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Underwater noise from airplanes: An overlooked source of ocean noise

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ABSTRACT

The effects of underwater noise pollution on marine life are of increasing concern. Research and management have focussed on the strongest underwater sound sources. Aerial sound sources have understandably been ignored as sound transmits poorly across the air-water interface. However, there might be situations when air-borne noise cannot be dismissed. Commercial passenger airplanes were recorded in a coastal underwater soundscape exhibiting broadband received levels of 84–132 dB re 1 μPa rms. Power spectral density levels of airplane noise underwater exceeded ambient levels between 12 Hz and 2 or 10 kHz (depending on site) by up to 36 dB. Underwater noise from airplanes is expected to be audible to a variety of marine fauna, including seals, manatees, and dolphins. With many of the world's airports lying close to the coast, it is cautioned that airplane noise not be ignored, in particular in the case of at-risk species in small, confined habitats.

1. Introduction

Ocean noise in many parts of the world is on the rise, mostly due to industrial development (Andrew et al., 2011; Frisk, 2012). Anthropogenic noise from shipping and seismic surveying can be heard in all the world's oceans (Hildebrand, 2009). From the perspective of marine fauna, noise is now recognized as a chronic, habitat-level stressor for many species that depend on acoustic signals for vital life functions (van der Graaf et al., 2012). Ocean noise can have a multitude of effects on marine fauna, ranging from behavioural disturbance to communication masking and physiological problems (e.g., Erbe et al., 2018; Hawkins and Popper, 2017).

Several jurisdictions around the world are trying to regulate underwater noise, but the majority of environmental impact assessments focus on strong marine industrial sources like seismic surveying or pile driving (e.g., Erbe, 2013). Environmental impact assessments for airports may consider effects of construction on adjacent marine habitats, but generally ignore the contribution of airplanes to underwater noise levels (e.g., Jefferson et al., 2009). Intuitively, this simplification is a reasonable starting assumption. Sources in air are typically absent from environmental impact assessments of underwater noise, because sound generally transmits very poorly across the interface of two media with greatly different acoustic impedances. Direct sound transmission from air into water only occurs within a 26^{O} cone radiating downwards (Urick, 1972). Underwater receivers at much greater horizontal range and in shallow water might still detect the aerial sound source, but the transmission path involves reflections and an associated decrease in amplitude. Underwater receivers inside this cone, however, might receive levels from aerial sources well above underwater ambient levels as demonstrated for aerial drones recorded underwater (Erbe et al., 2017). Two main factors cause us to reassess the contribution of airplane noise to important marine habitats in coastal waters. Firstly, global air traffic (revenue-passenger kilometres flown) has grown exponentially in recent decades, averaging 5% per annum.[1] Secondly, there is growing awareness of the need to understand and mitigate cumulative impact of anthropogenic activities on endangered marine animals (Williams et al., 2016) and their habitats (Maxwell et al., 2013). While marine mammals are used in the following as case examples, the premise can be applied to multiple marine fauna, for which sound is an important cue.

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There may be cases where it is important to consider whether sound transmission from air into water could affect the acoustic habitat quality of endangered marine mammal species, particularly those living in restricted habitats (e.g., Jefferson et al., 2009; Ross et al., 2011). A global review of the vulnerability of the world's major infrastructure to sea level rise found that 11% of the world's airports lie within low elevation (i.e., <10 m of mean sea level) coastal zones (Fig. 1; Nicholls and Kebede, 2010). Many of the world's busiest airports have coastal runways. Some examples include Tokyo (Japan, HND), New York (USA, JFK), Hong Kong (China, HKG), Schiphol (Netherlands, AMS), San Francisco (USA, SFO), Singapore (Singapore, SIN), Miami (USA, MIA), Reykjavik (Iceland, RKV), Vancouver (Canada, YVR), Anchorage (USA, ANC), Sydney (Australia, SYD), and Denpasar (Indonesia, DPS). Many of these border important habitats for highly resident and threatened populations of marine mammals. To be clear, we do not claim that airplane noise is a causal factor in the at-risk status of any marine mammal population, but as efforts are underway to better include noise in marine spatial planning and critical habitat designations for endangered marine fauna, it seems timely to re-assess the contribution of airplane noise into coastal marine habitats of threatened species. For example, critical habitat designation for endangered southern resident killer whales (*Orcinus orca*) includes its acoustic attributes (Fisheries and Oceans Canada, 2011), which is relevant given its proximity to Vancouver airport. Cook Inlet belugas (*Delphinapterus leucas*) have two major airports (Anchorage International and Elmendorf military airport) adjacent to their habitat. Hong Kong's airport operations affect important habitats to at-risk populations of Indo-Pacific humpback dolphin (*Sousa chinensis*) and finless porpoise (*Neophocaena phocaenoides*) (Jefferson et al., 2009). There's a small and at-risk population of bottlenose dolphins (*Tursiops aduncus*) in the highly urbanized estuary off Perth, Western Australia (Marley et al., 2017), and a number of small delphinids including spinner dolphins (*Stenella longirostris*), spotted dolphins (*Stenella attenuata*), Fraser's dolphins (*Lagenodelphis hosei*), Risso's dolphins (*Grampus griseus*), and bottlenose dolphins (*Tursiops* sp.) in the waters off Bali (Mustika et al., 2016).

While studying coastal soundscapes, we noticed regularly occurring, broadband, transient sounds coincident with direct overflights (Williams et al., 2018). We revisited archived data from two sites and estimated underwater received levels of commercial passenger airplanes.

2. Methods

Commercial passenger airplanes were recorded underwater with three autonomous recorders at two locations. Two recorders were deployed off Denpasar (Bali, Indonesia), below the flight path from Ngurah Rai International Airport. One recorder was deployed in the Canning River (Western Australia), below the flight path into Perth International Airport (Table 1, Fig. 2). Planes in Bali were recorded immediately after take-off, at a range of 800 and 1100 m from the end of the runway. Planes were climbing and accelerating at about 150–300 m altitude at the two recorders, being higher above the deeper recorder that was further away from the runway. In Perth, planes were about 10 km from the airport, at a height of 400–800 m. Flight path details were taken from FlightAware (flightaware.com), offering height, ground speed, and GPS location for each plane.

All of the recordings were taken using SoundTraps 202STD and 300STD (Ocean Instruments, New Zealand), which are autonomous recorders, that are factory-calibrated including a piston phone at 250 Hz, and that are programmed prior to deployment. They were attached to a metal frame with cable ties and duct tape and deployed on the seafloor which was flat at both sites (Fig. 3). The seafloor off Bali next to the runway consisted of soft mud. The river floor in Perth consisted of silty mud. The SoundTraps off Bali were in the field for several days and operated on a duty cycle of 4 min and 40 s recording out of every 5 min. The weather during this time was variable and included periods with sun, clouds, rain, and thunderstorms (temperature: 27 ± 2 °C; humidity: 82 ± 8%; wind speed: 9.4 ± 5.9 km/h). The SoundTrap off Perth was only in the field for 3 h, recording continuously. Temperature and humidity were 20 °C and 44%, respectively. Winds were light with gusts of up to 10 km/h. The river was calm with occasional ripples.

All of the datasets were inspected via audio and visual scrutiny of recordings and spectrograms, respectively. Guided by flight departure (Denpasar) and arrival (Perth) information from the airports' websites, a 20-s recording of sound was manually selected around individual plane overflights. In the case of Perth recordings, visual confirmation of the passing airplane at the time of recording was also collected. The broadband sound pressure level was computed in a series of 1-s windows for each selected 20-s sound clip. The strongest 1-s window was deemed to correspond to the plane's closest point of approach (CPA). Each 1-s recording at CPA was Fourier-transformed in 0.25-s windows with 75% overlap to yield a snapshot of power spectral density (PSD) at every overflight.

Ambient noise in the absence of airplanes, boats, and nearby marine fauna (fish, ducks) was identified in the recordings and also Fourier-transformed in 0.25-s windows with 75% overlap yielding PSD. Percentiles of PSD were then computed for ambient noise as well as over all 1-s plane overflights at CPA.

3. Results

Example spectrograms of the underwater sound recorded from a plane at the deeper Bali site and at the Perth site are shown in Fig. 4. Planes were detectable for 10–15 s off Bali and 30–40 s off Perth. There was a temporary increase in broadband ambient noise (up to 10 kHz off Bali and up to 3 kHz off Perth). In addition, engine tones were detected (up to 10 kHz off Bali and up to 500 Hz off Perth). A Doppler shift was visible in all plane overflights as tones swept from a higher frequency to a lower frequency around CPA.

Broadband received levels were highest at the deeper Bali site and least off Perth with medians of 117, 110, and 91 dB re 1 μPa at the deeper Bali, shallower Bali and Perth sites, respectively (Fig. 5). These levels were computed over 192, 170, and 33 plane overflights at the shallower Bali, deeper Bali, and Perth sites, respectively. The frequency bands over which broadband levels were computed comprised 12 Hz–10 kHz for the two Bali datasets and 12 Hz–2 kHz for the Perth dataset. These are the bands in which airplane noise exceeded ambient levels at the three sites.

Fig. 6 presents the PSD percentiles for the 1-s airplane spectra at CPA compared to those of ambient noise. The 1st, 5th, 25th, and 50th percentiles are plotted. These are the levels that were exceeded 1, 5, 25, and 50% of the time. The 50th percentile is the median. The peaks at 110, 180, 280, and 480 Hz in the 1st and 5th percentile of ambient noise at the shallower Bali site are due to fish vocalisations. The broad hump from 1 kHz to 30 kHz in all of the Bali ambient noise percentiles is due to snapping shrimp. The tones in the 1st percentile of airplane sound off Perth are due to strong engine tonals in some of the overflights recorded.

4. Discussion

Aerial noise from airplanes, effects on humans and terrestrial animals, and technological methods to reduce noise emission and exposures have been well studied (e.g., Casalino et al., 2008; Smith, 2004).

[1] https://www.icao.int/sustainability/Pages/Facts-Figures_WorldEconomyData.aspx

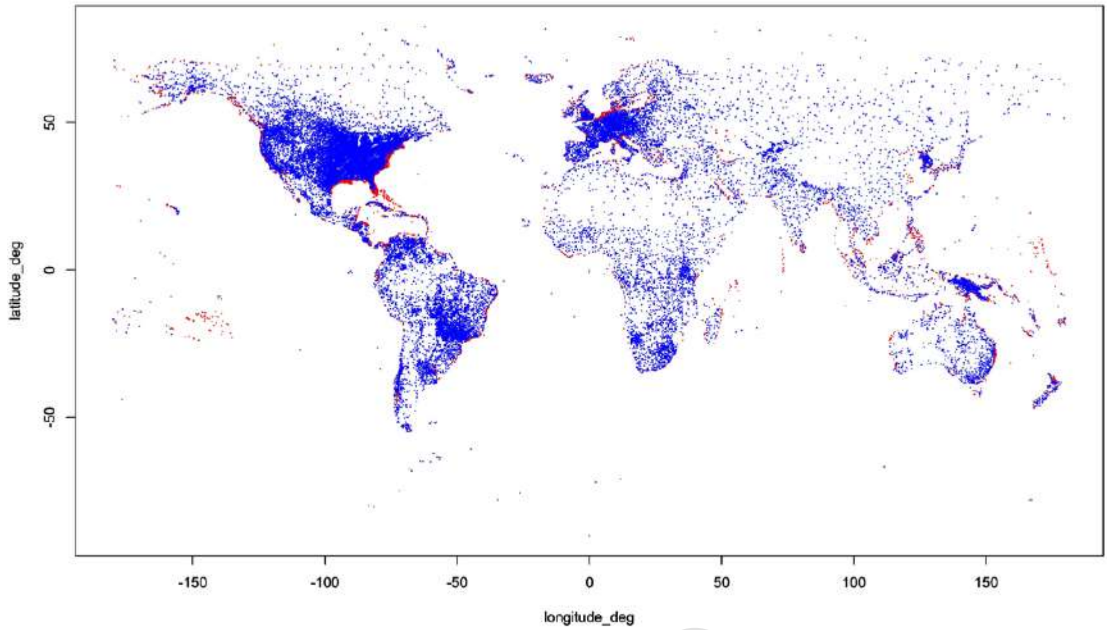

Fig. 1. Map of location of airports and airstrips (data courtesy OurAirports.com). Airports with runways < 10 m below mean sea level are shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Metadata table giving the dates, locations and specifications of the recordings, as well as the duration of ambient noise logged from the recordings.

Recorder	Dates	Location	Coordinates	Water depth	Sampling frequency	Duty cycle	Ambient record
SoundTrap 202STD	24–27 Mar 2017	Bali shallow	8°45′1.02″ S; 115°8′47.62″ E	7 m	96 kHz	4:40 min/5:00 min	95 min
SoundTrap 202STD	24 Mar–1 Apr 2017	Bali deep	8°44′59.14″ S; 115°8′37.29″ E	11 m	96 kHz	4:40 min/5:00 min	75 min
SoundTrap 300STD	27 May 2016	Canning River	32°1′5.66″ S; 115°53′44.89″ E	1 m	96 kHz	180 min continuous	1 min

Significant progress has been made in reducing noise emission by airplanes, however, at the same time, the number of flights has increased and the net result on noise exposure is variable (Astley, 2015). The aviation industry and regulators are continuing to work on reducing noise exposure and mitigating its effects on land. We note that regulations and management plans exist at both our study sites for airplane noise (http://jdih.dephub.go.id/produk_hukum/view/UzAwZ01qa2dWR0ZvZFc0Z01qQXdPUT09; https://www.perthairport.com.au/-/media/Files/CORPORATE/Perth-Airport-Aircraft-Noise-Management-Summary.pdf?la = en). Any reduction of emitted noise pressure levels in air will also reduce noise pressure levels received below the flight paths in water.

Noise exposure, by definition, is proportional to the amount of time over which a noise is received, and this study showed great variability in the duration of airplane noise reception in water. Overflights were detectable above ambient levels for about 10–15 s in the marine environment off Bali compared to about 30–40 s in the riverine environment off Perth. The difference is likely due to the greater height of flights over the Perth recorder, which results in a greater footprint of the 26° direct sound transmission cone.

Median broadband received levels were < 117 dB re 1 μPa under water. Broadband received levels varied by up to 32 dB at any one site. Such variability is common in air as well and due to different types of commercial planes, heights, angles, speeds, and sound propagation conditions (due to different environmental conditions such as temperature and humidity in air and temperature and salinity in water; e.g., Hubbard, 1991).

Received levels under water were below levels commonly considered in regulations of underwater noise (Erbe, 2013). However, airplane levels were up to 36 dB above ambient levels at certain frequencies at each of the three sites and are therefore expected to be heard by marine fauna sensitive at these frequencies. A bottlenose dolphin, harbour seal, and manatee audiogram were overlain with the PSD levels of airplanes. Whenever the noise levels are greater than the audiogram minus the critical ratio, the noise is expected audible (Erbe et al., 2016). With marine mammal critical ratios of 15–35 dB below 10 kHz (lower critical ratios at lower frequencies; Fig. 4 in Erbe et al., 2016), airplanes might be audible to dolphins, harbour seals, and manatees at frequencies above 100, 60, and 10 Hz, respectively. The lower airplane levels recorded in the Canning River would be audible to harbour seals and manatees, but might be just below the audibility of dolphins. However, recordings closer to the airport, where planes fly lower, are required to rule out acoustic detection by dolphins. The Canning River is home to a small population of bottlenose dolphins subjected to a diversity of anthropogenic stressors including noise (River Guardians, 2016).

Noise levels under the flight path sometimes exceeded the 120 dB re 1 μPa (broadband, root-mean-square) found to coincide with the onset of behavioural responses in a killer whale dose-response study to ship noise (Williams et al., 2014). Many small cetaceans are expected to be as sensitive to anthropogenic noise as killer whales, and cetaceans may be exposed to these relatively low-amplitude sounds frequently. Flight departures and landings took place every 3 min during peak travel times at Denpasar airport. With 10–15 s of noise per plane, the duty cycle of airplane noise under water was about 6–8%. The waters around Denpasar are home to a number of dolphin and baleen

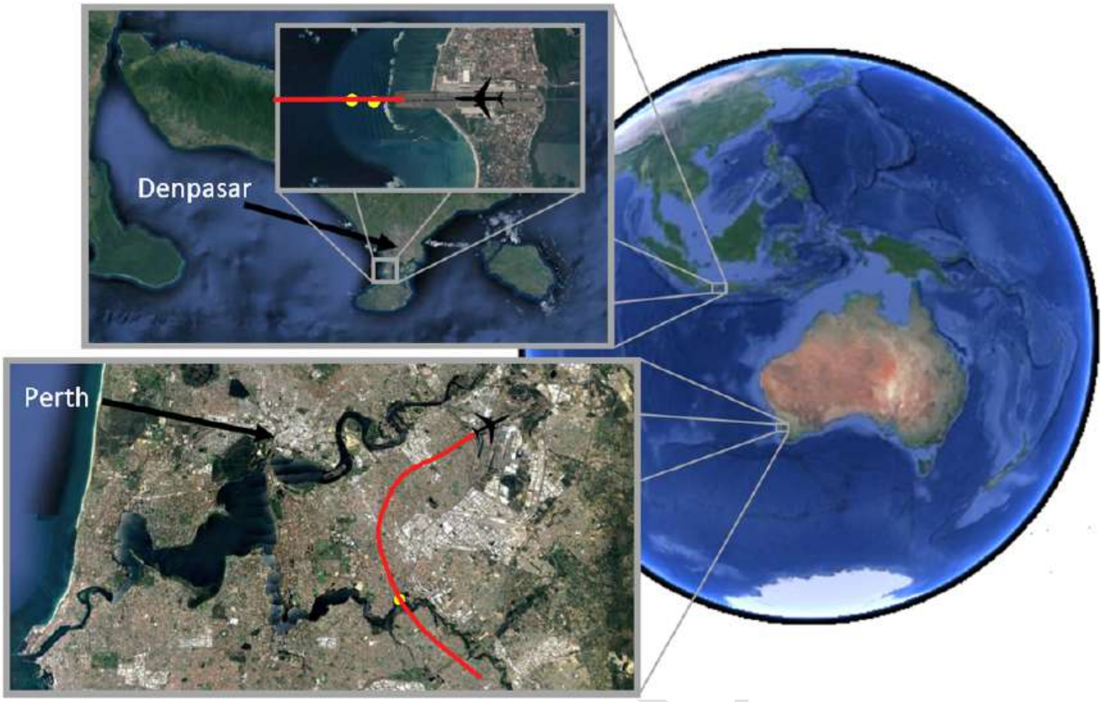

Fig. 2. Map of recording locations in the geographic region (right image) with expansions to show location of airports (highlighted by black plane), together with the approximate take off (Denpasar, Bali) and landing (Perth) routes (shown by the red lines) during recordings, and site of SoundTraps (yellow circles). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

whale populations whose conservation status has not been assessed formally (Williams et al., 2017). Depending on the intensity of airplane traffic in a region and the sensitivity of an animal population to noise, there may be scenarios in which airplane noise needs to be included in an ocean noise budget affecting marine habitat.

Our results suggest that airplane noise may be more audible underwater than commonly expected. This may warrant reconsideration of previous impact assessments that assumed propagation of airplane noise into important habitats was negligible. We concur with previous assessments that underwater noise from airport operations is low relative to noise generated during coastal airport construction (Jefferson et al., 2009), but here we show that the airplane noise itself is not negligible. We found that received sound pressure levels from airplanes flying over the hydrophones were similar to those from cargo and container ships transiting at ranges of 1–3 km, although airplanes and hence their noise passed much faster than ships and therefore sound exposures were less from airplanes (Williams et al., 2014). As introduced earlier, airplane noise may be of interest, for example, to the conservation and management of cetaceans near Hong Kong, belugas in Cook Inlet, or southern resident killer whales. While the bulk of the acoustic energy was below 300 Hz, the airplane spectrum extended to high frequencies which makes this relevant to low-, mid-, and high-frequency marine mammals, including pinnipeds, sirenia, baleen whales, and odontocetes (Erbe et al., 2016). These findings may be applicable to management plans for the endangered Hawaiian or Mediterranean monk seals (*Neomonachus schauinslandi* and *Monachus monachus*), or western grey whales (*Eschrichtius robustus*). Even if many marine mammals themselves have poor hearing at the peak frequencies of the airplane spectrum, many fish species are low-frequency hearing specialists (Popper and Fay, 2011), so it is equally important to consider indirect effects of noise on marine mammals via impacts on prey species. While focus examples of marine mammals have been given here, similar impacts may be evident in non-mammalian marine fauna, including fish, reptiles, or invertebrates, and these animals might be protected in their own right. In our view, the issue of airplane noise should be considered in impact assessments whenever a runway is built near a coast or on reclaimed land, or extends into the ocean.

In recent years, impact assessments regarding ocean noise have shifted from acute, high-amplitude sources to the cumulative impact of multiple low-amplitude sound sources (The National Academies of Sciences and Engineering, 2017). Similarly, recovery plans of many endangered populations of wildlife have required a paradigm shift from mitigating a single source of human-caused mortality to having to model and mitigate the cumulative impacts of multiple anthropogenic stressors (Williams et al., 2016). We lack data to assess whether marine mammals and other taxa may be sensitive to airplane noise, tolerate it, or habituate to it (Bejder et al., 2009). We encourage dedicated studies to assess this issue. As a precautionary measure, we see value in prioritizing future research efforts to address the scenarios where any effect of airplane noise may be of conservation concern. It would make sense to start with studies of small, endangered populations of coastal cetaceans or pinnipeds that are threatened with multiple anthropogenic stressors. We recommend focusing on species that show strong site fidelity to waters near airports. We suspect that promising case studies can be found among populations of bottlenose dolphins, belugas, monk seals, sea otters, or manatees.

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Fig. 3. Photographs of an airplane taking off from Denpasar at the time of SoundTrap deployment and of a SoundTrap strapped to a metal frame while deployed on the seafloor elsewhere.

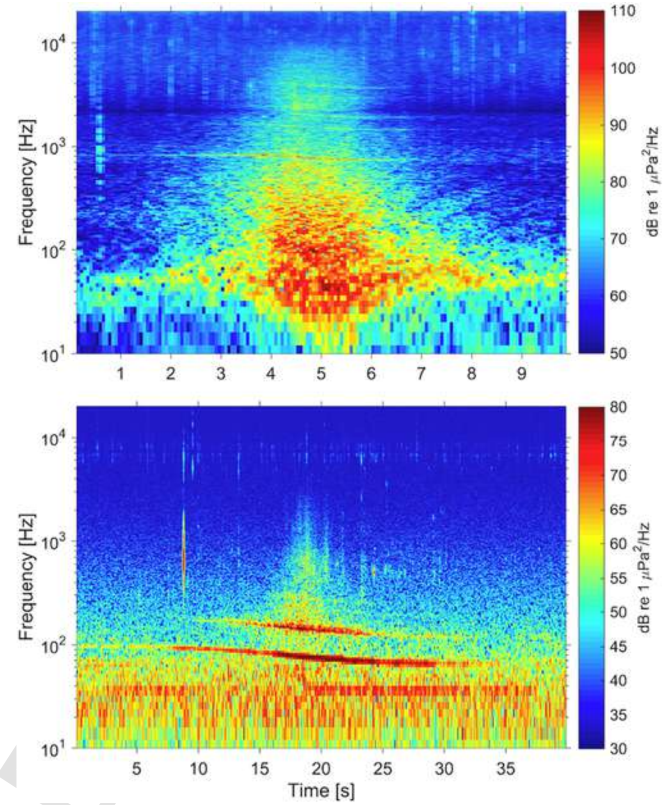

Fig. 4. Spectrograms of airplane noise recorded underwater at the deeper Bali site (top) and at the Perth site (bottom). Highest energy from engine tones can be seen beginning at approximately 800 Hz and 100 Hz on the top and bottom example spectrograms, respectively.

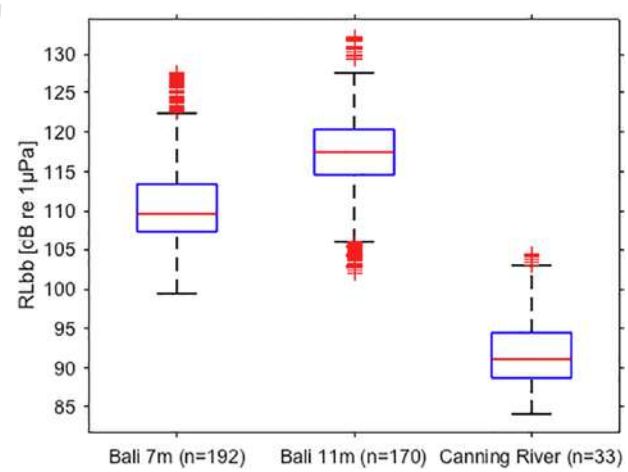

Fig. 5. Broadband received levels at the three sites.

Competing interests

The authors have no competing interests to declare.

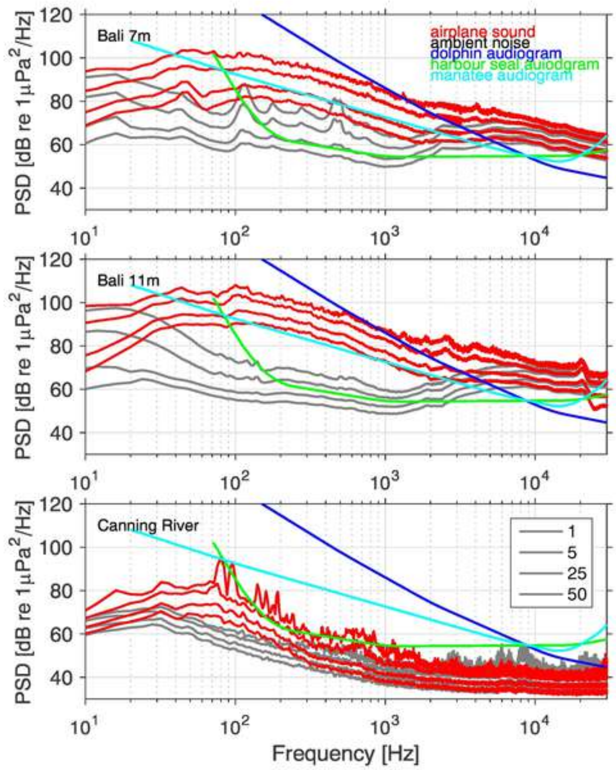

Fig. 6. Power spectral density percentiles for airplanes at 1-s CPA (red) and ambient noise (grey) at each of the three sites. While the four percentiles for each source have the same colour, the highest curve corresponds to the 1st percentile, followed by the 5th, then 25th. And the lowest curve corresponds to the 50th percentile (median). Partial (up to 30 kHz) bottlenose dolphin (*Tursiops truncatus*), harbour seal (*Phoca vitulina*) and manatee (*Trichechus manatus*) audiograms (summarised in Erbe et al., 2016) are shown for comparison. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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