Broadband ship noise and its potential impacts on Indo-Pacific humpback dolphins: Implications for conservation and management

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Ship noise pollution has raised considerable concerns among regulatory agencies and cetacean researchers worldwide. There is an urgent need to quantify ship noise in coastal areas and assess its potential biological impacts. In this study, underwater broadband noise from commercial ships in a critical habitat of Indo-Pacific humpback dolphins was recorded and analyzed. Data analysis indicated that the ship noise caused by the investigated commercial ships with an average length of 134 ± 81 m, traveling at 18.8 ± 2.5 km/h [mean $\pm$ standard deviation (SD), $n = 21$] comprises mid-to-high components with frequencies approaching and exceeding 100 kHz, and the ship noise could be sensed auditorily by Indo-Pacific humpback dolphins within most of their sensitive frequency range. The contributions of ship noise to ambient noise were highest in two third-octave bands with center frequencies of 8 and 50 kHz, which are within the sensitive hearing range of Indo-Pacific humpback dolphins and overlap the frequency of sounds that are biologically significant to the dolphins. It is estimated that ship noise in these third-octave bands can be auditorily sensed by and potentially affect the dolphins within 2290 ± 1172 m and 848 ± 358 m (mean $\pm$ SD, $n = 21$), respectively. © 2017 Acoustical Society of America. <https://doi.org/10.1121/1.5009444>

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I. INTRODUCTION

Over the past few decades, global waters have become increasingly noisy due to increased human activity, especially maritime traffic (Wenz, 1962; Ross, 2005; McDonald *et al.*, 2006; Andrew *et al.*, 2002; Andrew *et al.*, 2011). In particular, severe acoustic pollution exists in coastal areas as a result of acoustic by-products, which mainly originate from shipping operations (Hildebrand, 2009). Following a recent rapid expansion, global shipping is anticipated to rise indefinitely (Kaplan and Solomon, 2016). Many concerns have therefore been raised about the impacts of increasing noise levels on sound-sensitive or -dependent aquatic organisms such as marine mammals (Wright *et al.*, 2007).

Marine mammals rely heavily on emitting and receiving acoustic signals for underwater sensing and communication (Au, 2000; Au and Hasting, 2008; Surlykke and Nachtigall, 2014). The available acoustic space for marine mammals decreases with the ongoing increase in anthropogenic sounds, such as ship noise (Erbe, 2002; Foote *et al.*, 2004; Clark *et al.*, 2009). Ship noise therefore presents a serious risk of affecting marine mammals in regions of intense traffic, especially when these areas overlap with key habitats where vital functions, such as feeding, breeding, or nurturing frequently occur (Gervaise *et al.*, 2012). The components and characteristics of ship noise are highly variable and

strongly depend on many factors, such as ship specifications, operational conditions, and acoustic environment (McKenna *et al.*, 2012; McKenna *et al.*, 2013). Machinery components are most notably known to peak at low frequencies, < 1 kHz (Wagstaff, 1981; NRC, 2003; Kipple and Gabriele, 2004; McKenna *et al.*, 2012), whereas components from propeller cavitation can extend to several dozens or hundreds of kHz (Arveson and Vendittis, 2000; Gervaise *et al.*, 2012; Hermannsen *et al.*, 2014; Li *et al.*, 2015). Such broad bands span the audible frequency range and overlap biologically significant sounds for many marine mammals (e.g., the calls of some baleen whales or whistles of toothed whales) and might also reach the higher frequency bands used by toothed whales for echolocation in the service of navigating toward and detecting prey (Richardson *et al.*, 1995; Au and Hastings, 2008; Fenton *et al.*, 2014). Given the known potential detrimental impacts of broadband noise on marine mammals, ship noise pollution has become a primary focus of marine mammal studies and is of significant concern to regulatory agencies (Weilgart, 2007; Allen *et al.*, 2012; Simmonds *et al.*, 2014).

Indo-Pacific humpback dolphins (*Sousa chinensis*, Osbeck 1765) are distributed in coastal waters of the eastern Indian and western Pacific Oceans; they can be found at water depths generally shallower than 20 m and offshore distances of less than 10 km (Jefferson and Smith, 2016). At present, due to high-intensity human activities, such as maritime traffic (Würsig and Greene, 2002; Jefferson *et al.*, 2009; Sims *et al.*, 2012; Li *et al.*, 2015), their habitats are mainly noisy waters. With a measured sensitive hearing

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range of 5–120 kHz (Li *et al.*, 2012; Li *et al.*, 2013), Indo-Pacific humpback dolphins primarily vocalize relatively low-frequency “whistles” with fundamental frequencies between 0.5 and 33 kHz (Wang *et al.*, 2013) and broadband “clicks” with peak frequencies between 43.5 and 142.1 kHz (Li *et al.*, 2013; Fang *et al.*, 2015). Previous studies have shown that underwater noise from recreational boats or piling is audible to Indo-Pacific humpback dolphins, and interferes with their vocalization and masks their hearing (Würsig and Greene, 2002; Sims *et al.*, 2012; Wang *et al.*, 2014; Li *et al.*, 2015). Despite increased interest among conservation communities, there has been no comprehensive assessment of broadband underwater noise from commercial shipping operations nor has there been a corresponding evaluation of sensory distances (SSDs) within which potentially adverse impacts could affect Indo-Pacific humpback dolphins.

In this study, we recorded and analyzed broadband underwater noise from commercial shipping operations with typical ship speeds >15 km/h and ship lengths >50 m in a traffic-intense Indo-Pacific humpback dolphin habitat. The objective of our study was to provide insight into broadband ship noise characteristics and their potential impacts on the Indo-Pacific humpback dolphin to strengthen the baseline data used for conservation and management.

II. MATERIALS AND METHODS

A. Study area

The study area was approximately the midpoint of Longteng Channel in Zhanjiang, China (Fig. 1), which has a sandy/muddy seafloor. Longteng Channel is a main waterline and also a choke point, leading to intense traffic activity [Fig. 1(B)] at Zhanjiang Port, which is one of the 20 largest ports in China. Indo-Pacific humpback dolphins in Zhanjiang waters, including Longteng Channel [Fig. 1(C)], number in the low thousands; this population has been described as the world’s second largest humpback dolphin population (Xu *et al.*, 2015). The recording sites were nearby the core area inhabited by Indo-Pacific humpback dolphins [Fig. 1(C)], which was characterized by shallow water environment with water depth typically shallower than 40 m.

B. Acoustic recordings

Noise recordings were made using an icListen HF autonomous acoustic recorder (AAR; Ocean Sonics, Nova Scotia, Canada) with a calibrated icListen Smart hydrophone (sensitivity: -171 dB re 1 V/ μ Pa; frequency response: 0.01–200 kHz, ± 5.6 dB; sampling rate: 512 kHz). Figure 2(A) shows a diagram of the acoustic recording setup. The research vessel was anchored at fixed locations for recording positions [Fig. 1(C)]. The AAR was tied firmly with a strong rope, lowered vertically into the water, and anchored with a 5-kg iron weight at the bottom of the rope. Water depth was measured on board using a portable Hondex PS-7 sounder (Honda, Aichi-ken, Japan) to ensure that the AAR was lowered into approximately the middle layer of the water. Figure 2(B) illustrates the track of a passing ship (i.e., one of the target ships), including the approach, the closest point of approach

FIG. 1. (Color online) Map of the study area: (A) location of Zhanjiang Port; (B) enlargement of a choke point, displaying the shipping intensity in 2015; deeper colors indicate higher intensities¹; (C) location of Longteng Channel (—). The symbols “★” and “○” indicate recording positions #1–#4 for ship noise and the sites of Indo-Pacific humpback dolphin sightings, respectively.

(CPA), and the departure phases. When there was no interference (no other ships or dolphins within 2 km of the research vessel), we made noise recordings of passing ships. Using a similar methodology, ambient noise recordings were made at times when neither ships nor dolphins appeared within 2 km of the research vessel. All recordings were made at or below Beaufort Sea State 3. The engines, generators, and sounders of the research vessel were switched off during recordings.

C. Ancillary recordings

Dynamic ship information, including the position, distance, and speed of the recorded passing ships, was downloaded from the onboard FTGMDC FT-8700 Automatic Identification System (AIS) receiver (FEITONG, Fujian, China). Static information was also logged if provided by AIS; otherwise, ship information, including name, Maritime Mobile Service Identity (MMSI), and length (m) (Merchant *et al.*, 2012), was freely downloaded.¹

D. Data analysis

The spectrogram and waveform of each noise recording were checked in MATLAB 2014b (MathWorks, Natick, MA, USA). Power spectral density (PSD; dB re 1 μ Pa² Hz⁻¹) was calculated according to the method described by Li *et al.* (2015; hamming windows: 2048 points, 250 Hz bandwidth,

FIG. 2. (Color online) Schematic diagrams of (A) the hydrophone (icListen HF AAR) setup and (B) the track of a target ship including approach, closest point of approach (CPA), and departure phases.

and 50% overlap). To quantitatively analyze the noise levels of passing ships, each target ship was assumed as a point source (McKenna *et al.*, 2012). Using algorithms described by Pine *et al.* (2016), received third-octave noise levels (RTOLs, dB re 1 μ Pa) were quantitatively calculated over a time window of 10 s around the CPA. In total, 23 third-octave bands with standard center frequencies (F_c) from 1 kHz to 156 kHz were included (ANSI, 1984). We calculated 30 randomly selected 10-s segments of ambient noise in the same manner; these were averaged to assess the noise contribution of recorded ships relative to the ambient noise in different recording positions. Two previously measured audiograms of Indo-Pacific humpback dolphins (one from a young dolphin and another from an old dolphin; Li *et al.*, 2012; Li *et al.*, 2013) were also compared to the RTOLs and ambient noise levels.

Our initial examination showed that ambient noise levels were the limiting factor for hearing in the young dolphin in a frequency range between 5.6 and 108–128 kHz and in the old dolphin between 5.6 and 64–76 kHz. The hearing thresholds of the dolphins increased sharply outside of these frequency ranges, where hearing thresholds exceeded ambient noise levels and represented the limiting factor of the animals' hearing. To understand the contribution of recorded ship noise to ambient levels and the potential impacts of ship noise on Indo-Pacific humpback dolphins, excesses of ship noise RTOLs exceeding ambient noise levels were calculated for only 11 third-octave bands with F_c between 6.3 and 63 kHz. A primary analysis based on evaluating the averaged excess (i.e., sensory levels) of the noise levels of all analyzed ships to ambient noise levels across the described third-octave bands showed that there were two peaks in the averaged excesses of ship noise levels at F_c

values of 8 and 50 kHz, respectively, which are within the frequency ranges of Indo-Pacific humpback dolphin whistles (Wang *et al.*, 2013) and echolocation clicks (Li *et al.*, 2013; Fang *et al.*, 2015), respectively. Therefore, we focused subsequent analysis of ship noise on third-octave bands with F_c values of 8 and 50 kHz, where the sensory levels of Indo-Pacific humpback dolphins may be greatest and where their biologically significant sounds are more likely to be masked. For each target ship, a noise recording of approximately 5 min, including the approach, CPA, and departure phases, was divided into 10-s segments in order of time. Received levels (RLs, dB re 1 μ Pa) were measured for the two third-octave bands with F_c values of 8 and 50 kHz for all 10-s segments. Considering potential effects of environmental factors, such as water depth, on noise propagation, a curve of RLs vs distance was fitted for all analyzed data using the following:

$$\begin{aligned} \text{RL}(r) &= \text{SL} - \text{TL}(r) = \text{SL} - [\text{TL}(r)_1 + \text{TL}(r)_2] \\ &= \text{SL} - [\alpha \log(r) + \beta * (r)], \end{aligned} \quad (1)$$

where SL is the noise source level (i.e., sound pressure level at 1 m from the sound source; dB re 1 μ Pa at 1 m) of each investigated ship within a third-octave band with an F_c of either 8 or 50 kHz, assumed to be constant for each ship with a constant speed. TL is the transmission loss that could be divided into two parts: that is, spreading loss and attenuation loss; r is the distance between the recording hydrophone and the target ship calculated by the Pythagorean theorem based on the ship speed, time difference from the time at CPA, and distance at CPA; α and β are the spreading and absorption coefficients, respectively.

TABLE I. Details of noise recordings [positions #1–#4 correspond to the recording positions shown in Fig. 1(C)].

Recording position	Date	Depth (m)	Number of ship noise recordings	Number of ship noise recordings retained for further analysis
#1	May 16	20.5	8	4
#2	May 18	29.8	5	4
#3	July 8	24.2	7	4
#4	July 11	22.6	13	9
Total			33	21

The noise SLs of the analyzed ships were therefore the noise sound pressure levels back-calculated at the source distance (i.e., 1 m) following curve fitting. We assumed a sensory threshold for Indo-Pacific humpback dolphins of 0 dB (Erbe and Farmer, 2000; Pine *et al.*, 2016) above the ambient noise levels, because ambient noise levels were the limiting factor of the dolphins' hearing within the examined frequencies. The SSDs of ship noise for Indo-Pacific humpback dolphins were calculated according to the following:

$$AL = SL - [\alpha \log(SSD) + \beta SSD], \quad (2)$$

where AL (dB re 1 μ Pa) is the ambient noise level within third-octave bands with F_c value of either 8 or 50 kHz. Linear regression was applied to examine the dependence of SLs and SSDs on ship speed and length.

III. RESULTS

In total, 46 target ships were observed to access the channel during an approximate 10-h sampling effort within

four days between May and July, 2016; noise recordings of 33 ships (Table I) were collected with sufficient ancillary information for analysis (see supplementary material Table S1²). Given that some ships exhibited inconstant speed and/or changes in direction, only 21 noise recordings from 21 ships (Table I) were included in further analyses. The distance between the hydrophone and the recorded and analyzed ships at the CPA varied between 111 and 721 m [mean $\pm$ standard deviation (SD): 332 ± 163 m, $n = 21$]; ship speed varied between 15.7 and 23.0 km/h (mean $\pm$ SD: 18.8 ± 2.5 km/h, $n = 21$), and ship length varied between 53 and 333 m (mean $\pm$ SD: 134 ± 81 m, $n = 21$; Table II).

A. Characteristics and components of ship noise

An example spectrogram and waveform for a 5-min ambient noise and ship noise recording (HAIGUANSHAN 266, ship speed: 15.7 km/h, ship length: 53 m, CPA distance: 111 m) is shown in Figs. 3(A)–3(D). In the time scale, “0” represents the CPA time, negative values indicate the approach phase, and positive values indicate the departure phase [Fig. 2(B)]. The spectrograms and waveforms showed that noise levels have clearly been elevated across a broad frequency band up to and exceeding 100 kHz relative to the ambient noise due to ship operations.

B. RTOLs

The RTOLs for each ship are shown in Figs. 4(A)–4(D), with data for recording positions 1–4 in Fig. 1(C); the representative ambient noise levels at each recording position and two audiograms of Indo-Pacific humpback dolphins are also presented. The RTOLs are characterized by peaks at 1–20 kHz,

TABLE II. Basic parameters of analyzed ships and SSDs (m) related to the ability of Indo-Pacific humpback dolphins to auditorily sense ship noise recorded at positions #1–#4 in third-octave bands with center frequencies of 8 and 50 kHz. CPA: closest point of approach; SLs: noise source levels.

Recording position	Number	Ship name	Speed (km/h)	Length (m)	CPA distance (m)	SLs (dB re 1 μ Pa)		SSDs (m)	
						8 kHz	50 kHz	8 kHz	50 kHz
#1	1	GUO YUAN 16	22.1	225	720	143.8	135.9	2115	763
	2	XIN SU ZHOU	23	263	721	143.7	139.3	2308	1038
	3	XIN HENG HUA	18.1	83	260	142.3	133.3	2520	846
	4	CHANG HAI 9	16.1	96	518	141.2	136.3	1415	882
#2	5	AN HE 8	15.9	112	241	140.6	130.9	1400	415
	6	JIANG SU SAN HANG 6	18.5	98	296	140.3	138.8	1161	820
	7	HAI GUAN SHAN 266	15.7	53	111	135.5	127.6	601	392
	8	JIN HANG 689	15.8	100	176	144.5	136.1	1442	627
#3	9	HUI JIN QIAO 218	16.9	69	320	147.9	137.7	2632	718
	10	YU SHUN 106	20.7	54	345	136.8	127.7	683	385
	11	HAI GUAN SHAN 129	21.3	53	257	139.8	131.4	1022	460
	12	WAN HAI 282	17.8	182	410	146.6	141.3	3290	1028
#4	13	AN SHENG 17	16.9	118	210	146.2	140.6	2000	936
	14	VIEN DONG 3	19.4	103	334	150.4	142.5	3429	975
	15	ZHONG WEI	15.8	71	500	140.4	134.8	1415	767
	16	YU LIN HAI	22.4	225	262	149.9	147.8	5192	1482
	17	QUEEN JHANSI	20.6	190	259	148.2	146.4	4172	1562
	18	LIAN XING HU	20.7	228	308	149.6	148.9	3802	1508
	19	OLYMPIC LEADER	21.5	333	250	145.1	143.6	2339	1225
	20	XIN CHEN GUANG 20	16.8	98	151	146.6	139.6	3059	531
	21	HUI HANG 126	18.5	53	316	140.3	132.3	2095	442
Mean $\pm$ SD			18.8 $\pm$ 2.5	134 $\pm$ 81	332 $\pm$ 163	143.8 $\pm$ 4.3	137.8 $\pm$ 6.1	2290 $\pm$ 1200	848 $\pm$ 367

FIG. 3. (Color online) (A), (C) Spectrogram and (B), (D) waveform examples of a 5-min ambient noise and ship noise recording (HAIGUANSHAN 266), respectively.

gradually decreasing with an increase in frequency within the examined third-octave bands. Ship noise has caused a substantial decibel (2–15 dB) increase in the ambient noise levels across a broad frequency band up to and exceeding 100 kHz.

Figure 4 shows that the ambient noise levels were higher than the hearing thresholds of the young dolphin at frequencies between 5.6 kHz and 108–125 kHz, and they were higher than those of the old dolphin at frequencies between 5.6 kHz and 64–76 kHz. The RTOLs of all 21 analyzed ships clearly exceeded ambient noise levels along all examined frequency bands and also exceeded the hearing thresholds of

Indo-Pacific humpback dolphins within most of their sensory frequency bands.

C. Excesses of ship noise levels over ambient noise levels

The noise excesses of each ship over ambient noise levels varied considerably among all 11 third-octave bands between 6.3 and 63 kHz (Fig. 5). The highest excess was recorded at 8 kHz, with an average of 9.5 ± 2.5 dB re $1 \mu\text{Pa}$ (mean $\pm$ SD) among all 21 analyzed ships; the second highest

FIG. 4. (Color online) Received third-octave levels (RTOLs, dB re $1 \mu\text{Pa}$) of all analyzed ships ($n = 21$), with representative ambient noise levels, and two audiograms of Indo-Pacific humpback dolphins (audiogram 1: old dolphin; audiogram 2: young dolphin; adapted from Li *et al.*, 2013); plots in (A)–(D) correspond to recording positions #1–#4 in Fig. 1(C), respectively.

FIG. 5. Average excess (mean $\pm$ SD, dB re 1 μ Pa) of ship noise from all analyzed ships ($n=21$) above ambient noise level in third-octave bands with center frequencies between 6.3 and 63 kHz (a total of 11 third-octave bands).

excess was recorded at 50 kHz, with an average 8.4 ± 3.2 dB re 1 μ Pa (mean $\pm$ SD, $n=21$).

D. RLs—Distance curve fit

Figure 6 shows an example (HAIGUANSHAN 266) of the curve fit for RLs ($F_c=8$ or 50 kHz) and distance between the hydrophone and the target ship, which are expressed by $RL_1(r) = 135.5 - [14.19 \log(r) + 0.00026r]$ ($R^2=0.83$) and $RL_2(r) = 127.6 - [14.49 \log(r) + 0.0066r]$ ($R^2=0.77$), respectively. Within the examined third-octave bands ($F_c=8$ and 50 kHz), the RLs of the target ships gradually decreased with an increase in distance and peaked close to the CPA. The curve fit results of 21 analyzed ships are summarized in supplementary material Table S2.²

E. Source levels and SSDs

The source levels (SLs) and SSDs of ship noise for Indo-Pacific humpback dolphins are summarized in Table II.

FIG. 6. Curve fit of the ship noise recording (HAIGUANSHAN 299 as a representative example) between RLs (dB re 1 μ Pa) and distances for third-octave bands with center frequencies of 8 and 50 kHz.

In the examined third-octave bands ($F_c=8$ and 50 kHz), back-calculated SLs were an average of 143.8 ± 4.3 and 137.8 ± 6.1 dB re 1 μ Pa (mean $\pm$ SD, $n=21$), respectively; Indo-Pacific humpback dolphins would be able to auditorily sense these ship noises within 2290 ± 1172 and 848 ± 358 m (mean $\pm$ SD, $n=21$) in third-octave bands with F_c values of 8 and 50 kHz, respectively.

Figures 7(A) and 7(B) show the dependence of SLs on ship speed and length, respectively. Within the third-octave bands with F_c values of 8 and 50 kHz, ship speed suggested a positive relationship with SLs as the functions $SLs = 0.49V + 134.5$ ($R^2=0.32$) and $SLs = 0.99V + 119.1$ ($R^2=0.25$), respectively (where V is the ship speed); ship length also suggested a positive relationship to SLs as the functions $SLs = 0.03L + 140.2$ ($R^2=0.26$) and $SLs = 0.05L + 130.8$ ($R^2=0.47$), respectively (where L is the ship length). Figure 7(C) and 7(D) suggested the dependence of SSDs on ship speed and length, respectively. Within the third-octave bands with F_c values of 8 and 50 kHz, ship speed suggested a positive relationship with SSDs as the functions $SSDs = 195.7V - 1394.9$ ($R^2=0.26$) and $SSDs = 72.7V - 522.1$ ($R^2=0.43$), respectively; ship length also suggested a positive relationship with SLs as the functions $SSDs = 7.8L + 1243.3$ ($R^2=0.28$) and $SSDs = 3.3L + 403.4$ ($R^2=0.54$), respectively.

IV. DISCUSSION

A. Ship noise

1. Components and general characteristics of ship noise

Compared to ambient noise [Fig. 3(A)], mid-to-high frequency noise components (>1 kHz) from ship noise [Figs. 3(C), 4, and 5] were prominent, particularly when the ship distances from the recording sites were close to that near the CPA [Fig. 3(C)]. This result was in agreement with the findings of previous studies (Sims *et al.*, 2012; Hermannsen *et al.*, 2014; Li *et al.*, 2015), which showed that recreational boats and commercial ships produce loud and broadband noise at close distances. In general, ship noise components include propeller cavitation, machinery, and hydrodynamic components (Arveson and Vendittis, 2000; Gloza, 2004), the sources of which differ onboard ships. Machinery noise components commonly peak at low frequencies <1 kHz (NRC, 2003). In contrast, propeller cavitation components peak at mid-to-high frequencies, typically up to and exceeding 100 kHz (Li *et al.*, 2015), which are more dominant than low-frequency components if ships are operating at high speeds (Aguilar Soto *et al.*, 2006; Jensen *et al.*, 2009; Sims *et al.*, 2012; Hermannsen *et al.*, 2014; Li *et al.*, 2015). Our data showed that all analyzed noise from the investigated ships substantially elevated the ambient noise levels across third-octave bands with center frequencies up to and exceeding 100 kHz (Fig. 4), and particularly elevated the level of peaks in the 8 and 50 kHz frequency bands (Fig. 5). These dominant mid-to-high frequency characteristics may be attributed to the relatively high speed of the investigated ships, which was typically close to or exceeding 20 km/h (Table II). This result was further confirmed by the SLs of

FIG. 7. SLs (dB re 1 μ Pa at 1 m) of ship noise and SSDs (m) to ship noise ($n = 21$) for Indo-Pacific humpback dolphins as a function of two variables: ship speed (A) and (C) and ship length (B) and (D) for third-octave bands with center frequencies of 8 and 50 kHz.

the third-octave bands with F_c values of 8 and 50 kHz based on the fit of the curve describing received ship noise levels and noise receiving distances (Fig. 6). The data presented in Fig. 7 show that the SLs of the ship noise increased with the ship speed [Fig. 7(A)] and ship length [Fig. 7(B)] for the examined mid-to-high frequency third-octave bands with F_c values of 8 and 50 kHz. High speed and large ship size may be linked to high engine horsepower (Kipple and Gabriele, 2004; McKenna *et al.*, 2013), which would produce relatively high acoustic energy at mid-high frequency bands due to high-speed rotating propellers (NRC, 2003; Aguilar Soto *et al.*, 2006; Jensen *et al.*, 2009).

2. Propagation of ship noise in shallow water

The propagation characteristics of ship noise are crucial in evaluating their potential effects on local wildlife; the propagation of noise in shallow waters is complex (McKenna *et al.*, 2012). The RLs of ship noise in shallow waters are dependent on ship specifications, operational conditions (i.e., noise sources; McKenna *et al.*, 2012; McKenna *et al.*, 2013), and the acoustic environment, such as water depth, temperature, and so on, which can affect transmission loss (Au and Hasting, 2008). We simplified ships as point sources in this study; however, noise levels and propagation can be affected by interference patterns caused by multiple radiation points from the ship and multipath propagation (Jensen *et al.*, 2009; McKenna *et al.*, 2013). The curve fit of the RLs of the ship noise and noise receiving distances in the present study showed a high correlation between RLs and distances with relatively high r^2 values, which were close to or higher than 0.5 for all investigated ships (see supplementary material Table S2²). The spreading coefficient α was approximately 13–16 with slight differences among ships and slightly higher in the 50 kHz frequency band than in the 8 kHz frequency

band. This was expected, because the spreading coefficient α is known to depend largely on sound frequency, water depth, and the distance between the sound source and the receiver (Au and Hasting, 2008; Pine *et al.*, 2016). In this study, the water depth of the recording positions varied slightly between 20.5 and 29.8 m (Table I), and the distances between the recorded ships and the hydrophone (typically longer than 200 m; Table II) were greater than eightfold depth, indicating that transmission loss differed between spherical spreading ($20 \log r$) and cylindrical spreading ($10 \log r$; Au and Hasting, 2008). The absorption coefficient β was approximately 0.0002 and 0.008 dB/m, for noise in the 8 and 50 kHz frequency bands, respectively. These values matched those calculated based on the equations proposed by Fisher and Simmons (1977) very well, considering that environmental factors differed slightly among the ships. The ranges of the calculated absorption coefficient β were 0.000213–0.000214 dB/m and 0.0079–0.0088 dB/m for noise in the 8 and 50 kHz frequency bands, respectively, given the environmental factors in the present study (i.e., sea surface temperature of 25–30 °C and seawater salinity of 30‰). However, considering potential effects of environmental factors, such as water depth and temperature, on propagation of underwater ship noise, the noise propagation model fitted in this study could be slightly or even dramatically different from those in waters other than the investigated ones.

B. Potential impacts on Indo-Pacific humpback dolphins

Mid-to-high frequency components are likely to be of concern for mid-frequency cetaceans, such as Indo-Pacific humpback dolphins (Southall *et al.*, 2007; Li *et al.*, 2015). Nevertheless, some previous studies have focused only on the low-frequency components of ship noise (Gervaise *et al.*, 2012; Sims *et al.*, 2012), inevitably ignoring the potential

impacts of mid-to-high frequency components on dolphins. The broadband ship noise measurements and analysis in this study will therefore help in evaluating potential impacts of ship noise on humpback dolphins. The present study showed that broadband ship noise from the recorded ships could be auditorily sensed by humpback dolphins within thousands of meters (Table II; Figs. 4 and 5) and thus could potentially adversely affect dolphins within a remarkable distance.

1. Impacts on hearing

Masking has previously been highlighted as the main and immediate impact of ship noise on marine mammals (Richardson *et al.*, 1995; Erbe *et al.*, 2016), potentially interfering with the detection of navigational sounds, communication sounds, and other important biological-environmental sounds. Masking was expected to occur if ship noise was strong enough relative to the received sound, which would be partially or entirely “masked” and undetectable for dolphins (Southall *et al.*, 2007). Figure 4 shows that ambient noise levels were a limiting factor for hearing across frequency bands between 5.6 kHz and 108–128 kHz in the young dolphin and between 5.6 kHz and 64–76 kHz in the old dolphin. Within these frequency bands, all analyzed ship noise clearly increased ambient noise levels (Fig. 4) and could be auditorily sensed by the dolphins. The excesses of ship noise levels above ambient noise levels reached two peaks in the third-octave bands, with F_c values of 8 and 50 kHz (Fig. 5), which were within the auditorily sensitive frequency range of both the young and old humpback dolphins and within the frequency range of the communication whistles (Wang *et al.*, 2013) and echolocation clicks (Li *et al.*, 2013; Fang *et al.*, 2015) of Indo-Pacific humpback dolphins, respectively. Therefore, masking impacts of the ship noise on the hearing system of Indo-Pacific humpback dolphins are likely to occur in both communication and biosonar systems. The data in Table II and Figs. 7(C) and 7(D) show that the masking impacts on the communication system of humpback dolphins could occur within a range of approximately 1500–3500 m, and they might occur on biosonar systems within a range of approximately 500–1500 m, depending on ship speed and length. However, it should be mentioned that it is possible for all of the biologically important sounds from conspecifics being produced at a very close distance that the ship noise does not impede detection and use of the conspecific sounds. Therefore, while masking is certainly possible it may not occur in all situations where dolphins are exposed to ship noise.

Temporary or permanent threshold shifts (TTS or PTS) also have important potential effects (Finneran *et al.*, 2005) on dolphins. Based on available data from bottlenose dolphins (*Tursiops truncatus*), the TTS-onset of mid-frequency cetaceans is assumed to be at sound exposure levels (SELs) 160–202 dB re $1 \mu\text{Pa}^2 \text{ s}$ for non-pulse sounds (Finneran, 2015). In this study, the highest SL (150.4 dB re $1 \mu\text{Pa}$) was calculated from the ship VIEN DONG 3 at a speed of 19.4 km/h in the third-octave band of 8 kHz (see Table II and supplementary material Table S2²). For this frequency band alone to reach an SEL of 160–202 dB re $1 \mu\text{Pa}^2 \text{ s}$ for non-

pulse noise, the dolphins would need to be within 1 m of a ship noise source with point source being assumed that was traveling at approximately 20 km/h for only 10 s, or within approximately 5 m of a ship for 100 s, to achieve a TTS. If broadband energy and potentially higher speed were taken into consideration, especially the mid- to high-frequency energy of ship noise, TTS might be expected to occur at a greatly reduced duration and longer distance of exposure.

2. Impacts on behavior

Ship-avoidance behavior in response to shipping operations have been observed in humpback dolphins in Hong Kong waters (Ng and Leung, 2003; Sims *et al.*, 2012). The probability of ship-avoidance behavior has been observed to be higher when ships appeared at closer distances and at higher speeds (Ng and Leung, 2003). During our ecological investigation, adverse behavioral reactions to shipping operations in Indo-Pacific humpback dolphins, including fluke-up deep diving, swim direction switches, and rapid acceleration, were also observed in Zhanjiang waters. These short-term behavioral responses of animals to shipping operations can hopefully be further studied in detail in the future by tagging free-swimming animals with data-loggers (Johnson and Tyack, 2003; Li *et al.*, 2010; Dong *et al.*, 2011). With frequent and excessive exposure to long-term ship noise, more severe impacts might be induced, such as habitat displacement, which has been observed in humpback dolphins in Sanniang Bay, China (Li *et al.*, 2015). However, habituation might also occur in the Indo-Pacific humpback dolphin as a potential impact of chronic exposure to ship noise. Long-term passive acoustic monitoring could be useful to learn more information about the potential habitat displacement, and other behavioral impacts, such as feeding and reproductive behavior alteration, due to chronic noise exposure.

C. Implications for conservation and management

The SLs of ship noise increased with ship speed and length [Figs. 7(A) and 7(B)]; consequently, the SSDs of the humpback dolphins to ship noise also increase with ship speed and length [Figs. 7(C) and 7(D)]. At speeds of approximately 16 km/h, the 50 kHz frequency band of ship noise could be auditorily sensed by humpback dolphins at approximately 500 m, and the 8 kHz frequency band could be sensed at approximately m. At speeds of approximately 22 km/h, the 50 kHz frequency band of ship noise could be auditorily sensed by humpback dolphins at approximately 1000 m, and the 8 kHz frequency band could be sensed at approximately 3000 m [Fig. 7(C)]. Thus, we recommend that the distances of ships operating at low speeds (<16 km/h) should be strictly restricted to greater than 1500 m, and the distances of ships operating at high speeds (≥ 22 km/h) should be strictly restricted to greater than 3000 m. At lengths of approximately 50 m, the 50 kHz frequency band of ship noise could be auditorily sensed by humpback dolphins at approximately 600 m, and the 8 kHz frequency band could be sensed at approximately 1700 m; at lengths of approximately 250 m, the 50 kHz frequency band of ship noise could be auditorily sensed by the humpback dolphins at approximately 1500 m,

and the 8 kHz frequency band could be sensed at approximately 3500 m [Fig. 7(D)]. Thus, we recommend that the distances of small ships (length <50 m) to dolphins should be strictly restricted to greater than 1700 m, and the distances of large ships (length >250 m) should be strictly restricted to greater than 3500 m.

However, given that the humpback dolphins are usually difficult to spot and the geographic area in which the study was conducted is restricted by landmasses, that would reduce the ability of ships to get around dolphins if they were observed; it will be more practical to restrict the speed of ship in waters close to the habitat of the local humpback dolphins lower than 15 km/h, and restrict distance to any encountered dolphin population to be more than 1500 m. Local administration can also take some management measures into consideration, such as establishing protected areas with traffic restriction, or setting visually apparent floated guidance in the sensitive area to remind crewmen of avoiding the encounters of dolphins at high speed and close distance. Certainly, noise level reduction at the source could be one of the most effective approaches to mitigating the adverse impacts on Indo-Pacific humpback dolphins. We therefore strongly recommend the development and use of quieter alternative technologies and noise-reducing techniques to be equipped with ship engines, which should be codified in the regulation of maritime noise management (IMO, 2013; Simmonds *et al.*, 2014).

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¹www.marinetraffic.com (Last viewed Aug. 25, 2016).

²See supplementary material at <http://dx.doi.org/10.1121/1.5009444> for ship specifications and recording details of recorded ships, as well as curve fit of RLs and distances in two third-octave bands with center frequencies of 8 and 50 kHz.

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