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Biosonar activity of the Indo-Pacific humpback dolphin (*Sousa chinensis*) near the tunnel section of the world's longest cross-sea bridge—the Hong Kong-Zhuhai-Macao Bridge—is negatively correlated with underwater noise

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Underwater noise pollution from the world's longest cross-sea bridge—the Hong Kong-Zhuhai-Macao Bridge (HZMB)—which stretches across the Chinese White Dolphin National Nature Reserve (of the People's Republic of China, PRC) in the Pearl River Estuary may affect the distribution of local humpback dolphins. In this study, static passive acoustic monitoring was applied to monitor biosonar activity of humpback dolphins and underwater noise adjacent to the tunnel section of the HZMB for more than one year. During the monitoring period, dolphin biosonar signals were detected on 88.5% of days. A significant temporal pattern occurred in dolphin biosonar activity and in anthropogenic noise. Biosonar activity was significantly higher at night than during the day, whereas underwater noise occurred more in the day than at night. Significantly more echolocation signals were detected in winter-spring than in summer-autumn, and highest acoustic activity occurred significantly more during high tide than at other tidal periods. In addition, the negative correlation between elevated underwater noise and dolphin sonar activity in winter suggests that dolphins may avoid noisy waters for short periods, perhaps due to auditory stress, but fish prey movement cannot be ruled out. These findings facilitate understanding activity patterns of humpback dolphins in the Pearl River Estuary and may contribute to conservation efforts.

KEYWORDS

Indo-Pacific humpback dolphin, passive acoustic monitoring (PAM), sonar activity, underwater noise, Hong Kong-Zhuhai-Macao Bridge

1 Introduction

Human-derived underwater noise in the ocean is ubiquitous and has posed health risks to cetaceans. For example, underwater noise can interfere with the reception of natural signals by cetaceans. This reduces communication space (Richardson et al., 1995; Erbe et al., 2019), leading to changes in cetacean habitat use and distribution patterns (Morton and Symonds, 2002; Merchant et al., 2014). Moreover, high-intensity noise can even cause auditory system damage to animals (Wang et al., 2014b; Finneran et al., 2015; Leunissen et al., 2019; Wang et al., 2020). Cetaceans serve as sentinel and indicator species for assessing marine ecosystems, and they rely on their sophisticated biosonar system for pivotal life activities, including communication, navigation, localization, foraging, and predator avoidance (Richardson et al., 1995; Au et al., 2008). Therefore, monitoring cetacean acoustic signals can clarify the distribution of these species and their behaviors (Gregorietti et al., 2021). Investigating the potential effects of anthropogenic noise pollution on local cetaceans is crucial to direct appropriate conservation management measures.

Nearshore estuaries, as transitional zones linking land and sea at the interface of saltwater and freshwater, often have high primary productivity (Mallin et al., 1991), and these areas also tend to be important habitats for most marine mammals (Jefferson and Hung, 2004; Hornby et al., 2016; Monteiro-Filho et al., 2018). However, human activities in nearshore estuaries, including shipping traffic, bridge construction, and shoreline development, crowd out the habitats of marine mammals, raise ambient native noise levels and increase the risk of their extinction (Davidson et al., 2012). The Pearl River Estuary (PRE) in southern China has typical nearshore estuarine features and is home to the world's largest population of Indo-Pacific humpback dolphins (IPHD, *Sousa chinensis*), comprised of approximately 2500 individuals (Chen et al., 2010). However, recent demographic analyses indicate that the IPHD population in the PRE is decreasing at a rate of 2.5% per year (Huang et al., 2012).

IPHD are distributed in shallow coastal waters of the eastern Indian Ocean and western Pacific Ocean, with their range overlapping closely with areas of human activity (Jefferson and Curry, 2015; Jefferson and Smith, 2016). This dolphin species is classified as "Vulnerable (VU)" by the International Union for Conservation of Nature (IUCN) Red List of Threatened Species and categorized as a Grade One National Key Protected Animal by the Chinese Wild Animal Protection Law. However, in the various areas of China inhabited by IPHD, noise pollution from boat traffic, water construction projects, and other heavily anthropogenic activities has impacted the local cetaceans (Yamagiwa and Karczmarski, 2014). For example, the communication and echolocation signals of IPHD might be masked by various shipping noises (such us small high-speed boats and commercial ships) up to 1000 m from the source (Li et al., 2015; Liu et al., 2017). Furthermore, increases in noise pollution may force IPHD to change their vocalization frequency to avoid sound masking (Yuan et al., 2021).

Among the numerous water infrastructure projects in the PRE, the world's longest sea-crossing bridge—of the Hong Kong-Zhuhai-Macao Bridge (HZMB), which began operating in 2018, has attracted the more concerned. The HZMB connects Guangdong, Hong Kong, and Macao, promoting economic and trade growth in the Greater Bay Area and the wider world. The structure comprises the bridge, islands, and tunnel schemes, and has a total length of 55 km of which the section passing through the Pearl River Estuary Chinese White Dolphin National Nature Reserve is approximately 20 km (Xiao, 2020). Additionally, the east and west artificial islands are located in the core area of the reserve. The stretch of water between these two artificial islands is an essential channel for ships to enter and exit the port of Guangzhou. Piling noise during HZMB construction and its impact on local IPHD was assessed (Wang et al., 2014b); however, noise pollution during bridge operation and its potential negative impact on local dolphins has yet to be investigated.

Visual expeditions and acoustic monitoring are mainly used for marine mammal surveys. Passive acoustic monitoring (PAM) allows continuous tracking of marine mammals and habitats over longer time scales compared with traditional visual surveys (Zimmer, 2011; Todd et al., 2020), as well as at night and under extreme weather conditions (Thompson et al., 2015). In this study, PAM was employed to investigate IPHD sonar activity and the varying temporal patterns of underwater noise in the waters near the HZMB tunnel, aiming to inform underwater noise mitigation and conservation management strategies for humpback dolphins.

2 Materials and methods

2.1 Study area

A PAM station (22°16′36′′N, 113°48′18′′E) was deployed in a fairway beacon located in the core area of the Pearl River Estuary Chinese White Dolphin National Nature Reserve at approximately 700 m from the HZMB, 4 km from the east artificial island, and 2 km from the west artificial island (Figure 1). This beacon was located on the channel boundary, approximately 150 m from the center of the waterway, and provides an essential indication of the entry and departure of ships from the Lingding waterway.

2.2 Data collection

An acoustic recorder (SoundTrap 300 HF, Ocean Instruments Ltd, New Zealand) was fixed to the anchor chain of the beacon 5 m underwater by a diving support service. The effective operating frequency range of this hydrophone was 20 Hz to 150 kHz, with a 3 dB margin of error. The hydrophone was equipped with a 16-bit analog-to-digital converter. Acoustic sound was continuously recorded for 24 h at a sampling rate of 288 kHz, and the recorded audio files (.wav) were imported into a computer. Data were collected seasonally between July 2021 and March 2022 (Table 1).

2.3 Data analysis

Dolphin sonar signals were identified using a custom-written analysis program in MATLAB R2021b (The Math Works, Natick,

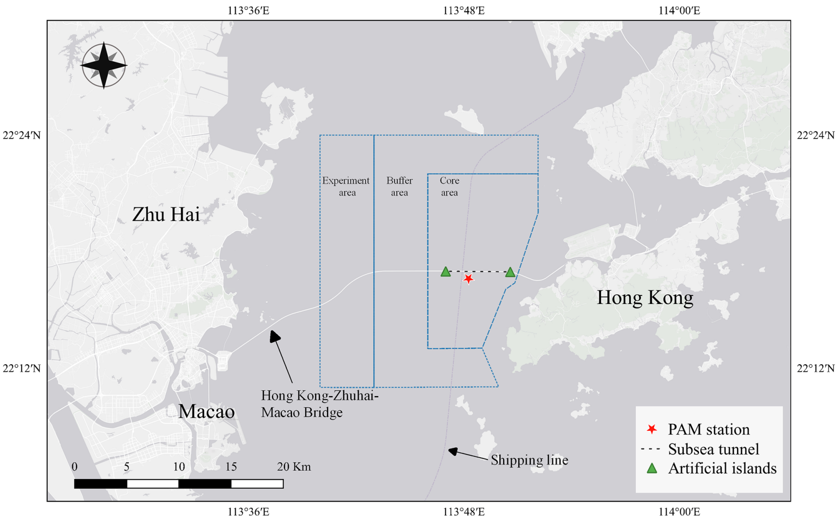

FIGURE 1
Locations of passive acoustic monitoring stations. Two triangles show the east and west artificial islands. The black dashed line indicates the subsea tunnel. The blue area is the Pearl River Estuary Chinese White Dolphin National Nature Reserve, and from left to right are the experimental, buffer, and core areas.

MA, USA). The WAV files were uploaded into the program, which first divided the waveform data into several tone frames in seconds, and filtered out low-frequency (20 kHz) noise through a high-pass filter. Filtered signals with a sound pressure level (SPL) greater than 120 dB were marked as specific frames and Fourier transformed to calculate the power spectral densities of each frame (Window size = 0.01 s, 90% frame overlap; Time resolution = 0.001 s, Frequency resolution = 100 Hz). The peak frequency, center frequency, −3 dB bandwidth and the rms bandwidth were calculated. These were then compared to the pulse parameters of IPHD (Fang et al., 2015), marking and extracting the frames that matched the statistical range of the four parameters simultaneously.

Spectrograms of each file (.wav) were examined with Raven Pro 1.6 (The Cornell Lab of Ornithology, Ithaca, NY, USA) to manually verify the dolphin sonar activity. MATLAB R2021b sequentially cut and analyzed acoustic data each second and calculated the root mean square sound pressure level (SPL_{rms}) for each clip of underwater noise (Au et al., 2008).

The diel phase was divided into daytime (sunrise time to sunset time) and nighttime (sunset time to sunrise time) (Deconto and Monteiro-Filho, 2015; Guan et al., 2015). The seasons were defined as spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February). The tidal phase was divided into four phases: high, ebb, low, and flood. The high and low phases were the highest water level (Th), and the lowest water level (Tl) of the tidal phase pushed forward and backward by 1.5 h, respectively. Ebb and flood phases were the periods between the high-to-low and low-to-high phases, respectively (Wang et al., 2015b). The times of Tl and Th were obtained from the website of China Shipping Service (https://www.cnss.com.cn/tide/).

Biosonar and noise data were partitioned into 10-min bins for convenient analysis and statistical evaluation (Todd et al., 2009; Wang et al., 2015b). Each 10-min bin was assigned to different diel, seasonal, and tidal phases to investigate the pattern of IPHD sonar activity and underwater noise under different diel, tidal, and

TABLE 1 Acoustic recorder deployment and detection of humpback dolphin biosonar activity.

Recording period	Recording duration (days)	No. days with dolphin sonar detection	No. click trains	No. buzzes	Echolocation encounter duration (min)			
					N	Mean	Max	Min
04 July to 16 July 2021	13	9	592	11	17	436.87	1914.59	0
28 September to 10 October 2021	13	11	977	8	16	622.62	1826.99	0
30 November to 12 December 2021	13	13	3094	139	28	1323.01	6697.84	0.38
16 March to 28 March 2022	13	13	4329	304	35	1357.26	6332.36	2.22
Total	52	46	8992	462	96	934.94	6697.84	0

Biosonar statistical parameters include the number of click trains and buzzes and the duration of the echolocation encounter.

seasonal patterns. A collection of click trains with spacing of 10 min or less was considered an echolocation encounter (Carlstrom, 2005; Todd et al., 2009; Wang et al., 2015b). The seasonal acoustic signal detection rate was calculated by dividing the number of detections each season by the total number of hours recorded per season.

2.4 Statistical analysis

Descriptive parameters were calculated, including the mean and standard deviation of the number of click trains per 10-min and buzzes per 10 min (Wang et al., 2015a). The Kolmogorov–Smirnov test was used to test for normality. Owing to the discrete non-normally distribution of most of the acoustic data, the variables of the median, interquartile range (IQR), 5th percentile (P5), and 95th percentile (P95) were adopted to describe the SPLrms data. A Mann-Whitney U test (Mann and Whitney, 1947) was used to compare the biosonar activity between daytime and nighttime. For comparison of multiple data groups, Kruskal–Wallis analysis of variance (Kruskal and Wallis, 1952) tested the overall variability, and Dunn's *post hoc* test (Zar, 1984) compared the variability of each group. Spearman correlation analysis was employed to investigate the relationship between underwater noise and the sonar activity of IPHD. All statistical analyses were completed using IBM SPSS Statistic 26.0 (IBM, Armonk, NY, USA).

3 Results

Acoustic monitoring data were collected for 52 days, consisting of 1209 hours of data that could be divided into 7254 10-min bins. Dolphin sonar was detected on 46 days, accounting for 88.5% of the total monitoring period. Overall, 96 IPHD echolocation encounters were monitored, 40 of which contained buzzes (Table 1). Among the 10-min bins, 260 bins contained click trains, representing 3.6% of the total dataset, and 8992 echolocation signals were monitored (Figure 2).

The values for noise SPL_{rms} were 136.98 ± 9.70 dB (median ± IQR) with a range of 125.81–149.80 dB for P5–P95 (Figure 3).

3.1 Sonar activity

The detection rates of humpback dolphin acoustic signals at the monitoring station were 16% and 12% in winter and spring, respectively, which were higher than those in summer (6%) and autumn (5%) (Figure 4). Kruskal-Wallis tests showed significant differences in IPHD acoustic activity between seasons (number of click trains per 10 min: $\chi2 = 74.326$, df = 3, $P < 0.05$; the number of buzzes per 10 min: $\chi2 = 53.993$, df = 3, $P < 0.05$). Dunn's *post hoc* multiple comparisons revealed that the number of click trains per 10 min and the number of buzzes per 10 min were significantly higher in winter and spring than in summer and autumn ($P < 0.05$) (Figure 5A).

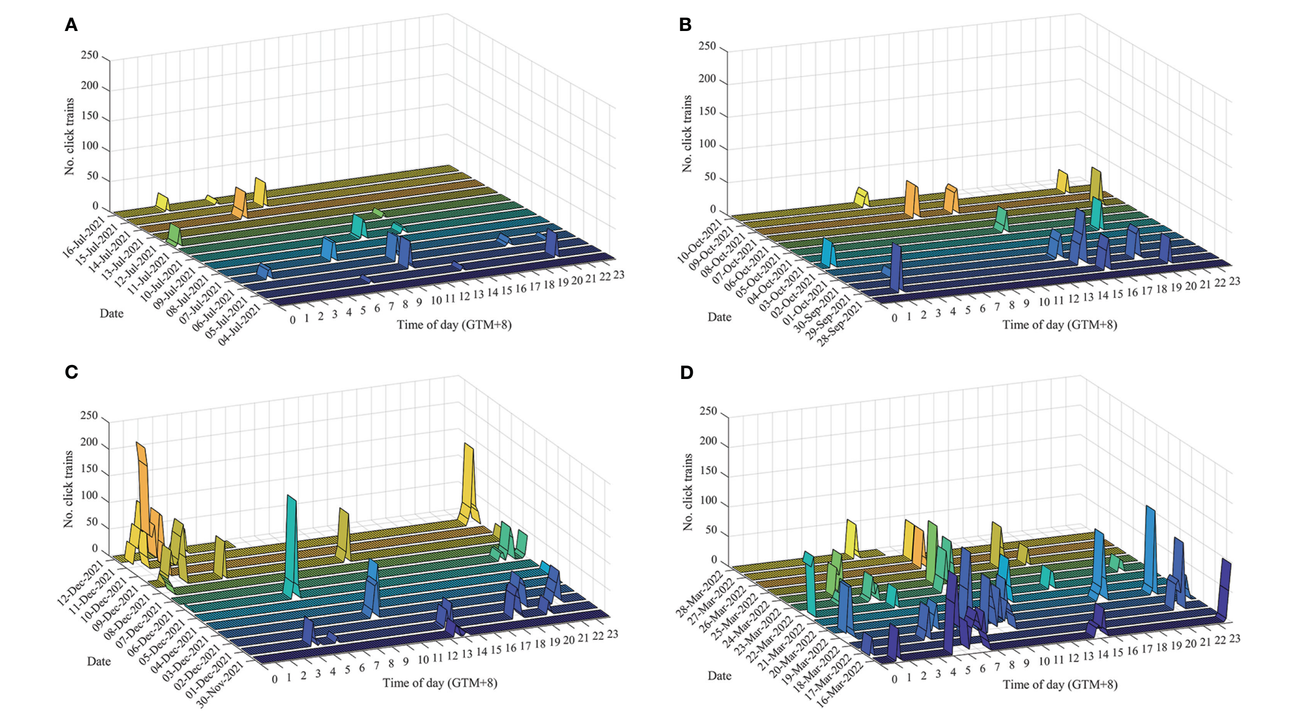

FIGURE 2
Daily occurrence of dolphin click trains per 10 min by the time of day in **(A)** summer 2021, **(B)** autumn 2021, **(C)** winter 2021, and **(D)** spring 2022.

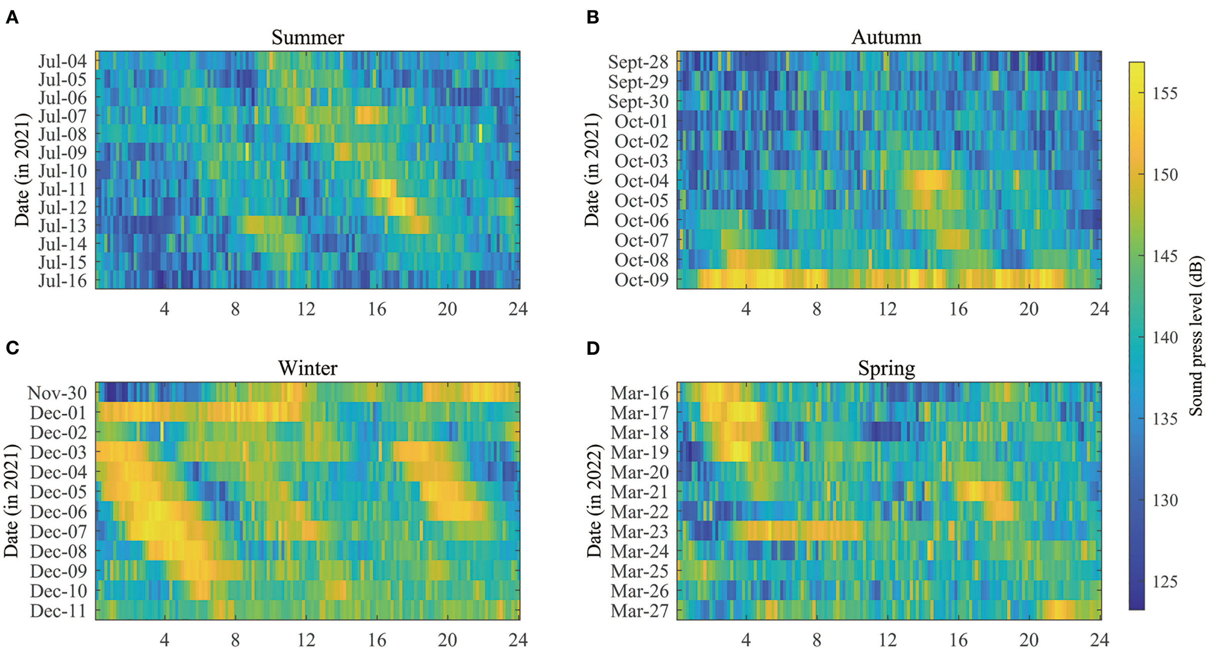

FIGURE 3
Sound pressure levels (SPL_{rms}) of the water environment in different seasons as a function of time of day (X-axis) and date (Y-axis), **(A)** summer 2021, **(B)** autumn 2021, **(C)** winter 2021, and **(D)** spring 2022.

At high tide, the number of click trains per 10 min and the number of buzzes per 10 min was 2.29 ± 0.30 and 0.10 ± 0.03 (mean ± SD), respectively, which were significantly higher than those of other phases at this station ($\chi 2$ = 41.867, df = 3, $P < 0.05$, number of click trains per 10 min; $\chi 2$ = 21.402, df = 3, $P < 0.05$, number of buzzes per 10 min). No significant differences in the dolphin biosonar activities were found during flood, ebb, and low tide (Figure 5B).

The number of click trains and the number of buzzes per 10 min at the monitoring site did not show significant differences during the day or night (Figure 5C). However, dolphin echolocation detection rates during daytime and nighttime were 4% and 2% in summer, 2% and 3% in autumn, 3% and 8% in winter, and both 8%

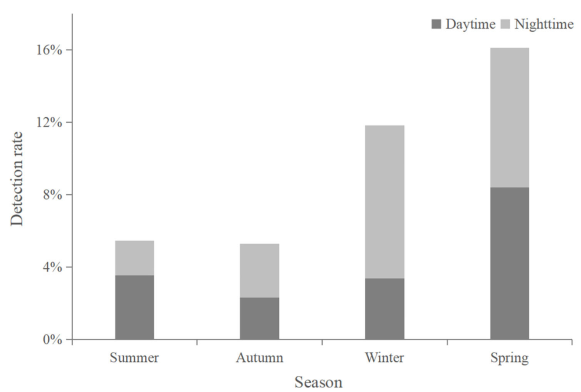

FIGURE 4
Echolocation detection rates of Indo-Pacific humpback dolphins in different seasons and during day and night.

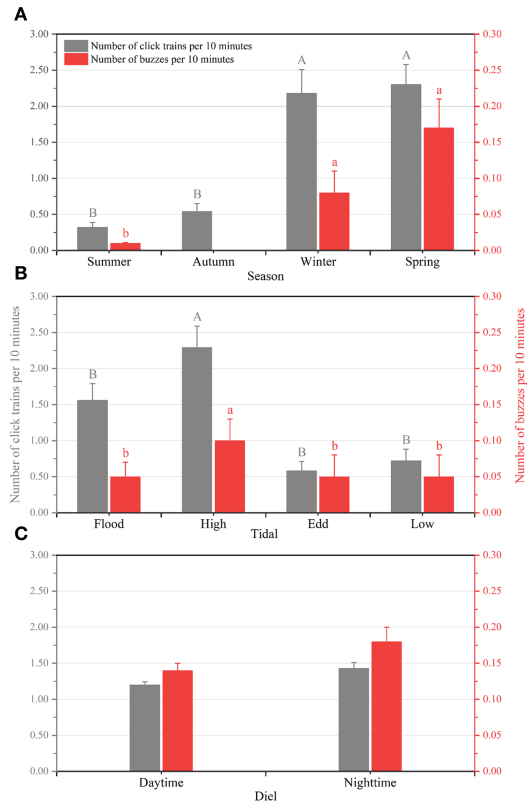

FIGURE 5
Number of click trains and number of buzzes per 10 min as a function of **(A)** seasonal, **(B)** tidal, and **(C)** diel phases. Error bars with different uppercase and lowercase letters refer to post-hoc Dunn's multiple comparison tests with click trains and buzzes, respectively.

in spring, respectively (Figure 4). In winter, the number of click trains and buzzes per 10 min was significantly higher at night than during the daytime ($P < 0.05$), while no differences were found in other seasons (Table 2).

3.2 Underwater noise

Underwater noise SPL_{rms} of the monitoring station exhibited significant differences between seasons ($\chi 2 = 2487.139$, df = 3, $P < 0.05$), with significantly higher SPL_{rms} in winter (median ± IQR: 144.45 ± 6.94 dB) than in summer (133.26 ± 6.96 dB), autumn (136.21 ± 7.85 dB) and spring (136.15 ± 8.19 dB). Furthermore, SPLrms in autumn and spring was significantly higher than in summer (Dunn's *post hoc* multiple comparisons, $P < 0.05$) (Figure 6). Throughout the acoustic monitoring period, SPL_{rms} was significantly higher during the day than at night (Mann-Whitney U test, $P < 0.05$).

There was a significant negative correlation between SPL_{rms} and the number of click trains per 10 min, only in winter (Spearman's rho = −0.073, $P < 0.01$, n = 1776).

4 Discussion

PAM has previously been used to monitor IPHD biosonar activity in the PRE (Wang et al., 2015b; Pine et al., 2017; Wang et al., 2019; Liang et al., 2020). The subsea tunnel of HZMB is located within the core area of the Pearl River Estuary Chinese White Dolphin National Nature Reserve. Sonar signals of dolphins were detected near the HZMB subsea tunnel on 88.5% of monitoring days in this study, indicating the frequent occurrence of dolphins in the vicinity.

4.1 Sonar activity

Monitored biosonar activity revealed significant seasonal, tidal, and diurnal rhythms of IPHD. The echolocation detection rate and biosonar activity of dolphins in winter and spring were higher than those in summer and autumn. These findings are in contrast to those of the IPHD populations in the adjacent Hong Kong waters, in which a higher dolphin abundance was observed in summer than in winter (Chan and Karczmarski, 2017). The possible explanation for the difference between this study and the Hong Kong waters was that seasonal flux of dolphins may exist between mainland and Hong Kong waters. In western Taiwan, the spatial distribution of humpback dolphins in an estuary habitat varied seasonally, with the dolphins inhabiting waters close to the estuary during the dry period and migrating outside the estuary during the abundant period (Lin et al., 2014). The seasonal variation pattern observed in this study is consistent with that of the eastern waters of the PRE, Xiamen waters, and the western waters of Taiwan (Chen et al., 2008; Chen et al., 2010; Lin et al., 2014; Wang et al., 2015b). The seasonal variations of IPHD in various places reveal their multiple patterns of habitat use in different seasons.

Seasonal changes in cetacean distribution are often related to the availability of their prey (Forcada, 2009). Owing to seasonal variations in the amount of freshwater entering the ocean, which causes fish migration, dolphins are more likely to hunt in areas where their fish prey are more prevalent (Hung and Jefferson, 2004; Wang and Lin, 2006). The higher dolphin predation signals in the subsea tunnel water during the dry season may be explained by higher feeding activity in that period. Research on fish resources in the Chinese White Dolphin National Nature Reserve showed that the average biomass and abundance of the main prey of IPHD in the PRE—including the spiny head croaker (*Collichthys lucidus*), taper tail anchovy (*Coilia mystus*)—were higher in autumn compared to spring (Huang et al., 2018). Moreover, after the overfishing period (July to February of the following year), dolphin food resources might decrease in winter and spring. In the vicinity of the subsea tunnel of the HZMB, fishing intensity is relatively weak owing to the restrictions of channel administrations. Therefore, when food availability is relatively limited in spring, the increased food rewards in the central fairway may motivate dolphins to select these riskier waters and make more frequent vocalizations to catch prey.

In this study, the acoustic activity of IPHD shows a significant diurnal difference in winter, with higher detection at night than during the day. The same diurnal patterns of dolphins were widely observed in other regions of the PRE and the southwest of Hainan Island (Wang et al., 2015b; Munger et al., 2016; Dong et al., 2017; Pine et al., 2017). However, in the other three seasons, there were no diurnal differences in biosonar activity, which was consistent with observations in western Taiwan (Lin et al., 2013). This finding may indicate that there are no marked differences between the daytime and nighttime activities of IPHD near the monitoring station of this study. Greater dolphin vocalization rates at night than during the day were widely observed

TABLE 2 Statistics of diel patterns between seasons based on Mann-Whitney U tests.

Biosonar characteristic		Summer			Autumn			Winter			Spring		
		d (Mean ± SD)	Z-value	*P*	d (Mean ± SD)	Z-value	*P*	d (Mean ± SD)	Z-value	*P*	d (Mean ± SD)	Z-value	*P*
No. of click trains	Daytime	0.40 ± 0.11	−0.858	–	0.61 ± 0.17	−0.634	–	1.03 ± 0.35	−3.943	**	2.81 ± 0.41	−1.674	–
	Nighttime	0.16 ± 0.08			0.47 ± 0.15			1.96 ± 0.42			1.96 ± 0.42		
No. of buzzes	Daytime	0.01 ± 0.00	−0.292	–	0.00 ± 0.00	−0.469	–	0.02 ± 0.01	−2.508	*	0.15 ± 0.04	−0.759	–
	Nighttime	0.01 ± 0.01			0.00 ± 0.00			0.12 ± 0.05			0.18 ± 0.08		

*$P < 0.05$. **$P < 0.01$.

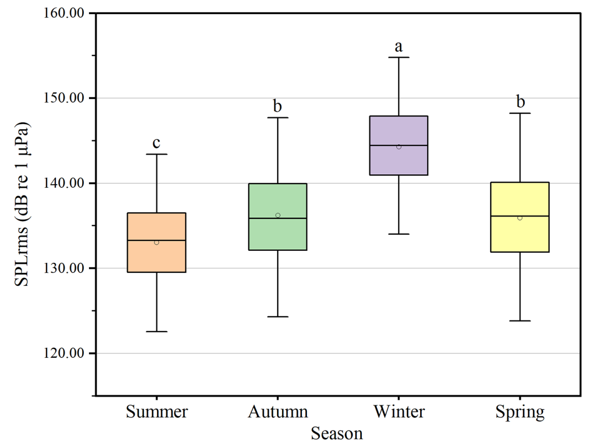

FIGURE 6
Comparison of broadband sound pressure levels (SPL_{rms}) among different seasons. Different lowercase letters refer to *post-hoc* Dunn's multiple comparison tests that yielded significant results ($P < 0.05$).

in previous studies conducted in the PRE (Wang et al., 2015b; Munger et al., 2016; Pine et al., 2017). However, this might be ascribed to a higher vocalizations rate per animal at night and is not necessarily indicative of increased dolphin abundance at night.

Tides are an environmental factor that can significantly influence nearshore cetacean activity, and various cetaceans display varied activity patterns during different tidal phases. Acoustic detections of bottlenose dolphins (*Tursiops aduncus*) in Baja California Sur, Mexico, peaked in floods and high tides (Gauger et al., 2022), while in the Shannon Estuary, Ireland, more detections occurred during ebb tide (Berrow et al., 1996; Philpott et al., 2007). Different subpopulations of the same species exhibit distinct variations in habitat usage patterns across different tidal cycles (Paitach et al., 2017). No significant tidal cycles for the biosonar activity of humpback dolphins were observed in the Modaomen estuary or the Guishan windfarms in the PRE (Wang et al., 2015b; Liang et al., 2020). Furthermore, tidal phases did not affect IPHD group size in Zhanjiang waters (Liu et al., 2021). In the nearshore area of Taiwan's west coast, the acoustic monitoring rate was lower in the ebb tide phase than the other phases. However, the four tidal phases in the offshore area were not significantly different (Lin et al., 2013). The acoustic activity of IPHD in this study was highest at high tide and there were no significant differences between the ebb, low, and flood tide phases. This suggests that IPHD in the tunnel waters of the HZMB may be unaffected by tidal rhythm. The interaction between freshwater and seawater might have an impact on the tidal-driven behavior of estuarine dolphins and their prey (Mendes et al., 2002; Lin et al., 2013). Consequently, the wandering of prey into the intertidal zone during the tidal phase may account for the varying activity patterns of humpback dolphins during different tidal cycles.

4.2 Underwater noise

Underwater acoustic investigations of habitats are essential to determine the relationship between marine mammals and their habitat, along with analyzing the effects of various biological and anthropogenic activities on marine mammals (Sueur and Farina, 2015).

The underwater acoustic environments of Guishan windfarm in the PRE, southwest of Hainan Island and the west coast of Taiwan have been quantitatively described. This description indicates that there are various spatial and temporal patterns (including geospatial, seasonal, diurnal, and tidal) of underwater noise in different areas and that the primary sources of underwater noise include, but are not limited to, shipping traffic, pile-driving pulses, and fishing activities (Guan et al., 2015; Wang et al., 2019; Caruso et al., 2020; Xu et al., 2020; Dong et al., 2021).

The underwater noise created by pile driving with vibratory hammers during the construction period of the HZMB and subsea tunnel could mask dolphin whistles and have physiological impact (Wang et al., 2014b). The broadband SPL_{rms} during the acoustic monitoring in this study was significantly lower than in the construction period (Wang et al., 2014b), and thus the impact on humpback dolphins during operation of the HZMB and subsea tunnel might be less than that during construction of the structure. However, compared with recordings prior to bridge construction, the ambient SPL_{rms} increased after operation. This may be attributed to the fact that various noises generated by vehicles driving on the bridge and in the tunnel are transmitted through bridge the deck to the piers and then into the water, and this is coupled with numerous vessels congregating through the few navigable holes in the bridge. The underwater acoustic environment of the Monitor–Merrimac Memorial Bridge–Tunnel exhibited diurnally variable characteristics that were closely correlated with the temporal distribution of vehicular traffic in the underwater tunnel (Reeder et al., 2020).

Furthermore, the ambient underwater noise near the HZMB subsea tunnel exhibited a significant pattern of temporal variation in this study. Compared with the other three seasons, winter had a significantly higher SPL_{rms} (median ± IQR: 144.45 ± 6.94 dB), which might be related to the increased waterway cargo flux during that season (http://gwj.gz.gov.cn/). In a previous study, there was no relationship between IPHD activities and underwater noise SPL_{rms} of Qi'Ao and Sanjiao islands in PRE, but had a positive correlation with fish activity (Pine et al., 2017). In the Yangtze River, the attractiveness of fish resources for Yangtze finless porpoise (*Neophocaena asiaeorientalis asiaeorientalis*) also exceeded the repelling effect of shipping (Wang et al., 2014a; Wang et al., 2015a), which signified that finless porpoises were forced to be exposure to ship noise when hunting. The high biosonar detection rate of the increased underwater noise in winter in the current study may indicate that IPHD were forced by survival pressures to select the main channel, with higher predation risk. Meanwhile, the negative correlation between noise and sonar monitoring rate may indicate that with the temporary increase in SPL_{rms} of underwater noise in winter, the fishery resources in this water area were insufficient to attract IPHD to overcome the auditory pressure forcing animals to avoid noisy areas of water in the short term.

Daytime traffic volumes on HZMB and in the channel waters of the subsea tunnel are larger than those at night, which may explain why SPL_{rms} at this monitoring site is significantly higher during the day than at night. One third octave sound pressure level provided information to assess the frequency components of underwater noise audible to dolphins (Blackwell et al., 2004). The dominant frequency of the underwater tunnel was primarily concentrated in the frequency band below 200 Hz (Hou et al., 2020); thus, the SPL in low-frequency bands (25–400 Hz) may be ascribed by underwater tunnels (Figure 7). The optimal hearing range of fish is mostly concentrated in the range 100–400 Hz (Popper et al., 2003). Consequently, the low-frequency noise generated by the subsea tunnel may drive some fish away from the tunnel waters, thereby affecting the distribution of dolphins in the vicinity.

The noise level was above the threshold of the IPHD audiogram at frequency bands between 5.6 and 128 kHz (Figure 7), indicating that these sounds may be perceived by dolphins and therefore limited their sound detection in these frequency bands. IPHD habitat overlaps heavily with the main channel of Guangzhou port. The increased vessel density of coastal regions frequently causes noise levels to rise significantly above ambient levels (Duarte et al., 2021). The Port of Guangzhou, a key global port, has one of the greatest shipping throughputs in the world, with massive cargo ships, tankers, fishing vessels, dredging or underwater operating vessels, and small speedboats passing through the subsea tunnel waters of HZMB. The busy vessel traffic in the Lingding waterway may further result in potential impacts on marine mammals including hearing masking and physiological damage to the auditory system (temporary threshold shift: TTS; permanent threshold shift: PTS), thereby shortening the communication distance of marine mammals (Merchant et al., 2014; Liu et al., 2017; Marley et al., 2017). When ships were presented, dolphins reduced vocalization behavior and emitted shorter calls in shorter frequency patterns, including whistles and echolocation signals (Hu et al., 2022). Hectic vessel traffic in the waters west of Hong Kong also interfered with the behavior and hearing of humpback dolphins (Sims et al., 2012).

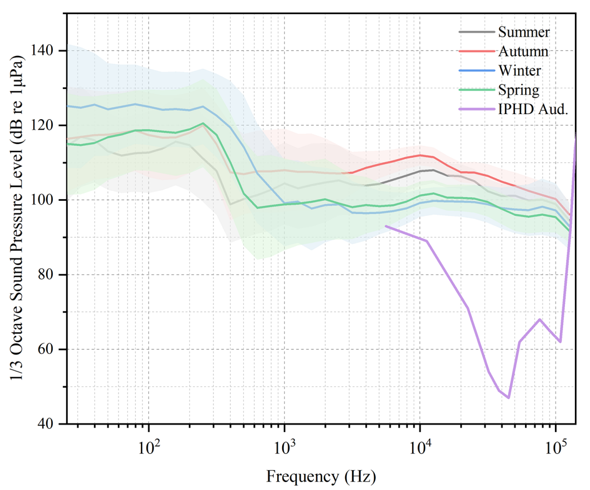

FIGURE 7
One third octave sound pressure level in different seasons and the average audiogram of the Indo-Pacific humpback dolphin (IPHD). Shaded areas denote the range from P25–P75, with the lower and upper boundaries representing P25 and P75, respectively. The purple line represents the average audiogram of young IPHD, which was adopted from Li et al., 2012.

Altering ship routes to limit the distance between vessels and dolphins, and reducing ship speed are essential measures to mitigate ambient noise levels in the habitats of marine mammals (Li et al., 2018; Schoeman et al., 2020). However, navigational safety restrictions, especially in coastal areas, mean it is not always possible to reroute a vessel (Conn and Silber, 2013). Vessel speed restrictions reduce engine noise and increase the chances of the crew spotting marine mammals, thereby reducing the probability of a collision between the vessel and animal (Vanderlaan and Taggart, 2007; Gende et al., 2011). Humpback whale-vessel collisions are much more likely to occur at speeds of more than 12 knots (6.2 m/s), independent of the size of the vessel (Gende et al., 2011; Currie et al., 2017). A forecast model suggested that the best compromise between noise exposure time and noise level is achieved at a cruising speed of 8 knots/h (McKenna et al., 2013).

This study provides baseline data of the relationships between underwater noise and dolphins in the HZMB tunnel waters of the PRE. However, the data are limited by the single monitoring site close to the tunnel and the two-week monitoring period for each season. Future research could improve information on IPHD acoustic activity and habitat use by increasing the number of monitoring sites and extending the monitoring duration to several years. In addition, the noise source is not solely correlated with traffic flux but also with the distance between the boat and the monitoring site, the boat type, the vessel traffic on the bridge, weather conditions, and the noise of buoy chains. Consequently, an attempt should be made to establish a noise calculation model to thoroughly assess the impact of various underwater acoustic sources on IPHD, including fish chorus, ship noise, and tunnel operation noise.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical review and approval was not required for the animal study because In this study, noninvasive passive acoustic monitoring methods were used, and data were acquired from ambience without causing harm to the area dolphins.

Author contributions

XA: conceptualization, methodology, data curation, validation, investigation, and writing-original draft preparation. PD: data curation, investigation, and reviewing and editing. WL: software and reviewing and editing. JY: investigation and reviewing and editing. YC: investigation and reviewing and editing. FF: reviewing and editing, XD: reviewing and editing, YX: investigation and reviewing. XC: investigation and reviewing. DW: conceptualization, supervision and reviewing and editing. ZW: conceptualization, methodology and reviewing and editing, project administration. KW: supervised, conceptualization and reviewing and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author WL is employed by the company Wuhan Pindu Technology Co.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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