall et al., 2007; Branstetter et al., 2017).

The models were also restricted in their representation of the full vocal repertoire of SRKW. The use of 10 kHz in the noise modeling represented the range of fundamental frequencies of omnidirectional SRKW whistles (Ford 1989, 1991; Miller, 2002; Thomsen et al., 2002), which is also within the range described for the focus of pulsed calls (1-15 kHz, Reisch et al., 2006).

Also, while the use of 50 kHz for echolocation is consistent with previous studies (see Au et al., 2004), it does not capture the full echolocation range of SRKW.

Refinements of the vessel noise model would improve representation of the actual sound fields relevant to killer whales in the study area. For instance, the modelled acoustic frequencies could be extended to include the frequencies of importance to SRKW, rather than extrapolating from the 125 Hz model to the communication and echolocation frequency ranges. Also, ongoing work to refine estimates of the transmission losses of calls in the study area, and to define the directionality and source levels of SRKW calls will reduce the large uncertainties in the present model results. Mapping noise while accounting for species audiograms and known call characteristics may also help better assess the degree of masking associated with each behaviour or identified areas.

As the noise models described above were constructed with AIS Class A data, they are biased toward impacts from commercial vessel traffic. Inclusion of the AIS Class B data into the model would extend our understanding of the overall impacts of vessel noise. However, further information about vessel types and representative source levels are required to increase the accuracy of the model outputs. The noise contribution from smaller, non-AIS vessels is variable throughout the SRKW critical habitat, and is challenging to quantify. The use of 50 kHz as an acoustic marker to indicate small vessel presence represents a promising novel methodology for evaluating the impact on SRKW active range, with a focus on echolocation range loss. This approach is being explored as a means of quantifying both small vessel presence and noise contribution. Validation of the methodology is currently underway, with visual vessel surveys occurring concurrently with deployment of recorders in strategic locations.

Consequences of Disturbance

Anthropogenic noise levels in the world's oceans are acknowledged to be a risk to the survival and recovery of cetaceans (Clark et al., 2009; Hatch et al., 2012), especially to acoustically-sensitive species such as SRKW (Weilgart, 2007; Simmonds et al., 2014). Additions to the sound field in the form of vessel noise affect vital behaviours through impacts on foraging efficiency, social cohesion, navigation, passive listening and situational awareness. Displacement from important habitats is another consequence of noise and is often difficult to quantify. The presence of SRKW in the Salish Sea is strongly correlated with Chinook migratory patterns from the Fraser River and Puget Sound stocks (Ford et al., 2017; Hanson et al., 2010, 2021). Displacement from foraging areas is of concern, as the population trajectory is currently in stasis and fecundity is low. The lack of recovery in this population is thought to be multifactorial, with decreased prey availability identified as a primary threat. As prey availability is affected by both prey abundance and accessibility, noise impacts on echolocation and potential for displacement from key foraging areas are of concern.

As the distance between a source and receiver increases, signal strength is diminished through transmission loss. For SRKW, this principle of sound transmission sets limits on the detectability of prey, or the range over which they can effectively communicate with other individuals. The results presented here align with previous studies that indicate a decrease in the foraging efficacy and prey detection by SRKW when in close proximity to vessels (Au et al., 2004; Holt et al., 2009). Impacts to the communication range suggest that social calls used to coordinate foraging efforts or prey sharing also could be affected by masking. This research adds to ongoing efforts to predict noise-induced changes in acoustic ranges, or 'active space' (Clark et al., 2009) quantification for killer whales (also see Bain and Dahlheim et al., 1994; Erbe, 2002; Miller, 2006; Veirs and Veirs, 2011; Williams et al., 2014a).

Adaptive calling to overcome masking from vessel noise has been noted in SRKW. Compensation techniques such as calling louder or in altered frequencies, termed the Lombard effect, are used to maintain acoustic contact (Holt et al., 2009, 2011). In the presence of noise, call duration may also increase (Foote et al., 2004). These compensatory mechanisms to overcome the effects of vessel noise have energetic implications. Metabolic assessment of vocalization in bottlenose dolphins indicated that the cost of producing sound increased with call duration and the physical demands of sound production required a period of recovery to return to a metabolic baseline (Noren et al., 2013). For individuals that are prey-limited and nutritionally stressed, these impacts add to an already depreciated energy budget (Williams et al., 2006; Noren et al., 2011). Impacts related to avoidance of foraging areas, or transitioning from foraging to traveling behaviours have been observed in the presence of vessels, which could result in lost opportunities to forage (Williams et al., 2006; Lusseau et al., 2009; Noren et al., 2009; Holt et al., 2021). The implications of increased energy expenditures and reduced energy intake are heightened for the SRKW population, where an overall decrease in body condition has been observed (Fearnbach et al, 2011; 2020).

The level, duration, and seasonality of the noise received by an individual can modify the severity of impact (Southall et al., 2007; Erbe et al., 2016; Holt et al., 2021). The complexities in describing the soundscape and understanding how whales interact with it, and the dynamics of 'active space' are also not fully captured here. Further work to refine the 3D nature of the vessel noise model and greater details on how noise impacts individuals will add to our understanding.

Vessel presence and collision risks

The physical presence of a vessel has the potential to affect life processes by directly impeding movement patterns or altering behaviour in other more subtle ways (Pirotta et al., 2015). While the co-occurrence of large AIS class A vessels was well captured by this exercise, this was not the case for smaller vessels that may get in closer proximity to SRKW. For example, the majority of AIS vessel present in Haro Strait for June through September was from AIS Class B vessels. While this vessel class consists of recreational vessels and other types of smaller vessels, the absence of a mandatory requirement to carry AIS makes this dataset incomplete and to an unknown extent (Vagle et al., 2021). However, it is clear from both AIS Class B data and aerial survey of vessels that recreational vessel presence is substantial in areas of high SRKW intensity of occurrence, particularly in the summer months.

A more obvious risk related to vessel presence is that of vessel strike. The probability of occurrence and the likelihood of lethality from a vessel strike increase with speed (Vanderlaan and Taggart, 2007; Gende et al., 2011; Conn and Silber, 2013). While large commercial vessels were not always the most prevalent vessel category, they were predominant among vessels traveling at higher speeds (> 10 knots) in all months for both Swiftsure Bank area and Haro Strait. Given their speed and large size, these vessels would be expected to pose an elevated risk of lethal vessel strikes in the areas where they co-occur with whales (Vanderlaan and Taggart, 2007; Conn and Silber, 2013; Kelley et al., 2020). However, even smaller vessels, or those travelling at slower speeds can pose a risk of serious injury or mortality, particularly with strikes to areas with thinner tissue layers over the bone, such as the head (Kelley et al., 2020). As such, the abundance of small recreational vessels recorded in this study should not be wholly excluded from considerations of vessel strike risk, despite their smaller size and lower typical speeds. Additionally, the majority of studies of vessel strike risk to date have focused on larger whale species, such as the North Atlantic right whale (Vanderlaan and Taggart, 2007; Conn and Silber, 2013). To improve estimates of strike risk to SRKW, models that specifically assess the effects of vessel size and speed, but also of whale maneuverability and dive behaviour on the likelihood and severity of vessel strikes would be beneficial.

Mitigation actions that increase the distance between vessel traffic and areas of high SRKW occurrence have been implemented in some areas. For example, a voluntary inshore lateral displacement of vessels was undertaken in Juan de Fuca Strait to reduce physical and acoustic disturbance to SRKW. The transit routes of tugs and barges were requested to shift southwards and away from areas where SRKW frequently occur. These measures were found to be successful in reducing vessel presence and vessel-derived acoustic additions in the areas frequently used by SRKW (Vagle and Neves, 2019; Vagle, 2020; Burnham et al., 2021b).

Conclusions

The development of this co-occurrence framework to evaluate impacts to SRKW combines the best available information on SRKW occurrence and behaviour with a detailed analysis of vessel presence, speed, and noise contributions to the environment. Application of species-specific noise metrics to capture the effects of abiotic and anthropogenic noise in an animal-centric way has substantially improved our understanding of noise impacts to SRKW and will support decisions to focus mitigation in key areas. Evaluation of altered sound fields and the repercussions for SRKW communication and echolocation in areas of foraging and travelling highlights areas of particular importance and co-occurrence. This analysis shows the value of considering change in soundscapes in both horizontal and vertical space, with implications of noise seen for both near-surface dives and pursuits of prey at depth. Identification of noise levels in the frequency ranges of importance to whale communication and echolocation will result in greater efficacy of mitigation actions and support recovery of the endangered SRKW population.

5. TABLES

Table 1. Selected locations from areas of SRKW foraging or traveling that were identified in the behaviour analyses (Figure 4 and 5).

Predominant Behaviour	Location Label	Latitude (°N)	Longitude (°W)	Depth (m)	Location Name
Foraging	F1	48.6496	124.9330	62	Swiftsure North
Foraging	F2	48.5292	124.8090	189	Swiftsure Foreslope
Foraging	F3	48.4499	123.0900	212	Haro Strait
Travelling	T1	48.4943	124.9190	86	Swiftsure Bank
Travelling	T2	48.4321	124.3130	171	Juan de Fuca Strait
Travelling	T3	48.6432	123.2010	190	Turn Point approach

Table 2. Areas of high SRKW occurrence in Haro Strait and the Swiftsure Bank area indicated by the space-time models at the 0.9 probability and 70% SRKW frequency of occurrence level.

Month	Haro Strait Area (km^2)	Swiftsure Area (km^2)
May	169	822
Jun	330	1893
Jul	394	2292
Aug	383	2442
Sep	422	1853
Oct	316	1139

6. FIGURES

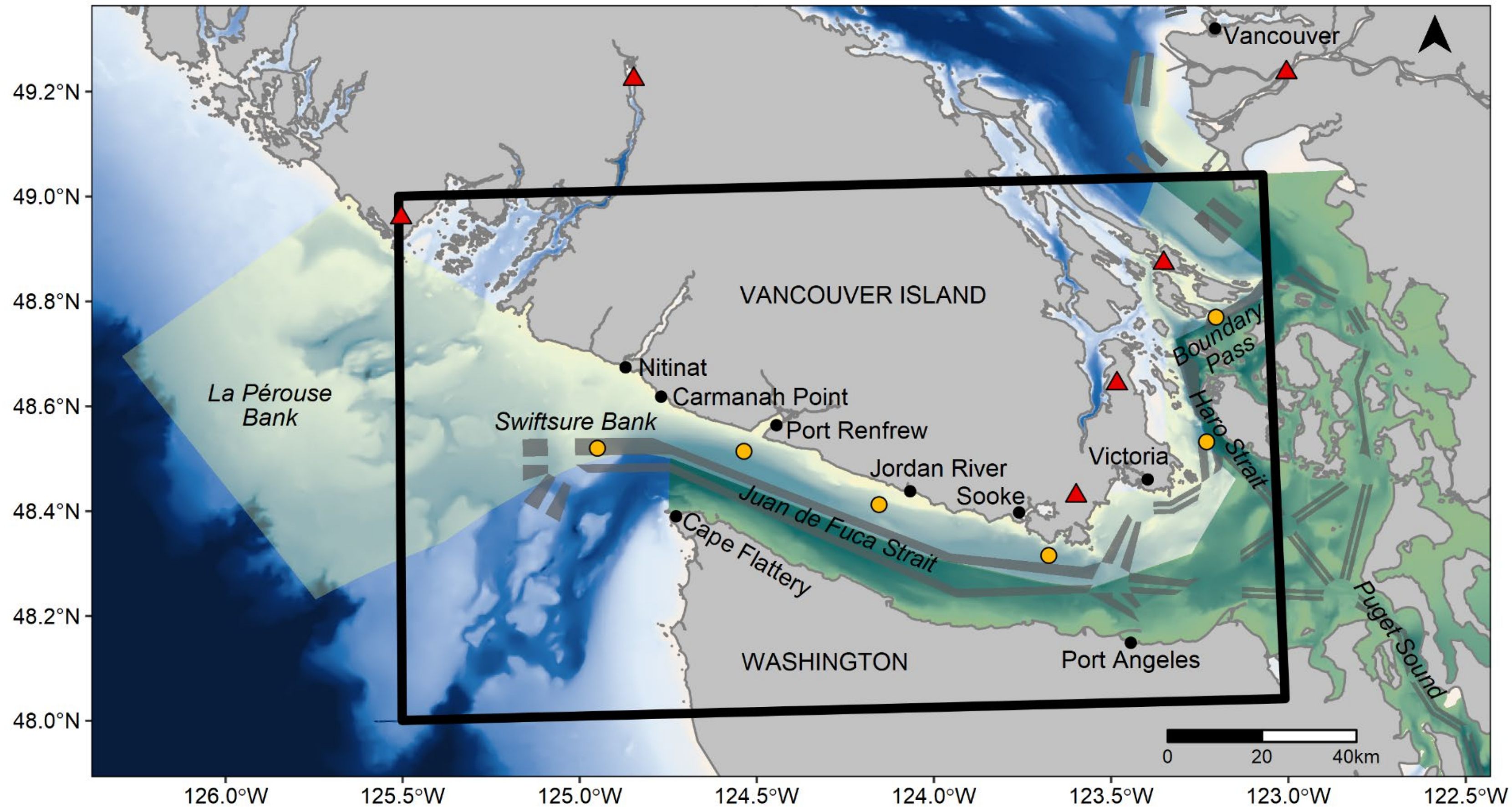
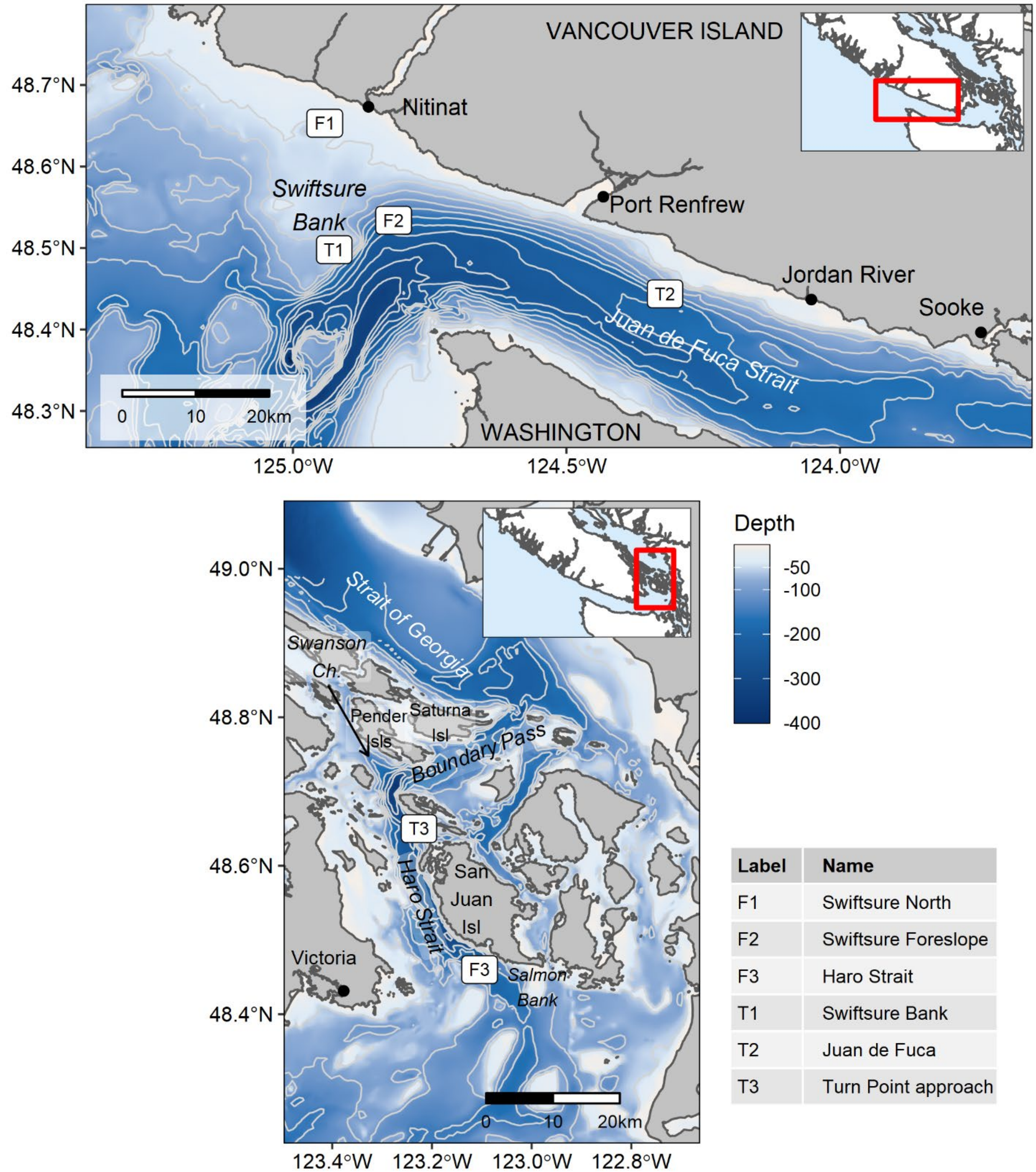


Figure 1. The waters around southern Vancouver Island, British Columbia. The study area is bounded by a black box, 49.0°N, 125.5°W; 49.0°N, 123.0°W; 48.0°N, 125.5°W; 48.0°N, 123.0°W. The shaded yellow area delineates SRKW critical habitat (CH) in Canadian waters; areas shaded in green are SRKW CH in US waters. Shipping lanes are indicated in grey, yellow circles show locations of acoustic moorings and red triangles indicate AIS receiver locations.



Label	Name
F1	Swiftsure North
F2	Swiftsure Foreslope
F3	Haro Strait
T1	Swiftsure Bank
T2	Juan de Fuca
T3	Turn Point approach

Figure 2. Bathymetry of the study area showing representative locations in forage (F) and travel (T) areas that were selected for acoustic analyses.

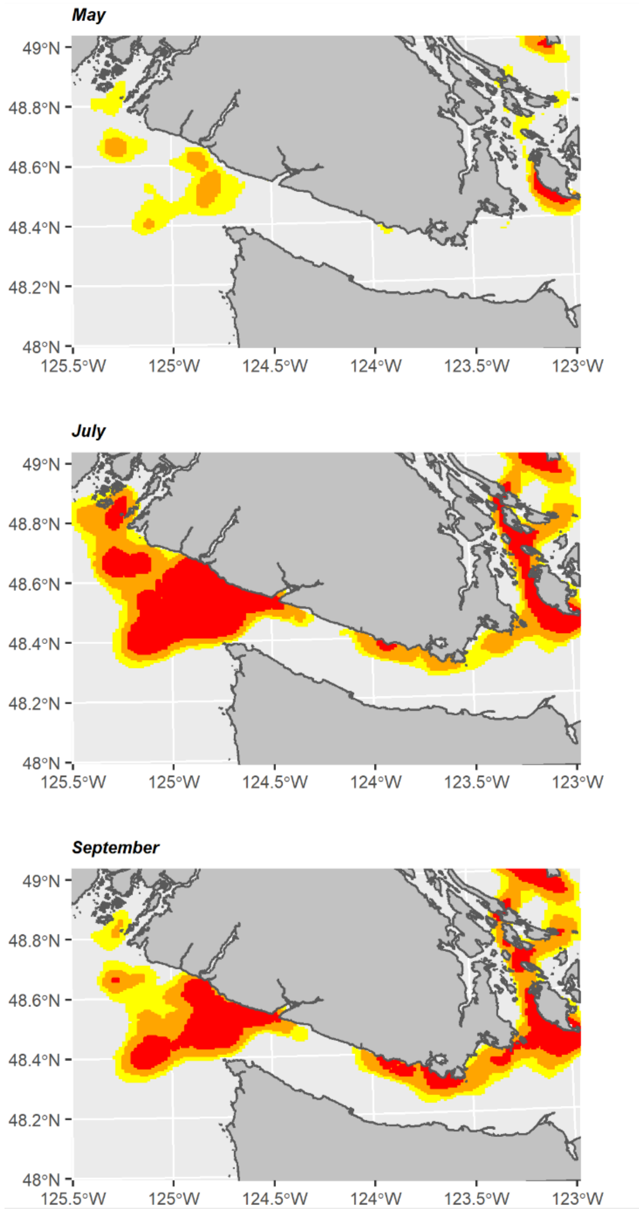
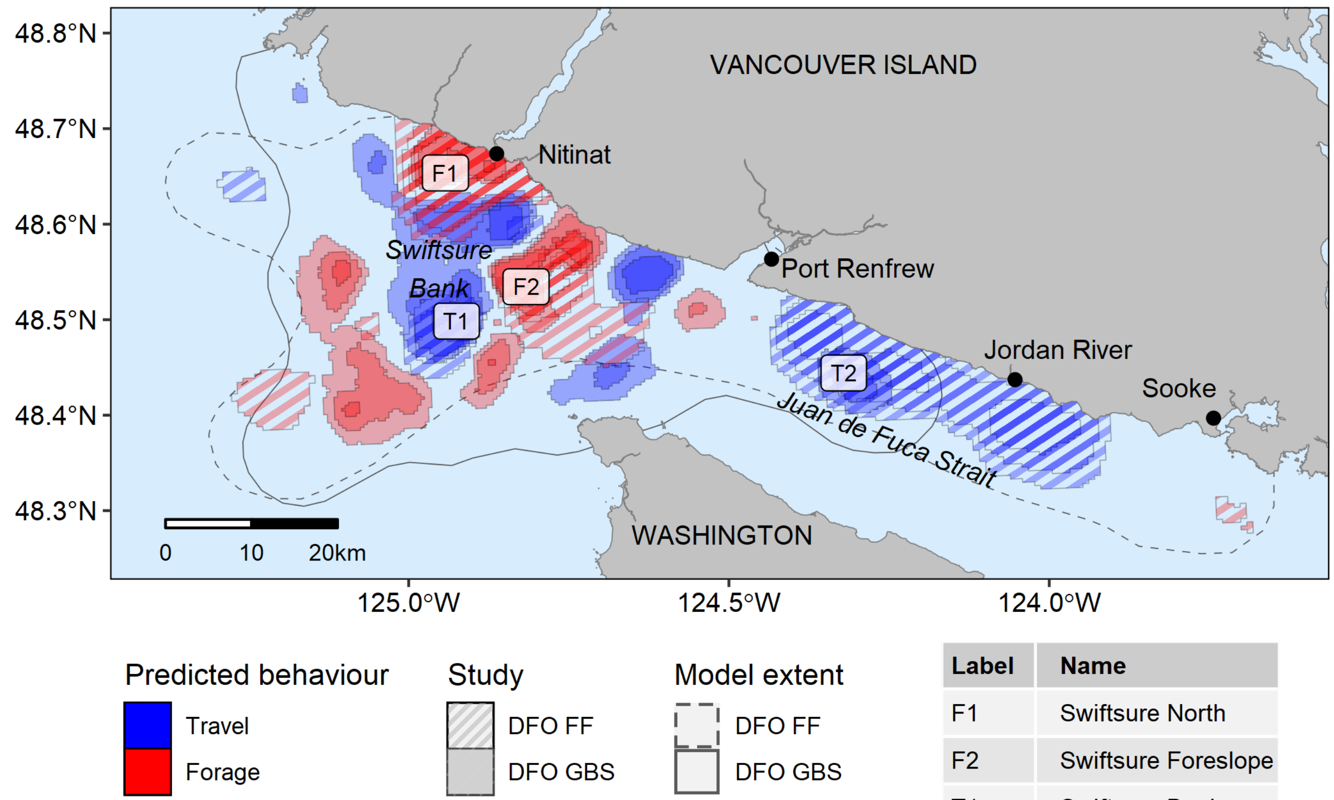
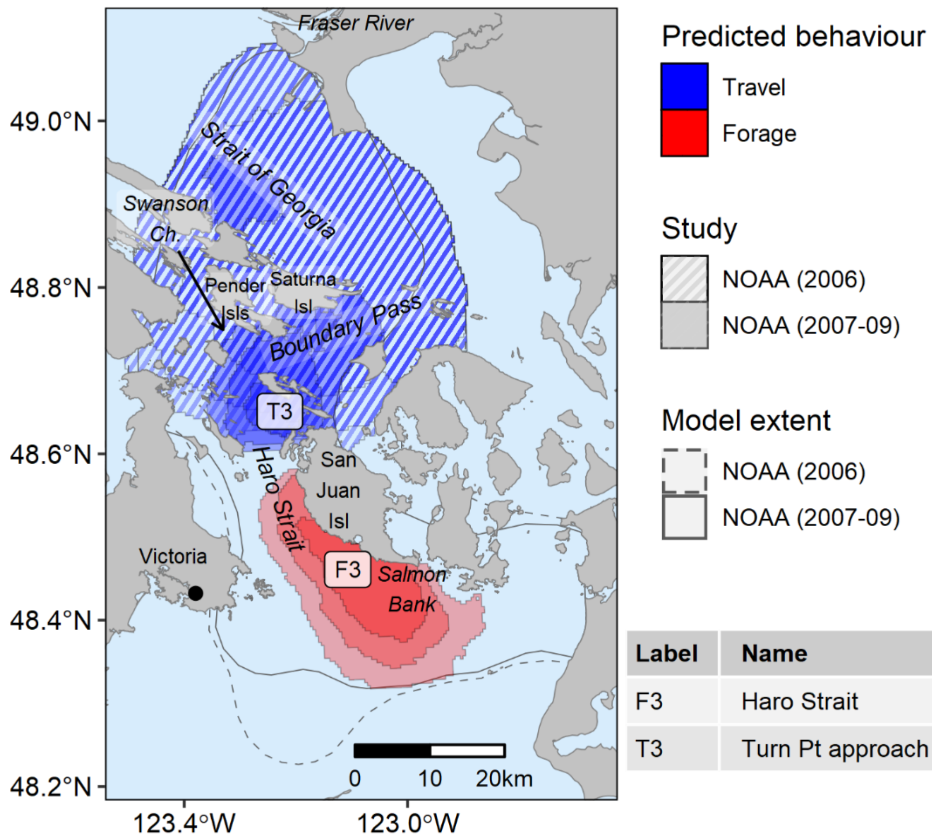


Figure 3. Areas of high SRKW frequency of occurrence across the region represented by intensity polygons - 70% (yellow), 80% (orange), and 90% (red) are displayed for each month. The frequency of occurrence values are computed across all months (May to October); probabilities greater than 0.90 are displayed (Thornton et al, 2022).



Label	Name
F1	Swiftsure North
F2	Swiftsure Foreslope
T1	Swiftsure Bank
T2	Juan de Fuca

Figure 4. Areas of likely forage and travel behaviour in the Swiftsure Bank area, as indicated by DFO focal follow (FF) and group behavioural survey (GBS) models. Areas were defined by locations exhibiting greater than median values (50% exceedance) of the given behaviour in >0.7, >0.8 and >0.9 of model posterior samples (shown in decreasing transparency, respectively). Extents of model predictions, as well as Foraging (F) and Traveling (T) locations for analysis of changes in acoustic ranges are also shown (Thornton et al, 2022).



Label	Name
F3	Haro Strait
T3	Turn Pt approach

Figure 5. Areas of likely forage and travel behaviour in the Haro Strait area, as indicated by NOAA focal follow (2006) and behavioural sampling (2007-09) models. Areas were defined by locations exhibiting greater than median (50% exceedance) of the given behaviour in >0.7, >0.8 and >0.9 of model posterior samples (shown in decreasing transparency, respectively). Extents of model predictions, as well as Foraging (F) and Traveling (T) locations for analysis of changes in acoustic ranges are also shown (Thornton et al, 2022).

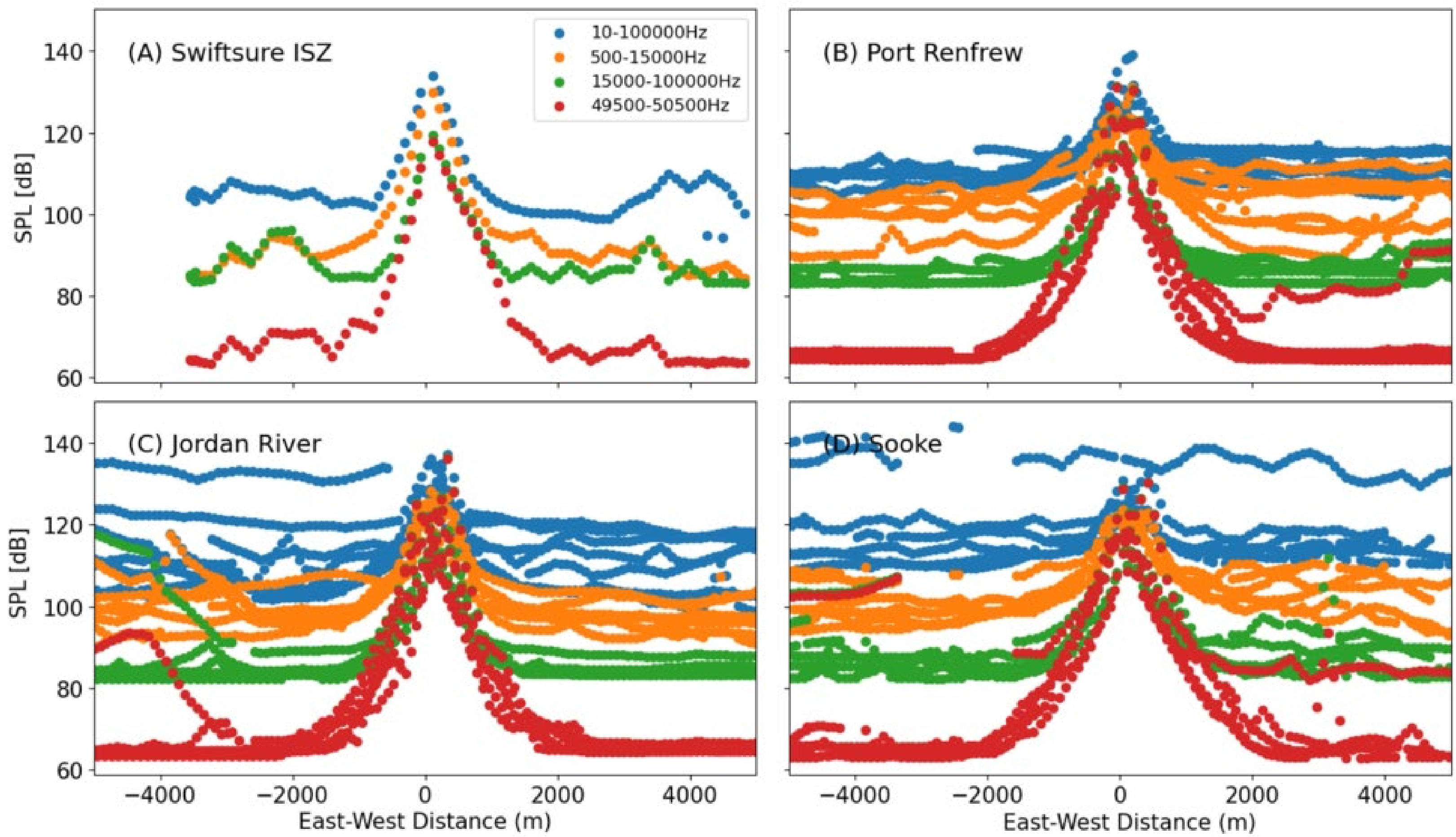


Figure 6. Detection range estimation using an experimental noise source, CCGS VECTOR, at known distances away from the passive acoustic monitor (PAM) moorings along transect lines (from 0 to 10km away). Detection ranges were estimated for recordings on the Swiftsure Interim Sanctuary Zone (A), Port Renfrew (B), Jordan River (C) and Sooke (D) mooring.

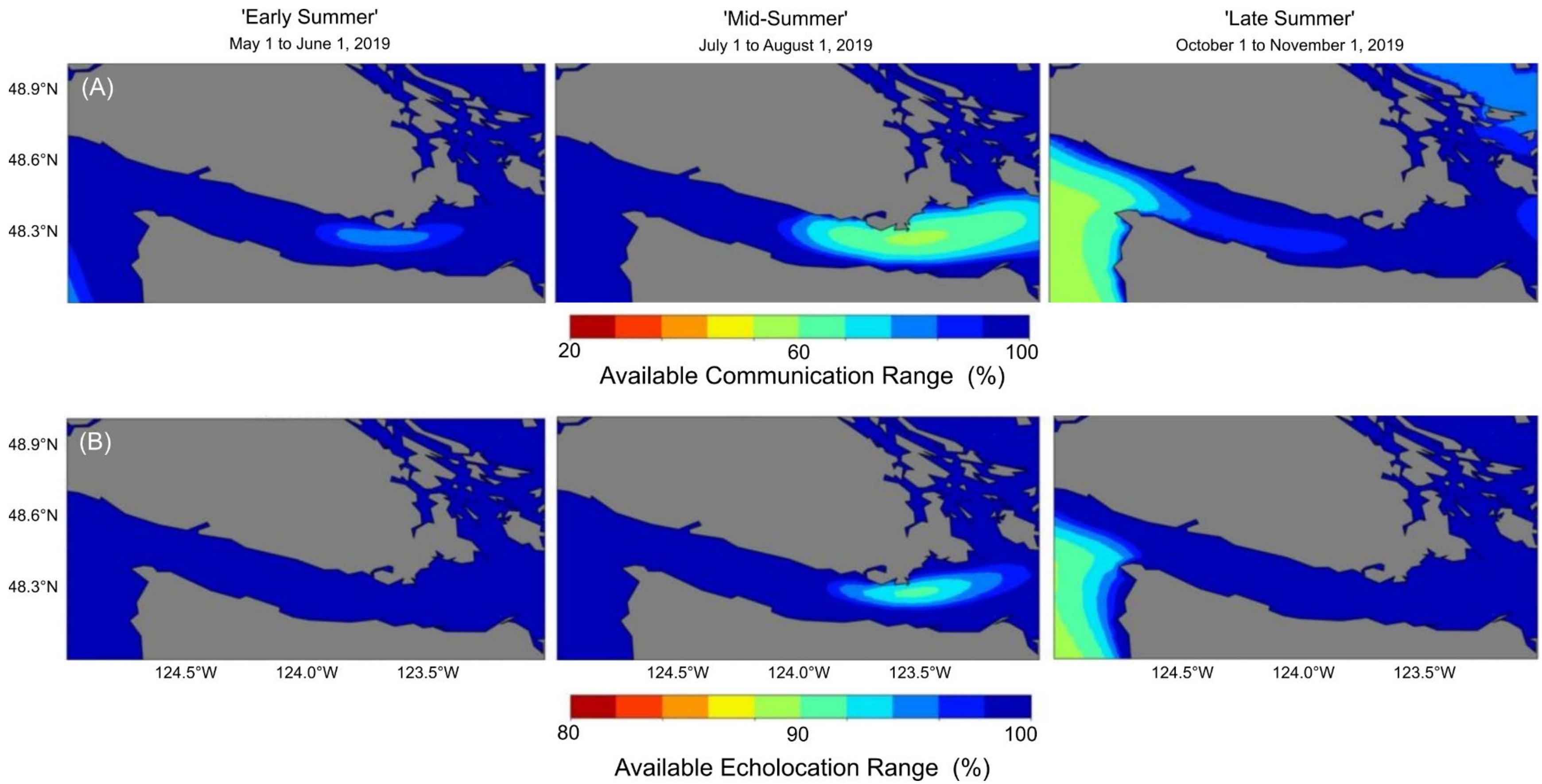


Figure 7. Proportional reduction in the (A) SRKW communication range of 500-15000 Hz at 10 kHz) and (B) SRKW echolocation range 15-100 kHz at 50 kHz as a result of median summer wind patterns (using L_{50} exceedance). Panels (A) and (B) use different scales of colour gradation, to better depict variation within each panel.

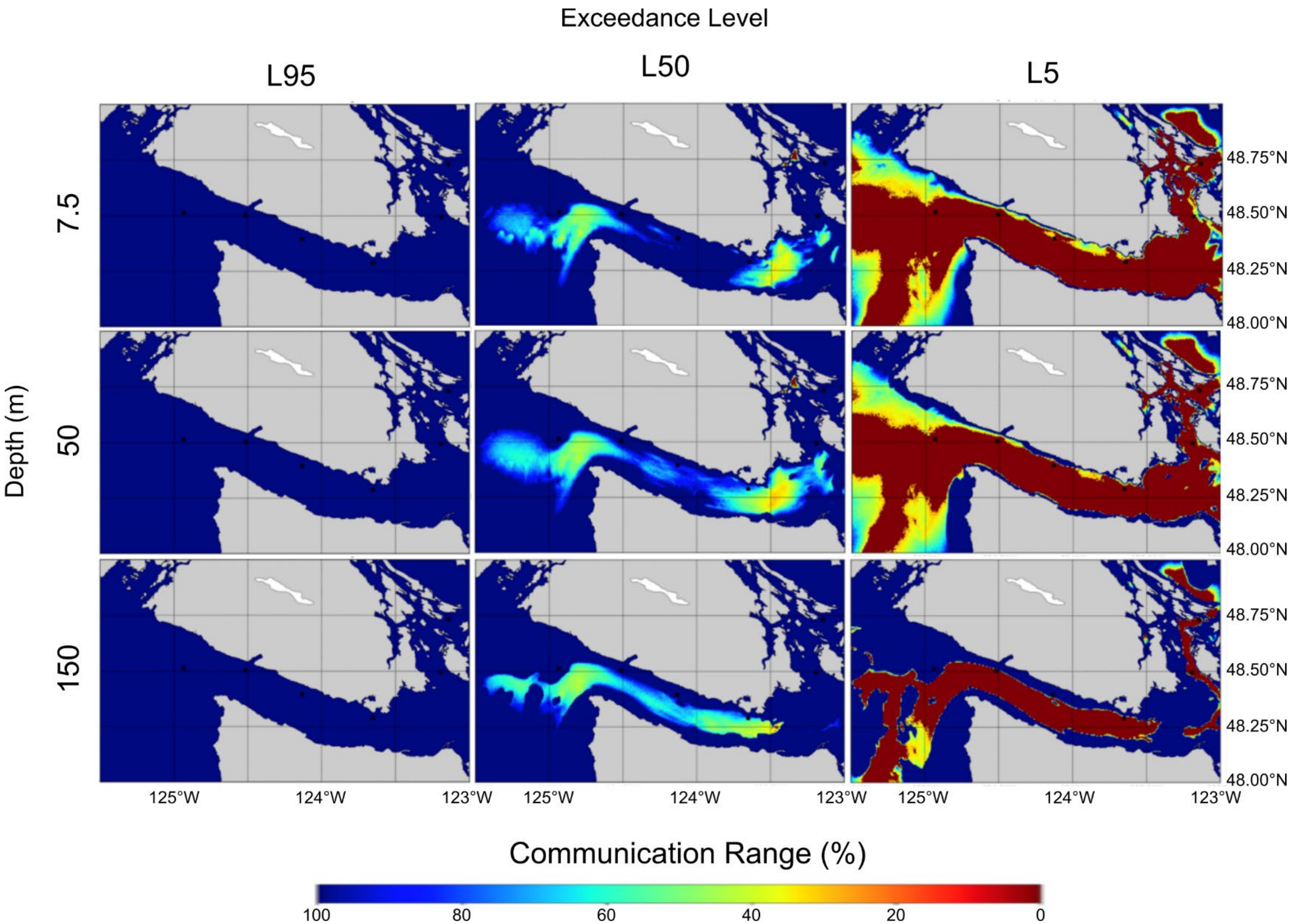


Figure 8. The changes in SRKW communication range resulting from vessel noise relative to 'minimum ambient' noise levels. July 2018 is shown as a representative month for the summer period. Comparisons were made between the L_{95}, L_{50} and L_5 exceedance levels of at 10 kHz, and through the water column at 7.5 m, 50 m, and 150 m depth.

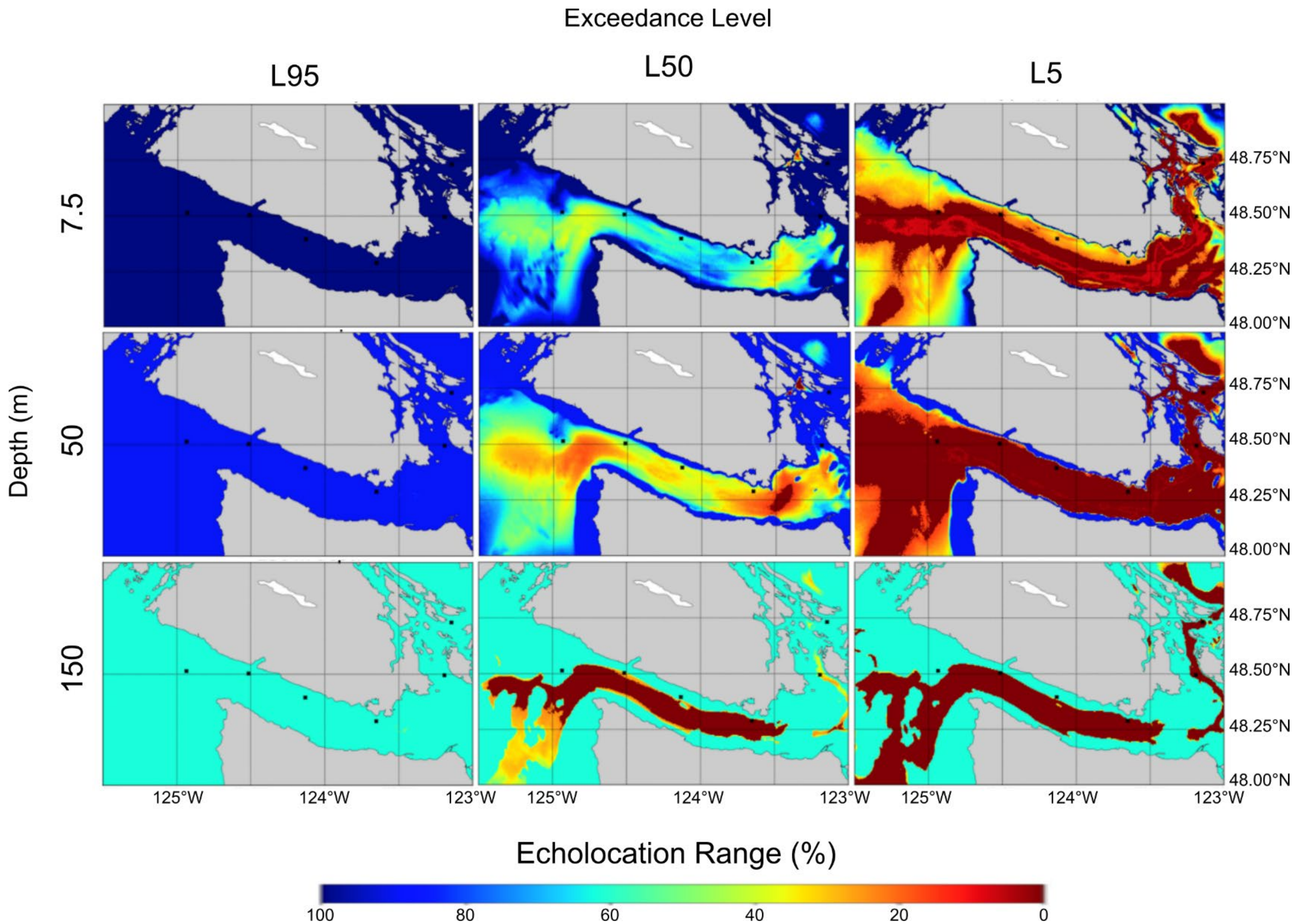


Figure 9. The changes in SRKW echolocation range resulting from vessel noise relative to 'minimum ambient' noise levels. July 2018 is shown as a representative month for the summer period. Comparisons were made between the L_{95}, L_{50} and L_5 exceedance levels of SPL at 50 kHz, and sending an echolocation click from 10 m to a target at 7.5 m, 50 m, and 150 m depth.

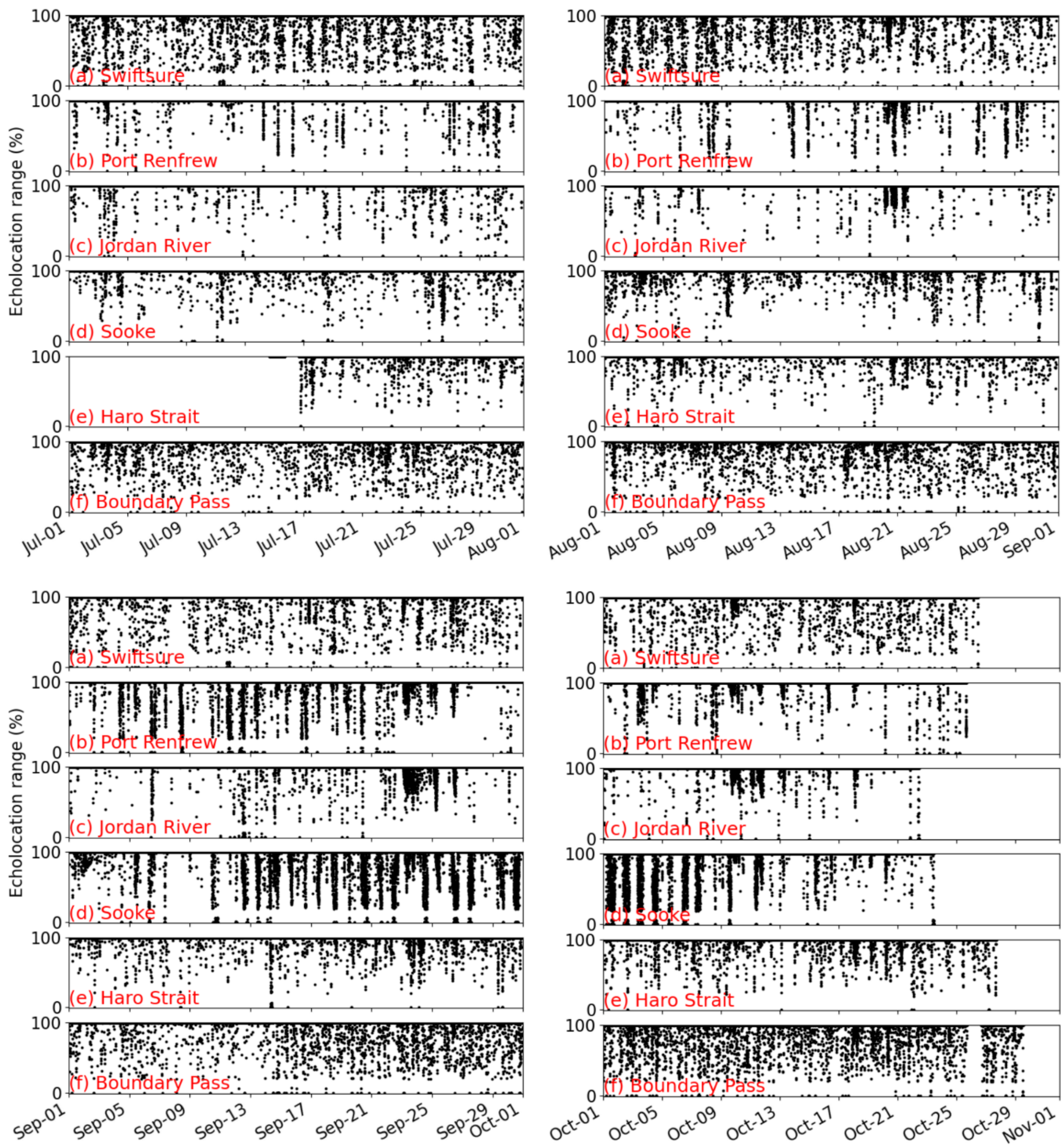


Figure 10. Percentage of echolocation range available in presence of small vessels, characterized by SPL levels in the 50 kHz frequency range. Minute-wise data from July to October 2020 are shown in monthly panels for each mooring: Swiftsure Bank (a), Port Renfrew (b), Jordan River (c), Sooke (d) Haro Strait (e) and Boundary Pass (f).

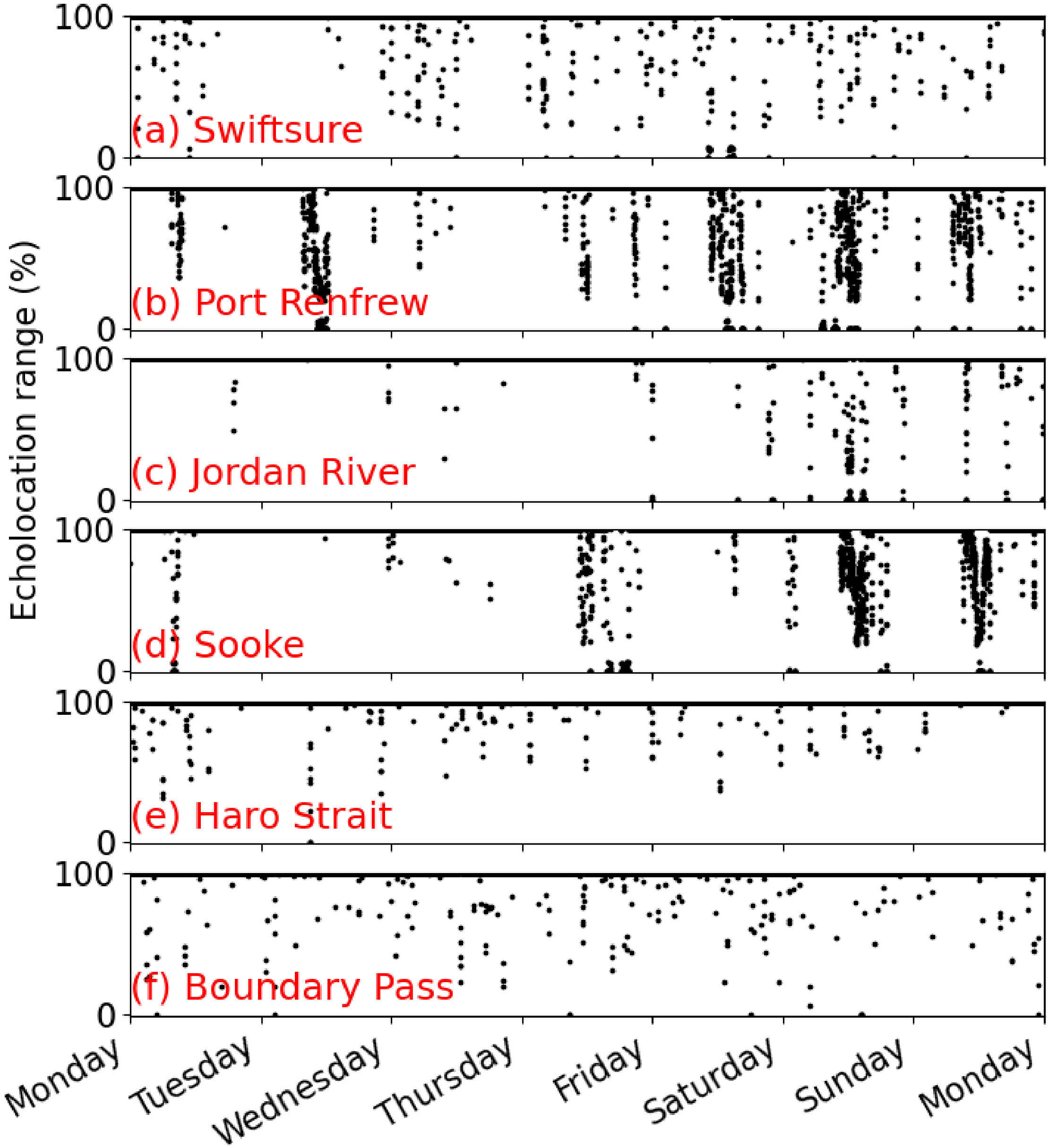


Figure 11. Percentage of echolocation range available affected by the presence of small vessels, characterized by SPL levels in the 50 kHz frequency range. Minute-wise data from September 7-14, 2020 are shown in panels for each mooring: Swiftsure Bank (a), Port Renfrew (b), Jordan River (c), Sooke (d) Haro Strait (e) and Boundary Pass (f).

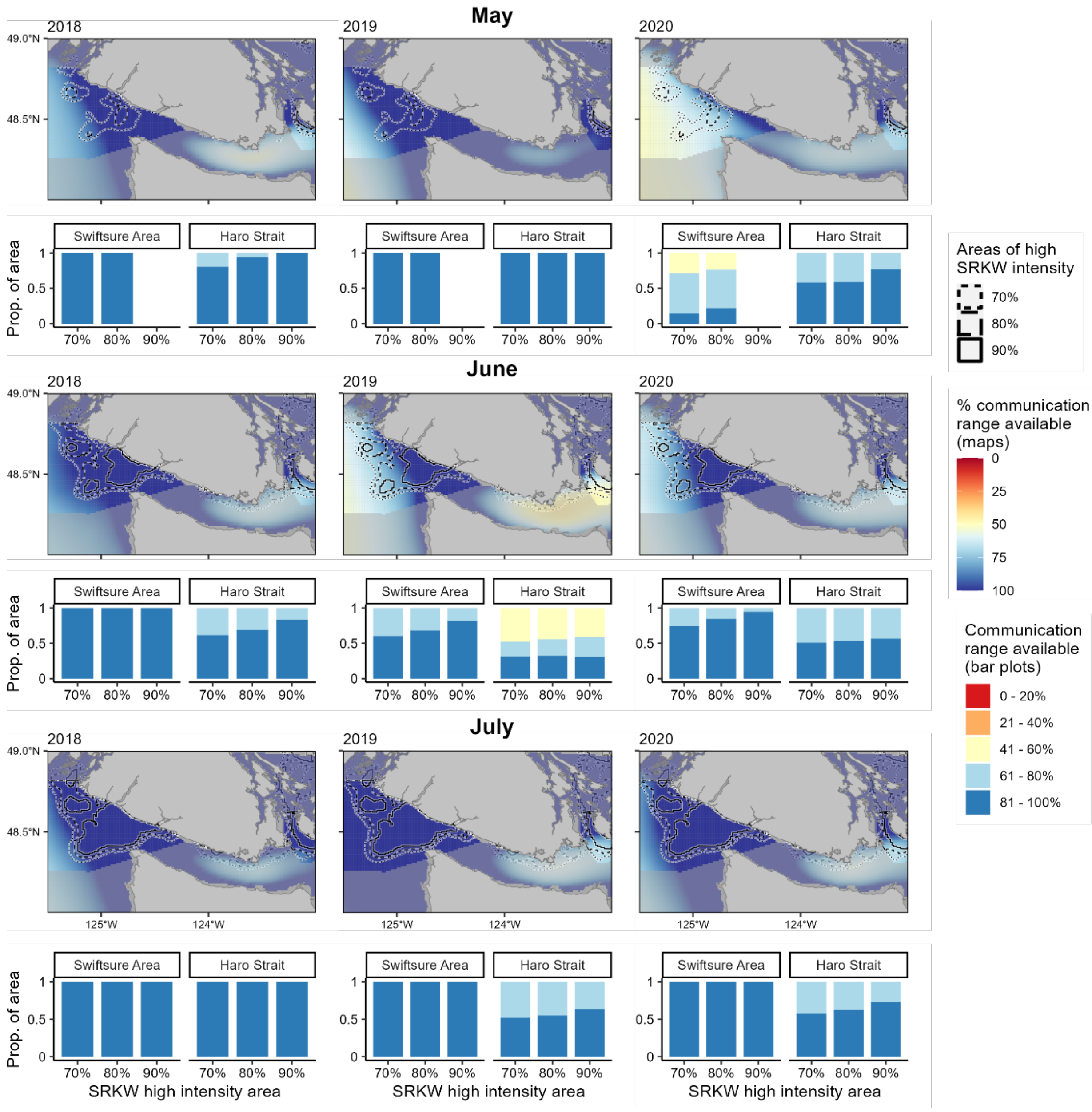


Figure 12. The loss of communication range resulting from wind noise in Haro Strait and the Swiftsure Bank area (bounded by grey shading) per month and year at 25 m depth. Communication range loss was calculated using L_{50} exceedance level and monthly averages, overlaid with the areas of high SRKW intensity defined by the space-time models for the same period.

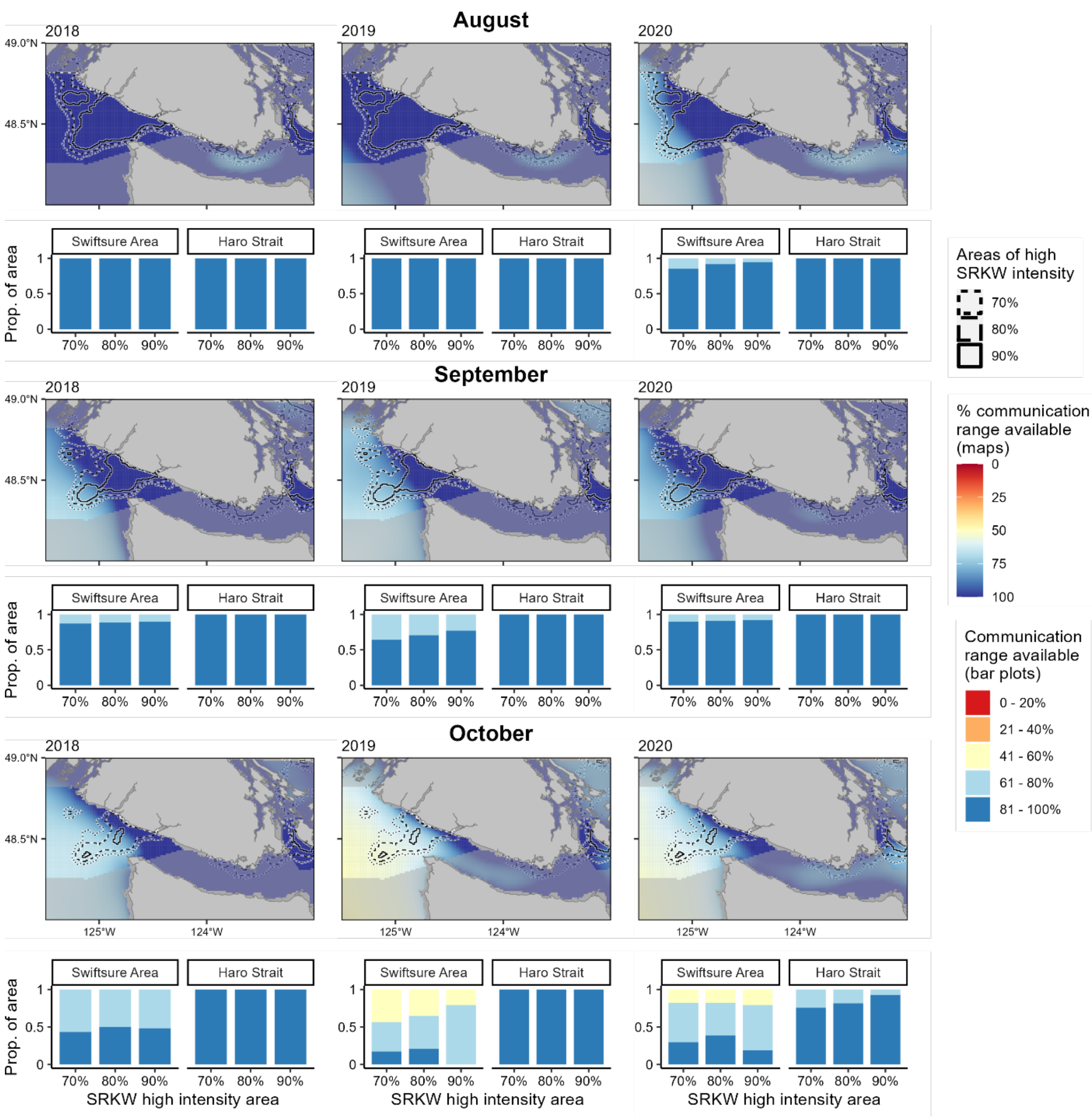


Figure 12. Continued.

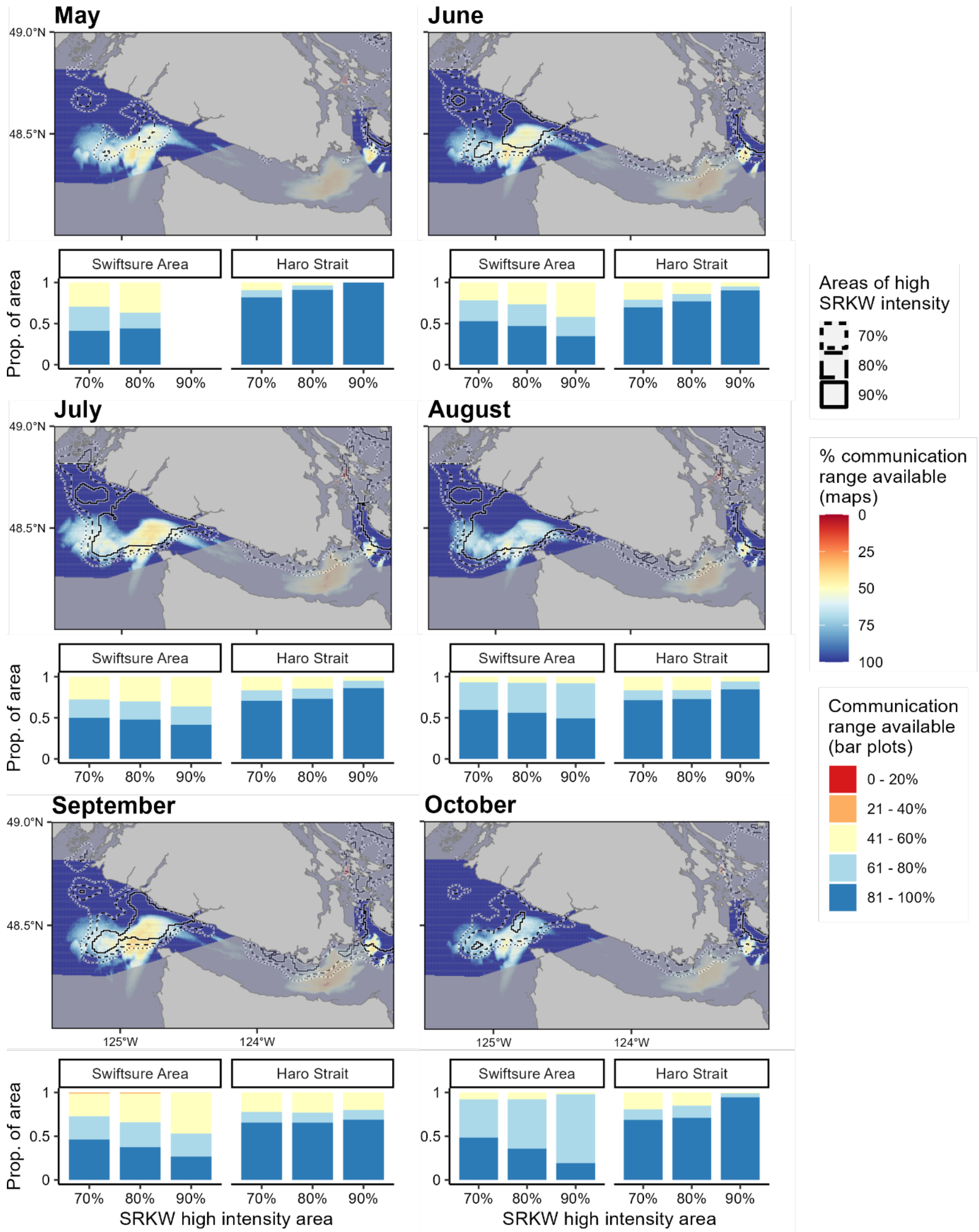


Figure 13. The loss of communication range resulting from vessel noise in Haro Strait and the Swiftsure Bank area (bounded by grey shading) per month. Only results at a 10 m depth are presented given the similarity of effects across depths. Communication range loss was calculated using L_{50} exceedance level and monthly averages from 2018, overlaid with areas of high SRKW intensity defined by the space-time models for the same period.

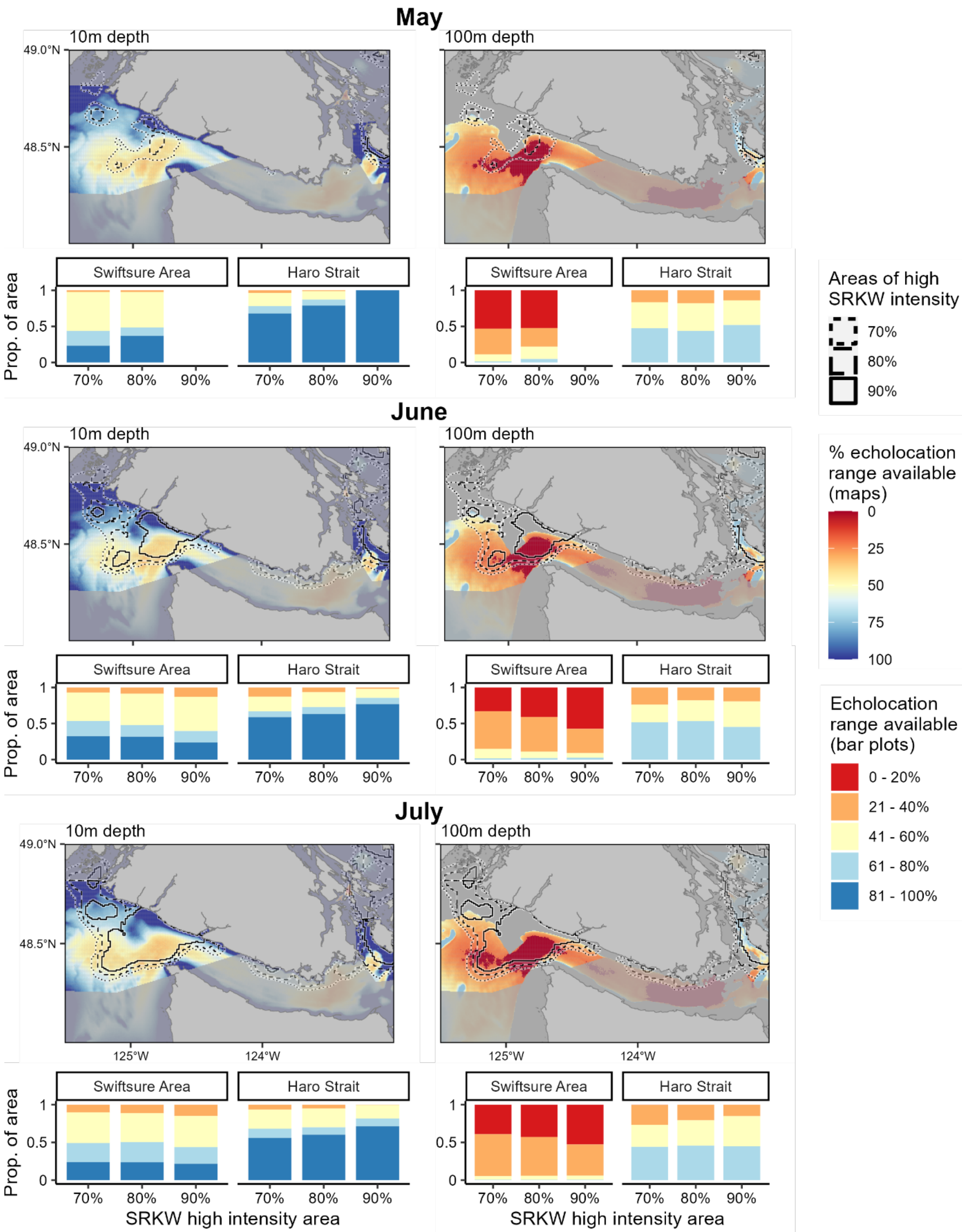


Figure 14. The loss of echolocation range as a result of vessel noise in Haro Strait and the Swiftsure Bank area (bounded by grey shading) per month at 10 m and 100 m depths. Echolocation range loss was calculated using L_{50} exceedance level and monthly averages from 2018, overlaid with areas of high SRKW intensity defined by the space-time models for the same period.

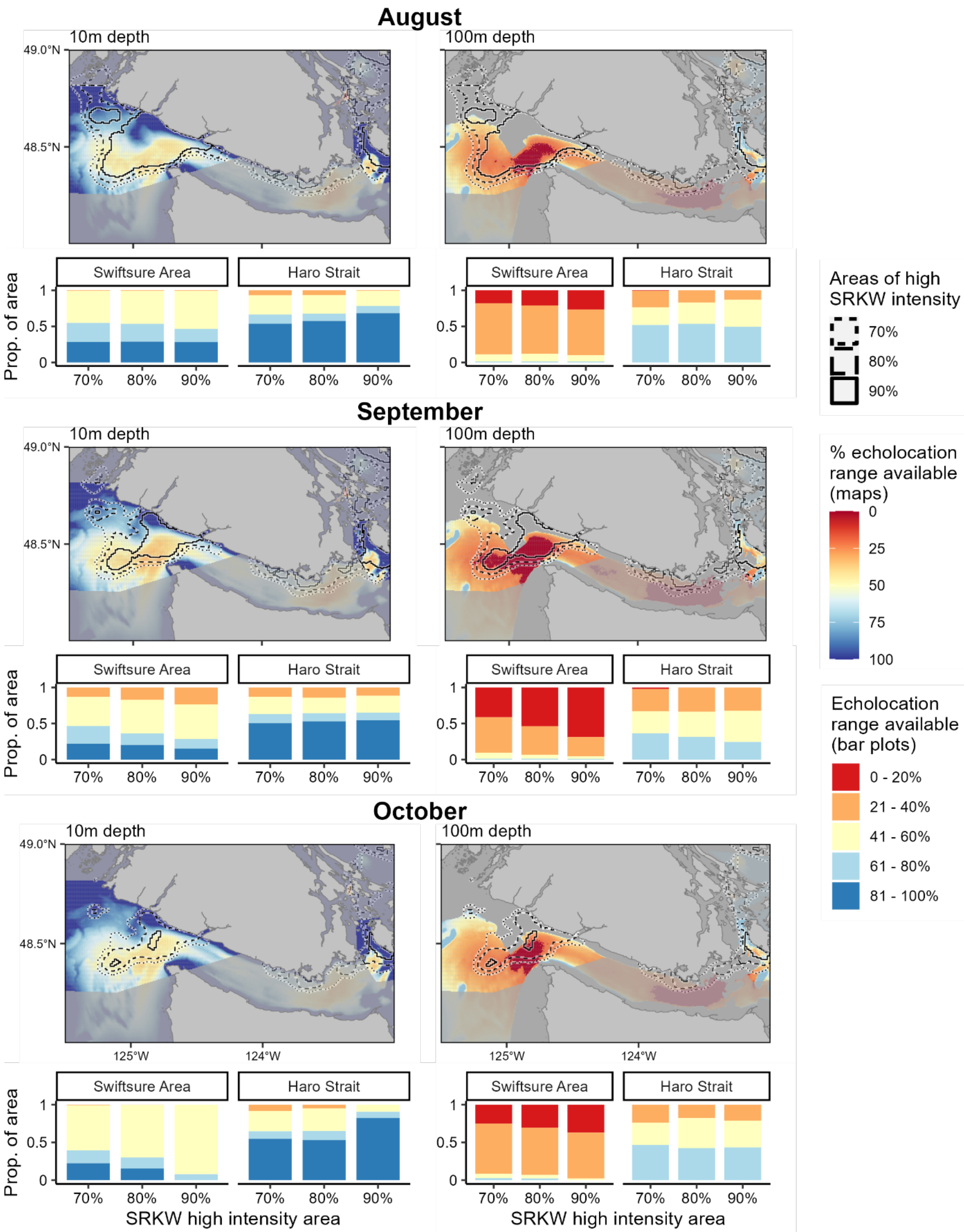


Figure 14. Continued.

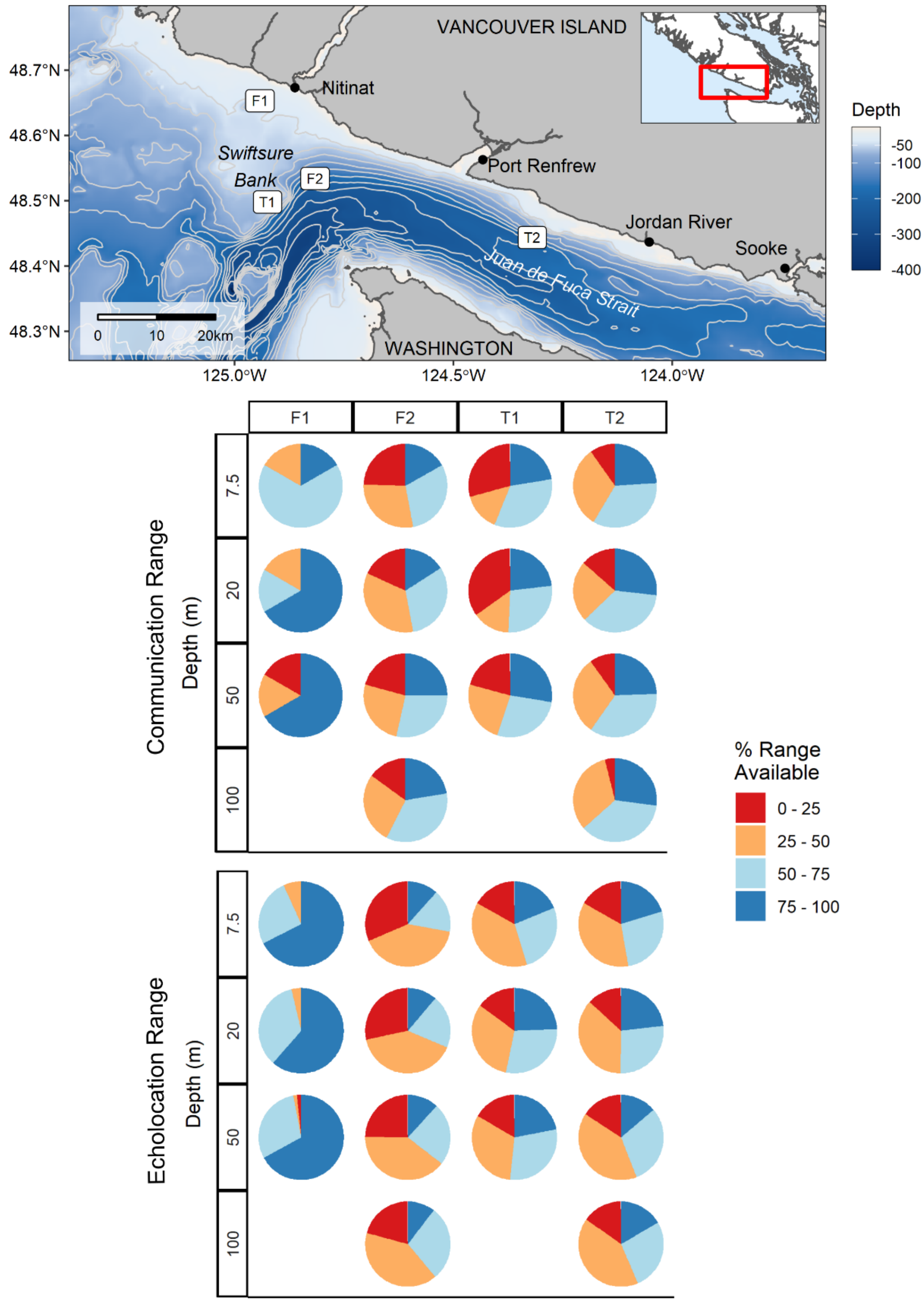


Figure 15. Proportion of time for which a given percentage of 'minimum ambient' acoustic range was available to SRKW over the week of August 1-7th, 2018, at locations in the Swiftsure Bank area. Communication range and echolocation range available are shown at four depths in locations where the predominant behaviour is travel (T1: Swiftsure Bank and T2: Juan de Fuca Strait) or forage (F1: Swiftsure North and F2: Swiftsure Foreslope). For communication range the whale is at the depth indicated, for echolocation range the whale is at 10 m echolocating to a target at the depths indicated.

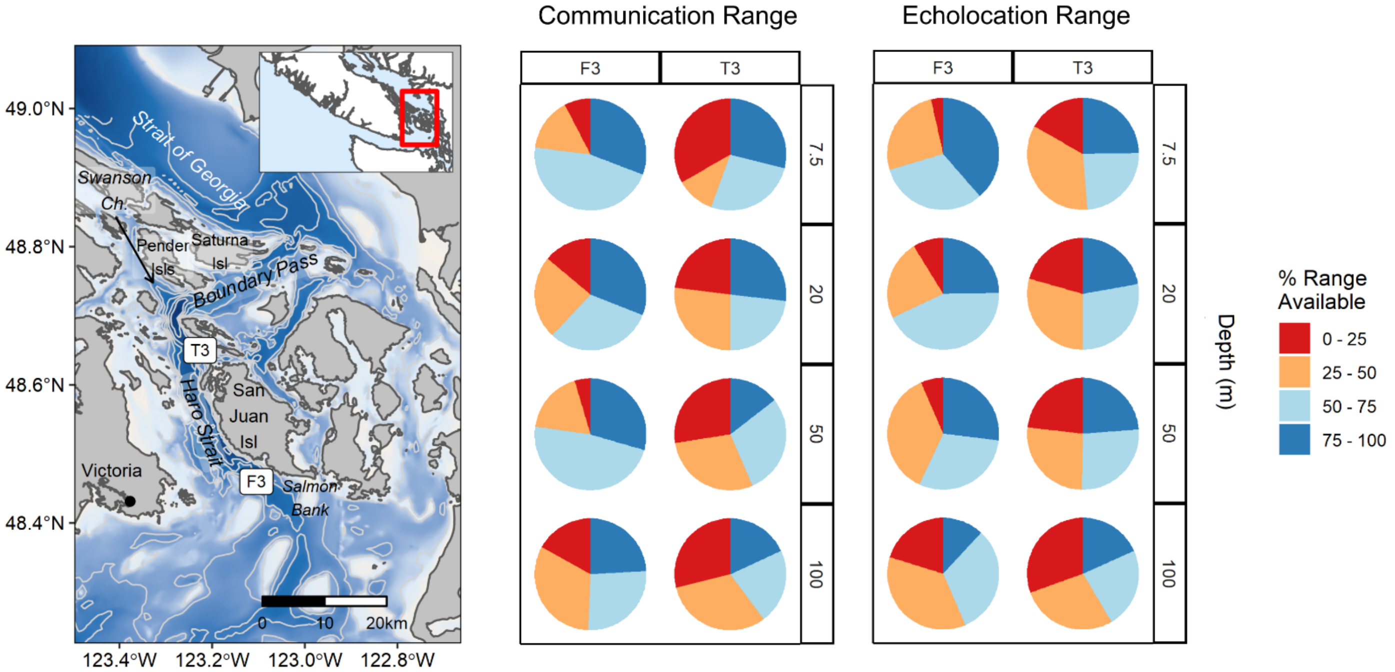


Figure 16. Proportion of time for which a given percentage of 'minimum ambient' acoustic range is available to SRKW over the week of August 1-7th, 2018 at locations in the Haro Strait area. Communication range and echolocation range available are shown at four depths in locations where the predominant behaviour is travel (T3: Turn Point approach) or forage (F3: Haro Strait). For communication range the whale is at the depth indicated, for echolocation range the whale is at 10 m echolocating to a target at the depths indicated.

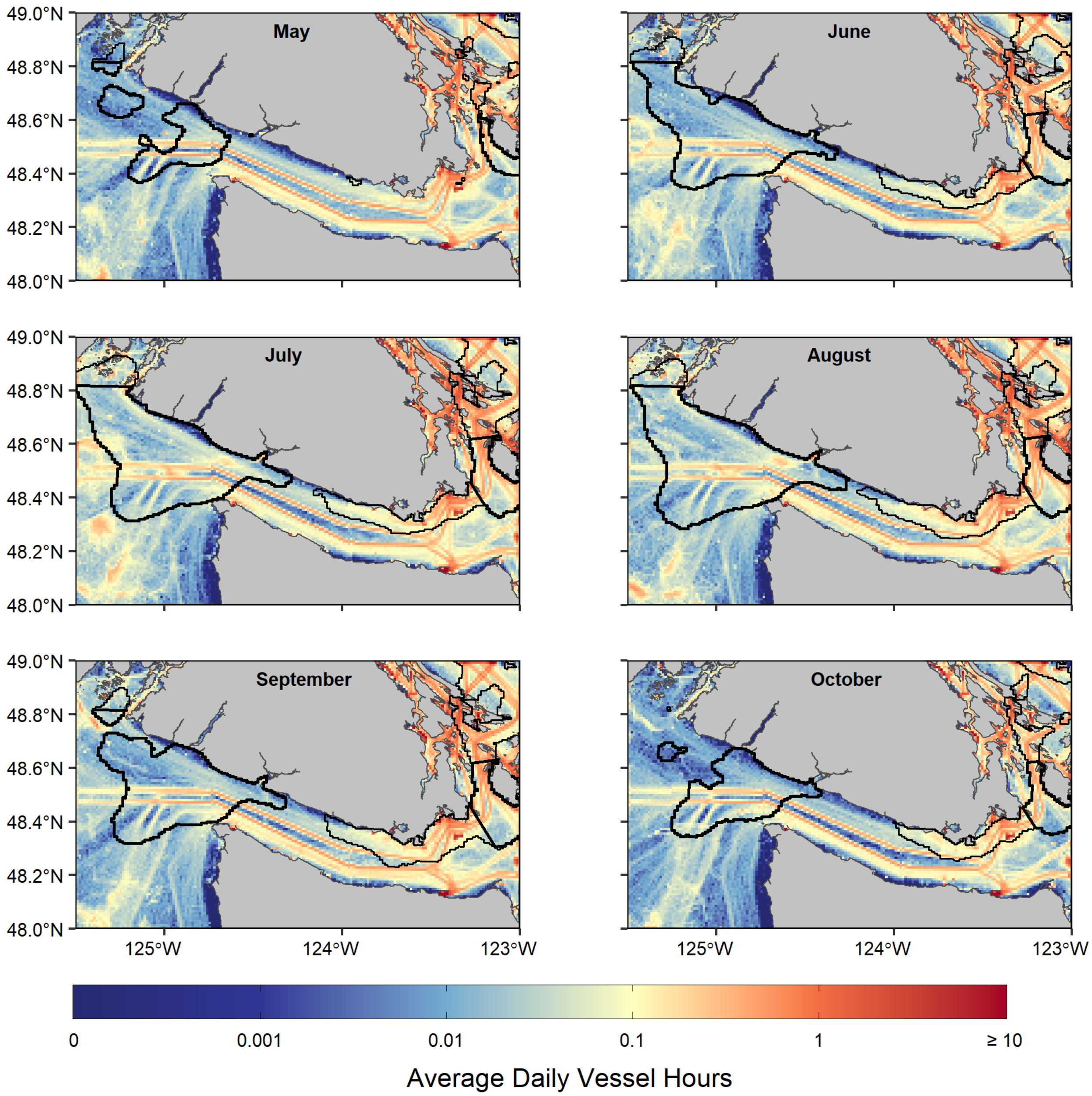


Figure 17. Co-occurrence of all AIS vessels and areas of high SRKW intensity (indicated by black lines, 0.9 probability at 70% frequency of occurrence). Vessel presence is average daily presence (in hrs/km^2) each month for 2018 to 2020. The Swifture Bank area and Haro Strait regions used for the detailed analysis of vessel presence (Figure 18) are indicated by bold black lines.

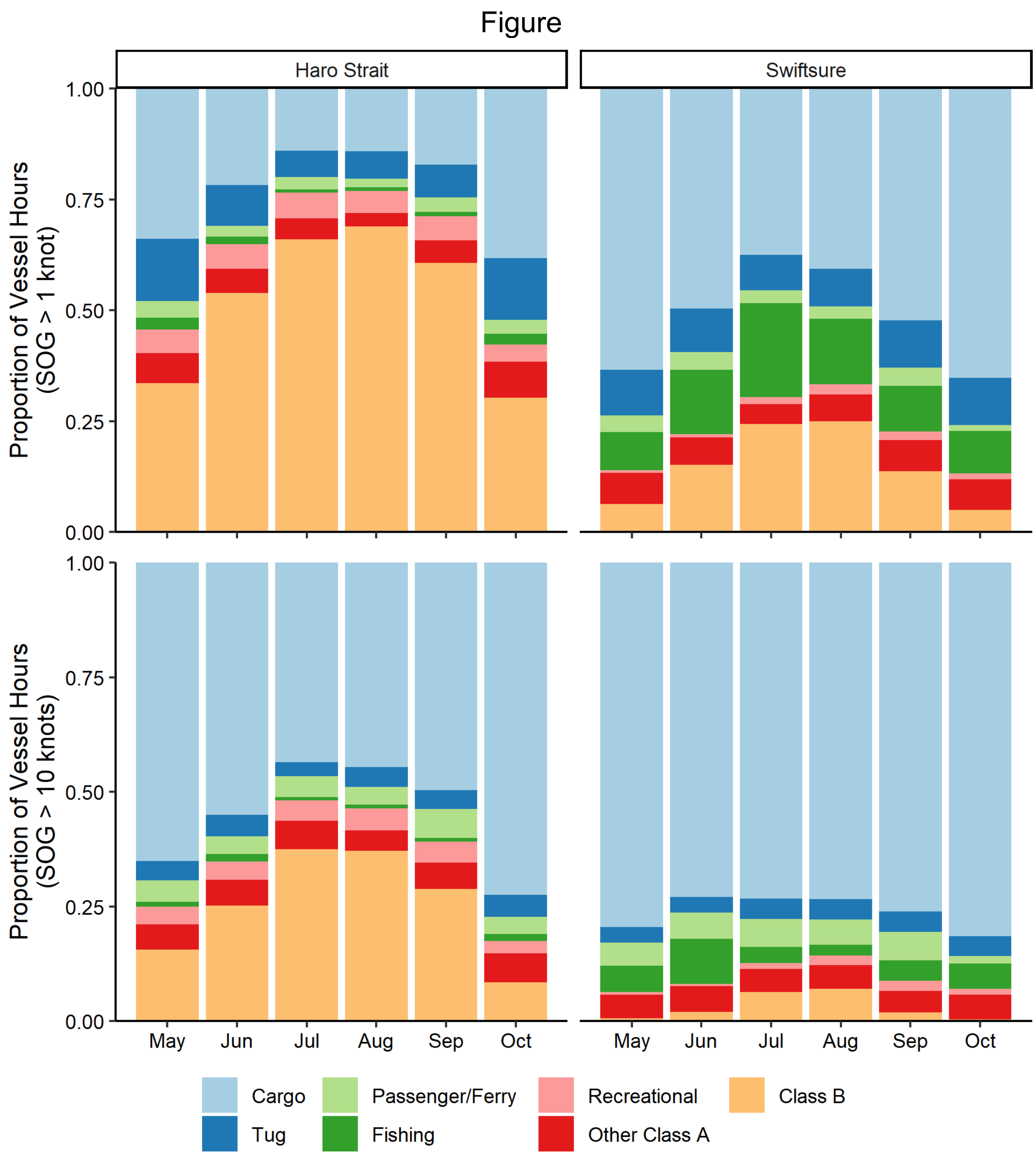


Figure 18. Proportional vessel presence by type in Haro Strait and on Swiftsure Bank area (0.9% SRKW probability at 70% exceedance level). The relative proportions are shown for vessels making way (SOG> 1 knot) and for vessels travelling at speed (SOG> 10 knots). AIS is generally mandatory for large commercial vessels (i.e. cargo and passenger/ferry), but most other vessels are not required to carry AIS; presence of these vessels are underrepresented in this figure.

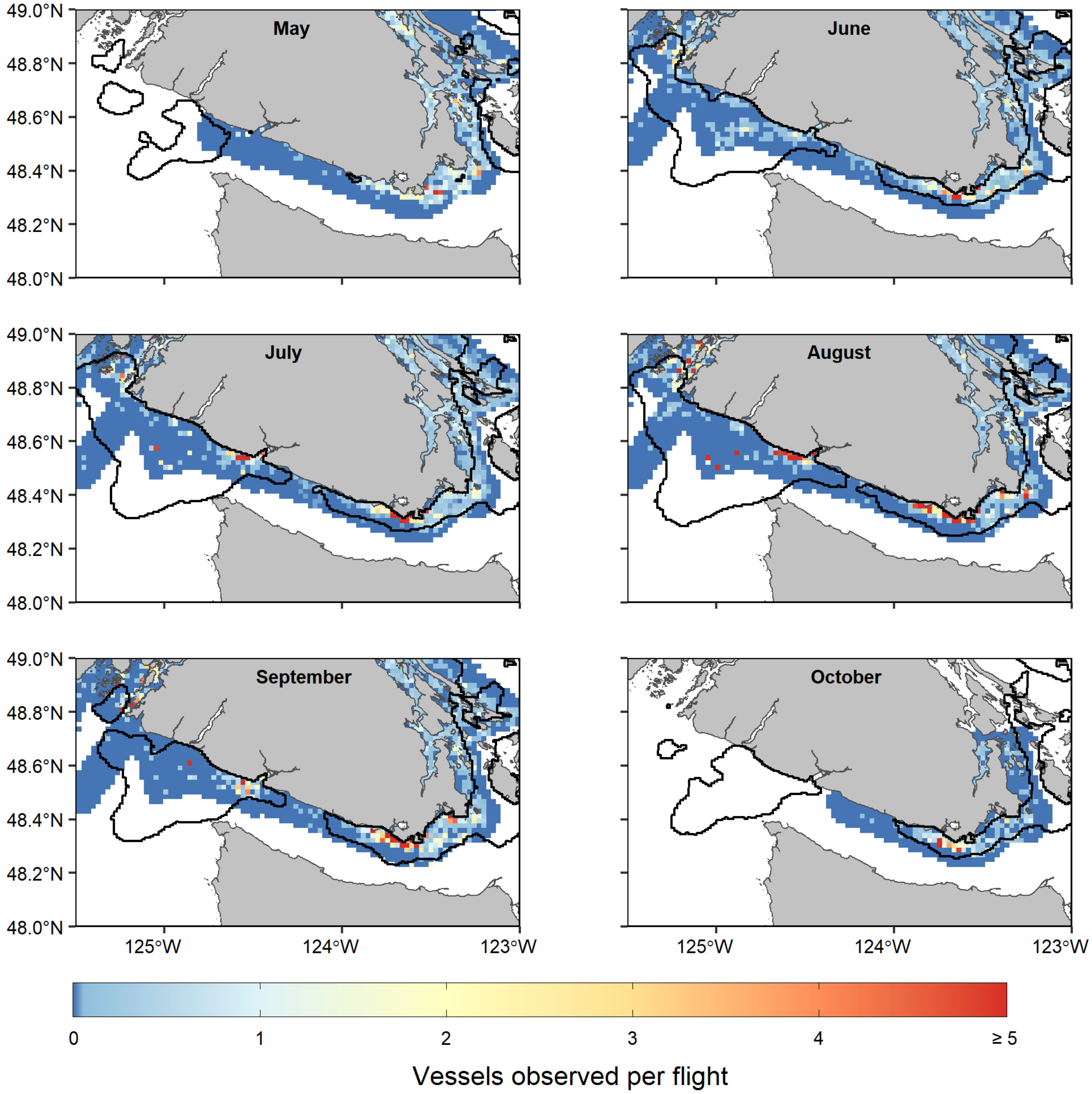


Figure 19. Co-occurrence of recreational fishing vessels and areas of high SRKW intensity (indicated by black lines, (0.9 SRKW probability at 70% frequency of occurrence).Vessel presence is the average number of vessels observed per DFO Creel aerial survey with coverage of the grid cell, by month in 2018-2020. Areas with no survey effort are shown in white.

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APPENDIX A

Table A1. Proportion of time for which a given percentage of 'ancient ambient' active space is available to SRKW over the week of August 1-7th, 2018 at locations in the Swiftsure Bank area and the Haro Strait area. Communication range and echolocation range available are shown at four depths in locations where the predominant behaviour is travel or forage.

				Range Available			
Range Type	**Primary Behaviour**	**Location Name**	**Depth (m)**	**75 - 100 %**	**50 - 75 %**	**25 - 50 %**	**0 - 25 %**
Communication	Forage	Swiftsure North	7.5	16.7	66.7	16.7	0
			20	66.7	16.7	16.7	0
			50	66.7	0	16.7	16.7
		Swiftsure Foreslope	7.5	16.8	30.3	28.4	24.5
			20	15.9	31.2	34.8	18.1
			50	25	28.6	25.7	20.7
			100	22.4	35.1	27.6	14.9
		Haro Strait	7.5	30.8	46.2	15.4	7.6
			20	31	31	24.1	13.9
			50	29.5	47.7	18.2	4.6
			100	24.1	26.5	32.5	16.9
	Travel	Swiftsure Bank	7.5	22.5	33.7	14.6	29.2
			20	23.2	27.5	14.5	34.8
			50	27.6	27.6	24.1	20.7
		Juan de Fuca	7.5	24	34.6	31.7	9.7
			20	26.8	36.1	23.7	13.4
			50	24.5	35.3	30.4	9.8
			100	27.1	36.4	32.7	3.8
		Turn Point Approach	7.5	28.9	26.7	11.1	33.3
			20	26.9	23.1	26.9	23.1
			50	14.5	29	29	27.5
			100	18.1	21.7	31.3	28.9
Echolocation	Forage	Swiftsure North	7.5	67.6	25.7	6.7	0
			20	61.5	34.9	3.7	0
			50	67.1	30	1.4	1.5
		Swiftsure Foreslope	7.5	11.6	16.3	40.7	31.4
			20	11.2	20.2	40.3	28.3
			50	11.8	23.7	39.7	24.8
			100	10.4	28.5	40.4	20.7
		Haro Strait	7.5	38.6	31.8	26.1	3.5
			20	24.8	43.2	23.2	8.8
			50	26.9	30.1	36.5	6.5
			100	11.9	31.6	36.3	20.2
	Travel	Swiftsure Bank	7.5	18.8	26.5	38	16.7

Range Type	Primary Behaviour	Location Name	Depth (m)	Range Available 75 - 100 %	50 - 75 %	25 - 50 %	0 - 25 %
			20	24.5	28.8	31.9	14.8
			50	22	29.7	31.8	16.5
		Juan de Fuca	7.5	20.2	27.1	36	16.7
			20	23.2	27	36.7	13.1
			50	13.8	30.3	40.2	15.7
			100	16.6	27	41.3	15.1
		Turn Point Approach	7.5	24.8	23.9	34.5	16.8
			20	22.2	27.8	29.4	20.6
			50	23.8	26.5	26.5	23.2
			100	18.3	23.2	28	30.5