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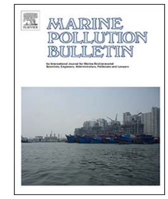

Natural and anthropogenic events influence the soundscapes of four bays on Hawaii Island

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A B S T R A C T

The soundscapes of four bays along the Kona Coast of Hawaii Island were monitored between January 2011 and March 2013. Equivalent, unweighted sound pressure levels within standard 1/3rd-octave bands (dB re: 1 μPa) were calculated for each recording. Sound levels increased at night and were lowest during the daytime when spinner dolphins use the bays to rest. A tsunami provided an opportunity to monitor the soundscape with little anthropogenic component. We detected a decrease in sound levels and variability in one of the busiest bays. During the daytime in the 3.15 kHz 1/3rd octave band, we detected 92 loud outliers from vessels, aquaculture, and military mid-frequency active sonar. During one military mid-frequency active sonar event sound levels reached 45.8 dB above median ambient noise levels. The differences found in the bays illustrate the importance of understanding soundscapes to effectively manage noise pollution in marine ecosystems.

1. Introduction

The sounds from living organisms, geological features and processes, and human activities, sometimes referred to as the biophony, geophony, and anthrophony respectively, during a specified time period form the acoustic environment, or the soundscape (Krause and Gage 2003, Dumyahn and Pijanowski 2011). Since sound travels efficiently underwater, marine animals rely heavily on sound, and their soundscape, for critical life functions (e.g. Cato et al. 2005). However, we also know that ocean noise levels have been increasing over the past decades (see Frisk (2012)) posing a risk to marine animals (Williams et al. 2014). Given the importance of sound for marine animals, it is critical to monitor the soundscape of marine ecosystems and understand the natural and anthropogenic factors that influence it.

Soundscape ecology, compared to the "species centered" field of bioacoustics (Towsey et al. 2014), is a more holistic approach to understanding sound (Dumyahn and Pijanowski 2011). A growing body of marine soundscape literature has established important baseline data to monitor change and assess how natural and anthropogenic events transform the acoustic environment (for examples see Staaterman et al. (2013), Merchant et al. (2014), Kaplan and Mooney (2015), Nedelec et al. (2015), Sánchez-Gendriz and Padovese (2016)). However, McWilliam and Hawkins (2013) acknowledged that there are still "large gaps" in our understanding of marine soundscapes in this growing field. Staaterman et al. (2014) published the first study to compare more than a year's worth of recordings at multiple coral reef environments. Only in the last few years have studies explicitly characterized the acoustic environment of marine mammals (Rice et al. 2014, Clark et al. 2015, Guan et al. 2015). For reasons related to the focal species, several studies focus on frequencies below 2 kHz (Staaterman et al. 2014) or even lower frequencies for fish (Kaplan and Mooney 2015). Consequently, there is a paucity of knowledge on a large and essential component of the soundscape for most marine mammals. There is also a need to understand intra-site temporal and seasonal variability and inter-site variability (Dumyahn and Pijanowski 2011) across "ecologically significant" areas (Rice et al. 2014). Moreover, to contextualize the current soundscape, there is a need to characterize "pristine" areas, or to otherwise determine a baseline soundscape (Chapman and Price 2011, Au et al. 2012, Rodriguez et al. 2014).

Anthropogenic sounds are an increasingly prominent component of

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many marine soundscapes (Gage and Axel 2014). Thus, it is essential to quantify how humans affect this important aspect of the ecosystem. In many marine soundscapes, the 10 to 500 Hz frequency range (as characterized by Hildebrand (2009)), is dominated by human-made sounds, especially those from commercial shipping. An important component of the band between 500 Hz and 25 kHz in shallow areas is the sound from small vessels with a majority of the sound energy between 1 and 5 kHz (Hildebrand 2009) extending to 10 kHz (Lobel 2009). Military mid-frequency active (MFA) sonars also contribute to this range of frequencies in areas where a testing and training occurs (Hildebrand 2009).

Environmental sounds are present in low frequencies between 1 and 50 Hz in the form of volcanic activity (Au and Hastings 2008) and sounds from wind in frequencies less than 100 Hz (Tricas and Boyle 2014). The sounds of breaking waves and rainfall also contribute to sound between 500 Hz and 25 kHz (Hildebrand 2009).

In this study, we monitored the soundscape of four shallow bays with popular coral reefs and recreational areas on the Kona Coast of Hawaii Island for 20 to 27 months between January 2011 and March 2013. These bays are economically important for many recreational and commercial uses (Heenehan et al. 2014). They also serve as important resting habitats for Hawaiian spinner dolphins (*Stenella longirostris*) (Tyne et al., 2015). Due to the predictable presence of spinner dolphins in these areas, they are frequented by a year-round dolphin-focused tourism industry (O'Connor et al. 2009). Since the bays are easily accessible and popular destinations, we expected a wide range of sounds produced by human activities. As foundation species (Altieri and van de Koppel 2014), corals support some of the most diverse marine habitats (Côté and Knowlton 2014), including a range of species that produce sounds. Since these areas included coral reef habitat, the winter breeding areas of humpback whales and important coastal areas for Hawaiians spinner dolphins (Tyne et al. 2015) we expected a diverse range of biological sounds contributing to the soundscape in the bays.

Biological sounds in these areas span most frequencies (Hildebrand 2009). Spinner dolphins use the bays year-round to rest during the day with peak rest occurring in the late morning and early afternoon (Tyne et al. 2015, Tyne et al. 2017). Their sounds, including whistles, clicks and burst pulses range from 2 to 140 kHz and aid in navigation, foraging and conspecific communication (Brownlee and Norris 1994, Lammers et al. 2003, Bazúa-Durán and Au 2004, Lammers et al. 2004, Benoit-Bird and Au 2009). Between mid-February and mid-March, humpback whale song is a major feature of the soundscape with peak frequencies between 200 Hz and 2 kHz (Au et al. 2012). Snapping shrimp, a major component of shallow inshore soundscapes, produce loud snapping sounds to stun prey and defend territory (Au and Banks 1998, Versluis et al. 2000) at a broad range of frequencies with peak frequencies in at 2.5 kHz (Au et al. 2012) but also contain energy to 200 kHz (Au and Banks 1998). Another important component of the soundscape is fish sounds (Hildebrand 2009). Many coastal fish species of the Hawaiian Islands use sound for "agonistic interactions and resource defense, reproduction, nest defense, feeding and vigilance" and dominate the frequencies between 100 and 300 Hz extending up to 6 kHz (Randall 2007, Tricas and Boyle 2014).

In this study we aimed to help fill some of the gaps in the marine soundscape literature by comparing more than a year's worth of recordings at multiple coral reef environments, explicitly characterizing the soundscape of important marine mammal habitat, exploring inter and intra-site variability for our four sites, and determining a baseline soundscape for these areas. This study describes the ambient noise in four bays focusing on large changes to the soundscape documented in each of the four bays. To achieve these goals this paper is organized into three sections in which we: 1) characterize the overall hourly soundscape in each of the four bays; 2) focus on the soundscape during the tsunami event of March 2011 to approximate a natural or baseline soundscape; 3) focus on the daytime hours to determine who or what is creating the loudest soundscape perturbations and quantify those perturbations.

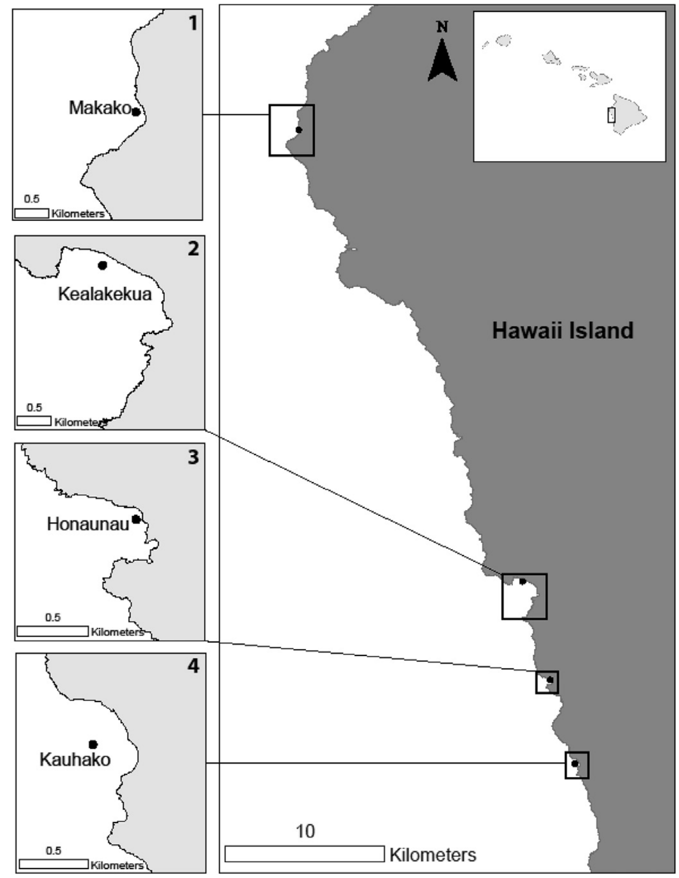

Fig. 1. Map of the four study sites on the west Kona coast of Hawaii Island, the biggest of the main Hawaiian Islands between 19 55° 37′N, 155 53° 45′W and 19 99 21° 40′N, 155 53° 31′W. From North to South the four bays are Makako Bay 1, Kealakekua Bay 2, Honaunau Bay 3 and Kauhako Bay 4. Each is important marine animal habitat. For example, for marine mammals, each bay is a spinner dolphin resting area and is frequented by humpback whales during their breeding season. These bays also have important benthic habitat for marine animals, including coral reefs in Bay 1, Bay 2 and Bay 3 and therefore home to numerous fish and invertebrate species.

2. Methods

2.1. General methods

We deployed passive acoustic recorders to study the long-term soundscapes of four bays along the Kona Coast of Hawaii Island: Makako (Bay 1), Kealakekua (Bay 2) Honaunau (Bay 3) and Kauhako (Bay 4) (Fig. 1, between 19 55° 37′N, 155 53° 45′W and 19 99 21° 40′N, 155 53° 31′W). Each logger was deployed in a sandy area of the bay (Supplemental Appendix B more information on logger location and bottom type). We made calibrated 30-second recordings every 4 min between January 8, 2011 and March 30, 2013 at a sampling rate of 80 kHz with DSG-Ocean Acoustic Loggers (Loggerhead Instruments, Sarasota, FL, USA) outfitted with HTI-96-Min/3V hydrophones (hydrophone sensitivity: within 1 dB of -186.6 dBV μPa^{-1}, calibrated by High Tech Inc., Gulfport, MS, USA) and a 16-bit computer board. All four bays were recorded between January 8, 2011 and August 30, 2012 with the Bay 2 logger continuing to record for an additional seven months through March 30, 2013. Certified scientific divers deployed the acoustic loggers in depths between 15.8 and 24.6 m (Supplemental Appendix B more information). Approximately every two weeks we recovered, serviced and returned the loggers to the bottom of the bay in the same location. Each recording day was initially processed and marked as successfully recorded or not. We excluded malfunctions and logger servicing days from this analysis (for more details see Heenehan et al. (2016)).