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Research Article

High-Speed Vessel Noises in West Hong Kong Waters and Their Contributions Relative to Indo-Pacific Humpback Dolphins (*Sousa chinensis*)

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The waters of West Hong Kong are home to a population of Indo-Pacific humpback dolphins (*Sousa chinensis*) that use a variety of sounds to communicate. This area is also dominated by intense vessel traffic that is believed to be behaviorally and acoustically disruptive to dolphins. While behavioral changes have been documented, acoustic disturbance has yet to be shown. We compared the relative sound contributions of various high-speed vessels to nearby ambient noise and dolphin social sounds. Ambient noise levels were also compared between areas of high and low traffic. We found large differences in sound pressure levels between high traffic and no traffic areas, suggesting that vessels are the main contributors to these discrepancies. Vessel sounds were well within the audible range of dolphins, with sounds from 315–45,000 Hz. Additionally, vessel sounds at distances ≥100 m exceeded those of dolphin sounds at closer distances. Our results reaffirm earlier studies that vessels have large sound contributions to dolphin habitats, and we suspect that they may be inducing masking effects of dolphin sounds at close distances. Further research on dolphin behavior and acoustics in relation to vessels is needed to clarify impacts.

1. Introduction

Natural and anthropogenic sounds are part of the ocean environment. Natural sound is produced by physical (e.g., sea state, wind speed, precipitation, earthquakes) and biological (marine mammal vocalizations, fish communication, and snapping shrimp) sources ([1, 2] provide summaries). Anthropogenic sound, often termed "noise," is caused by human activities such as explosives, seismic exploration, sonar, ships, industrial activities, and acoustic deterrent and harassment devices [1, 3]. Some of these noises affect marine mammal communication sounds, including Indo-Pacific humpback dolphins [4–7]. Additionally, short-term behavioral changes can occur in cetaceans due to noise (e.g., changes in surfacing, diving, and movement patterns [8–10]), but long-term or physiological impacts have been less well explored. Chronic sources of noise pollution have been hypothesized to contribute to population differences in the sound repertoire of various species, but this evidence is observational in nature and does not exclude intrinsic population differences, such as subspeciation [11–13]. Thus, a detailed investigation of the potential impacts of these local chronic noises may help to clarify the nature of population differences in marine mammal sounds and deepen our understanding of the potential effects of chronic noise exposure.

Hong Kong waters are particularly busy, with many sources of anthropogenic disturbance (e.g., land reclamation, construction, dredging, heavy vessel traffic, chemical pollution, piling, dolphin tourism, etc.) throughout the area [14, 15]. These waters are also home to Indo-Pacific humpback dolphins (*Sousa chinensis*) and Indo-Pacific finless porpoises (*Neophocaena phocaenoides*) and are considered important habitat for these cetaceans [16]. Previous research [8, 17] focused on various anthropogenic disturbances that impacted local marine mammals, but only a few researchers

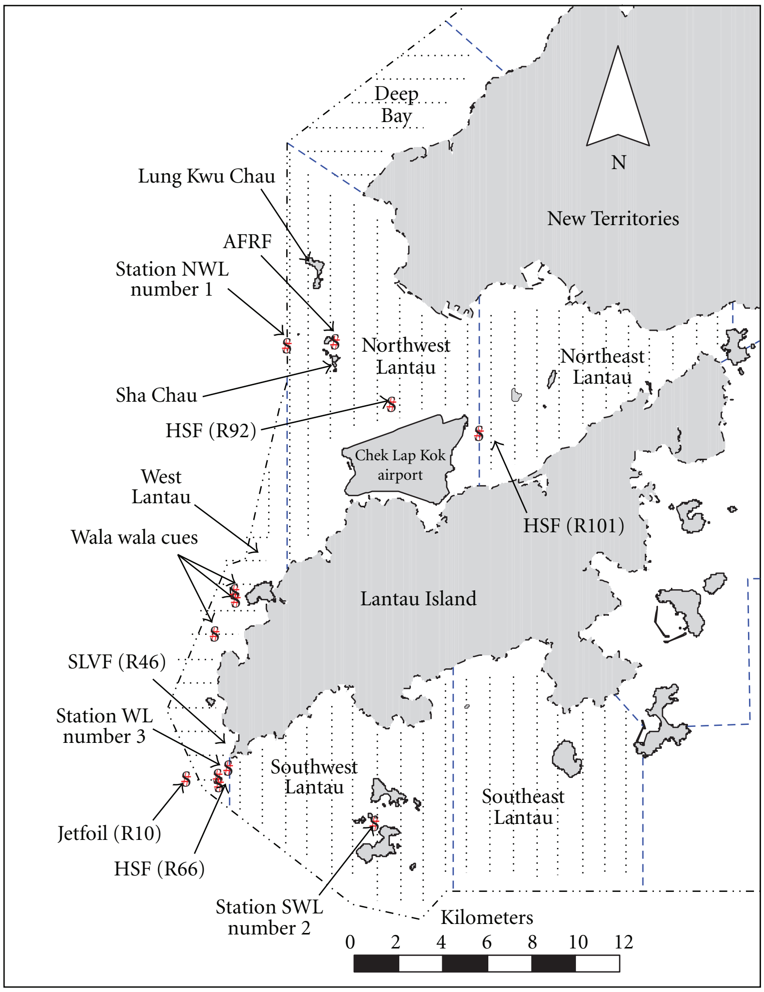

Figure 1: A map of Lantau Island in Hong Kong with recording stations, recording locations, and transects. The letter "R" and the following number correspond to the individual recording number associated with the location name. "HSF" stands for an unidentified high-speed ferry, "Jetfoil" is the name of an identified high-speed ferry, and "Wala wala" is an arbitrary name associated with the small tour boats in the area. The "SLVF" is the South Lantau Vessel Fairway and the "AFRF" is the retired Aviation Fuel Receiving Facility.

have studied the effects of noise pollution on these local species [18, 19]. Würsig and Greene [19] documented sound pressure level (SPL) relationships to different frequencies associated with tankers and tugs either offloading, approaching, or departing the Aviation Fuel Receiving Facility (AFRF, Figure 1). Their findings showed that North Lantau waters are relatively noisy, but the vessels in question still meet airport authority requirements; however, they also noted that the effects of these sound disturbances to the cetaceans (almost exclusively humpback dolphins in North Lantau waters) inhabiting the area are yet to be documented.

Our objectives of the current study were to broaden the scope of Würsig and Greene's [19] research by additionally examining the sound contributions of abundant high-speed vessels in the area and better quantify their various contributions to the high levels of background noise. Recent data indicate that the various activities of these vessels may be partially related to recent declines of Indo-Pacific humpback dolphins in Hong Kong waters [20]. Thus, we provide a summary of select high-speed vessel sounds relative to background sound levels and dolphin hearing and communication sounds. Understanding the various sound contributions of these vessels will be useful in determining their effects on marine mammals in the area and provide data for potential attempts at mitigation. Additionally, this research may also generate further insights into whether differences in sound repertoires between the Hong Kong and Australian humpback dolphin populations can be attributed to ambient noise.

2. Materials and Methods

2.1. Field Methods. We sampled vessel, ambient, and Indo-Pacific humpback dolphin sounds at various area stations (Figure 1) in the waters surrounding Lantau Island in Hong Kong (latitude 22°15′00′′, longitude 113°55′00′′), from April to October 2010 and from February to August 2011. Samples were taken in conjunction with a long-term sound monitoring program conducted by the Hong Kong Cetacean Research Project. This program annually conducts line transects throughout the Hong Kong Special Administrative Region, which is divided into twelve different survey areas, with line-transect surveys conducted among six of these areas (i.e., Northwest (NWL), Northeast (NEL), West (WL), Southwest (SWL), Southeast Lantau (SEL), and Deep Bay (DB) Figure 1). We recorded vessel, ambient, and Indo-Pacific humpback dolphin sounds from the stern of a 15-m diesel vessel, the "standard 31516", with vessel noise off and the vessel drifting. We used a Cetacean Research Technology spot-calibrated hydrophone (model: CR1; sensitivity: 197.69 dB, re. V/μPa; linear frequency range listed as: 0.0002 kHz–48 kHz ± 3 dB; usable frequency range listed as: 0.00004 kHz–68kHz ± 3/−20 dB, only analyzing sounds up to 48 kHz due to our linear frequency range) to record sounds, and a Fostex digital recorder (model: FR-2; frequency response: 20 Hz–80 kHz ± 3 dB) with a preamplified signal conditioner (model: PC200-ICP; precision gain: x0.1–x100; frequency range: >100 kHz; system response: 1 Hz–100 kHz ± 0.25 dB) to prevent overloading. The hydrophone, suspended by a 2 m spar buoy, was lowered into the water at 3 to 7 m depths and recorded (sampling rate: 24-bit at 192 kHz) various durations in Broadcast Wave Format, ranging from 21 s to 15 min and 16 s. The spar buoy acted to prevent excessive hydrophone movement from wave and boat motion. During each sampling event, we recorded vessel type, distance from the recording vessel at cue time, vessel activity, and dolphin presence. The distance to vessels was noted using Bushnell laser rangefinding binoculars (distance accuracy ±0.5 m up to 700–800 m). We also recorded the date, start and end times, hydrophone and water depths, Beaufort sea state, area, start and end location, gain, event, and any additional notes for each sampling event. We determined locations using a Garmin eTrex Legend H GPS unit. A total of 219 recordings were taken over 2010-2011, both with and without the presence of various vessel types; however, many recordings took place in the presence of multiple vessels.

2.2. Data Analysis. We selected and analyzed recordings of high-speed ferries, small tour boats, dolphins, and the ambient noise of various sites using SpectraLAB software (version 4.32) on a Lenovo ThinkPad T400 7417-PLU notebook PC. We divided vessel selections into two categories of solitary and multiple vessels present during the recording. We defined vessels as solitary if there were no other vessels present within 2 km from the recording vessel throughout the duration of the recording. Recordings in which there were two or more vessels within 2 km of each other in the study area were classified as having multiple vessels. We analyzed solitary vessel selections at specific cue times that described vessel distance and direction. These selections were analyzed over 5 s segments, ±2.5 s of the cue time to accurately capture their sound pressure level without averaging out their sounds. We computed 1/3 octave band sound pressure levels and narrowband spectra in 1 Hz bands using SpectraLAB's "compute average spectrum" analysis for solitary vessel selections. We used a 1/3 octave bandwidth because of its general approximation to cetacean auditory bands [21] and narrowband spectra for finer scale detection of vessel tonal signatures. These two measurements (1/3 octave band sound pressure levels and narrowband spectra) allowed us to describe the sound pressure levels and tonal sound signature, respectively, of the individual vessel at specific distances, relative to dolphin hearing and sounds. The multiple vessel recordings were used to gauge the relative contribution of the individual vessels to ambient sounds when multiple ships were present.

For ambient noise measurements, we took 10 s nonoverlapping section measurements throughout the recording starting at the beginning. Most recording times were not a multiple of 10, and we only measured the full 10 s clips for these. To avoid sound selection bias, we also repeated our measurements starting from the end of the recording. Furthermore, we randomly selected 18 of these selections and averaged them for each ambient sound recording to compute 1/3 octave band ambient sound pressure levels. To reduce geographic or nearby traffic differences between ambient sites and individual recordings, we selected sites near the individual vessel recording for ambient sound comparisons as recordings of the site with no vessels present were not available. These ambient sounds were used to assess individual vessel sound contributions relative to the natural background sounds (i.e., without ships).

For dolphin sounds, we played back spectrograms (fast Fourier transform (FFT): 8192; smoothing window: hanning; postprocess: 192 kHz; bandwidth: 1 Hz; FFT window overlap: 50%) to visually select sounds of interest, particularly sounds associated with social communication, for example, burst pulses and whistles [22]. We only used recordings of dolphin sounds when no ships were present. Dolphin proximity during recordings varied and ranged from around 50 to 200 m of our vessel during sound recordings. We analyzed selected dolphin sounds as narrowband spectra to compare to vessel spectral sounds. We compared these sounds to assess potential vessel sound masking effects on dolphin social communication. While only one audiogram is available for Indo-Pacific humpback dolphins [23], several exist for common bottlenose dolphins (*Tursiops truncatus*, hereafter simply "bottlenose dolphins") [24, 25]. Popov et al. [25] observed variation amongst individual bottlenose dolphin audiograms; as such, the single audiogram available for Indo-Pacific humpback dolphins may not accurately represent the mean hearing sensitivity of the species. Past research on humpback dolphin communication frequencies [12, 22] indicates that they share similarities in repertoire and frequency range to bottlenose dolphins, suggesting that these two species may also share similar audiograms. Therefore, we used published audiograms of both bottlenose dolphins [24, 25] and the single audiogram of an Indo-Pacific humpback dolphin [23] for comparison with the received sound pressure levels. For the bottlenose dolphin audiograms, we used the average sound pressure level for each frequency band since both audiograms gave multiple sound pressure level thresholds per frequency unit. For the Johnson [24] audiogram, we converted dB re 1 μbar to dB re 1 μPa by adding 100 to the recorded sound pressure level [21].

The data for all sound selections were saved to Microsoft Excel 2007 and subsequently plotted using R statistical software 2.13.1 [26].

3. Results

Of the 219 available recordings, only four were available for analysis of solitary High-Speed Ferries (HSF), specifically the Jetfoil and three different unclassified High-Speed Ferries. We also examined three recordings of a small speed boat ("Wala wala") escorting tourists to watch dolphins, in isolation. We measured the ambient sounds of four areas: Southwest Lantau Station number 2 (SWL number 2, Figure 1), South Lantau Vessel Fairway (SLVF, Figure 1), Northwest Lantau Station number 1 (NWL number 1, Figure 1), and West Lantau Station number 3 (WL number 3, Figure 1); see Table 1 for site details. We used SWL number 2 and NWL number 1 for comparisons to natural ambient sounds, while WL number 3 was used as a comparison to a usually busy traffic area with only one HSF present. Lastly, we used SLVF near Fan Lau (the southwest tip of Lantau Island; Figure 1), for an ambient sound recording of a generally busy traffic area with moderate vessel traffic (i.e., the presence of a shrimp trawler and several HSFs; Table 1).

3.1. Ambient Noise. A comparison of ambient sound levels for the four sites revealed several notable differences. The SLVF ambient sound levels were markedly higher throughout most of the frequency range of SWL number 2, (i.e., 50–10,000 Hz; Figure 2). SLVF ambient sound levels were also higher than parts of NWL number 1 and WL number 3's frequency ranges, particularly frequencies 316–20,000 Hz for NWL number 1 and both 50–500 Hz and 3162–25,000 for WL number 3. However, the differences in ambient sound levels between SLVF and WL number 3 were progressively less pronounced when approaching both above and below a frequency of 1,000 Hz. In fact, WL number 3 sound pressure levels slightly exceeded SLVF ambient sounds around 1,000 Hz. The relatively high sound pressure levels associated with SLVF correspond with the presence of several ships, a shrimp trawler, and three HSFs; as such, it is labeled as a busy traffic area.

In contrast, WL number 3, also considered a busy traffic area, had only one vessel present (a HSF away at 702 m) during the recording. For the lower frequencies (50–316 Hz), WL number 3 had the lowest sound pressure levels; however, sound pressure levels rapidly rose from 316–1,000 Hz and gradually declined to an equilibrium around 10,000 Hz at 100 dB re 1 μPa (Figure 2).

One of the areas considered to have quiet background sound levels, NWL number 1, maintained relatively low sound pressure levels throughout the frequency range, except in the lower frequencies, 50–400 Hz (Figure 2). In this short frequency range, NWL number 1 sound pressure levels remained near 95 dB re 1 μPa, which were the highest sound pressure levels of the four ambient sound recordings, until SLVF levels exceeded NWL number 1 around 160 Hz. Additionally, NWL number 1 displayed a brief spike in sound pressure levels to 108 dB re 1 μPa at 25,000 Hz, the peak sound pressure level for that site.

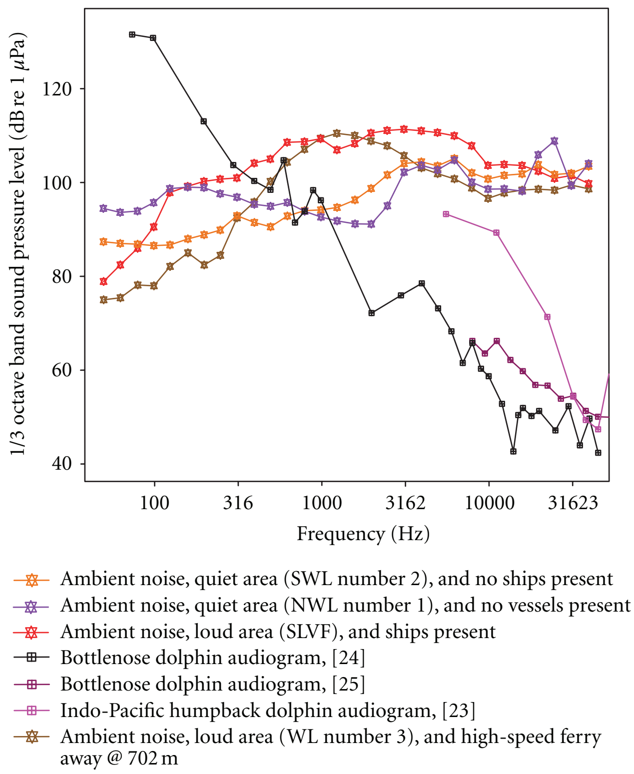

Figure 2: Ambient sounds of the four areas varying in general ship traffic and types of ships present. Bottlenose and humpback dolphin audiograms show the magnitudinal difference between vessel sounds and minimum audible levels for the dolphins. Southwest Lantau number 2 (SWL number 2) is between the Soko Islands with very little boat traffic and a Beaufort sea state (Bss) of 3. Likewise, Northwest Lantau number 1 (NWL number 1) is described as having very little boat traffic, located within the Sha Chau and Lung Kwu Chau Marine Park, recorded during a Bss of 3. West Lantau number 3 (WL number 3) is within the very busy shipping route at South Lantau Vessel Fairway with a high-speed ferry away at 702 m, Bss 3. South Lantau Vessel Fairway (SLVF) was recorded with several ferries and a shrimp trawler present during a Beaufort sea state of 0.

Lastly, SWL number 2, also considered to be a quiet area, was consistently in the relatively lower range of sound pressure levels to about 6,300 Hz, where it slightly exceeded the sound levels from two other sites by a few decibels (Figure 2). Sound pressure levels gradually began to increase at 160 Hz and peaked around 6,300 Hz, ranging in sound pressure levels from 93 to 104 dB re 1 μPa.

We also compared the dolphin audiograms to the ambient sounds to describe the audibility of the average background sound levels. The Johnson [24] bottlenose dolphin audiogram extended above all ambient sound levels to around 400 Hz, where it dropped below the ambient sounds of SLVF (Figure 2). All audiograms for the dolphins (bottlenose and humpback) followed a declining pattern as frequency increased, thereby augmenting the difference

Table 1: Descriptions of ambient noise recordings.

Location	Site description	Beaufort sea state	Vessel(s) present	Recording date
West Lantau Station no. 3 (WL no. 3)	Within the very busy shipping route at South Lantau Vessel Fairway	3	High-speed ferry	June 30, 2010
South Lantau Vessel Fairway (SLVF)	A busy area which experiences much traffic, particularly from ferries	0	Shrimp trawler, high-speed ferries: turbo jet, NWT, and zuhai	May 30, 2010
Southwest Lantau Station no. 2 (SWL no. 2)	Between the Soko Islands with very little boat traffic	3	None	September 1, 2010
Northwest Lantau Station no. 1 (NWL no. 1)	Within the Sha Chau and Lung Kwu Chau Marine Park with very little boat traffic	3	None	August 13, 2010

in sound pressure levels between dolphin hearing thresholds and the various ambient sounds. However, we found interspecific variation in the magnitude of the difference between dolphin hearing thresholds and sound pressure. Notably, the difference between the humpback dolphin audiogram and SLVF sound pressure levels was smaller as compared to the bottlenose dolphin audiogram and SLVF sound pressure levels. For example, near 5,600 Hz the difference for humpback dolphins was ~17 dB re 1 μPa compared to ~37 dB re 1 μPa for bottlenose dolphins. However, this interspecific difference between audiograms and SLVF rapidly decreased as frequencies increased, with the two species converging around 31 kHz. While our study did not extend to frequencies above 48 kHz, it should be noted that the humpback audiogram diverged from the bottlenose audiogram and increased in sound pressure levels following frequencies above 48 kHz. We also observed intraspecific variation in hearing thresholds between the bottlenose audiograms. The Popov et al. [25] audiogram declined at a slower rate as compared to the Johnson [24] audiogram. Additionally, the Popov et al. [25] audiogram was an average of 13 bottlenose dolphin subjects and may be a more accurate representation of a bottlenose audiogram. We were limited by the existence of only one available audiogram from a single humpback dolphin, and individual variation may potentially bias our observed differences. While both bottlenose audiograms show a clear continuing trend of decline, the Popov et al. [25] audiogram appeared to begin leveling out around the end of the frequency range, that is, 48,000 Hz. The data from Johnson [24] audiogram did not extend beyond an upper frequency limit of 45,000 Hz; likewise, Popov et al. [25] did not record responses to frequencies below 8,000 Hz. Because of these data gaps, we display both audiograms for better clarity in frequency and sound pressure auditory thresholds in bottlenose dolphins.

3.2. High-Speed Ferry and Small Tour Boat Sounds. At most distances, the HSF and small tour boat (also referred to as "Wala wala") sounds were much louder when compared to the corresponding natural ambient sound levels from either SWL number 2 or NWL number 1 (Figures 3 and 4, but see Figure 5). These higher sound pressure levels were consistent throughout the frequency range, though they usually declined to levels similar to those of the natural ambient sound in the upper frequencies (e.g., 4,000–10,000 Hz). HSF and some small tour boat sound pressure levels generally extended beyond the SLVF ambient sounds, but this tended to be at the closer distances, for example, between 100 and 400 m of apparent sound sources (Figures 3 and 4, but see Figure 5). The frequency ranges varied for sound pressure levels exceeding the SLVF ambient sounds. Some HSF sounds stayed above the SLVF ambient sounds throughout the frequency range (Figures 3(c), 4(c)) while others only exceeded the SLVF ambient sound levels across select frequencies (Figures 3(a), 4(a), and 5(a)). Sound pressure levels also tended to peak between 100–3,000 Hz, although the exact peak varied between vessels. The highest sound pressure levels peaked around 120 dB, except for one HSF (Figure 4(c)). These peaks were associated with a range of distances, from <100–556 m. The direction of the vessel (i.e., approaching or away) may have affected some of the received sounds. In some cases, received sounds were higher from distances away than from approaching (Figures 4(a), 4(c), and 5(a)). Additionally, in a few cases, sound levels were generally higher for stopped rather than moving tour boats (Figure 3(a), at 43 m from 1,500–4,000 Hz).

We found differences between the vessel generated sounds and the dolphin audiograms similar to those described for ambient sounds. However, most vessel sounds exceeded the ambient sound levels, increasing the differences in sound levels between vessels and dolphin audiograms. This increased difference was readily apparent in Figures 3(a), from frequencies 1,000 to 10,000 Hz, 4(a), from frequencies 316 to 2,500 Hz, and 4(c), from frequencies 316 to 45,000 Hz. While ambient sounds did not appear to be audible to bottlenose dolphins around frequencies ≤400 Hz, vessel sound pressure levels reached or exceeded the dolphin auditory threshold at lower frequencies, from 200–300 Hz (Figures 3(a), 3(c), 4(a), and 4(c)). Our humpback dolphin audiogram did not extend below 5,600 Hz, so we were unable to determine if humpback dolphins show similar decreases in hearing sensitivity to bottlenose dolphins in the lower frequencies.

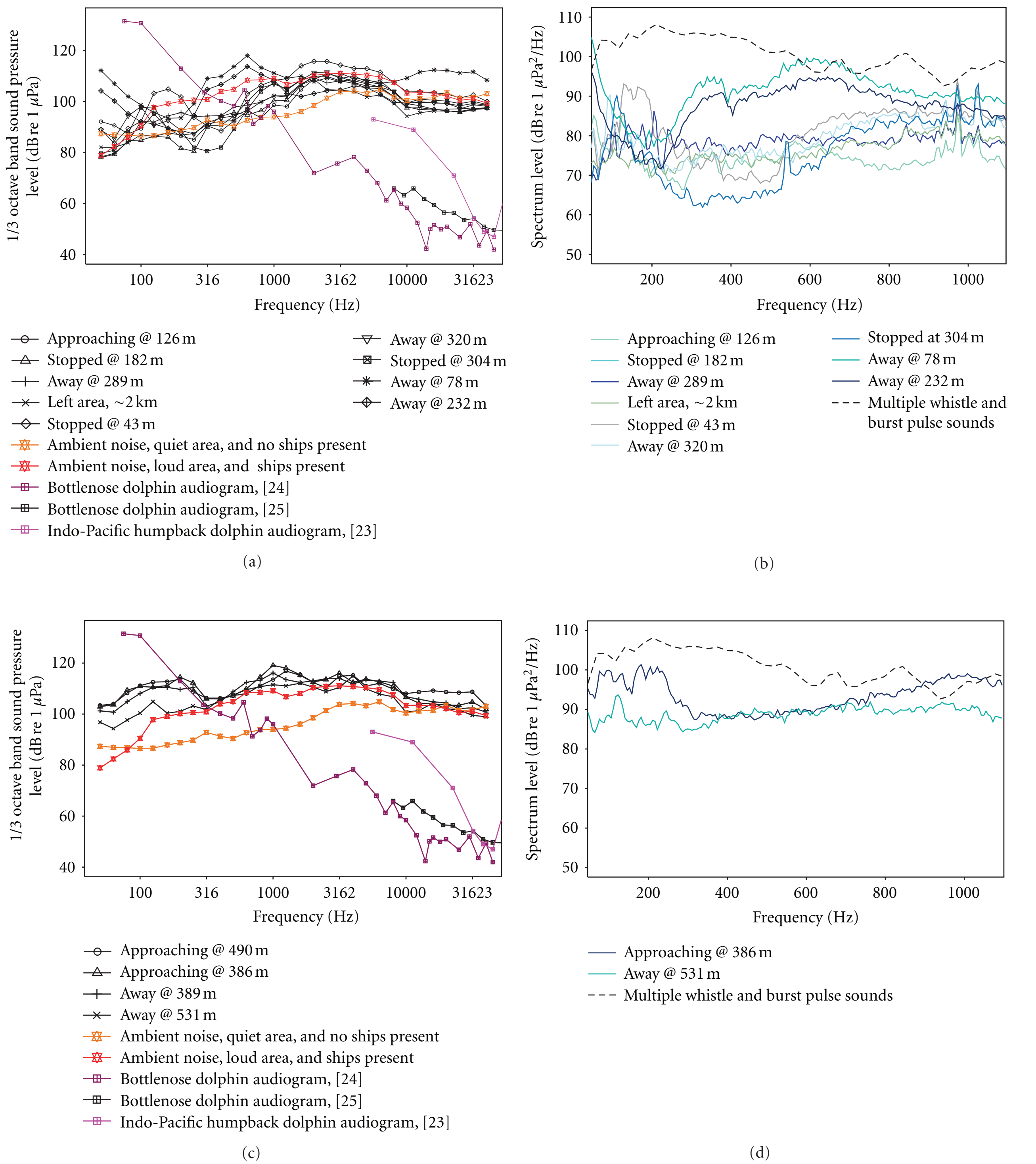

FIGURE 3: 1/3 octave band sound pressure levels for a small tour boat (referred to as "Wala wala") in West Lantau (a), Beaufort sea state of 1. The orange line indicates the ambient sounds of Southwest Lantau number 2, located between the Soko Islands with very little boat traffic and no vessels present during recording. The red line indicates South Lantau Vessel Fairway, a busy traffic area, especially for ferries. South Lantau Vessel Fairway was recorded with several ferries and a shrimp trawler present. Selected sound spectra for the small tour boat and humpback sounds are displayed below (b). (c) shows the distribution of sound pressure levels for the Jetfoil high-speed ferry at varying distances, with a Beaufort sea state of 4 at West Lantau Station number 3. The ambient sound levels are the same as those for the small tour boat. (d) shows selected sound spectra for the Jetfoil compared to those of humpback dolphin communication sounds at a distance ≤100 m.

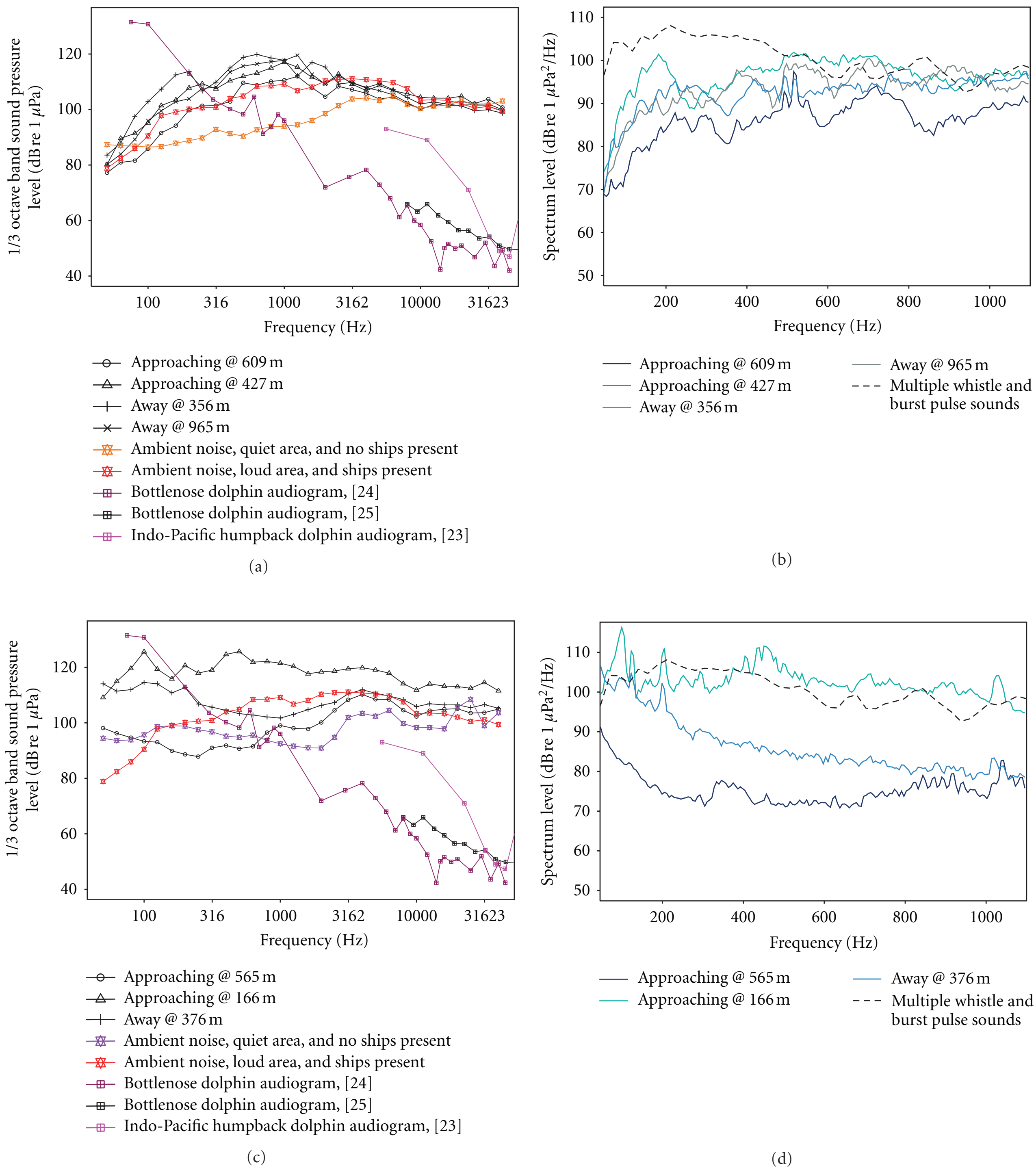

Figure 4: The various sound pressure level contributions of a high-speed ferry (R66; a), at West Lantau number 3 with a Beaufort sea state of 2. The orange line indicates the ambient sounds of Southwest Lantau number 2, located between the Soko Islands with very little boat traffic and no vessels present during recording. The red line indicates South Lantau Vessel Fairway, a busy traffic area, especially for ferries. South Lantau Vessel Fairway was recorded with several ferries and a shrimp trawler present. (b) shows selected sound spectra of the above high-speed ferry in comparison to the spectra of humpback dolphin communication sounds at a distance of ≤100 m. (c) The various sound pressure level contributions of a high-speed ferry (R92), at Northwest Lantau number 5 with a Beaufort sea state of 4. The ambient noise level (represented in purple) was taken from Northwest Lantau number 1, an area with very little boat traffic, located within the Sha Chau and Lung Kwu Chau Marine Park. The red line is the same as that in (a). Sound spectra are represented below (d) for the high-speed ferry, including the same humpback dolphin spectra as (b).

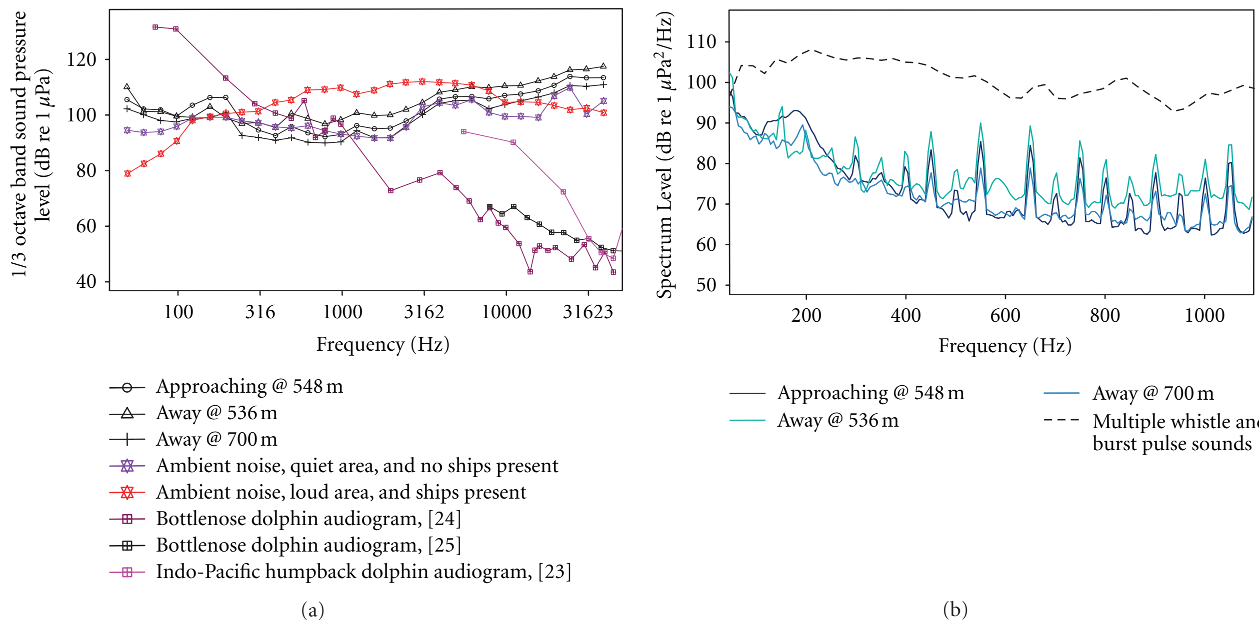

Figure 5: (a) The various sound pressure level contributions of a Hi-Speed Ferry (R101), at Northeast Lantau Station number 1 with a Beaufort sea state of 2. The ambient noise level (represented in purple) was taken from Northwest Lantau number 1, an area with very little boat traffic, located within the Sha Chau and Lung Kwu Chau Marine Park. The red indicates the South Lantau Vessel Fairway (SLVF), a busy traffic area, especially for ferries. SLVF was recorded with several ferries and a shrimp trawler present during a Beaufort sea state of 0. (b) shows selected sound spectra of the above high-speed ferry in comparison to the spectra of humpback dolphin communication sounds at a distance of ≤100 m.

Sound spectra for the HSFs and small tour boat were highly variable among vessels. Sound spectra for which spectral components from all distances converged on each other indicated that these sounds were likely part of the ambient background sounds and not due to vessel inputs (Figure 5(a), from 0 to >1,000 Hz). Some spectra were clearly distinct in the upper frequencies (e.g., Figure 3(b), from around 300–800 Hz and Figure 4(b), from 0 to >1,000 Hz), suggesting that these spectra may have been individual vessel tonal elements. Distinctive spectral components were also present in the lower frequencies that appeared only at closer distances, indicating they were not ambient sounds (e.g., Figure 3(b), gray line from 100 to 300 Hz).

The selected humpback dolphin section contained multiple burst pulse and whistle sounds, which are associated with social behavior and communication [22]. Spectral analysis revealed high spectrum levels for humpback dolphin sounds, which were maintained between 95–104 dB re 1 μPa^2/Hz. In most vessel spectrum plots, the humpback dolphin sounds were much higher than the vessel sounds present throughout much of the frequency range (but see Figures 4(b) and 4(d)); however, these dolphin sounds were recorded at distance ≤100 m in comparison to vessel distances, which could range from <100 to >700 m.

4. Discussion

We determined that vessels contribute appreciable sound levels to the ambient environment. Greater vessel traffic appeared to be associated with higher sound pressure levels across most frequencies. South Lantau Vessel Fairway had the highest sound pressure levels across most of the frequency range and the greatest number of vessels present, that is, four. Though other sites also had relatively high sound level peaks, none were maintained across the majority of the frequency band. The other site which maintained relatively high sound pressure levels, though over smaller frequency range, was WL number 3, in which a HSF was present during recording. It is unlikely that these differences can be attributed to Beaufort sea state (Bss), as SLVF was a Bss of 0, and the other sites, including WL number 3, were Bss of 3. Because recordings were taken over such short time periods, seasonal differences are not likely to be responsible for the observed differences in sound pressure levels. These results suggest that the presence of vessel traffic contributes to increases in ambient sound levels. However, it seems unlikely that the presence of one HSF at 702 m would contribute to such a high sound pressure level after ambient sounds were averaged. We propose that the unexpectedly high sound level peak in WL number 3 may be due to other anthropogenic activity outside the immediate vicinity, for example distant vessel traffic as WL number 3 is located directly in the path of the Southern Lantau vessel route. No recordings were available for WL number 3 in which vessels were absent, so we are unable to eliminate the possibility that those sites with vessel traffic are louder due to factors besides vessel traffic. Nevertheless, it seems likely that vessels are important contributars to the current ambient sound environment in both SLVF and WL number 3, particularly when coupled with the individual sound pressure level data from the HSFs and small tour boat.

While SLVF maintained the highest ambient sound levels across the largest frequency range, NWL number 1 noticeably peaked in the ambient sound to a level at or above that of SLVF at the same frequency (125 and 25,000 Hz resp.). This result is not consistent with the expectation that ambient sounds from quiet areas (NWL number 1) would be lower than those of busy areas (SLVF). We doubt that Bss is the cause of these peaks as they do not appear in the other quiet ambient site having the same Bss of 3 as NWL number 1. An examination of Knudsen's predictions for Bss of 3 (converted to 1/3 octave sound pressure levels in [27]) shows sound levels decreasing at a constant rate from ∼94 decibels as frequencies increase from the beginning at 100 Hz. While Bss may account for sounds in the lower frequencies (≤2,500 Hz) for NWL number 1 and SWL number 2, the Knudsen curves do not indicate a similar correspondence for sounds in the upper frequencies (>2,500 Hz) for either NWL number 1 or SWL number 2. Additionally, Knudsen curves predict sound levels beginning around 92 dB at 100 Hz, which SWL number 2 sound levels do not reach until 400 Hz. At 100 Hz, SWL number 2 sound levels are 86 decibels, about 6 decibels below the expected sound pressure level. Thus, Knudsen curves for Bss of 3 may only explain the sound levels present in the lower frequencies of NWL number 1. We hypothesize that nearby traffic accounts for the unexpected sound peaks in NWL number 1, whereas local geography may be reducing sound propagation in SWL number 2. As summarized by Malme et al. [28], sound transmission can vary greatly in shallow environments due to acoustic effects of the bottom and surface.

We used both bottlenose and a humpback dolphin audiograms to compare vessel sound outputs to dolphin hearing. Only one audiogram exists for Indo-Pacific humpback dolphins [23], and recent research indicates that they share similar communication frequencies and repertoire as bottlenose dolphins [12, 22], thus we used the Johnson [24] bottlenose dolphin audiogram as a proxy for humpback hearing sensitivity in frequencies below those in the humpback audiogram. The sound pressure levels for SLVF peak around 110 decibels from around 800–10,000 Hz, at the hydrophone (with unknown levels at a standard 1 m distance from the sound source), well within the lower audible range of bottlenose dolphins [24, 25] and partially so for humpback dolphins [23]. Extrapolation of the bottlenose dolphin audiogram to humpback dolphins in lower frequencies may be questionable based on some of the observed differences where humpback hearing threshold data overlap with those of bottlenose dolphins. However, individual variation in audiograms exists in bottlenose dolphins [24, 25] and humpback dolphins likely exhibit similar differences as well. Thus, any conclusions of species differences or similarities in hearing thresholds should be taken cautiously until more data are available on variability in humpback dolphin hearing thresholds.

It is unknown if ambient noise of the level that we observed may cause physiological damage, increased stress, or behavioral changes since long-term data are not available for these traits in the Hong Kong population of humpback dolphins. However, humpback dolphins exhibit behavioral changes in response to high levels of traffic, with greater occurrences of longer dives associated with the presence of some oncoming vessels, particularly those at high speeds [8]. It is assumed that increasing diving duration in response to oncoming and high levels of vessel traffic results in elevated stress levels. Furthermore, humpback dolphins increase their whistling rates after a vessel (<1.5 km) has passed, which is hypothesized to function as reestablishing group cohesion [7]. Thus, humpback dolphins may experience increased stress and both physical and communicative behavioral changes in busy traffic environments such as SLVF.

The ambient noise level of SLVF may be a conservatively low estimate since these data were collected during the presence of multiple ships, all of which changed in proximity to the hydrophone throughout the recording. No ships were present during the recordings for SWL number 2 and NWL number 1, so this issue does not pertain to them. Due to the random nature of our selections, it is likely that the represented noise levels are a mixture of both near and far ship distances. Ships closer in proximity will generate higher sound pressure levels, thus our estimated ambient noise level is likely more representative of the average sound levels recorded from the average distance of ships during our recording. This is potentially problematic in determining the effects of noise on the local dolphins, since it is presently unknown what distances dolphins maintain (or attempt to maintain) from ships. Ng and Leung [8] documented differences in humpback dolphin responses to vessel type and distance; however, they did not describe dolphin responses to specific vessel types at varying distances. They report higher rates of vessel avoidance by humpback dolphins in response to high-speed vessels, but it is unknown at what distances these behavioral changes were documented. However, Piwetz et al. [29] found behavioral changes, such as mean leg speed and reorientation rate, in response to small tour boats and trawlers within 1 km. Additionally, many of the vessels present in SLVF are HSFs, which are fast moving vessels, known to make abrupt entrances and departures at high speeds [29]. These HSFs could quickly increase their proximity to dolphins, and sound pressure levels can elevate rapidly, potentially causing startle or other reactions. Indeed, some research indicates increased unpredictability in vessel movement can have stronger effects on dolphin behavior [30, 31]. The potential magnitude of ambient noise levels for SLVF is dependent upon the assumption that the local dolphins maintain distances similar to the average distances between the hydrophone and ships recorded in our analyzed selections. This highlights a need for further research on humpback dolphin proximity and behavior in the presence of various ships to determine potential differences in behavior at varying distances and vessel types.

The difference in most sound pressure levels between vessels and ambient sound recordings highlights a potentially disruptive contribution to the local noise levels, particularly when compared to the quiet ambient background sounds. Most of the vessel sounds exceeded the quiet ambient background at the majority of distances; however, this difference was generally constricted to distances of 100–500 m of apparent sound sources when compared to the busy ambient recordings. Thus, the impact of these increased levels depends on the proximity of dolphins to the vessels. Many of the spectra present at short distances were not present at farther distances, indicating that vessel sounds generally did not propagate to distances ≥600 m. The overlap of spectra above the dolphin sounds suggests that some vessel sounds at distances ≥100 m may disrupt humpback dolphin communication sounds. Considering the fast speeds that these vessels can undertake, dolphins may not have adequate time to distance themselves and may suffer physiological impairment or stress in addition to masking effects on communication. On a long-term scale, this could result in chronic damage, stress, and communication disruption. Indeed, differences in whistles among populations of bottlenose dolphins have been attributed to site differences in vessel traffic and ambient noise and also have been found to vary with the number of vessels present [11, 32]. Thus, it is possible that the differences in the local noise environment may account for differences in communication sounds between the Hong Kong and Australian humpback dolphin populations [12].

One HSF displayed sound pressure level was consistently lower throughout the HSF frequency range for SLVF and around the ambient sound levels for NWL number 1 (Figure 5). This result may be due to individual differences in vessel structure or speed a likely explanation as the other four HSF recordings displayed opposite sound pressure levels, with the majority of their sounds being at or above ambient noise levels. Additionally, the wide variation in HSF sounds suggests individual differences in sound output among all ferries; however, it is unclear whether these discrepancies are from unique ship structures, differences in vessel speeds, or local habitat characteristics [1, 28].

In sum, it appears that the HSFs and small tour boats make important contributions to the local sound environment, although the influence of factors such as local topography and vessel sound propagation and attenuation have yet to be studied. As these vessels are numerous in West Hong Kong waters, management of their speeds and distribution are important in mitigating potential effects on the local dolphin population. Future research should focus on understanding how dolphins distribute themselves spatially relative to these vessels, and how this may vary with differing speeds and distances. The uncertainty in interspecific differences and/or similarities in audiogram hearing thresholds highlights a need for more Indo-Pacific humpback dolphin audiograms to help determine the extent that local and global delphinids may be affected by small high-speed vessels. Additionally, population differences in sound repertoire between Hong Kong and Australian humpback dolphins have yet to be resolved, but provide an opportunity to investigate the potential role of noise pollution in these differences. As an ultimate goal, determination of both the acute and chronic effects of different sound pressure levels on delphinid physiology, behavior, and communication will help to assess and manage anthropogenic ship disturbances of cetacean populations.

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