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Anchored bulk carriers have substantial impacts on the underwater soundscape in Cowichan Bay, British Columbia

Kelsie A. Murchy[a,*], Svein Vagle[b], Francis Juanes[a]

[a] Biology Department, University of Victoria, Victoria, British Columbia, Canada
[b] Institute of Ocean Sciences, Fisheries and Oceans Canada, Sidney, British Columbia, Canada

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ABSTRACT

In recent decades shipping traffic has increased, leading to elevated underwater ambient noise levels. Research has been conducted on the noise generated by ships underway, however little is known about potential noise from ships at anchor. In coastal regions, commercial vessels can seek anchorages prior to entering port, leading to concern regarding the impacts on the soundscape and marine ecosystems. Cowichan Bay, British Columbia, a coastal region (800 Ha) 70 km away from the Port of Vancouver, was examined as a case study to understand the possible soundscape contribution from anchored bulk carriers. When a carrier anchored, sound pressure levels (SPL: 20–24,000 Hz) were elevated 2–8 dB re: 1 μPa throughout the bay. These results demonstrate the change anchored carriers can have on underwater soundscapes and is an important step in understanding the potential impact these vessels may have on marine organisms and important ecosystems.

1. Introduction

The number of global commercial shipping vessels has increased four-fold during the last 20 years (Tournadre, 2014), adding substantially to underwater ambient sound levels in low frequencies (<1000 Hz; Ross, 1976; Veirs et al., 2016). Large bulk carriers and container ships produce sound at 184.2–188.1 dB re: 1 μPa^2 (source level) at frequencies between 20 and 1000 Hz with higher levels detected from the stern (McKenna et al., 2012). Individual commercial vessel passages can elevate sound levels (100–15,000 Hz) by as much as 20 dB above ambient levels (Veirs and Veirs, 2006). Additionally, the speed and size of commercial vessels influences the sound levels produced (Ross, 1976; Arveson and Vendittis, 2000). For container ships, vessel speed was the best predictor of source levels, but trends in the influence of total length and gross tonnage were also observed (McKenna et al., 2013). Research to date has focused on the impacts on the underwater soundscape from these vessels while moving, and noise additions from anchored commercial vessels awaiting access to port are often unaccounted for.

When carriers are in motion, most of the noise is from propeller cavitation, but with some noise generated by generators and other machinery onboard the vessel, especially at lower speeds (Arveson and Vendittis, 2000). When a carrier drops its anchor to the seafloor in order to remain stationary (anchoring), noise from propeller cavitation would be removed. Previous studies have documented elevated sound levels, and altered habitat use of marine species from recreational vessels (González Correa et al., 2019) and cruise ships (Ivanova et al., 2020) at anchor. Anchoring recreational vessels have also been documented to disrupt the physical benthic environment (Panigada et al., 2008). To our knowledge, no previous research has examined noise produced from bulk carriers at anchor, but likely noise produced from generators or other machinery would be produced while at anchor.

Passive acoustic monitoring is an important tool in evaluating the contribution of geophony, biophony and anthropophony to underwater soundscapes (Pijanowski et al., 2011), and has been previously used to quantify the influence of natural geophony (e.g., wind and waves) and anthropogenic noise in the waters around Vancouver Island, British Columbia (BC), also known as the Salish Sea (Burnham et al., 2021). A high presence of ships has been documented in the Salish Sea throughout the year (Erbe et al., 2012), and some of these commercial vessels are also anchoring in coastal regions around the Southern BC Coast with no time limit on how long they can anchor for (Canada Shipping Act, 2001). Here we consider the acoustic impact of anchored bulk carriers in Cowichan Bay, Vancouver Island, British Columbia (BC) as a case study of their potential influence on marine soundscapes. This is a highly industrialized site, frequently used by bulk carriers waiting for access to the Port of Vancouver, located approximately 70 km away.

* Corresponding author at: Biology Department, University of Victoria, 3800 Finnerty Rd., Victoria, British Columbia, Canada.
E-mail address: kmurchy23@gmail.com (K.A. Murchy).

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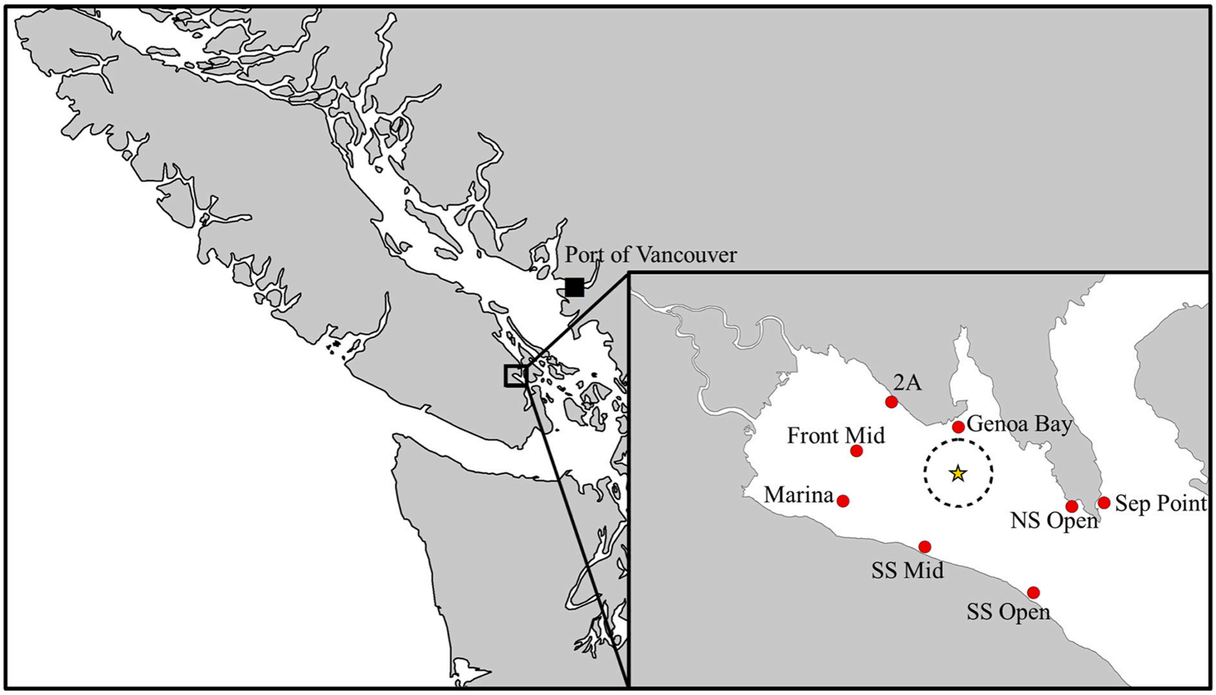

Fig. 1. Map of Vancouver Island with portions of lower British Columbia and Western Washington State. Black box denotes location of the Port of Vancouver. Inset: Map of Cowichan Bay, BC. Red circles show SoundTrap hydrophone mooring locations around the bay and the yellow star denotes a bulk carrier anchorage location. Black dashed circle denotes 500 m radius around anchorage location. Map provided from Natural Earth and BC Provincial data catalog. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
SoundTrap moorings and Cowichan Bay vessel anchorage information.

Location	Latitude (N)	Longitude (W)	Water depth (m)	Hydrophone depth (m)
2A	48.7589	123.6124	19	18
Front Mid	48.7523	123.6194	45	44
Marina	48.7455	123.6221	23	3
Genoa Bay	48.7556	123.5987	19	18
SS Mid	48.7394	123.6054	22	20
NS Open	48.7450	123.5755	18	17
Sep Point	48.7456	123.5689	25	24
SS Open	48.7334	123.5832	15	13
Anchorage location	48.7495	123.5987	58	NA

2. Methods

2.1. Study location

Cowichan Bay, British Columbia, is located on the east coast of Vancouver Island at the mouth of the Cowichan River (48.7525 N, –123.6205 W). The bay is approximately 4 km long and 2 km wide (~800 Ha). Water depth increases gradually from 0 m at the head of the bay to approximately 70 m at the mouth (Fig. 1). Within the bay there is one commercial anchorage site, with five more sites located outside extending southwards towards Saanich Inlet.

2.2. Passive acoustic recordings

Seven SoundTrap (300 STD/300 STDHF, Ocean Instruments, New Zealand) internally recording hydrophone systems were deployed throughout Cowichan Bay from 14 August 2019 to 4 November 2019, and then redeployed from 10 August 2020 to 28 October 2020 (Fig. 1, Table 1). All SoundTraps were deployed in water approximately 15–45 m deep, with six deployed at the bottom. Five SoundTraps were deployed in shallow water (~20 m), and anchored to the shore using leaded line. Polysteel lines connected to 200 mm trawl floats were used to keep the hydrophones vertical in the water column at a distance of 1–2 m off the bottom. A sixth system was deployed in deeper (45 m; 1 m off bottom) water and was equipped with an acoustic release for retrieval. The final SoundTrap was the only one deployed from the surface and was secured to a leaded line that was connected to a 7 kg cannon ball and attached to a mooring buoy. This SoundTrap was deployed at a depth of 3 m from the surface, in 23 m of water. In 2020 an additional SoundTrap was deployed with an acoustic release outside Cowichan Bay from 12 August to 22 October in 25 m water depth (Fig. 1).

All hydrophone systems sampled at 48 kHz at 16 bits. Two recorders, Front Mid and NS Open, were duty cycled, recording for 15 min every hour, while all others recorded continuously. The SoundTraps were calibrated by the manufacturer at 250 Hz using a B & K 2236 pistonphone at a source level of 120 dB re: 1 μPa before being deployed. Data were stored as compressed sud files (.SUD) on internal memory of individual SoundTraps until retrieval at end of the study.

Data were decompressed and downloaded after SoundTrap retrieval, using SoundTrap Host software (Ocean Instruments, New Zealand), with subsequent analysis conducted using original code written in Python (version 3.7). Sound Pressure Level (SPL) time series were calculated for three frequency bands (100–1000 Hz, 7500–8500 Hz and 20–24,000 Hz) to represent the soundscape at a low-frequency range (100–1000 Hz), a mid-frequency range previously shown to be a good indicator of wind generated noise (7500–8500 Hz: Vagle et al., 1990; Burnham et al., 2021) and broadband representing the full recording range of the hydrophones based on the selected sampling rate (20–24,000 Hz). Additionally, the frequency band of 100–1000 Hz overlaps with the known hearing range of Chinook salmon, *Oncorhynchus tshawytscha* (Oxman et al., 2007), which were migrating back to the Cowichan River during our study period. The soundscape was described by comparing results from each of the recorder locations using 15-minute averaged data. Data were not filtered to remove any abiotic, biotic, or anthropogenic

Table 2
Specifications for bulk carriers anchored inside Cowichan Bay in 2019 and 2020.

Year	Name	Length (m)	Breadth (m)	Gross tonnage	Length of stay (days)
2019	Vessel 1	329	32	43,300	18.5
2020	Vessel 2	225	32	40,000	10.9
2020	Vessel 3	200	36	38,200	15.4
2020	Vessel 4	200	32	35,800	22.2
2020	Vessel 5	225	32	40,100	2.7

(recreational boats, shore noise) influences, these were occurring everyday throughout our study so were assumed to be a constant. Biotic noise sources could originate from resident species of invertebrates, fish or marine mammals, but no vocalizing species of marine mammals (e.g., humpback whales (*Megaptera novaeangliae*), southern resident killer whales (*Orcinus orca*)) were observed during the sampling period.

2.3. Anchored vessel analysis

All internationally travelling vessels over 300 gross tonnage and domestic travelling vessels over 500 gross tonnage are required to report position and identifying information using Automatic Identification System (AIS) during their passage and while at anchor (IMO, 2015). AIS position data (±1 m) were obtained for every vessel equipped with AIS in 5-minute bins for an approximate 5 km radius around Cowichan Bay during August through October of 2019 and 2020. These data for each bulk carrier to enter Cowichan Bay were used to track each vessel during their arrival, at-anchorage and departure. Sound pressure level data from each station were then combined into two time periods: (1) no vessel and (2) vessel anchored. The 'no vessel' time period was defined as when no vessel was within 500 m of the anchorage location (yellow star in Fig. 1) inside Cowichan Bay, and once a vessel was within 500 m of its anchorage (area within dashed circle in Fig. 1) the period was labelled as 'vessel anchored'. The 'vessel anchored' time period was further broken down into vessel arriving, vessel at anchor (stationary, with anchor on bottom) and vessel departing at only the closest hydrophone mooring location, Genoa Bay. The arrival period was defined by a vessel being within 500 m of the anchorage location to the end of the first day. The beginning of the first full day at anchor to the end of

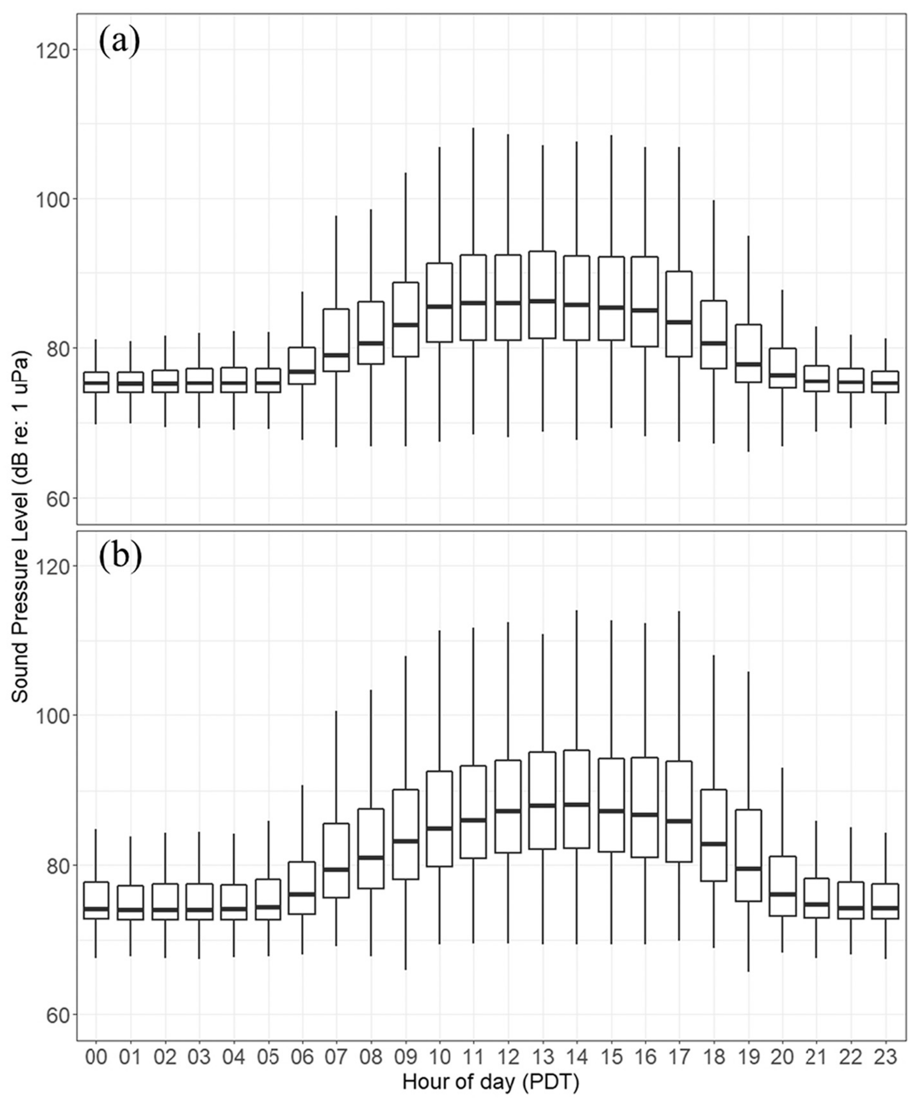

Fig. 2. Boxplots representing the diel pattern of sound pressure levels (SPL) in the 7500–8500 Hz range using data from 2019 (a) and 2020 (b) from all hydrophones. Hour of the day shown in local daylight savings time (PDT).

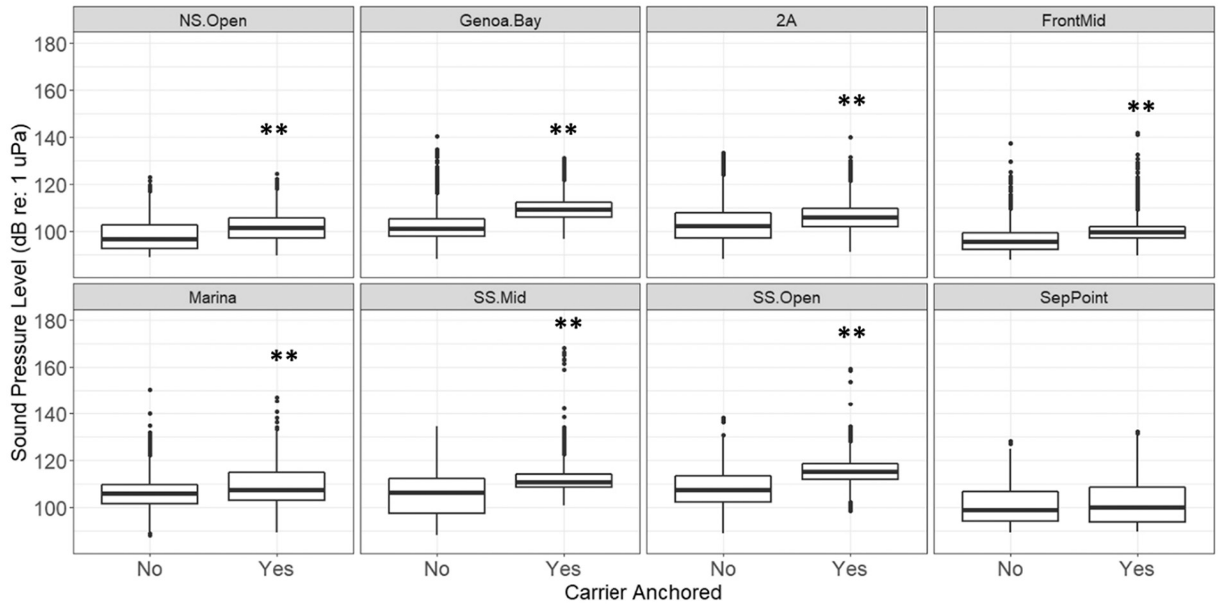

Fig. 3. Boxplots of sound pressure levels (SPL) (broadband: 20–24,000 Hz) at each station in Cowichan Bay, with data from both years combined. Median sound pressure levels increased when a bulk carrier was anchored at all stations except SepPoint. Asterisks indicate significantly different ($p < 0.0001$) sound pressure levels using Mann-Whitney-Wilcoxon *t*-Tests.

last full day at anchor was defined as at-anchor, and the start of the final day to the time when the vessel reached 500 m from the anchorage was defined as departing.

Power spectral density (PSD) is a conventional way to present temporal and frequency dependent variation in a given soundscape (e.g., Merchant et al., 2015). PSDs were calculated for each bulk carrier over a consecutive three-day period (24 h prior to vessel arriving (no vessel); 24 h with vessel arriving at hour 12 (arriving); and first 24 h of the vessel at anchor (anchor)) using 1/3 octave bands at the 5th, 50th, and 95th percentiles. However, the first vessel of 2020 (Vessel 2, Table 2) arrived prior to the SoundTraps being deployed, so it was not included in this analysis.

The PSDs from each arriving and at-anchor vessel were subtracted from their respective no-vessel PSDs to understand sound level changes for the entire frequency range collected (20–24,000 Hz). We also calculated the empirical probability densities, which presents the full range of observations in the form of normalized histograms (Merchant et al., 2015), computed from minute-by-minute averages of the PSD. Here we calculated over two one-week periods in September 2019, representing periods without and with an anchored bulk carrier present. Diel comparisons were made, whereby the period between midnight and 05:00 (PDT), represented night-time conditions and the period between 11:00 and 16:00 (PDT) to represented daytime conditions.

Positional information was used to define the circle the vessel made around the anchor spot as a result of the changing tide in the bay. The AIS information established the exact anchor location, which was used with the vessel motion to investigate the directional variability of the received noise field. Vessel 1, anchored in the bay in 2019, was used as an example vessel and was the only vessel analyzed for positional information.

Comparisons of median sound pressure levels between times when a bulk carrier was present versus times when no carrier was at anchor, and between the different time periods for individual carriers (Arrive, Anchor, Depart) were not normally distributed, and therefore non-parametric Mann-Whitney-Wilcoxon *t*-Tests and Kruskal–Wallis ANOVAs with Dunn's post hoc tests were used for analysis. All statistical tests were performed in RStudio version 4.1.2.

3. Results

3.1. Soundscape description

Acoustic recordings were collected for between eight to ten weeks in 2019 and 2020 (depending on hydrophone), except for one location (marina) in 2019, which was missing a few days in the middle of the deployment, resulting in approximately 7 weeks of recordings. Cowichan Bay has a high level of anthropogenic noise that originates from recreational boats entering and leaving two marinas, and from commercial activity on shore. The soundscape of the bay exhibited a strong diel pattern both in 2019 and 2020 that was broadband in nature but showed the strongest pattern at frequencies between 7500 and 8500 Hz (Fig. 2). Median (5 %, 95 % CI) sound levels increased to 76.5 dB re: 1 μPa (71.0, 93.0 dB) starting at 06:00 (PDT) each day and peaked at a level of 87.2 dB re: 1 μPa (76.5, 101.5 dB) at 13:00 (PDT) before dropping to 76.3 dB re: 1 μPa (71.3; 93.3 dB) at 20:00 (PDT). Overnight (21:00–05:00) levels ranged between 74.7 dB re: 1 μPa (70.2, 84.5 dB; 0200) and 75.2 dB re: 1 μPa (70.7,87.0 dB; 2100) depending on the hour. This pattern was detected throughout the study area in both years without any observable shifts in the onset time and duration. The source of this sound increase is yet to be fully determined.

3.2. Anchored vessel analysis

The anchorage location inside Cowichan Bay (Fig. 1) was used by bulk carriers in both years. In 2019, during the first 25 days of the study no vessels anchored until 8 September when one arrived and stayed for 18.5 days (Table 2). During the remaining 27 days of the study no bulk carrier was present. In contrast, in 2020 there were only 25 days when a bulk carrier was not anchored, with four different bulk carriers anchoring between 12 August and 30 October. These vessels stayed at anchor between 2 and 22 days. All bulk carriers for both years were of similar size (200–329 m total length), but with slight differences in reported tonnage (35,800–43,300 gross tonnage; Table 2).

Longer-term broadband timeseries showed the bulk carriers' acoustic impact on the bay. Broadband sound pressure levels measured at the closest SoundTrap (Genoa Bay: 700 m) from the anchorage location increased significantly from a median value of 101 dB re: 1 μPa (93, 115

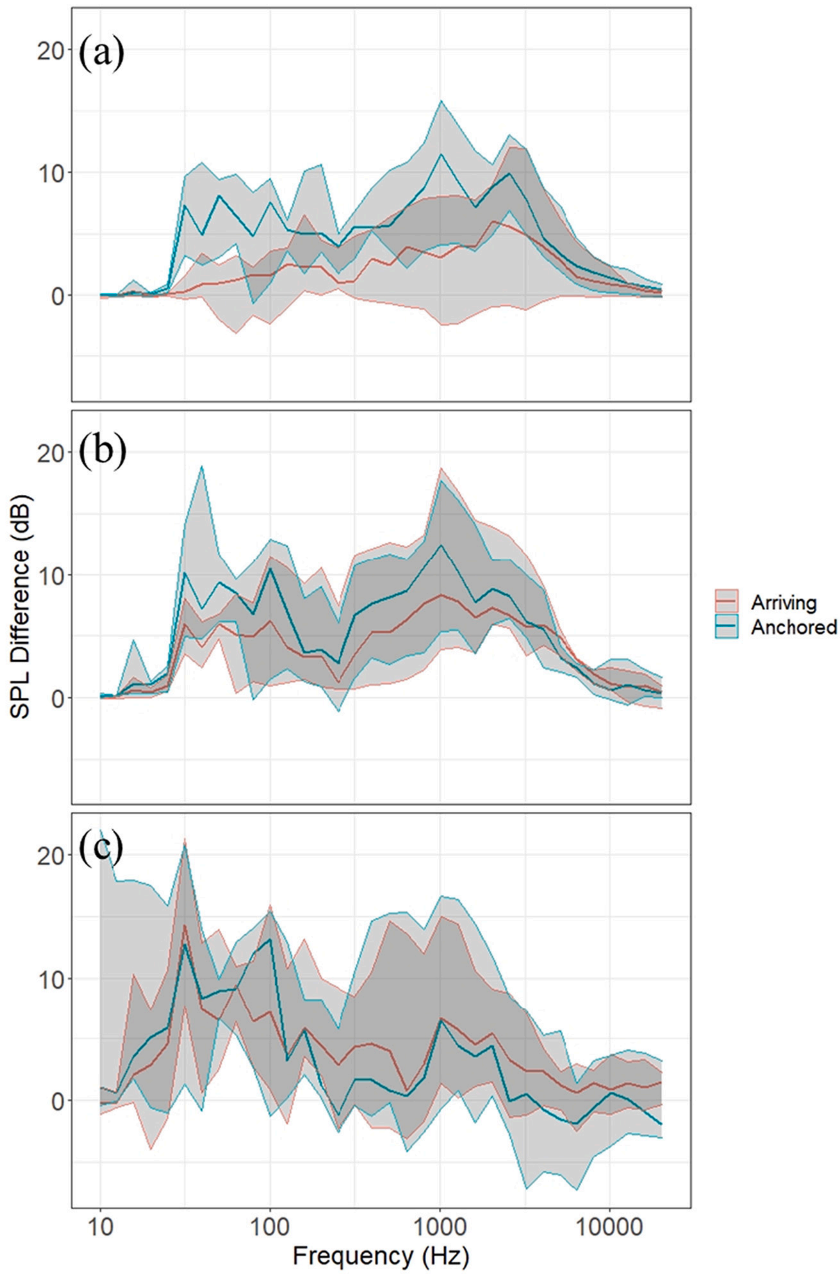

Fig. 4. Sound pressure level (SPL) differences between when no bulk carriers were in Cowichan Bay and when bulk carriers were arriving (red lines) and anchored (blue lines) for 5th (a), 50th (b), and 95th (c) percentiles as functions of frequency. Shaded areas represent 5th and 95th confidence intervals around the median for each 1/3 octave band for the full frequency range of the recorder (20–24,000 Hz). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dB; 5 %, 95 % CI) when no carriers were anchored, to 109 dB re: 1 μPa (103; 117 dB) when a single carrier was anchored (Mann-Whitney-Wilcoxon *t*-Test, $p < 0.0001$, W = 7,261,392). The increase in sound pressure levels were observed for the entire time of a carrier being at anchor (S1), which varied from 2 to 22 days (Table 2). Additionally, the increase in sound pressure levels with an anchored vessel was significantly elevated at all stations (2–8 dB increase: Mann-Whitney-Wilcoxon *t*-Test, $p < 0.0001$) located inside Cowichan Bay but was not observed at the Sep Point station (~1 dB increase: Mann-Whitney-Wilcoxon *t*-Test, $p = 0.244$, W = 3,820,744) which was the only station located outside the bay (Figs. 1, 3).

Median power spectral density plots showed bimodal changes in the frequency composition when a bulk carrier was arriving in the bay and while it was at anchor (Fig. 4). Frequencies most impacted (>5 dB re: 1 μPa median difference) were observed at <100 Hz and between 1000 and 5000 Hz, specifically in the 5th and 50th percentiles. The 95th percentiles were the least impacted by an anchored bulk carrier for the full frequency range but were still impacted at frequencies below 100 Hz.

The Genoa Bay SoundTrap data were used for empirical probability density analysis (Fig. 5). The nighttime periods between midnight and 05:00 (PDT) with no bulk carrier anchored in the bay were relatively quiet at all frequencies (Figs. 5(a) and 6) with the spread of PSD values < 30 dB re: 1 μPa. At frequencies above 3 kHz the data were constrained by the noise floor of the instrument. During daytime hours in the absence of any anchored vessel the variability increased significantly, and the maximum to minimum difference in observed PSDs increased to 60 dB (Fig. 5c), presumably due to increased boating activity in the bay combined with the unexplained daytime increase in noise levels shown in Fig. 2 (Fig. 5c). At frequencies above 3 kHz there is a secondary modal ridge approximately 5 dB above the sensitivity level of the instrument, presumably as a result of this unexplained noise source. Also, at frequencies below 60 Hz, during periods with no anchored vessel present, the PSDs are lower than the sensitivity of the instrument and therefore

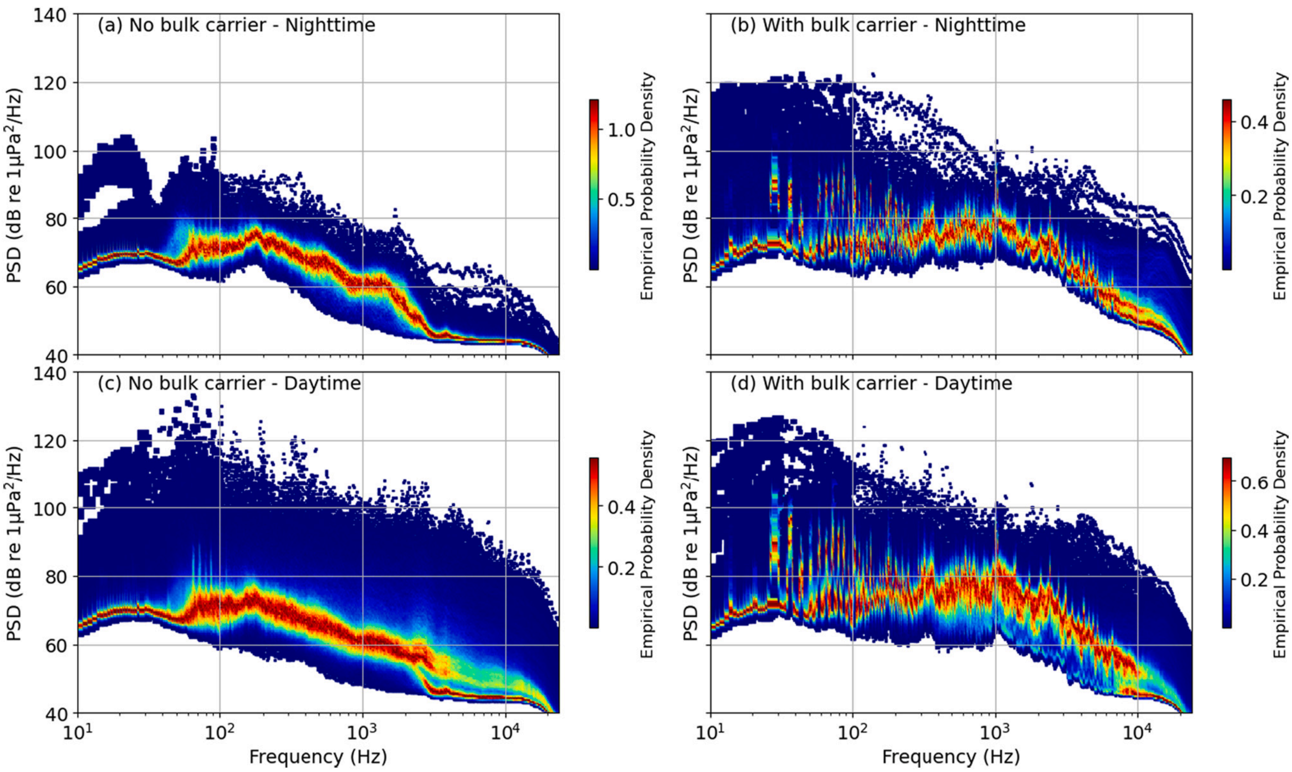

Fig. 5. Empirical probability densities of the Genoa Bay deployment for two 7-day periods without an anchored bulk carrier (1 September–8 September 2019) ((a) and (c)) and with a vessel present (10 September–18 September 2019) ((b) and (d)). Due to the significant day to night difference observed in the bay, the data have been further separated into midnight to 05:00 (PDT) ((a) and (b)) and into 11:00 to 16:00 (PDT) in the afternoon ((c) and (d)).

not detectable. When a bulk carrier was anchored in the bay the PSDs and empirical probability densities changed significantly (Fig. 5b, d). Except for at frequencies below 20 Hz, where the observed noise levels did not go below the sensitivity of the instrument and there were minimal differences between daytime and nighttime. The vessel noise also masked the unexplained daytime noise source. The PSDs when a carrier was anchored showed a change in the frequency composition. A broad peak centered around 1 kHz, but additionally a number of harmonics and bimodal structure between about 30 Hz and 300 Hz were observed (Figs. 5–6).

Individual bulk carriers also had different effects on the soundscape while arriving, at anchor, and when departing Cowichan Bay (Fig. 7). The largest bulk carrier (vessel 1) by gross tonnage was anchored in 2019 and vessel 4 was the smallest (anchored in 2020), both anchored the longest over the 2 years (Table 2). When vessel 1 was arriving median (5 %, 95 % CI) sound pressure levels were 112 dB re: 1 μPa (106; 121 dB; 95 CI), which was significantly elevated compared to the levels observed when the smaller vessel 4 arrived (median sound pressure levels of 108 dB re: 1 μPa (104; 115 dB)) (Kruskal-Wallis, $p < 0.0001$, df = 3). A similar trend was observed while vessel 1 was at anchor, where median sound pressure levels were 112 dB re: 1 μPa (104; 118 dB), compared to when vessel 4 was at anchor and the median sound pressure levels were 107 dB re: 1 μPa (103; 113 dB) (Kruskal-Wallis, p < 0.0001, df = 3). Lastly, vessel 1 also had higher median sound pressure levels when departing (112 dB re: 1 μPa (103; 120 dB), as compared to when vessel 4 departed (105 dB re: 1 μPa (103; 116 dB) (Kruskal-Wallis, p < 0.0001, df = 3).

3.3. *Directionality of noise from an anchored bulk carrier*

The AIS data from vessel 1 (Table 2) at anchor in Cowichan Bay between 8 and 26 September 2019 were used to determine the actual anchor location from positional variations as the vessel rotated due to tidal forcing (Fig. 8a). This location was 632 m away from the Genoa Bay SoundTrap mooring. As the vessel spun around the anchor the observed SPL in a frequency range of 0.01–20 kHz varied by as much as 7.5 dB re: 1 μPa as the vessel turned, with the highest noise levels when the bow was towards the hydrophone, and lowest levels when the stern was pointed towards the same hydrophone (Fig. 8b, c). A port-starboard asymmetry was also seen for this vessel, with no significant differences between the bow towards the hydrophone and starboard side of the vessel towards the same hydrophone, while a reduction of several dBs was noted when the port side was towards the mooring. Frequency dependent changes were also observed between different headings, with the largest difference detected at frequencies below 60 Hz (Fig. 8d–f). Frequencies below 60 Hz were lower when the bow or stern of the vessel was pointed towards the hydrophone compared to non-head-on headings (90° or 270°).

4. Discussion

Our soundscape analysis of Cowichan Bay showed a strong diel pattern in sound levels. Sound levels between 7500 and 8500 Hz were elevated during daytime hours (06:00–20:00 PDT), with this unaltered with changing daylength during our study period. This pattern was also not connected to tidal or wind patterns for the area during this period (S2 and S3). Additionally, since the consistent pattern was observed throughout the bay and not just by marinas or high boat traffic, we assume it to be from a biological source. One potential option is snapping shrimp (*Betaeus* spp.). Other species (*Alpheus* spp. and *Synalpheus* spp.) have been observed to increase their snap rate during the day compared to overnight (Lillis and Mooney, 2018) and individual *Synalpheus paraneomeris* can produce sounds as loud as 190 dB re: 1 μPa (Au and Banks, 1998). Snapping shrimp residing in Cowichan Bay could be the cause of the strong diel pattern observed in our study, but further investigation would be required to confirm.

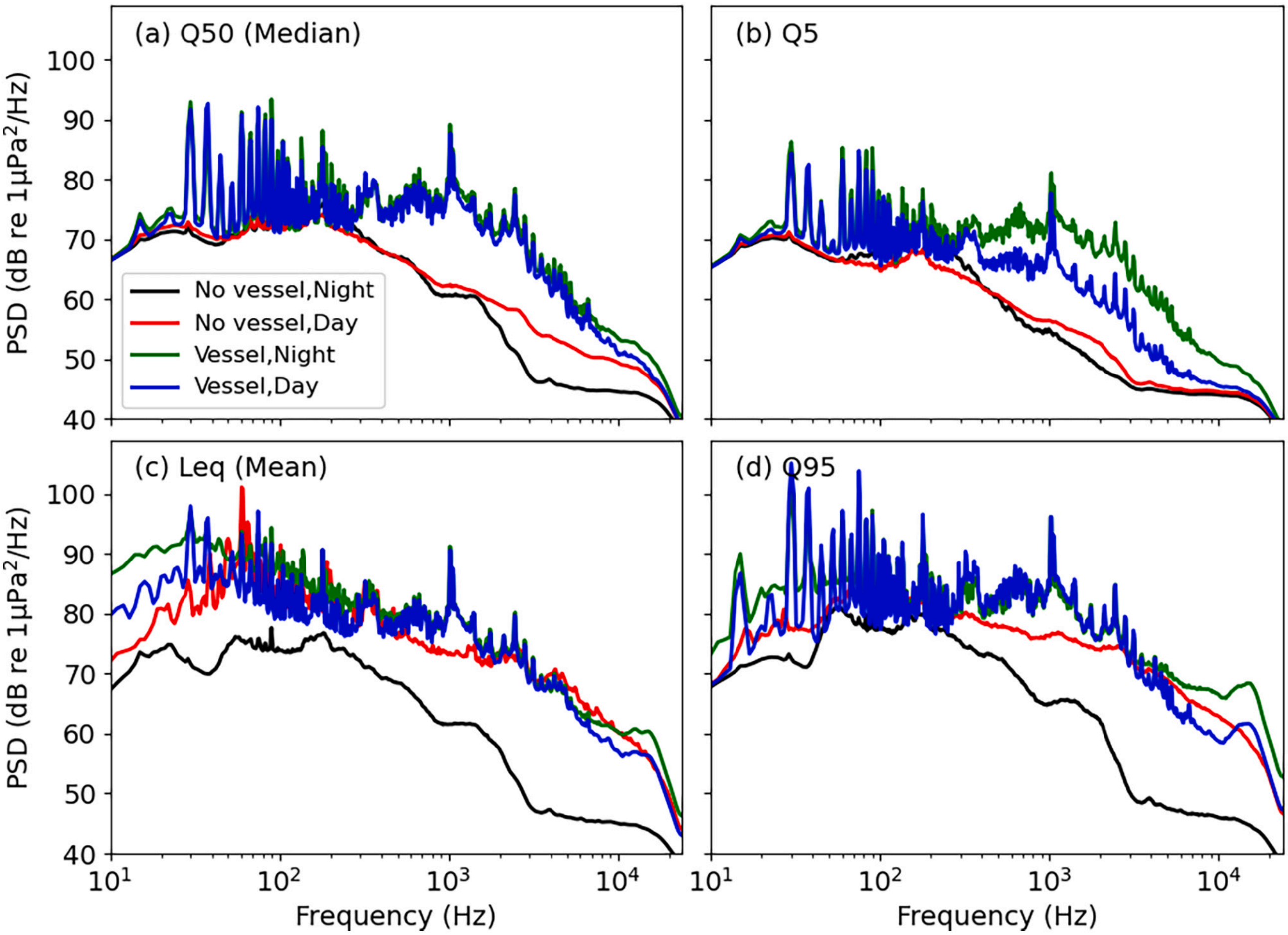

Fig. 6. Metrics extracted from the empirical probability density data shown in Fig. 5 for the two one-week periods without and with a bulk carrier present and calculated for the daytime and nighttime periods. (a) Observed median values (50th percentile), (b) 5th percentile, (c) mean values (Leq) and (d) 95th percentile.

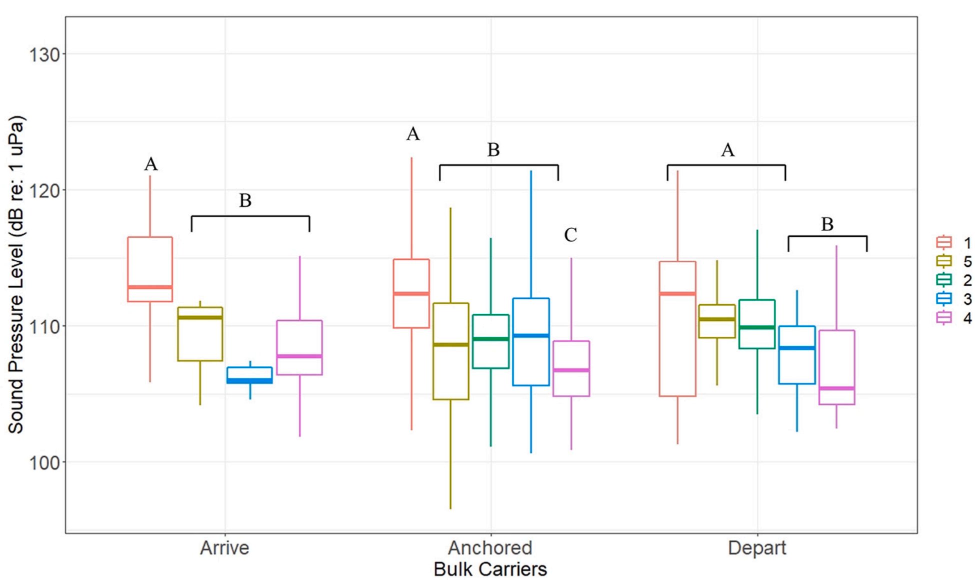

Fig. 7. Box plots of Sound Pressure Levels (SPL) (broadband: 20–24,000 Hz) for each of five bulk carriers arriving, at anchor, and departing Cowichan Bay. Letters indicate significantly different sound pressure levels within a time point using Kruskal-Wallis One-way ANOVA. Bulk carrier IDs are defined in Table 2 and ranked from largest to smallest by gross tonnage. No arrival data for vessel 2 as that carrier arrived before our recorders were deployed in 2020.

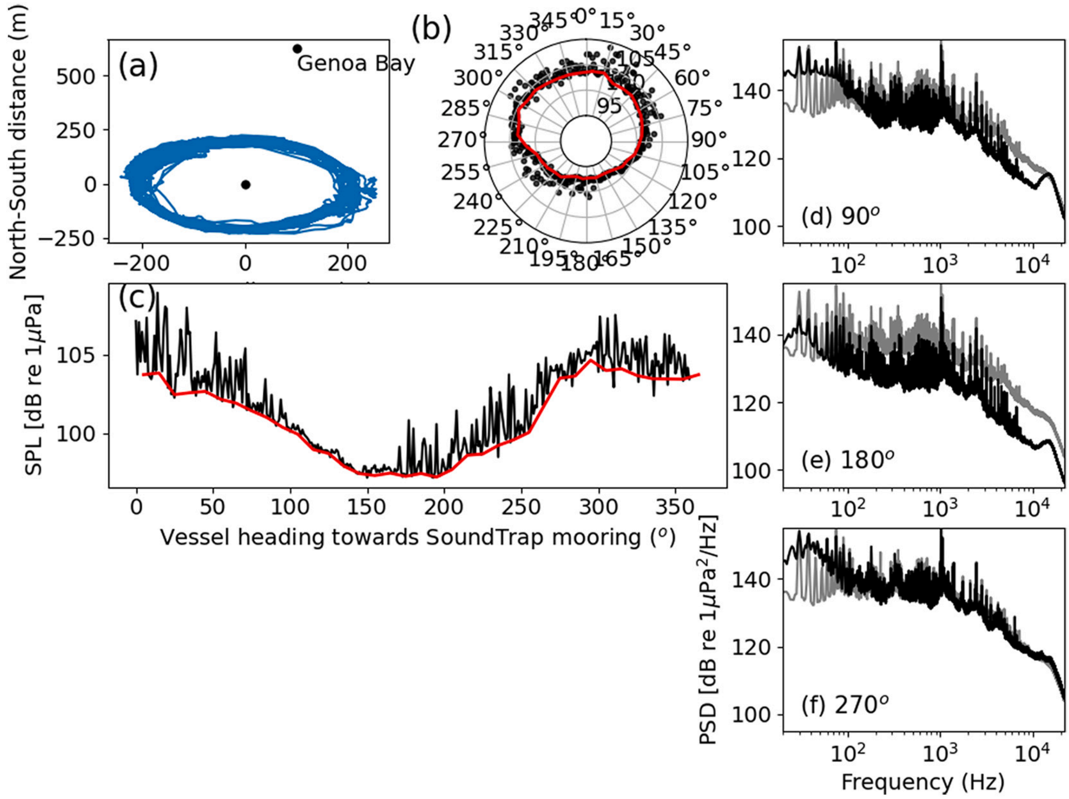

Fig. 8. Vessel noise directionality from vessel 1 (Table 2) anchored in Cowichan Bay between 8 and 26 September 2019. (a) AIS track and locations of anchor and Genoa Bay hydrophone mooring. (b and c) Polar and x-y plots of SPL (0.01–20 kHz) (black) as received by the Genoa Bay SoundTrap 632 m north. Red lines show the 10th percentile every 10° in compass direction. (d) (e) (f) PSD at three different angles relative to the vessel anchor-SoundTrap direction. The PSD at 0° has been included in each figure as a reference (grey lines). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Our data from Cowichan Bay showed anchored bulk carriers can have substantial impacts to the underwater soundscape in coastal marine systems. Large ships like bulk carriers anchoring in coastal habitats can generate extensive underwater noise that is detectable at least 2 km away at the furthest station from the anchorage location (SS Open: Fig. 1), but could potentially be detected further. Change was most detectable using the 5th percentiles, while the 95th percentiles were less impacted, indicating that anchoring bulk carriers are reducing the amount of time at lower sound pressure levels (<95 dB) in the bay, but not elevating maximum sound pressure levels observed.

Diesel generators aboard commercial vessels produce tonal harmonics, with harmonics at 24 and 30 Hz detected even when the vessel is in motion and are independent of vessel speed (Arveson and Vendittis, 2000). Harmonics at 24 and 30 Hz were visible in the empirical probability density (Fig. 6) while a bulk carrier was anchored in Cowichan Bay and could be generated from the generators aboard these carriers. Additionally, AC power lines to other machinery on these vessels can produced harmonics of 60 Hz (Arveson and Vendittis, 2000), and could be contributing to the noise produced. Finally, the anchor and attaching chain could be producing sounds, but more research would be needed to confirm these noise sources.

The analysis clearly showed that the noise field emanating from an anchored bulk carrier is highly directional. Previous research demonstrates that when vessels are travelling, higher sound pressure levels are detected originating from the stern (McKenna et al., 2012). However, in our study we found the opposite. While at anchor the propulsion machinery and propeller(s) are stopped, so other noise sources clearly dominate the noise generated by the ship. It is therefore expected that the directional characteristics of this noise will be different than when the vessel is underway. Future research could aid in examining the specific origin of these directional changes in sound levels and frequency composition.

In the waters around Vancouver Island, anchored bulk carriers are common in areas like Cowichan Bay, for example, 350 carriers were recorded to be anchored in the southern portion of Vancouver Island (Victoria to Nanaimo BC; 45 total locations) in 2019, and 606 anchored in 2020. Some are anchored for more than two weeks as was observed in this study, adding to the soundscape for extended periods (S1). Cowichan Bay anchorage locations represent ~13 % (6/45) of the anchorage locations in Southern Vancouver Island but can also accommodate larger vessels (>220 m length) potentially leading to more demand for anchoring in Cowichan Bay (Transport Canada, unpublished data). Between 2019 and 2020 the six anchorages in Cowichan Bay accommodated 15 %–20 % of the yearly anchorages of bulk carriers.

Additionally, the use of anchorage locations varies year to year but appears to have been impacted by the COVID-19 pandemic. For example, the six anchorage locations in and around Cowichan Bay had between 5 and 9 carriers anchored during August–October of 2016/2018/2019, while in 2020 there were 16 carriers that were anchored during the same period. The use of the anchorages around Cowichan Bay appears to have resumed to normal levels in 2021 when 10 carriers were anchored during August and October. Marine systems have been documented to have been quieter during the global shutdown of shipping activities in 2020 (Bates et al., 2021; Thomson and Barclay, 2020), however, bulk carriers could not come into ports and were restricted to anchoring in coastal waters for extended periods of time.

Cowichan Bay hosts many fish and invertebrate species, and forms part of the key migration corridor for Pacific Salmon (*Oncorhynchus* spp.). Fish exhibit changes in behavior in the presence of elevated noise levels, with reduced foraging effort and success observed in three-spined stickleback (*Gasterosteus aculeatus*) and European minnow (*Phoxinus phoxinus*) while exposed to noise from a single boat passage (Voellmy et al., 2014). Ivanova et al. (2020) noted horizontal displacement and changes in behavior patterns of tagged Arctic cod (*Boreogadus saida*) while cruise ships were anchored and moving into a bay in the Arctic. In addition, a stress response has been documented for fish and invertebrate species subject to vessel noise (Wysocki et al., 2006; Celi et al., 2015). Results from this study demonstrate a further source of human activity that could alter their habitat quality.

Anchored bulk carriers in Cowichan Bay demonstrated a significant alteration to the underwater soundscape, however, our study is not without some limitations. Our study only examined one anchoring location in Cowichan Bay that is the furthest away from the next closest anchorage (2 km), which is not seen in other locations around British Columbia or the globe where multiple vessels are anchored at the same time in close proximity (~1 km). Future research should examine the influence of multiple anchored carriers to examine how the underwater soundscape would be altered with more anchored vessels. Additionally, only one type of commercial vessel was examined, it is unknown how different vessel types (e.g., container ships) might influence the soundscape. Differences in spectral characteristics have been observed while different types of commercial vessels are moving (McKenna et al., 2012), so it is likely differences could be observed while at anchor. Lastly, our study was conducted in a shallow (<60 m water depth), sheltered bay over a two-month window. Seasonal oceanic conditions have been documented to influence noise produced by container ships, with higher source levels observed during the spring (April/May) compared to summer or fall (McKenna et al., 2013). This difference was potentially linked to warmer water at the surface in summer and fall that can trap sound waves (Jensen et al., 2011). Our study was conducted between August and October with warmer surface temperatures, which could reduce the noise produced by the anchored carriers. Future research should examine the anchorage of different types of vessels, at different maximum depths and bathymetries over extended periods of time (year) to aid in understanding the impact that these carriers might have on a larger scale.

The global shipping industry has been changing the ambient underwater soundscape for the past few decades (reviewed in Hildebrand, 2009), with noise levels in the Northeastern Pacific Ocean increasing by ~3 dB per decade (McDonald et al., 2006). However, anchoring of these vessels prior to going into ports is minimally accounted for in the literature. Our study demonstrates the substantial impact anchored bulk carriers have on the underwater soundscape and represents a starting point to explore their impact further.

CRediT authorship contribution statement

Kelsie A. Murchy: Conceptualization, Investigation, Formal analysis, Writing – original draft. **Svein Vagle:** Conceptualization, Formal analysis, Writing – original draft. **Francis Juanes:** Conceptualization, Funding acquisition, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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