Chapter 4
From Shrimp to Whales: Biological Applications of Passive Acoustic Monitoring on a Remote Pacific Coral Reef

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Abstract Passive acoustic monitoring (PAM) can be an effective tool for studying marine fauna in coral reefs and other ecosystems. We analyzed PAM data from 2006 to 2009 at French Frigate Shoals (FFS) in the Northwestern Hawaiian Islands. We measured received sound pressure levels (SPL) over time within different frequency bands from 0 to 20 kHz, and used automated and manual techniques to detect parrotfish scrapes and cetacean vocalizations. SPLs were greatest overall in the snapping-shrimp-dominated bands above 2.5 kHz, and they increased at night and decreased during cold months. In frequency bands <1.5 kHz, containing mainly fish sounds (and seasonal whale song), SPL peaked at dawn and dusk. Humpback whale song was detected in December through April; occurrence was greater during 2008–2009 than 2006–2007, possibly reflecting an increase in whale density near FFS. Parrotfish bite sounds were detected year-round, and parrotfish foraged most actively during the afternoon. Dolphins were detected on 12–64 % of days per month, with low levels of activity during the day that increased in late afternoon and were highest at night. More frequent detections of dolphins in February/March 2007, October 2008, and February/March 2009 may correspond to pulses of food availability via the mesopelagic prey community. Minke whale "boing" sounds were detected from late October, with one or two peaks in the December–March period; during March 2009 minke whale calls were present nearly every day. The results provide the first long-term record of minke whales in the NWHI, and show the potential of PAM on remote coral reefs to monitor patterns over time of many trophic levels, from herbivores to apex predators.

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4.1   Introduction

Long-term ecological monitoring of coral reefs is crucial for assessing the effective-
ness of management efforts and documenting changes over time in reef health and
biodiversity. However, traditional visual survey techniques are labor intensive,
expensive, and logistically challenging in remote areas, potentially disruptive to
organisms, limited to daylight and good weather/sea conditions, and often provide
only a "snapshot" view of an ecosystem at a particular time. Passive acoustic moni-
toring (PAM) can be an effective and complementary tool for coral reef research and
long-term monitoring of both biotic and abiotic sound sources. Passive acoustic
recorders can be relatively cost effective (e.g., compared to ship and personnel
time), cause minimal disturbance, can operate during nighttime and poor weather
conditions, and can autonomously collect continuous data for months to years.
These data sets can provide information on the distribution, abundance, and behav-
ior of numerous species concurrently, as well as environmental conditions, anthro-
pogenic noise, and changes of the soundscape over time.

   The use of sound for communication and perception of the environment is essen-
tial for many marine animals. In coral reef and other nearshore ecosystems, numerous
animal taxa such as crustaceans, fish, and cetaceans produce repeated and identifiable
sounds within a variety of behavioral contexts. The most ubiquitous sound on tropical
and subtropical reefs is produced by snapping shrimp in association with feeding (Au
and Banks 1998; Lammers et al. 2006a; Versluis et al. 2000), but sounds are known
from other crustaceans such as the defense sounds of spiny lobsters (e.g., Bouwma
and Herrnkind 2009; Patek et al. 2009; Staaterman et al. 2009) and mantis shrimp
(Patek and Caldwell 2006). Numerous fish species on coral reefs are also known to
produce sounds associated with a variety of behavioral functions, including feeding,
courtship, spawning, territorial defense, agonistic, and other behaviors (e.g., Boyle
and Cox 2009; Lobel 2002; Lobel and Kerr 1999; Lobel et al. 2010; Mann et al. 2009;
Maruska et al. 2007; Myrberg et al. 1993; Myrberg 1997; Parmentier et al. 2005,
2009; Rountree et al. 2006; Tricas et al. 2006; Tricas and Boyle 2014). Marine mam-
mal (especially cetacean) calls have been extensively characterized for many species
and populations, and passive acoustic monitoring (PAM) has become a reliable tech-
nique to investigate species occurrence and their distribution, behavior, population
structure, abundance, and ecology (Mellinger et al. 2007; Van Parijs et al. 2009).

   Taken together, the cumulative "soundscape" of biological and environmental
sounds is an important feature of the nearshore environment in and of itself, and
varies distinctly between localized habitats (Radford et al. 2010). The sound signa-
ture of coral reefs has been documented to be an important attractant for the pelagic
larvae of some corals, crustaceans, and reef fish to find suitable habitats for settle-
ment (e.g., Leis and Lockett 2005; Montgomery et al. 2006; Vermeij et al. 2010),
with the component produced by snapping shrimp being the primary noise to which
some larval fish are attracted (Simpson et al. 2008). Snapping shrimp noise intensity
(and therefore the overall soundscape) varies cyclically on diel, lunar, and seasonal
time scales, as well as in response to environmental variables such as rainstorms

(Lammers et al. 2006a, 2008a) and water quality (Watanabe et al. 2002), and may also be a good indication of habitat quality measures such as substrate rugosity. As such, soundscape-level patterns in acoustic activity on coral reefs can be indicative of reef health and resilience, and ever-increasing anthropogenic noise in the ocean may have negative impacts on reef communities over time by disrupting or masking biologically relevant sounds.

As technology for underwater recording and storage/transmission of acoustic data continues to advance, so does the potential for acoustic monitoring to provide valuable information on a range of biological, spatial, and temporal scales (Van Parijs et al. 2009). Passive acoustic monitoring of coral reefs has the potential to provide a wealth of information on the biodiversity, health, and change over time of coral reef and other marine communities. In this chapter, we explore the application of long-term PAM over a three-year period at French Frigate Shoals, a remote atoll within the Papahānaumokuākea Marine National Monument (Northwestern Hawaiian Islands). We examine variation of the soundscape over time by calculating received sound pressure levels within different frequency bands, each of which broadly represents a different group of sound-producing taxa. We then present case studies of specific organisms whose known sounds were detected within the data sets: parrotfish feeding scrapes and the calls/songs produced by three marine mammal taxa: delphinids, humpback whales, and minke whales. Each of these groups represents a different trophic level and plays an important ecological role either on the coral reef itself or within the broader nearshore ecosystem. Parrotfish scrapes represent instances of fish feeding on reef algae and are therefore an indicator of a primary consumer's activity on the reef. Cetaceans use nearshore habitats for the purposes of feeding, resting, calving, nursing, and breeding. They interact with the ecosystem in a variety of ways, including as secondary consumers, prey and vectors for nutrient influx (Smith et al. 2013; Lavery et al. 2014), and microbial transport (Apprill et al. 2011).

4.2 Methods and Results

NOAA's Pacific Islands Fisheries Science Center (PIFSC), in partnership with the Hawaii Institute of Marine Biology, initiated a passive acoustic coral reef monitoring program in 2006. Long-term data were obtained using Ecological Acoustic Recorders (EARs; Lammers et al. 2008a), which record autonomously on a programmable sampling schedule for months to years (Fig. 4.1). EARs were deployed by divers between 2006 and 2010, in conjunction with vessel-based surveys at over 50 locations on reefs throughout the tropical Pacific, including several in the Northwestern Hawaiian Islands. We examined data from an EAR deployed at French Frigate Shoals (FFS), located in the northwestern Hawaiian Islands. The EAR was first deployed on 6 September 2006 at Rapture Reef on the south side of FFS (23° 38.1 N, 166° 11.1 W) at a depth of 23.5 m (Fig. 4.2). The site is adjacent to the slope of the shoals and is approximately 1.5 km from the 500-m isobath and 2.2 km from the 1000-m isobath.

Fig. 4.1 EAR deployed on a coral reef
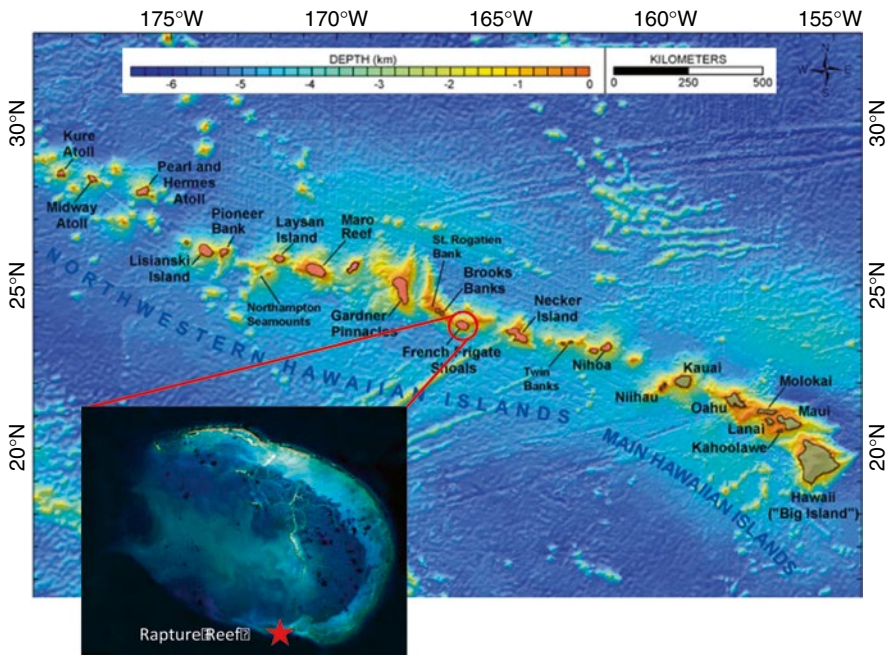
Fig. 4.2 Hawaiian Island archipelago and NOAA bathymetric map of French Frigate Shoals (*inset*). The *red star* indicates the location of Rapture Reef

The EAR was programmed to record for 30 s every 15 min at a sampling rate of 40 kHz, providing an effective recording bandwidth of 20 kHz. The first deployment recorded ambient sounds until the EAR ran out of power on 31 May 2007. That unit was replaced on 25 September 2007 with a new EAR. This second deployment obtained data between 1 October 2007 and 8 February 2008. The third and final deployment was made on 15 September 2008 and data were recorded between 21 September 2008 and 14 July 2009.

4.2.1   Frequency Band Analysis

The soundscape at Rapture Reef was analyzed by calculating ambient noise received levels within different frequency bands of recording. For each of the 30-s recordings, root-mean-square (RMS) sound pressure levels (SPL) were calculated in Matlab™ using

$$\text{RMS SPL} = 20\log\sqrt{\frac{1}{T}\int_0^T p^2(t)\,\mathrm{d}t}$$

where T is the duration of each file and $p(t)$ is pressure p re 1 μPa at time t of the acoustic waveform. This calculation was performed for the full frequency band (0–20 kHz) and also the five following 1-octave bands: 0–1.25, 1.25–2.5, 2.5–5, 5–10, and 10–20 kHz. The RMS SPL values for each recording were averaged over each day to provide a time series of ambient noise variability over the duration of the deployment, and were also averaged by the hour of the 24-h day (e.g., 8 AM, 9 AM) to investigate diel patterns over the warm (May–Oct) and cold (Nov–Apr) month periods.

Ambient sound levels were 5–10 dB greater in the two highest frequency octave bands (>5 kHz) than in the three bands below 5 kHz, with the lowest sound levels in the 1.25–2.5 kHz band (Fig. 4.3). Sound levels decreased slightly by 1–2 dB between warm and cold periods, but exhibited higher variability during cold months (Fig. 4.3). This variability was more pronounced in the two lowest octave bands (0–1.25 and 1.25–2.5 kHz), and was due primarily to the seasonal occurrence of singing humpback whales in the NWHI during winter months (Lammers et al. 2011).

Ambient noise increased at night in all frequency bands greater than 1.25 kHz (Fig. 4.4). Acoustic energy in the 0–1.25 kHz band was either unchanged or greater during daytime hours. In addition, this band exhibited consistent peaks in sound levels of 3–5 dB during crepuscular periods at dawn and dusk (~0600–0700 and ~1800–2000), concurrent with the shift from daytime to nighttime levels in the other frequency bands, The octave band between 1.25 and 2.5 kHz contained the lowest amount of acoustic energy and had either a weak or no diel trend, reflecting an intermediary pattern between the lowest octave band and the bands above 2.5 kHz (Fig. 4.5).

These differences in temporal patterns by frequency band are suggestive of an acoustic niche partitioning process by sound-producing animals on the reef similar to ones described for animals in tropical and temperate woodlands (Depraetere et al. 2012; Sueur et al. 2008). Snapping shrimp (family Alpheidae) produce the major component of reef noise at frequencies above 2 kHz. Individual shrimp produce high-amplitude (~190 dB re 1 μPa) broadband clicks (~2 to >200 kHz) while capturing zooplanktonic prey with large frontal chela (claws) and also during territorial defense (Au and Banks 1998; Versluis et al. 2000). These sounds dominate the ambient noise field in most tropical and temperate nearshore reefs and can easily be heard by human swimmers and divers as a constant crackling sound. The reduction in acoustic received level in the octave bands associated with snapping shrimp activity (≥2.5 kHz) during cold months in 2006–2007 and 2008–2009 is consistent with seasonal trends previously reported by Lammers et al. (2006a), which documented
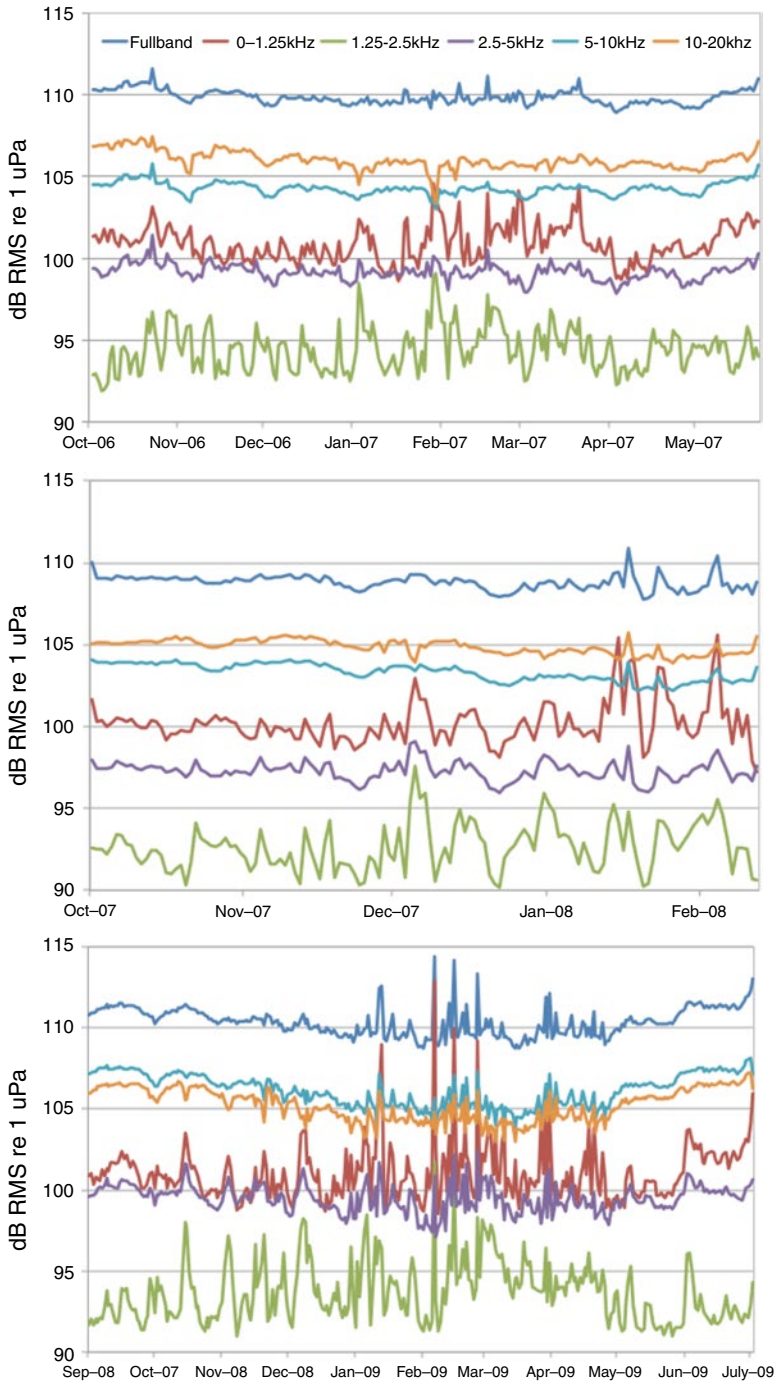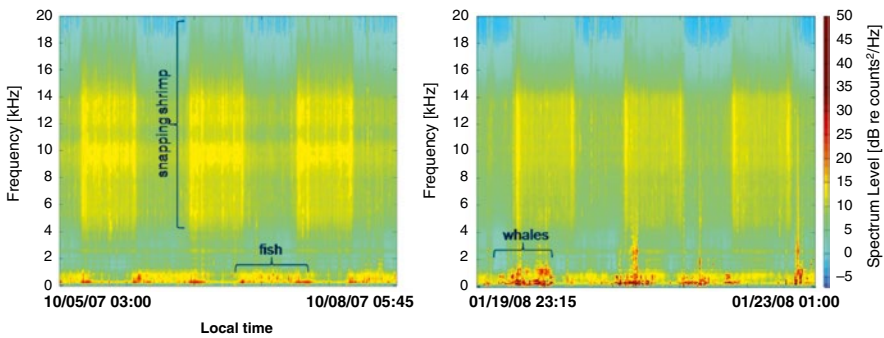
Fig. 4.3 Daily mean RMS sound pressure level within the full effective bandwidth and five octave bands measured at Rapture Reef, French Frigate Shoals between Oct 2006 and May 2007, Oct 2007 and Feb 2008, and Sep 2008 and Jul 2009
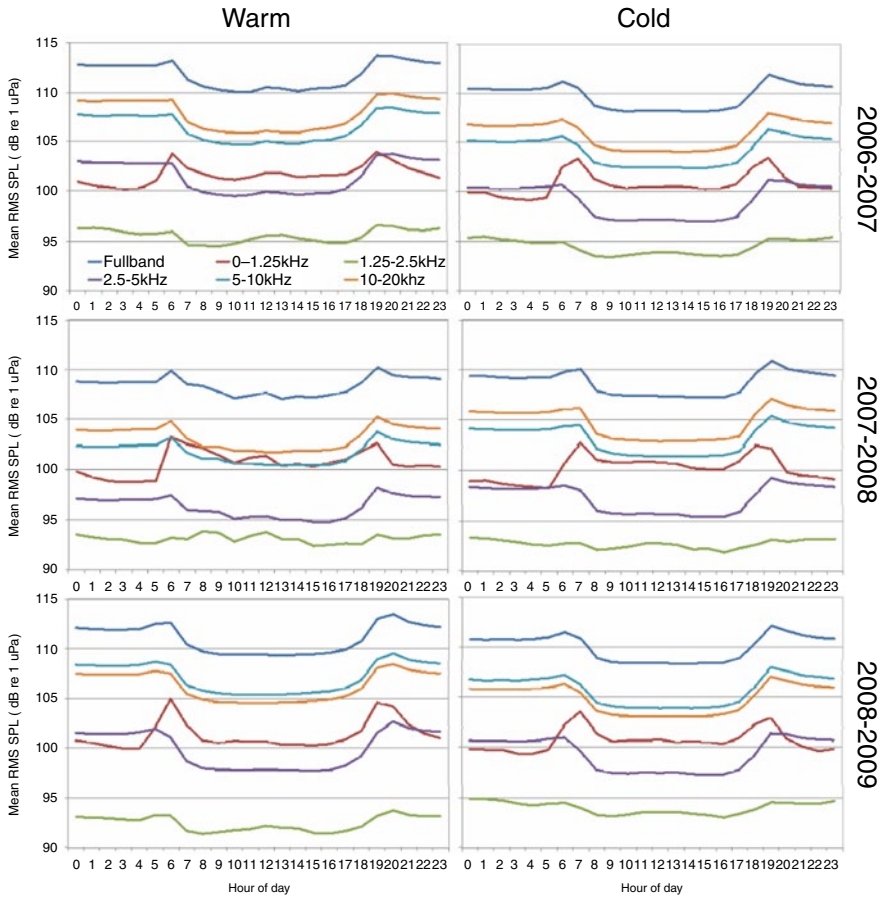
Fig. 4.4 Hourly averaged SPL during warm (May–Oct) and (Nov–Apr) cold months at French Frgate Shoals, for EAR deployments between 2006 and 2009

Fig. 4.5 Long-term spectrograms of 3-day periods from French Frigate Shoals during October 2007 (*left*) and January 2008 (*right*)

reduced snapping shrimp acoustic activity with lower water temperatures. In 2007–2008, only one month of warm period data (October) was obtained, which precluded comparison between warm and cold periods.

At frequencies below ~2 kHz, reef fish are the predominant source of acoustic signaling. Tricas and Boyle (2014) recently characterized the acoustic properties of 85 sounds produced by 45 species of Hawaiian reef fish. Of these, 95.3 % had peak frequencies below 1.4 kHz. Thus, it is reasonable to presume that the temporal patterns observed in the 0–1.25 kHz band most likely reflect the acoustic activity patterns of reef fish near the EAR. There was little variation between warm and cold-water periods in the diel pattern of the lowest octave band, suggesting that in aggregate, reef fish sound production is not a predominantly seasonal phenomenon. Small (1–2 dB) interannual variations were observed between deployments in this and also other bands, but it is not clear whether these reflect changes in acoustic activity from year to year or variations in hydrophone sensitivity between the EAR units used for each deployment. The minimum in ambient sound levels within the 1.25–2.5 kHz frequency band may reflect the transition from frequencies dominated by fish (and seasonally, humpback whales) to invertebrate-dominated frequencies.

4.2.2   Parrotfish Analysis

The data set obtained between September 2008 and July 2009 was examined for the presence of bite and scrape sounds produced by grazing parrotfish. To search for these sounds, EAR data were filtered using an eighth-order low-pass Chebyshev Type I filter with a cutoff frequency of 1600 Hz and downsampled to a new sample rate of 4 kHz (effective bandwidth = 2 kHz) prior to analysis. Due to the large volume of data, spectrogram data were searched manually for parrotfish sounds on a subset of data, every fourth day, and on that day each sound recording file was examined visually to detect potential parrotfish scrapes (Fig. 4.6), which were played back to the analyst to confirm identity as fish scrapes. The number of parrotfish scrapes within each file was recorded and given a subjective quality rating of 1 through 7, with 1 being the poorest quality (low SNR) and highest uncertainty (for example, not co-occurring with other scrape sounds or not audibly similar to known parrotfish scrapes), and 7 being the best quality (high SNR) and greatest confidence (occurrence with other sounds and resemblance to known parrotfish recordings and field observations). The highest uncertainty sounds were not included in further analyses. Parrotfish bite sounds were detected year-round at Rapture Reef (Fig. 4.7). Fish foraged most actively during the afternoon (Fig. 4.8), which is consistent with previous studies of parrotfish foraging behavior in other parts of Hawaii (Jayewardene 2009; Ong and Holland 2010).

Parrotfish are an important ecological component of tropical reef ecosystems. One potential application of PAM of fishes is estimating abundance, which would be a cost-effective and valuable management tool for ecologically important species such as parrotfish. As herbivores (and sometimes corallivores), parrotfish play a major role in algae removal, bioerosion of reef substrate, resilience, and benthic community structure (Mumby 2009; Rotjan et al. 2006). They are also heavily fished in many

Fig. 4.6 Spectrogram of broadband parrotfish scrapes (at 1, 2.7, 4.4, 5.8, and 8.9 s), and other unidentified fish sounds below 1 kHz (at ~1.8, 6, and 7.7 s)
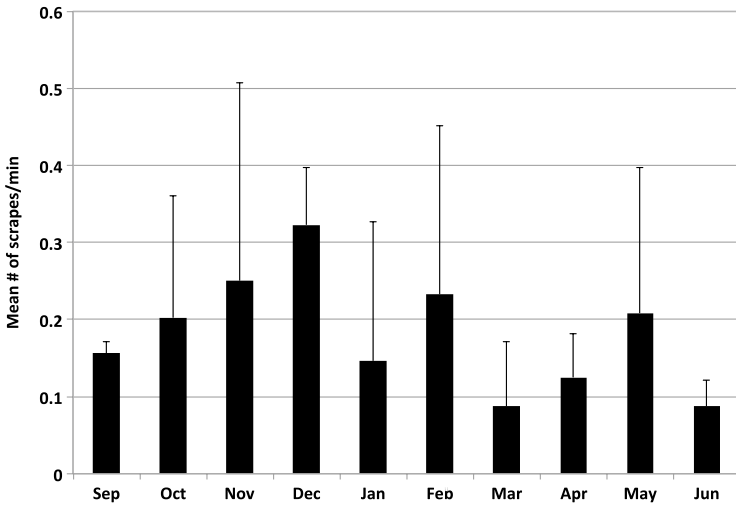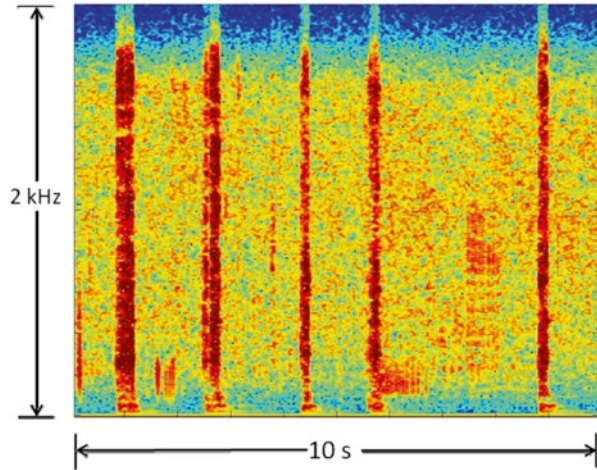
Fig. 4.7 Monthly mean and standard deviation of parrotfish scrapes per minute for the FFS EAR deployment made between September 2008 and July 2009

locations, which may lead to ecosystem-wide impacts such as increased algal cover. In the main Hawaiian islands, parrotfish are a high priority for resource managers, and population abundance is monitored by conducting visual surveys on SCUBA. However, parrotfishes are highly mobile and somewhat skittish around SCUBA divers, particularly in areas where fishing pressure is high, and are hence prone to being undercounted (Lobel 2005). Passive acoustic monitoring has potential as a tool for estimating abundance of parrotfish and other fish species of concern, and PAM could thus be a cost-effective tool for managers over long time periods and in remote areas.

In order to apply PAM as a tool for abundance estimation, further work is necessary to collect data on the characteristics and propagation distance of parrotfish
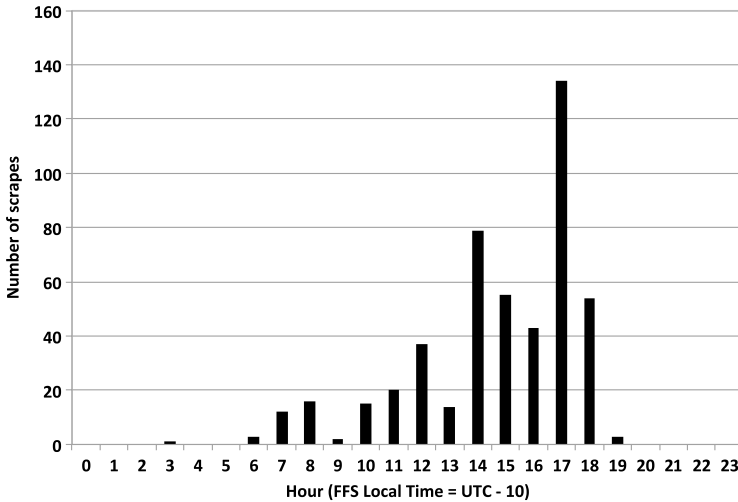
Fig. 4.8 Parrotfish scrape counts by hour of the day

foraging sounds. This information is required for acoustics-based abundance estimation using distance sampling methodology, similar to the methodology demonstrated for cetaceans using fixed passive acoustic sensors (e.g., Marques et al. 2009, 2011). Other required information for abundance estimates includes bite rates and the influence of covariates such as body size (Thomas et al. 2010), for which published information exists from visual surveys. Parrotfish bite rates and types (i.e., scraping versus excavating) vary by species, body size, and time of day (Ong and Holland 2010), and further characterization of the acoustic features of parrotfish bites may enable researchers to relate bite sounds to variables such as species and body size.

4.2.3   Cetacean Analysis

Data obtained from the EAR were processed for cetacean sounds using a custom (M. Lammers) Matlab™ script. The script was designed to identify periods of tonal signaling indicative of the presence of dolphin whistles and whale calls in the recordings (Lammers et al. 2008a). An automated short-time Fourier transform approach was used to find periods when tonal peaks greater than 3 dB above the averaged noise floor were present in the frequency spectrum. These periods were then summed for each recording, and those with tonality exceeding 1 % of the total recording time were visually examined to confirm the presence of cetacean signals. Recordings with confirmed dolphin or whale signals were designated "detections." In addition, to investigate the relative abundance of signals over time, 10 % of recordings from each site were randomly selected for each month and visually and aurally examined for the presence of signals. This provided a proportional measure of the number of recordings per month that contained certain kinds of cetacean
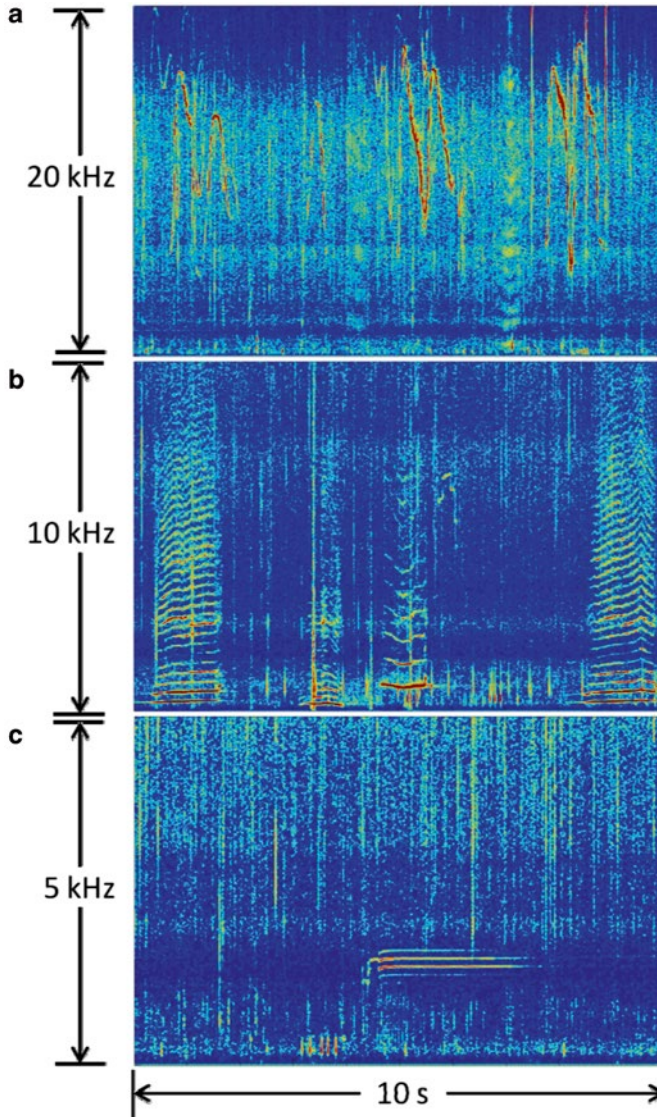
Fig. 4.9 Spectrogram examples of (**a**) dolphin whistles, (**b**) humpback whales song units, and (**c**) a minke whale boing call

signals. No attempt was made to identify calls below 50 Hz, such as those produced by blue whales (*Balaenoptera musculus*) and fin whales (*Balaenoptera physalus*), because such low-frequency signals do not propagate well in the relatively shallow waters in which the EAR was deployed (Urick 1983).

Three types of cetacean signals were found in the recordings: dolphin whistles (Fig. 4.9a), song units from humpback whales (Fig. 4.9b), and "boing" sounds produced by minke whales (Fig. 4.9c) (Rankin and Barlow 2005). The whistles produced by

dolphins could not be identified to the species level. However, the frequency range of the majority of whistles was between 7 and 17 kHz. Of the delphinid species occurring in nearshore Hawaiian waters, this range is consistent with the whistles of spinner dolphins (*Stenella longirostris*), bottlenose dolphins (*Tursiops truncatus*), and/or spotted dolphins (*Stenella attenuata*) (Oswald et al. 2007).

4.2.3.1   Dolphins

The occurrence of dolphins was relatively common at Rapture Reef, with detections occurring between 12 and 64 % of days per month during the monitored periods (Fig. 4.10). In general, the month of December had the fewest days of dolphins detected, whereas the period between February and March had the highest occurrence.

Except during the months of January and May, the 2008–2009 deployment period had more days with dolphin signals present per month than the other two monitoring periods. Significantly more detections were made at night between the hours of 20:00 and 5:59 than 6:00 and 19:59 (2-sample *t*-test; $t=3.03$; $P=0.004$) (Fig. 4.11). Over the 3-year period, daytime detections were consistently low during midday hours (1100–1459) and high during the late afternoon (1500–1759). Periods of anomalously high dolphin activity were detected in February/March 2007, May 2007, October 2008, and February/March 2009, when the number of night and/or daytime detections was multiple times greater than the monthly median occurrence (Fig. 4.12).

The consistent occurrence of dolphins at Rapture Reef suggests that one or more species are resident in the area. Of the three species identified as the likely source of the signals, both bottlenose dolphins and spinner dolphins are known to occupy the nearshore waters of FFS (Andrews et al. 2010; Lammers, pers. obs.). The occur-
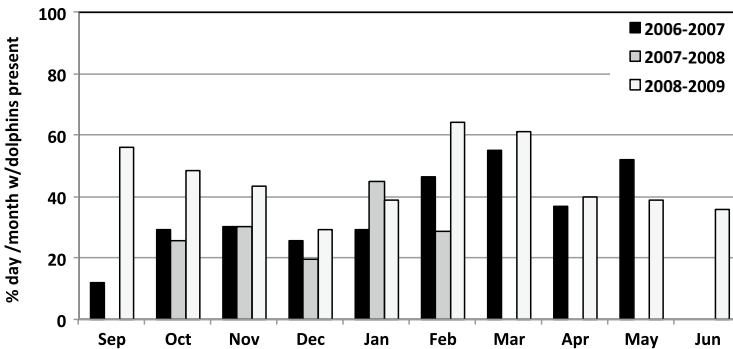
Fig. 4.10 Occurrence of dolphin whistles at Rapture Reef, FFS, measured by the percentage of days per month that dolphin whistles were detected in recordings between 2006 and 2009. *Note*: Months with no dolphin detections are due to an absence of recording effort in those months during those years, rather than to zero detections
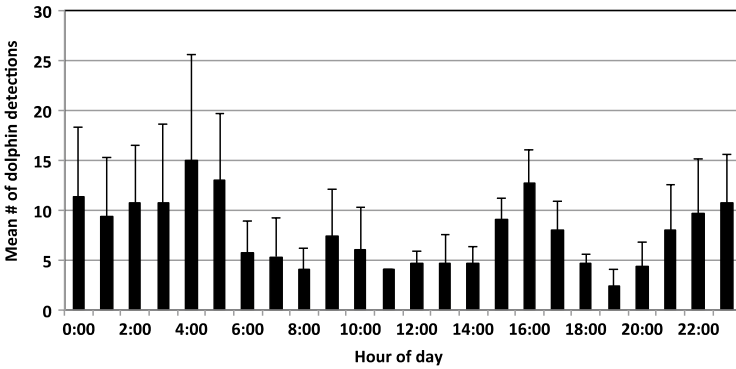
Fig. 4.11 The timing of dolphin whistles at Rapture Reef, FFS, detected by the automated algorithm separated hourly and averaged across the three deployment periods. Error bars represent standard deviations
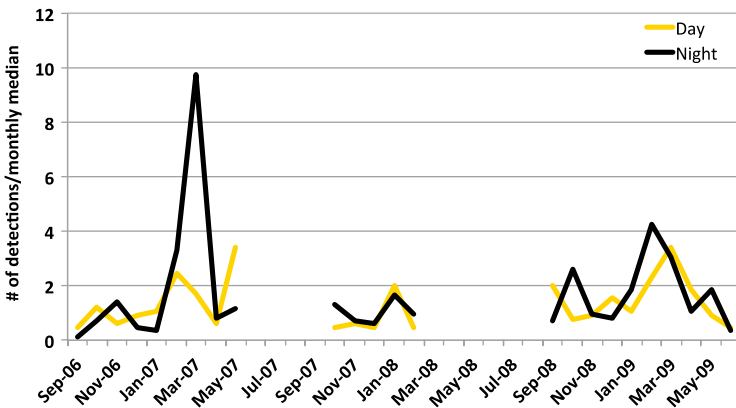
Fig. 4.12 The number of daytime and nighttime detections for each month normalized by the median of each category. High peaks indicated months that contained anomalously high numbers of dolphin acoustic detections

rence and timing of signaling in shallow waters are consistent with behavioral and acoustic patterns observed from spinner dolphins in the main Hawaiian Islands (MHI) (Lammers 2004; Lammers et al. 2008b). The low level of signal occurrence during midday hours followed by a late afternoon peak is characteristic of spinner dolphin acoustic behavior at resting locations (Lammers et al. 2008b). In both the MHI and NWHI, spinner dolphins seek out shallow water areas to rest during morning and midday hours and recover from nocturnal foraging activities (Karczmarski et al. 2005; Norris et al. 1994). In the late afternoon they become active again before moving offshore to begin foraging on the mesopelagic boundary community (MBC), a community of fish, shrimp, and squid that resides in deep waters during

the day, but migrates both vertically toward the surface and horizontally toward shore at night (Benoit-Bird et al. 2001; Benoit-Bird and Au 2004).

Echosounder surveys conducted at FFS have documented the nocturnal migration of a strong MBC associated with the island slope (Lammers et al. 2006b). Although it cannot be established whether spinner dolphins or another species are the primary source of nocturnal signals observed at Rapture Reef, the high incidence of signaling at night does suggest that dolphins are likely feeding in the area. In the MHI, spinner dolphins follow the MBC as it moves inshore at night (Benoit-Bird and Au 2003). Therefore, the consistent occurrence of dolphins in the area during nighttime hours suggests that the MBC's nocturnal migration reaches the inshore waters of Rapture Reef. This is ecologically significant because the MBC is an important source of prey for many species of benthopelagic and pelagic fish (Benoit-Bird et al. 2001) and likely contributes to the nutrient cycle of nearshore ecosystems (Benoit-Bird and Au 2004). Of special note are periods of peak nighttime dolphin occurrence. During February/March 2007, October 2008, and February/March 2009 dolphins were detected more frequently than usual at Rapture Reef at night, suggesting that these periods may reflect episodes of high MBC occurrence in the area tied to "pulses" of food availability, which may in turn be indicative of oceanographic or ecosystem processes that concentrate food in the area. Continued acoustic monitoring for the occurrence of dolphins could, therefore, help inform a long-term perspective on patterns in food availability and energy flux at this location.

4.2.3.2   Humpback Whales

Humpback whale song occurrence was seasonal, with the first singing whales detected each year around mid-December and the last whales recorded at the end of April or beginning of May. During the 2006–2007 deployment, a steady increase in the number of days per month with whale song detected occurred between December and March, followed by a rapid decline in April (Fig. 4.13). During the 2007–2008 deployment, the EAR only recorded until February 2008, but a similar seasonal trend in song occurrence was evident as in the previous year. In 2008–2009, the months with the highest number of days with song shifted to January and February, which were nearly equivalent. In addition, month by month, there were more days with humpback whale song in 2008–2009 than each of the previous two deployment periods, except in March when the number was slightly higher in 2007.

A statistical analysis of randomly selected recordings for each month comparing the 2006–2007 and 2008–2009 deployment periods confirmed that the latter period had significantly more recordings with whale song (Paired t-test, $t = 2.99$, $P = 0.04$). The increase in humpback whale singing activity between the two periods is also evident in the overall sound levels presented previously (Fig. 4.3). The period between January and April 2009 had both higher overall dB RMS levels and greater variability in the lower frequency bands, reflecting more humpback whale song energy than the same period in 2007. Whether the increases in humpback whale
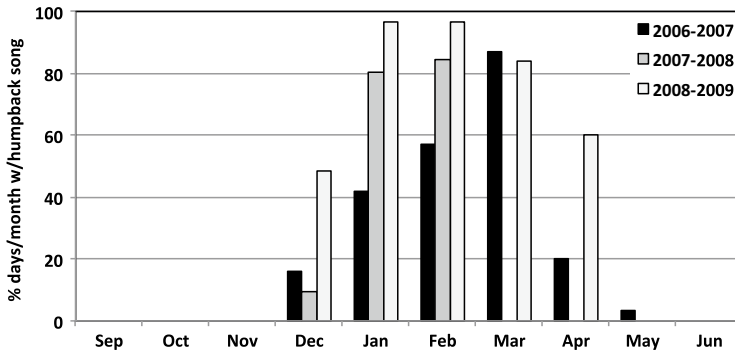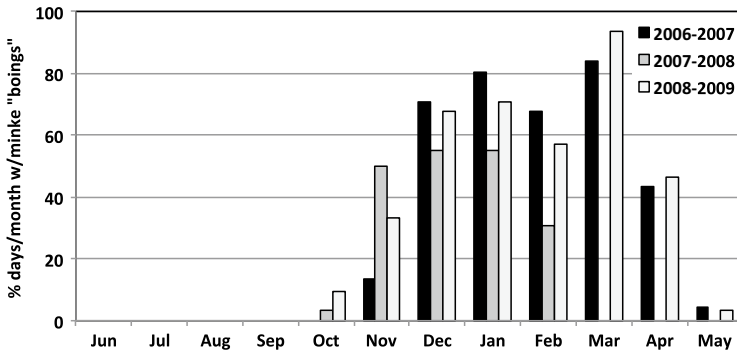
Fig. 4.13 Occurrence of humpback whale song units at Rapture Reef, FFS, measured by the percentage of days per month that whale song was detected in recordings between 2006 and 2009. *Note*: Months between March and May in 2007 without any detections are due to a lack of recording effort rather than an absence of detections

song observed at this location reflect changes in whale abundance at FFS is not clear, but certainly possible. The NWHI have been shown to be a more important wintering habitat than previously believed (Johnston et al. 2007; Lammers et al. 2011), so it is conceivable that the number of whales wintering at FFS increased proportionately to the estimated 6 % annual increase of the overall north Pacific population (Calambokidis et al. 2008). However, because these data do not allow us to localize or count singing animals near the EAR, the question cannot be directly addressed here.

4.2.3.3 Minke Whales

Minke whale boing sound occurrence was also seasonal and had a pattern similar to humpback whale song incidence (Fig. 4.14). However, whereas humpback whales were first recorded in December, minke whales began to be heard already in late October. In 2007–2008, the highest incidence of minke whale detections was evenly distributed between December and January. In both 2006–2007 and 2008–2009 there was an initial peak in January followed by a higher peak in March. In fact, in March 2009 minke whale calls were present nearly every day of the month. No diel variation in the occurrence of signals was evident. These data are the first long-term acoustic record of minke whale occurrence in the NWHI and suggest that this portion of the archipelago may be an important winter breeding area or a migration route. Of the approximately 19 species known or believed to regularly occur in the Hawaiian Archipelago (Barlow 2006), to date only spinner dolphin (*Stenella longirostris*) (Andrews et al. 2010; Karczmarski et al. 2005), humpback whales (Johnston et al 2007; Lammers et al. 2011), and false killer whales (Baird et al 2013) have received focused scientific attention in the NWHI. The data presented here suggest that minke whales also exploit the coastal waters of the NWHI and may be seasonally common near FFS.

Fig. 4.14 Occurrence of minke whale boings at Rapture Reef, FFS, measured by the percentage of days per month that minke whale calls were detected in recordings between 2006 and 2009. *Note*: Months between March and May in 2007 without any detections are due to a lack of recording effort rather than an absence of detections

4.3 Discussion

The results presented in this chapter demonstrate the potential of using long-term PAM sensors in remote coral reef ecosystems to address biological questions relating to the acoustic environment and a variety of taxa, from primary consumers to apex predators. Temporal patterns in the ambient soundscape reveal variations between seasons and years at French Frigate Shoals, and show division of the soundscape into acoustic "niches" (frequency bands) used by different groups of animals. Examining these niches in more detail and relating observed variations with other biotic (e.g., fish biodiversity, chlorophyll levels) and abiotic (e.g., temperature, turbidity) factors is likely to yield new insights into patterns of biological activity on coral reefs and the mechanisms that drive them. In addition, we have provided a starting place for monitoring the abundance of an ecologically important herbivore, parrotfish, and have shared new information on the occurrence of cetaceans in the Northwestern Hawaiian Islands (NWHI).

We have shown how a single acoustic sensor can potentially provide information on species diversity, trends in abundance, behavior, temporal patterns of presence or activity, and ecologically relevant patterns of soundscape variation. When combined with other remotely sensed and in situ data sets, a comprehensive view can emerge for how temporal, environmental, and biological variables affect the acoustic behavior of reef animals. Moreover, spatial comparisons using additional PAM data sets could reveal how the acoustic features of an area might be used as indications of biodiversity (e.g., Riede 1993, 1997; Sueur et al. 2008) and ecosystem health or resilience.

The use of passive acoustics as a research tool for long-term monitoring of biological communities on coral reefs is a comparatively young field. The utility of PAM has been demonstrated for studying the behavior of fish species in many

habitats and over a variety of time scales (e.g., Lobel 2002; Lobel et al. 2010; Locascio and Mann 2008, 2011; Luczkovich et al. 2008; Mann et al. 2009; Mann and Lobel 1995; Nelson et al. 2011; Van Parijs et al. 2009; Wall et al. 2013). However, many of the hundreds of sound-producing fish species are known only from laboratory studies, e.g., Fish and Mowbray (1970), and until recently, biological sounds have rarely been studied directly on coral reefs (Mann and Lobel 1995; Myrberg and Fuiman 2002; Tricas and Boyle 2014). There is a need for basic research to discover and further characterize the acoustic repertoires of coral reef fishes, as well as the behavioral context and temporal patterns in their sound production (Rountree et al. 2006). Similarly, more work needs to be conducted to identify other sounds on coral reefs to species, such as dolphin whistles and the sounds produced (directly or indirectly) by certain invertebrates (e.g., urchin skeletons rattling, Radford et al 2008).

More detailed studies are also needed in order to further utilize autonomous long-term recordings, particularly to develop techniques for abundance estimation using acoustic sensors. The data needs include the source levels of signals, information on propagation loss, background noise, the sound production rate of individuals, the behavioral contexts of sound production, and other biological and environmental covariates. Finally, another major challenge associated with long-term acoustic data collection is the processing and detection of signals of interest within large volumes of data. Much like the field of molecular biology decades ago, passive acoustic monitoring is presently still limited by the ability to process and interpret large data sets in a timely manner. This challenge will likely have to be solved by drawing from a combination of fields and technologies, including signal processing, computer science, and data mining.

Because of their reliance on sound as part of many biologically significant processes, marine organisms are vulnerable to acoustic disturbances, particularly from humans. These include short-term, local disturbances such as vessel transits, military sonar, seismic airgun exploration, industrial activities such as pile-driving and blasting, as well as long-term increases in ambient noise pollution due to increased human activity on a global scale (commercial shipping, industrial, etc.). As global climate change continues to drive changes in species distribution, disease, coral bleaching events, etc., continued monitoring of coral reefs and other environments is critical, and the use of PAM should be included as a tool in any comprehensive monitoring program, together with efforts to continue identifying and characterizing the vast number of sound sources in the ocean.

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