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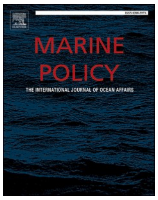

Whale-watch vessel noise levels with applications to whale-watching guidelines and conservation

Patricia Arranz[a,*], Natacha Aguilar de Soto[a], Peter T. Madsen[b], Kate R. Sprogis[b,c]

[a] *Department of Animal Biology, Edaphology and Geology, La Laguna University, Tenerife, Spain*
[b] *Zoophysiology, Department of Biology, Aarhus University, Aarhus C, Denmark*
[c] *Harry Butler Institute, School of Veterinary and Life Sciences, Murdoch University, Perth, WA, Australia*

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ABSTRACT

The number and size of whale-watching and swim-with-cetacean vessels are increasing worldwide, but the noise impact on targeted species depends on vessel source characteristics, which remain largely unquantified. Here, we report the acoustic characteristics from 13 whale-watching vessels from Australia and Canary Islands. Acoustic recorders were deployed to measure the frequency-weighted sound levels (for low [LF], mid [MF] and high frequency [HF] cetacean hearing types) of motor sailing, catamarans, and motor vessels operating at 4–8 kn representing the slow speed of whale-watch scenarios. The highest estimated source levels (SLs) were recorded from large catamarans with inboard engines (LF = 160 ± 3, MF = 148 ± 2, HF = 146 ± 2 dB re 1 μPa m). The lowest SLs were from smaller motor vessels and particularly by a hybrid vessel powered by electrical outboard engines (LF = 140 ± 3, MF = 136 ± 2, HF = 134 ± 2 dB re 1 μPa m). We demonstrate that at the same speed and distance, different vessels may produce very different received levels to the animals. To reduce disturbance to cetaceans we recommend tourism vessels meet a broadband (0.2–10 kHz) SL limit of <150 dB re 1 μPa (RMS) when within 500 m of cetaceans.

1. Introduction

Long term recorders monitoring low frequency noise in different parts of the world have registered an increase in underwater noise from anthropogenic sources, which is mainly associated with the rise in vessel traffic, including commercial shipping and small vessel operations [5,23,28,29]. Thus, underwater vessel noise is considered a persistent and widespread pollutant [47,77] with potentially negative impacts on a broad range of marine species, including fish, invertebrates and marine mammals [62,75,77]. In cetaceans, vessel noise from shipping or smaller vessels can cause behavioural disturbance, such as porpoising reactions [18], avoidance [22], reduced foraging [9,2,30,78], variation in frequency and/or intensity of vocalizations [25,41] and alteration of song patterns [12,63,72]. Furthermore, with an increase in broadband vessel noise there is potential for acoustic masking of communication and foraging sound cues in both baleen whales [13] and toothed whales [27,38]. An increasingly important source of vessels in coastal waters is from whale-watching and swim-with-cetacean activities which are rising in popularity globally [26,31]. These tourism activities deserve special attention inthe context of vessel noise effects as they inherently spend a substantial amount of time in close proximity of the targeted cetaceans; either from different vessels along migratory routes, or by the same vessels multiple times a day for resident populations further compounding concerns for negative effects.

Boat-based whale-watching can have wide-ranging short-term behavioural effects on cetaceans. Whale-watching vessels may cause foraging and resting to decrease, travelling to increase, swim paths to become more erratic, respiration and surface-active behaviours to increase, and changes in acoustic calling (for reviews see [56,59,45]). In the long-term, such short-term effects can in severe cases translate to population-level consequences from whale-watching, such as habitat displacement or reduced fitness [43,8]. The question of the primary driver of behavioural disturbance in cetaceans to whale-watching has been long-standing i.e., whether vessel proximity and/or vessel noise cause behavioural alterations [21,53,56,58]. However, through controlled exposure experiments simulating whale-watching scenarios it has recently been shown that noise level from a motorized vessel is the primary driver of disturbance in humpback whales (megaptera novaeangliae) [66], and given the limited visibility underwater we posit that the same is true for cetaceans in general.

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[*] Corresponding author.
E-mail address: arranz@ull.edu.es (P. Arranz).

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A range of vessels are used for whale-watching activities, including, catamarans, monohulls, sailboats, rigid-hulled inflatable boats (RHIBs, incl. zodiacs), and wooden boats [19,38,6,44,79]. The limited data available report broadband source levels (SLs) of these vessels moving at slow speed (<10 kn) from 138 to 169 dB re 1 μPa @ 1 m [38,6,79]. Source levels will vary, however, due to the size, hull design and material, horse power, propulsion system and maintenance of the vessel (i.e. if propellers are damaged or not operating synchronously), and with differences in vessel aspect, speed and whether its propellers are cavitating [19,38,79]. These vessel characteristics, along with noise propagation conditions, ambient noise levels, the style of driving, angle of approach and approach duration of targeted species will influence the probability that animals are affected. Furthermore, how cetaceans hear broadband vessel noise may also influence how they react to vessel noise. Broadly, cetacean hearing groups include low frequency (e.g. baleen whales), mid frequency (e.g. larger toothed whales and most dolphins) and high frequency (e.g. porpoises) cetaceans [64]. Because shipping noise is dominated by low frequency components, concerns about its effects on cetaceans has traditionally been focused on low frequency species such as baleen whales [52]. However, there is increasing data showing significant medium and high frequency components in boat noise [27] and strong behavioural response to higher frequencies components from high frequencies specialists, such as porpoises [18,78]. Further, because the cetaceans targeted for whale--watching are typically at or near the surface, low frequencies from vessels will cancel out due to the Lloyds mirror effect, putting a premium on quantifying vessel noise in a frequency band starting at several hundred Hz and upwards in the context of understanding noise effects of whale-watching vessels.

Cetaceans rely on sound to mediate many biological functions, underscoring the need to consider and mitigate noise in environmental assessments of the impacts of whale-watching and swim-with-cetacean activities. However, evaluating these impacts and designing measures to mitigate them is severely hampered by the limited number of acoustic recordings of vessels at speeds representative of whale-watching scenarios [6,79]. Hence, further studies to quantify the acoustic signatures and source levels of individual whale-watching vessels are needed to provide an informed basis for regulators, stakeholders and operators of the whale-watching industry to reduce adverse impacts on cetaceans and facilitate a sustainable industry. Accordingly, the aim of this study was to (i) measure the underwater acoustic noise signatures of a range of whale-watching vessels off Exmouth, Western Australia and off Tenerife, Canary Islands (Spain), (ii) evaluate the impacts of such source signatures in light of ambient noise conditions in these habitats, and (iii) use such data to inform a discussion of best practice noise limits for cetacean tourism vessels.

2. Methods

2.1. Study areas and whale-watch vessels

2.1.1. Exmouth, Western Australia

Australia is currently the second most common country for whale-watching globally [31]. Exmouth, Western Australia, is a critical cetacean habitat which hosts several species along Ningaloo Reef and in Exmouth Gulf, including humpback whales (*Megaptera novaeangliae*), killer whales (*Orcinus orca*), blue whales (*Balaenoptera musculus brevicauda*), southern right whales (*Eubalaena australis*), minke whales (*Balaenoptra acutorostrata*), Indo-Pacific bottlenose dolphins (*Tursiops aduncus*) and Australian humpback dolphins (*Sousa sahulensis*) [7,32,37,54]. Off Exmouth and Ningaloo, operators are licensed to conduct wildlife tours, which focus on whale-watching and swimming with humpback whales, whale sharks and manta rays [55,67]. Tours range in duration from a few hours on a sunset whale-watching cruise to a full day of swim-with-whale activities. In Exmouth Gulf, the water depth is < 22 m. Vessel noise records from whale-watching vessels were obtained in the absence of other vessels within 500 m of the recorded vessel on the outskirt of the Exmouth marina channel (21.95989º S, 114.14646ºE) in August and September 2019 and September 2019. Vessels under power had inboard diesel engines with fixed pitch, shaft driven propellers. Recordings were not made inside the marina.

2.1.2. Tenerife, Canary Islands (Spain)

Canary Islands is currently the fourth most common country for whale-watching globally [31]. Tenerife, Canary Islands, is a critical cetacean habitat with several resident species, including short-finned pilot whales (*Globicephala macrorhynchus*), bottlenose dolphins (*Tursiops truncatus*) and Blainville's beaked whales (*Mesoplodon densirostris*), as well as transient species such as, Atlantic spotted dolphins (*Stenella frontalis*) and common dolphins (*Delphinus delphis*) [11,61,74]. In south west Tenerife, operators conduct year-round boat-based whale-watching tours ranging from 2 to 5 hrs in duration using very different types of vessels that can carry from some 12–200 passengers per trip. Here, the water depth drops rapidly to hundreds of metres close to shore. Vessel noise recordings were measured from seven whale-watching vessels under power in the marina channel of Puerto Colón in June 2019, all but the zodiac (vessel #12) had inboard engines, and one hybrid vessel under both petrol and electric power in Puerto Los Gigantes on July 2020 (28.0489° N, 16.7116° W and 28.2446° N, 16.8401° W, respectively) (Table 2). The hybrid vessel had two 11 Hp electric engines powered by solar-powered batteries that were used predominantly when whale-watching in the presence of cetaceans and two 250 Hp outboard petrol engines, which were used primarily for transit to and from the marina to deeper oceanic waters. Sailing motor vessels were under power during the recordings. Recordings were not made inside the marina, rather in the channel to the adjoining ocean.

2.2. Vessel noise recordings

Autonomous acoustic recorders (SoundTrap 300 STD and HF, Ocean Instruments, New Zealand, www.oceaninstruments.co.nz) were used to record underwater noise (20 Hz to 20 kHz (±3 dB) bandwidth and 48 kHz sampling rate off Exmouth, and 20 Hz to 120 kHz (±3 dB) bandwidth and sampling rate 288 kHz in Tenerife, 16 bit, clip level 172 and 175 dB re 1 μPa (high gain), respectively. The SoundTrap recorders were calibrated by the manufacturer prior deployment using a piston phone, and later verified by relative calibration with a Reson 4032 hydrophone in a calibration tank at Aarhus University to render flat (±1 dB) in the frequency range of interest from 0.2 to 10 kHz.

SoundTraps were positioned close (100 m) and adjacent to the marina channel off Exmouth and Tenerife to capture side acoustic exposure of vessels, representing the noise received by whales and dolphins during line-abreast (i.e. parallel) whale-watching and swim-with-cetacean approaches [16,67]. The marina channels were selected for recording vessel noise as vessels are enforced to transit through the channels at slow speed (~4 kn), which is representative of whale-watching vessel speeds when in the presence of animals (Table 2). Off Exmouth, the SoundTrap recorder was 2 m below the surface attached to a vertical weighted rope that was taught in the water column. Recordings were conducted at high tide when the water depth was around 4 m. The vessels transited through the channel, which was around 4 m depth and composed of sand. Off Tenerife, the recorder was suspended 4 m below the surface from a rope attached to a series of 3 drifting buoys to reduce drag. The bottom substrate was sand at the position of the SoundTrap and water depth was ~10 m in low tide. A synchronized UTC GoProHero4 camera (GoPro, San Mateo, CA, USA) mounted on a headband was used to video record the passage of the vessel and simultaneously, the estimated vessel's slant range from readings of a Bushnell Pro rangefinder (Bushnell, Kansas City, MI, USA), taken every ~5 s on the vessel reference point (i.e. located transversely at the vessel centerline, longitudinally a quarter-length forward of the stern and vertically at the height of the sea surface). At least one data

Table 1

Examples for different countries regulations/guidelines for whale-watching and swim-with-cetacean activities for vessel approach distance, angle, speed, time duration and maximum number of vessels present. For more guidelines from other countries see the IWC Whale-watching Handbook [36]

Country	Distance	Angle	Speed (kn)	Time duration with a group	Max. number of vessels
Australia					
Whale-watching[a]	Whales 100 m (†300 m if calf present), dolphins 50 m (†150 m if calf present)	Side	6	–	3
Swim-with-humpback whale[b]	In-path at 150 m, side approach at 75 m (incl. calves>50% length of mother)	In front, side	8	60 min (combined for all vessels)	1
Canary Islands					
Cetacean-watching[c]	60 m	Side	4	30 min	3
Tonga					
Swim-with-humpback whale[d]	10 m (50 m if a calf is present)	Side	Slow speed	90 min (combined for all vessels[g])	1
Sri Lanka					
Whale-watching[e]	100 m	Side	Slow speed	–	–
Azores					
Whale-watching[f]	50 m (100 m when calves are present)	Side and rear	Slow speed	30 min total for all vessels	3 vessels at 50 m. When > 3 boats at 300 m for dolphins and 500 m for whales

[a] [14],

[b] For licensed whale-watch vessels only [15],

[c] [10,65],

[d] [69],

[e] [68],

[f] [60],

[g] After a 90 min break vessels can interact with the same group again. Side= parallel to the side of the group and side rear (e.g. not directly behind, or in front). '–'= not mentioned in the regulations. †for recreational vessels, not licensed whale-watch vessels.

Table 2

Characteristics of whale-watching vessels recorded off Exmouth (Western Australia) vessels #1–5 and Tenerife (Canary Islands) vessels #6–13. Description of the title of the columns: Vessel #: Unique identification number of the whale-watching vessel, assigned to preserve the anonymity name of the vessel. Vessel type: motor vessel, catamaran, sailing-motor vessel under power, zodiac motor vessel, and hybrid motor vessel. Vessel length: longitudinal distance between the forward-most and aft-most part of the vessel. Engine type: maximum power of the engine, in horsepower units, multiplied by the number of engines. Inboard engines #1–11, outboard engines #12–13. Vessel speed: known speed of the vessel when passing the SoundTrap in knots (*approximate speed). SL: Source levels for TOL bands (RMS) with 2 and 10 kHz centre frequency and for low-frequency ($_{LF}$), mid-frequency ($_{MF}$) and high-frequency ($_{HF}$) weighting, in dB re 1 μPa @1 m. `–´vessel specifications not available. †solar-battery powered electric engines.

Vessel #	Vessel type	Vessel length (m)	Engine type (Hp)	Vesselspeed (kn)	$SL_{2\ kHz}$ (dB 1μPa)	$SL_{10\ kHz}$ (dB 1μPa)	SL_{LF} (dB 1μPa)	SL_{MF} (dB 1μPa)	SL_{HF} (dB 1μPa)
1	motor	16.5	740	8	136	139	157	149	146
2	motor	20	750 × 2	6.5	127	130	148	140	137
2b	motor	20	750 × 2	7.6	129	137	152	149	146
3	motor	16.76	600	7	124	131	147	143	140
4	motor	16.13	550	8	134	138	148	144	142
5	catamaran	15	450 × 2	4.3	133	129	159	151	148
6	motor-sail	10	–	4 *	136	130	151	139	136
7	catamaran	22	–	4 *	140	138	159	147	145
8	catamaran	19.5	108 × 2	4 *	138	137	158	147	145
9	motor-sail	15.4	79	4 *	140	138	160	145	143
10	catamaran	22	450 × 2	7	145	142	164	151	149
11	motor-sail	11.9	–	4 *	138	134	163	149	147
12	zodiac	< 10	–	~4	140	137	152	136	133
13	Hybrid motor	11.30	250 × 2	4	137	132	151	139	137
13b	Hybrid motor	11.30	11 × 2†	4	132	130	136	140	134

entry from the closest point of approach (CPA) was taken for every whale-watching vessel leaving the marina channel. Vessels transited through the marina channels with the same relative orientation, the beam aspect of the vessel relative to the hydrophone was 360–180° relative to the bow, with CPA being roughly 270° (port side). The speed of the vessels when passing near the SoundTrap was obtained from the vessels Electronic Monitoring System (EMS) facilitated by some operators, otherwise speed was estimated as ~4 knots representing the permitted speed in the marina channel. All recordings were conducted in good weather conditions with no-low wave action (Beaufort sea state <2).

2.3. *Data analyses*

Vessel audio samples comprising 30 s before and 30 s after the vessels̀ CPA as derived from the video recordings were extracted for noise level calculations. Videos and spectrograms of audio samples were visually inspected to verify the recording of a single vessel. Vessel passes were discarded if another vessel passed at less than 500 m from the recorder within 30 s of the CPA. Extracted 60 s samples were analyzed in *Matlab* (R2017a v9.2.0.556344) to quantify root-mean-squared (RMS) received levels (RLs) in one-third octave levels (TOL). To maintain degrees of freedom across all frequency bands TOLs were estimated in 2 s windows to which we applied a Hann window with time segment overlap of 50%

(resulting in steps of 1 s resolution). The 2 s analysis window was moved in 1 s steps, resulting in 59 filtered samples per vessel with 1 s resolution. Perceived loudness of a sound can be approximated by 'species specific' parameters for weighting in time and frequency [70]. To relate RL to the auditory capabilities of both mysticeti and odontoceti, low frequency (LF, 0.2–19 kHz frequency range), mid frequency (MF, 8–110 kHz frequency range) and high frequency (HF, 12–140 kHz frequency range) weighting of the 60 s audio samples were computed using the 'fileweighting' package [70]. This package analyzes the full audio signal using a time constant specified by the user. We chose a 125 ms time window because it is a standard used in human audiometry and to facilitate comparability between studies and among species [71], resulting in 472 filtered samples per vessel with 125 ms resolution. Running time averages were computed using default exponential decaying kernel windows. Source level (SL) was estimated using a back-calculation of $20 \times \log_{10}(R(m))$ applied after filtering, to correct for the range dependent decrease of the sound intensity between the source and receiver, being R the mean of the range in m of the vessel to the acoustic recorder at the CPA and at the start of the noise record (30 s before the CPA). The average between the two range measurements, when available, was taken to account for the noise source passing by a stationary recorder. For Exmouth vessels only the range at the CPA was available and used to estimate R. Back-calculated SLs were estimated as 5th, median and 95th percentiles of the 2 s and 125 ms epochs at 1 m, for TOLs (N = 59 samples per vessel) and frequency weighting measurements (N = 472 samples per vessel), respectively. Two relevant TOL bands (2 and 10 kHz centre frequency, ranging 1.7–2.2 and 8.9–11.2 kHz, respectively) were extracted to compute estimated vessel source levels in commonly used bands for noise assessment [28], hereon $SL_{2\ kHz}$ and $SL_{10\ kHz}$, respectively.

2.4. Ambient noise

To augment existing ambient noise data [7,38] for evaluating potential whale-watching vessel noise contributions for the two habitats, we recorded ambient noise point samples using SoundTraps in coastal and offshore stations in Exmouth and Tenerife, respectively. In Exmouth Gulf, ambient noise recordings were measured continuously at three locations in water depths ranging between 15 and 18 m. The SoundTrap was moored at ~4 m depth from the surface using a 20 kg weight and a subsurface buoy for up to 12 hs during daylight periods, during the humpback whale season from August to October. Off Tenerife, ambient noise was recorded continuously at water depths ~1000 m depth, using two configurations: with the SoundTrap suspended from a 4 kg weighted buoy at (a) ~4 m depth from the surface for 5 min periods and (b) ~ 400 m depth from the surface for a 5 h period. Noise records were subsampled into 15 min blocks and RMS noise levels (NL) quantified in TOLs (2 s time averaging window, Hann window with 50% overlap). The 2 s analysis window was moved in 1 s steps, resulting in a number of samples per record equal to its duration – 1 s. Two relevant TOL bands (2 and 10 kHz) were selected for evaluating ambient noise in relation to vessel noise and estimate percentiles (5th, median and 95th). Analyses were run in MATLAB (R2017a v9.2.0.556344) using custom written scripts [39].

3. Results

3.1. Vessel noise recordings

A total of 15 vessel acoustic signatures (individual passes) were obtained from 13 different vessels (monohull motor vessels [N = 6], catamarans [N = 4], motor sailing vessels [N = 3]) (Table 2). Days with vessel noise recordings accepted for analyses were on the on 16th August, and 15th and 27th September 2019 off Exmouth, and the 19th June 2019 and 8th July 2020 off Tenerife. The average CPA for vessels transiting past the SoundTraps were 69.3 m (range = 46–82 m, SD = 14.8) and 66.7 m (range 27–100 m, SD = 26.8) off Exmouth and Tenerife, respectively. A spectrogram, waveform, TOL and frequency weighted levels as a function of distance for a representative whale-watching catamaran (vessel #7) are illustrated in Fig. 1.

The LF weighting shows the highest SLs followed by the MF and HF measurements (Fig. 2). Weighted measurements ranged more widely for the motor sailing category (12 dB difference across minimum and maximum measurements within each weighting group). Catamarans were the loudest across all weighting groups ($SL_{LF} = 160 \pm 3$, $SL_{MF} = 148 \pm 2$ and $SL_{HF} = 146 \pm 2$ dB re 1 μPa @ 1 m RMS (0.125 s)), followed by motor sailing ($SL_{LF} = 157 \pm 6$, $SL_{MF} = 144 \pm 5$ and $SL_{HF} = 142 \pm 6$ dB re 1 μPa @ 1 m RMS (0.125 s)) and motor vessels ($SL_{LF} = 149 \pm 1$, $SL_{MF} = 142 \pm 1$, $SL_{HF} = 140 \pm 1$ dB re 1 μPa @ 1 m RMS (0.125 s)).

The hybrid electric vessel running with the two electrical outboard engines was the quietest within the motor vessels, with the lowest SL's recorded across LF and MF weighting groups ($SL_{LF} = 140 \pm 1$, $SL_{MF} = 136 \pm 1$ dB re 1 μPa @ 1 m RMS (0.125 s)), with a vessel (zodiac) 1 dB lower for SL_{HF} ($SL_{HF} = 134 \pm 1$ dB re 1 μPa @ 1 m RMS (0.125 s) (Table 2).

3.2. Ambient noise

Ambient noise in Exmouth was recorded for periods 5–12 h long from 8 AM to 8 PM on 25th August (21.99828° S, 114.18327° E), 25th September (22.15614° S, 114.15694° E) and 25th October 2019 (22.05606° S, 114.15952°E). Off Tenerife, ambient noise was recorded for periods 5 min−5 h long from 8 AM to 1 PM on the 23th March (28.10534° N, 16.80551° W) and 24th March 2019 (28.16395° N, 16.87595° W and 28.18306° N, 16.8626° W). Ambient noise levels in Exmouth, quantified as medians for three days ranged $NL_{2\ kHz} = 76$–87 dB re 1 μPa RMS (2 s), 95th percentile across the three days 84–101 dB re 1 μPa RMS (2 s) and $NL_{10\ kHz} = 76$–89 dB re 1 μPa RMS (2 s), 95th percentile across the three days 82–95 dB re 1 μPa RMS (2 s) (Fig. 3). Off Tenerife, median ambient noise levels (SoundTrap at ~4 m depth from the surface) for two survey days were $NL_{2\ kHz} = 77$–79 dB re 1 μPa RMS (2 s), 95th percentile across the two days 80–81 dB re 1 μPa RMS (2 s) and $NL_{10\ kHz} = 73$ dB re 1 μPa RMS (2 s), 95th percentile across the two days 75–80 dB re 1 μPa RMS (2 s). Additionally, off Tenerife median ambient noise levels (SoundTrap at ~400 m depth from the surface) were $NL_{2\ kHz} = 78$ dB re 1 μPa RMS (2 s), 95th percentile 82 dB re 1 μPa RMS (2 s) and $NL_{10\ kHz} = 76$ dB re 1 μPa RMS (2 s), 95th percentile 79 dB re 1 μPa RMS (2 s) (Fig. 3). $SL_{2\ kHz}$ and $SL_{10\ kHz}$ of vessels were above ambient noise by, on average, 49–52 dB off Exmouth and 60 dB off Tenerife, for 2 and 10 kHz TOL bands, respectively (Fig. 3).

4. Discussion

As the noise level from man-made sources in the ocean is increasing Hildebrand et al. [29], primarily from vessels, it is important to mitigate against adverse impacts of vessel noise on marine animals. This is especially of importance for marine mammals, as hearing is their primary sensory modality for communication, navigation, and detecting predators and prey [56]. As whale-watching vessels inherently spend a large amount of time in close proximity to cetaceans, and wide-ranging short- and long-term impacts on cetacean species have been documented [45,59], decreasing vessel noise SLs will contribute to lessening any adverse impacts. It has recently been demonstrated that if sufficiently silent vessels transit at slow speed at 100 m range from resting humpback whale mother-calf pairs, there are no apparent behavioural effects [66]. However, if the same but louder vessel is used, at the same distance and speed, then behavioural changes are elicited, such as, the animal diving and swimming away, which is not beneficial for tourist viewing nor for the animal [66]. Here, we sought to quantify noise levels from different types of whale-watching vessels to evaluate differences in their

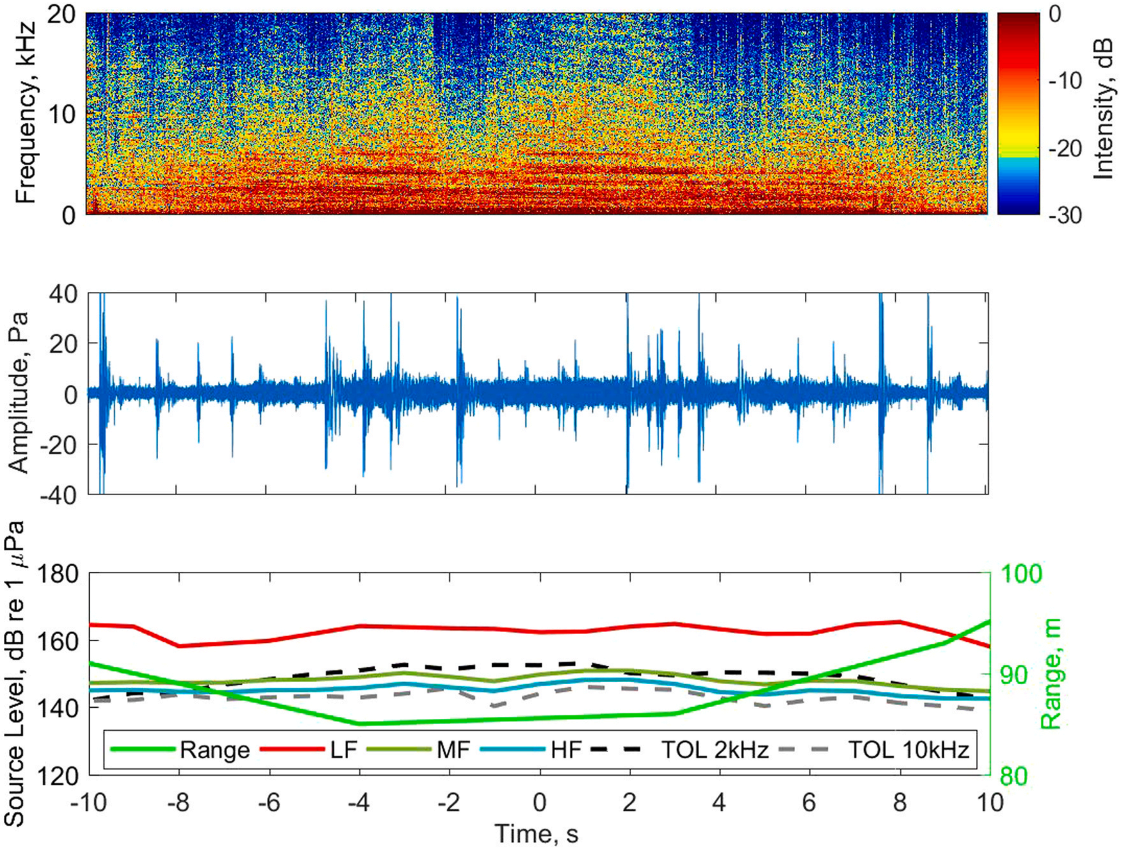

Fig. 1. Passage of a single whale-watching catamaran (Vessel #7) at slow speed (~4 kn) recorded off Tenerife, showing the closest point of approach (time 0 at 86 m distance of the recorder). (A) A spectrogram composed of power spectral densities (PSD) of the vessel noise (red higher intensity and blue lower intensity) recorded by the SoundTrap as a function of time (s) on the x-axis, (B) Received waveform of the same audio sample with time (s) on the x-axis, (C) Estimated RMS third-octave source levels centred at 2 and 10 kHz and low (LF), mid (MF) and high frequency (HF) weighted SLs. The range of the vessel to the acoustic recorder is shown on the right y-axis (green). Note that the SLs are highest 3–4 s after the vessel CPA. This is likely due to the radiation pattern of noise from the engine and hull.

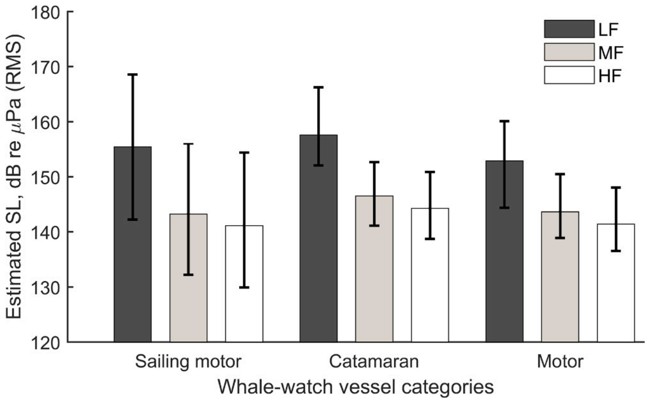

Fig. 2. Estimated frequency weighted source levels of acoustic signatures of whale-watching vessels passing the acoustic recorder off Exmouth (Western Australia) and Tenerife (Canary Islands). Recorded vessels are grouped in the following vessel categories; sailing motor (N = 3 vessels), catamaran (N = 4 vessels) and motor (N = 6 vessels), across the cetacean auditory weighting groups for Low Frequency (LF), Mid Frequency (MF) and High Frequency (HF) weighting. The vertical black lines represent the 95% confidence intervals.

impact on different hearing classes of cetaceans, and to inform discussions about development of noise emission standards for whale-watching vessels to minimize the impact of this global and multi-billion-dollar industry.

The noise sources from motorised vessels include propeller cavitation (provided that the propeller reaches cavitation speed), the engine, exhaust, shaft and gears [40,57], and vessel noise is accordingly a combination of narrowband tonal components at specific frequencies and broadband random components with energy spread over a range of frequencies [56]. Cetaceans hear this broadband vessel noise weighted by their sensitivity to specific frequencies, thus we estimated SLs from the whale-watching vessels according to three functional hearing types among cetaceans [48,70]. Vessel noise is dominated by energy at low frequencies, although weaker, energy at higher frequencies (up to tens of kHz) can occur at close range (<1 km) [29]. Despite our shallow recording depths, where low frequency energy below 100–200 Hz is cancelled out due to Lloyds mirror effects, our results also render the highest SLs at LF weighting (functional category of baleen whales), followed by MF weighting (larger odontocetes and most dolphins) and HF weighting (porpoises). Bearing in mind that the results are based on a limited number of vessels within each category type, the loudest SLs for LF, MF and HF weighting recorded were from large catamarans, followed by motor sailing and motor vessels at low speeds. In a similar study, Wladichuck et al. [79] measured broadband SLs among different vessel types at speeds < 7 kn and also found that catamarans had the highest $SLs_{0.5\text{–}15\ \mathrm{kHz}}$ (161 ± 3 dB RMS re 1 μPa @ 1 m), although frequency weighting was not used in their analyses. The quietest SLs for LF, MF and HF weighting within the motor vessels were recorded from the only hybrid vessel measured, powered by two small 11 Hp electrical engines, followed by a RHIB with a SL_{LF} 12 dB louder (Table 2). These low levels may likely stem from the fact that these electrical engines indeed were very small compared to the others measured and perhaps that electrical powered vessels lead to engine noise reductions when

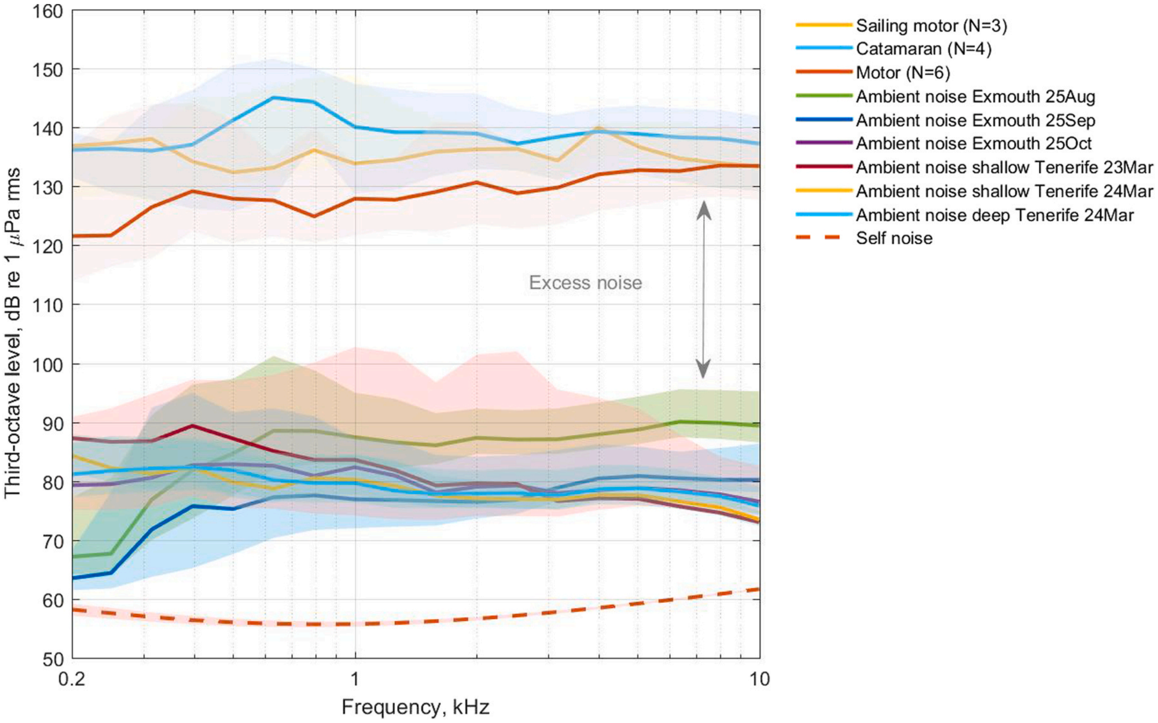

Fig. 3. Estimated third octave source levels of whale-watching vessels (N = 15) and ambient noise in adjacent thirds-octave bands from 0.2 to 10 kHz recorded off Exmouth (Western Australia) and off Tenerife (Canary Islands). Whale-watch vessels recorded at ≤ 8 kn at the marina channels and reported as back-calculated source levels for each vessel category. Ambient noise was recorded ~4 m depth from the surface (15–18 m water depth) off Exmouth across three days. Off Tenerife, recordings were made at water depth > 1000 m at ~4 and 400 m depth from the surface. Self noise of the soundtrap (dotted line).

compared with conventional engines, likely through the reduction of vibration and combustion/exhaust levels [17,4]. Future studies should be conducted on larger hybrid electric whale-watch vessels to measure the SLs of more powerful electrical engines with the same thrust as conventionally used petrol and diesel engines.

Estimated $\mathrm{SLs}_{2\ \mathrm{kHz}}$ ranged between 124 and 145 dB re 1 µPa @ 1 m RMS (2 s). The lowest $\mathrm{SL}_{2\ \mathrm{kHz}}$ was for a motor vessel (16 m, 550 Hp) and the highest was for a catamaran (22 m, 450 Hp x 2). Within the 10 kHz, $\mathrm{SL}_{10\ \mathrm{kHz}}$ of whale-watching vessels ranged 129–141 dB re 1 µPa @ 1 m RMS (2 s). The lowest $\mathrm{SL}_{10\ \mathrm{kHz}}$ was for a motor sailing vessel (10 m) and a catamaran (15 m, 450 Hp x 2), the highest corresponded to a catamaran (22 m, 450 Hp x 2). These measurements demonstrate that for the same speed and distance, different whale-watching vessels will produce very different received noise levels around the targeted species, and consequently have different noise impacts. SLs reported here are broadly comparable to the acoustic signatures from other whale-watching vessels recorded at low vessel speed in different locations (Table 3). For example, Au and Green [6] reported 1/3 octave band $\mathrm{SL}_{2\ \mathrm{kHz}} = 151$ dB re 1 µPa @ 1 m for a catamaran (12 m, 200 Hp x 2) and 149 dB re 1 µPa @ 1 m for a motor boat (165 Hp x 2). These are about ~10 dB higher than the average SL reported here for the same vessels category, however Au and Green [6] recorded vessels at ~10 kn, some ~5 kn above the average vessel speed of that recorded in our study, which could lead to 5–10 dB variation in vessel SL [57]. The same authors reported 1/3 octave band $\mathrm{SL}_{2.5\ \mathrm{kHz}}$ of 159 dB re 1 µPa @ 1 m RMS for a RHIB (5 m, 25 Hp outboard engine, ~ 10 kn), whereas Richardson et al. [56] reported 1/3 octave band $\mathrm{SL}_{6\ \mathrm{kHz}}$ of 152 dB re 1 µPa @ 1 m at that centre frequency for a similar sized and powered RHIB at unknown speed. Their results are higher than those reported here for the RHIB, although comparison for this vessel type is hampered by different recording speeds and reported frequency bands across studies. Other authors measured whale-watching vessel noise at lower frequencies with average $\mathrm{SL}_{0.8\ \mathrm{kHz}}$ ranging 133–161 (median 155) dB re 1 µPa @ 1 m RMS [13]. Importantly, apparent differences between vessel noise source levels may also stem from different recording conditions and assumed propagation models. It is neither practical nor meaningful to record

Table 3
Range of acoustic signatures (source level and frequency range) for whale-watching vessels at slow speed in other locations.

Vessel	Speed (kn)	SL dB re 1 µPa @ 1 m	Information and source
RHIB	< 7	160.9 ± 2.6 (0.05–64 kHz)	4 vessels included in this calculation, including 3 whale-watching vessels and 1 research vessel[79]. 200 m depth. Shipping lane off San Juan Island, USA.
Monohull, inboard and outboard	< 7	164 ± 2.8 (0.05–64 kHz)	10 vessels included in this calculation, including 6 whale-watching vessels, 2 research vessels and 2 fishing vessels [79]. 200 m depth. Shipping lane off San Juan Island, USA.
Catamarans	< 7	163.4 ± 3.2 (0.05–64 kHz)	2 whale-watching vessels included in this calculation[79]. 200 m depth. Shipping lane off San Juan Island, USA.
RHIB, 4.6 m, outboard, 25 hp	10	159 (2.5 kHz)	15–30 m depth. Maui, USA[6]. Reported sound pressure levels, and we quantified the SLs @ 1 m assuming spherical spreading transmission loss of 39 dB, reported in[56].

*[19] not displayed as the slowest vessel recorded was a 16 kn (30 km/h) Racer (with no vessel specifics reported) at SL 156 dB re 1 µPa @ 1 m (100 Hz–20 kHz).
**[56] not displayed as speed not reported for zodiac 5 m 25 Hp, SL 125 dB re 1 µPa @ 1 m, not reported if this represents a commercial whale-watching vessel.
***[79] two sailboats not displayed as are recreational vessels, and one landing craft not displayed as is a research vessel.

noise at the reference distance of 1 m from a vessel, meaning that source levels inherently must be back-calculated from received levels. Our measurements in this study were made in shallow and confined waters, where multipath and seabed interactions (i.e. multiple arrivals of the acoustic pulse due to waves being reflected by surface and seabed and reverberation) likely make the assumption of spherical spreading inaccurate [24,3]. However, the similar ranges in the same habitat means that the differences in inferred SL between different vessels holds up, even if the actual transmission loss is off by some dBs from the modelled.

4.1. Whale-watching vessel noise emission standards

To reduce disturbance to cetaceans, many whale-watching companies generally abide to national codes of conduct, regulations, guidelines and/or autonomous community regulations in the countries where they operate [36]. These regulations or guidelines (and their reinforcement) vary greatly among different areas, including minimum approaching distance, approach angle and speed, maximum number of vessels present at a given radius around the animals and maximum duration of vessel stay within this radius (examples of different countries guidelines in Table 1). During swim-with-cetacean activities vessels tend to be positioned closer to the animals compared to traditional whale-watching. For example, the vessel can approach as close as 10 m to humpback whales off Tonga [22] and 50–75 m off Ningaloo, Australia [67]. This implies that even for the same vessel SLs, the noise exposure to the animals will vary dramatically depending on the range restrictions imposed. Vessel noise emission standards are currently not incorporated in global whale-watching or swim-with-cetacean guidelines. Some guidelines do however recommend that vessels be as quiet as possible [14,35] and that operators, where possible, apply the International Maritime Organisation guidelines for the reduction of underwater noise from commercial shipping [33].

In Exmouth Gulf, low vessel SLs LF-weighted of 148 dB re 1μPa did not elicit any detectable behavioural responses in resting humpback mother and calves at 100 m distance on a breeding ground [66]. This led to the recommendation that vessel LF-weighted SLs at 100 m be < 150 dB re 1 μPa RMS @ 1 m in this habitat on this species. This vessel SL in the high ambient noise environment of Exmouth Gulf (Fig. 3; [7]) leads to a received level at a resting whale on the surface at 100 m distance that is close to ambient noise (depending on sea state and time period in the humpback whale season), which is perhaps audible to the whale, but with a very low perceived loudness [66]. The limited data available suggests that whale-watch vessels have SLs both below but mainly above such a LF-weighted SL of 150 dB re 1 μPa RMS @ 1 m ([6], Wladichuck et al. [79], thus introducing the question of what is the spread of SLs for whale-watching vessels. Here we supplement this limited data with 15 additional SL recordings to show that some of the vessels do comply with the 150 dB re 1 μPa RMS @ 1 m LF-weighted recommendation at slow speed suggesting that these vessels would not elicit behavioural responses on resting humpback whales in Exmouth Gulf (4 vessels; SL_{LF} 140–148 dB re 1μPa). However, 10 vessels (SL_{LF} 151–164 dB 1μPa) are above this threshold and are in some cases loud enough to likely elicit behavioural responses in baleen whales as per Sprogis et al. [66,67]. In the case of mid-frequency toothed whales in ambient noise habitats similar to Tenerife (Fig. 3), [38,46], the excess noise received at the whale of some 10 dB (Fig. 3) make us hypothesize that they would not be adversely affected by whale-watching vessels at a range > 100 m with SLs < 150 dB re 1μPa RMS (13 vessels, SL_{MF} 136–141 dB 1μPa) and a transmission loss on the order of 40 dB. Conversely, the perceived loudness at the same distance of 100 m and SL will be larger in areas of lower ambient noise levels, calling for experiments of whether it is the perceived loudness or absolute received levels that elicit short-term behavioural responses. If it is the perceived loudness of a vessel that is the driver of behavioural responses, it implies that quiet habitats with lower ambient noise (e.g. deeper water Tenerife) should use quieter vessels to maintain the same probability of response as louder vessels in higher ambient noise habitats (e.g. shallow water Exmouth Gulf). In this case, a greater proportion of whale-watch vessels are likely to elicit behavioural responses in lower ambient noise habitats. Further research on different species in varying behavioural states and ambient noise conditions are needed, in particular because of the growing notion that some species, such as porpoises and beaked whales [1,78], apparently employ very conservative predator assessment behaviours according to the risk-disturbance hypothesis, which in turn become maladaptive when perhaps weak vessel noise is perceived as a potential predation cue.

4.2. Ambient noise and excess noise

Ambient noise in the shallow water environment of Exmouth Gulf is predominantly composed of snapping shrimp (contributing to the high-frequencies) and humpback whale song during the whale season from singing males (contributing to the lower frequencies) [66,7]. Humpback whales arrive in Exmouth Gulf around late August, and the number of whales peak in September thus increasing the low frequency component of ambient noise by around 15 dB [66]. Humpback whales typically depart Exmouth Gulf in mid-late October [66], however in 2019 the number of humpback whales in the Gulf was relatively low compared to the previous season with minimal males singing in late October (Fig. 3) (Sprogis pers. obs.). Ambient noise in Tenerife has a lower high frequency component due to absence of snapping shrimp in deep water and the typically narrow shelf around oceanic islands, limiting the biomass of such noise-producing coastal-associated biological communities (Jensen et al., 2019). Despite these differences in habitat composition and structure, the ambient soundscape within the 2 and 10 kHz TOL bands compared in this work was broadly similar off Exmouth and Tenerife (Fig. 3). A mean 5 dB difference in $NL_{10\ kHz}$ was found between the two sites ($NL_{10\ kHz}$ 82 ± 6.5 and 77 ± 2.5 dB 1 μPa RMS (2 s), respectively), which could be explained by the lowest contribution of snapping shrimp in Tenerife and other environmental conditions. At lower frequencies both areas exhibited comparable median levels ($NL_{2\ kHz}$ 81 and 80 dB 1μPa RMS (2 s), respectively).

All whale-watching vessels reported here had higher $SL_{2\ kHz}$ and $SL_{10\ kHz}$ values than respective ambient noise $NL_{2\ kHz}$ and $NL_{10\ kHz}$ by, on average, 49 and 52 dB in Exmouth and 60 dB in Tenerife, respectively. In Exmouth, a vessel would need to not exceed a $SL_{2\ kHz} = 121$ dB re 1μPa @ 1 m RMS or a $SL_{10\ kHz} = 122$ dB re 1 μPa @ 1 m RMS to be received at a level equal to the ambient noise at 100 m from the vessel when assuming a transmission loss of 40 dB. In Tenerife, the same would be true if whale-watching at 100 m range does not exceed a $SL_{2\ kHz} = 120$ dB re 1 μPa @ 1 m RMS or $SL_{10\ kHz} = 117$ dB re 1 μPa @ 1 m RMS. Excess noise may, if there is a spectral overlap, interfere actively with the ability of cetaceans to echolocate, communicate and navigate through masking [20,38,51,73]. This is particularly relevant in areas of intense whale-watching activity were cetaceans would potentially be exposed to multiple co-occurring noise sources [49]. Ambient noise profiles from Tenerife and Exmouth shown in Fig. 3 suggest that if vessel SL TOLs are below 120 dB re 1μPa (RMS), the received noise levels will be equal to the average ambient noise levels in the same bands at a vessel range of 100 m. That may not exclude that the vessel noise is audible to the whales due to the directional nature of the vessel noise and the often omnidirectional nature of the ambient noise, but the potential for behavioural or masking effects will be very small in that case.

5. Conclusion and recommendations

Whale-watching vessels spend targeted and potentially a large amount of time in close proximity to whales and dolphins, thus to reduce adverse impacts on cetaceans from vessel noise and facilitate a sustainable industry, it is of interest for regulators, stakeholders and operators to pay heed to the acoustic signature and levels of vessels. In this study we present data to reinforce the notion that SLs of whale-watching vessels moving at slow speeds may vary by up 20 dB. We show that some whale-watching vessels already comply with the recommend broadband (0.2–10 kHz frequency band) $\mathrm{SL}_{\mathrm{LF}}$ limit of < 150 dB re 1μPa (RMS) for humpback whales when transiting at 4 knots, suggesting that such vessels would not elicit behavioural responses on resting humpback whales in Exmouth Gulf, as per Sprogis et al. [67,66]. Furthermore, we outline how moving vessels with TOL SLs < 120 dB re 1μPa have the potential to not add excess noise to the ambient noise at 100 m distance from cetaceans, suggesting that the risk of behavioural effects and masking will be low for such scenarios. However, given the paucity of studies where reactions to known vessel exposure levels are known, we encourage further testing of such vessel levels on a broader range of species. We also welcome a discussion and standardization on how to quantify whale-watching vessel source levels under more predictable propagation conditions than was conducted here. Ideally, for whale-watch vessel noise quantification, recording standards should comply with the International Organization for Standardization (ISO-17208–1:2016) [34], and the challenges of how to record potentially very quiet vessels in the far field at appropriate signal to noise ratio for quantification need to be solved. We posit that a whale-watching industry standard of no source third octave level exceeding 120 dB re 1μPa (RMS) will do much to ensure a low noise induced impact on targeted populations, and we argue for discussions towards an international low noise certification of whale-watching vessels.

Under that scheme, some vessels are better designed to minimize underwater noise emissions and so are more appropriate for whale and dolphin watching and swim-with-cetacean activities. Noise reduction in whale-watching vessels can be achieved by (i) reducing speed, as an increase in speed elevates propeller cavitation which causes a rise in noise level [19,38,79], (ii) avoiding gear-shifts which cause high-level transients in the sound [38] and (iii) increasing the distance to the focal whales [66]. To permanently reduce underwater noise levels in vessels, noise reducing measures can be applied, for example, by using larger, slower moving propellers to minimize cavitation, converting to quieter/electric engines (see vessel #13b, Table 2) and/or installing noise absorption gear [33]. Furthermore, the operator can maintain their propeller and check for chips and cracks to ensure their vessel is operating efficiently with no excess cavitation. Ideally, the skipper drives with slow, consistent movements, as fast, erratic maneuvers disturbs cetaceans [38,42,50,56], and drives in parallel to the group, as driving directly towards cetaceans or in their path of travel causes behavioural disruptions [16,67,76]. When departing a group of cetaceans, the skipper can move off slowly rather than increasing speed too early which also disturbs cetaceans. Lastly, to contribute to the highest-standards of whale-watching, regulators can limit the number of vessels that are permitted to target a group of cetaceans at any one time to avoid cumulative noise effects.

CRediT authorship contribution statement

Patricia Arranz: Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Funding acquisition. **Natacha Aguilar de Soto**: Resources, Writing – review & editing, Project administration. **Peter T. Madsen**: Conceptualization, Methodology, Resources, Writing – review & editing, Project administration. **Kate R. Sprogis**: Conceptualization, Investigation, Resources, Writing – original draft, Visualization, Funding acquisition.

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