New Passive Acoustic Monitoring in Monterey Bay National Marine Sanctuary

Exploring natural and anthropogenic sounds in a deep soundscape

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***Abstract*—Understanding the marine soundscape is of growing importance to the National Marine Sanctuaries. In the center of Monterey Bay National Marine Sanctuary, a new Passive Acoustic Monitoring (PAM) project has begun. Using the power and communications infrastructure of the Monterey Accelerated Research System (MARS) cabled observatory, we deployed a broadband, digital, omnidirectional hydrophone on Smooth Ridge, near the MARS node (36°42.75'N, 122°11.21'W; depth 891 m). The system has been recording almost continuously since 28 July 2015. Natural biological sound (biophony) dominated long-term spectral average results at frequencies below 50 Hz, showing seasonal patterns in baleen whale vocalizations. Prevalence of blue whale vocalizations during August through October 2015 was succeeded by prevalence of fin whale vocalizations during November 2015 through January 2016. Diel variations (stronger signal at night) were evident for both species. In the high-frequency range, beaked whale clicks have been detected and represent a focus for advancing automated detection and classification methods. Biophonic richness in this soundscape was also indicated by human-expert analysis results for a one-week period, during which biological sound events were detected 86% of the time. Examination of natural physical sound (geophony) has included rainfall and the relationship between wind speed and ambient sound. The first 10 months of data showed that sound levels at 2 kHz followed Wenz curve predictions for wind speeds above 5 m/s. Examination of human-made sound (anthrophony) has included noise from vessel traffic and explosions detonated underwater during fishery operations. This new PAM project is providing extensive information on biophony, geophony, and anthrophony in this deep soundscape, information that is essential to understanding and managing acoustic habitat of the Sanctuary.**

Keywords*—passive acoustic monitoring; hydrophone; cabled observatory; marine mammals; marine noise; Monterey Bay National Marine Sanctuary

I. Introduction

Understanding the soundscape, as well as the impacts of human generated noise on natural acoustic habitat and populations, is growing in importance in both terrestrial and aquatic systems. As environments for which federal agencies are charged with stewardship, National Parks and Marine Sanctuaries are important foci for informing management through soundscape monitoring and research [1-3]. In marine environments, noise concerns include both acute and chronic effects [3,4]. While acute noise sources have received attention due to dramatic impacts on marine mammals observed in some regions, chronic noise is increasingly being recognized as a global issue that must be addressed regionally through ecosystem based management [3]. Chronic noise can persistently and progressively degrade acoustic habitat, thereby interfering with essential life activities of animals who rely on sound for communication, navigation and foraging.

Because marine biophony, geophony and anthrophony (soundscape components catagorized as in [5]) span a vast frequency range, effective soundscape research requires recording at a high sample rate across a broad frequency range. Data storage and power requirements can limit stand-alone hydrophone deployments, reducing duration or requiring discontinuous time-series collected in duty cycles. The communications and power infrastructure of cabled observatories can bypass these constraints, enable more effective recording of marine soundscapes, and allow real-time observation. In this project, we employ the Monterey Acclerated Research System (MARS) cabled observatory, which extends from the coast of central Monterey Bay, California, offshore to the continental slope (Fig. 1).

The MARS site, in the heart of Monterey Bay National Marine Sanctuary (MBNMS, Fig. 1) was expected to be an effective location for soundscape research. It was anticipated that this deep environent would be less impacted by sound sources typical of shallower environments, including

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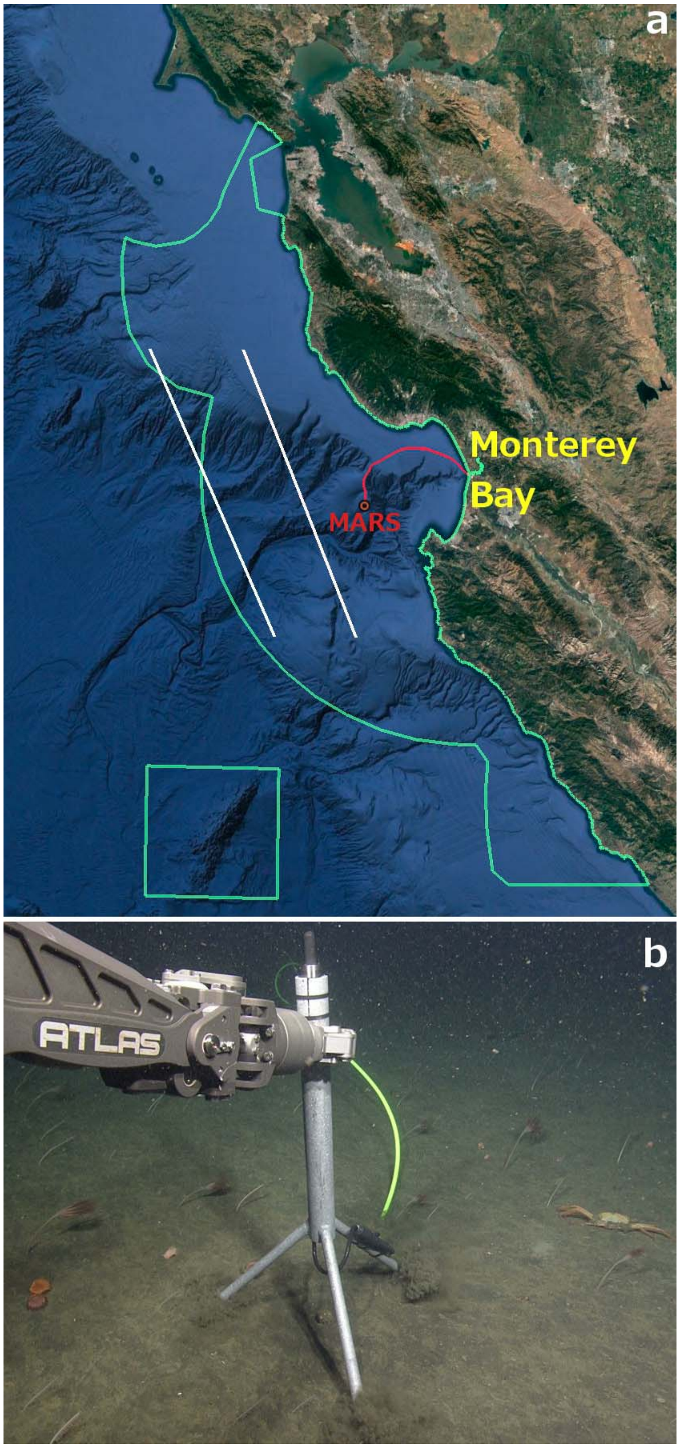

Fig. 1. Passive acoustic monitoring in Monterey Bay National Marine Sanctuary. (a) Sanctuary boundaries are in green; the red line shows the path of the MARS cable, with the terminal node on Smooth Ridge (36°42'45'' N, 122°11'13''W, 891 m depth). The white lines show the western and eastern boundaries of commercial ship traffic lanes in the Monterey Bay region. (b) Hydrophone deployment on 28 July 2015, following connection to the MARS node and spooling 70 m of extension cable. The hydrophone is affixed to the top of the tripod, approximately one meter above the seafloor.

recreational boat traffic, snapping shrimp, and surf break. MARS is also well placed relative to the migration paths of species that move equatorward and poleward along the California coast [6-8] and is adjacent to blue whale foraging habitat along the continental shelfbreak, where dense krill swarms form [9]. MARS was also considered to be a potentially good location from which to acoustically study one of the more enigmatic marine mammals, beaked whales. These odontocetes live in small groups, are deep divers, and have a relatively low visual profile during surfacing, thus making them difficult to study using visual surveys [10-12]. Hydrophones in deep water (840 m) off Point Sur, at the southern end of Monterey Bay, recorded beaked whales in each of four deployments between August 2008 and August 2010. These recordings also indicated the value of continuity, as the most frequent detections of beaked whales occurred in the deployment having the highest percentage of recording time (50% duty cycle of 5 minutes on/off). In this deployment about 1/3 of the total days contained at least one bout of beaked whale vocalization [13]. The whales' deep-water foraging, and the short range over which their high-frequency clicks can travel (< 4 km) motivate research employing continuous recording in deep water, as the MARS infrastructure provides.

It is a formative time for ocean noise policy. In June 2016 NOAA released a draft Ocean Noise Strategy Roadmap intended to inform and coordinate agency-wide action in marine soundscape management [3,4]. The roadmap identifies the National Marine Sanctuaries as key assets to achieve the ecological goals of acoustic habitat protection. Located in the central MBNMS, this new passive acoustic monitoring project aims to better understand the biophony, geophony, and anthrophony of a deep-water protected environment, to explore relationships between biophony and ecosystem variation over time scales ranging from episodic (upwelling) to interannual (El Niño – Southern Oscillation), and to examine the intersection of biophony and anthrophony toward informing management of acoustic habitat.

II. Methods

A. Data Acquisition

Soundscape recording employs an Ocean Sonics icListen HF, a broadband, digital, omnidirectional hydrophone with a bandwidth of 10 Hz to 200 kHz. It has sampled almost continously at 256 kHz since deployment on 28 July 2015. Data are streamed directly to the Ocean Sonics Lucy software for shore-side recording. Delayed detection of network problems occasionally caused recording outages lasting from hours to days, however improvements to the recording infrastructure reduced outages as the time-series progressed.

B. Data Analysis

To examine the first ten months of recordings (August 2015 through May 2016), we computed power spectral density estimates using the Long-Term Spectral Average (LTSA) method in Triton (cetus.ucsd.edu/technologies_Software.html), adapted for efficient execution in a HTCondor pool of computers [14]. These computations were parameterized for three frequency ranges, appropriate for vocalizations from different species (Table I). Daily LTSA results were bin averaged to monthly means resolved at 15s resolution through the day, essentially describing sound energy variation through an average day during each month. We present results for the low-frequency range to illustrate seasonal and diel variations in blue and fin whale vocalizations.

TABLE I. LTSA PARAMETERIZATION FOR TRITON

Parameter	Signal frequency range		
	low	*mid*	*high*
Frequency range (Hz)	0 to 1,280	0 to 6,400	0 to 128,000
Frequency bin (Hz)	1	10	100
Sample rate (s^{-1})	2,560	12,800	256,000
Samples per FFT	2,560	1,280	2,560
Time bin (s)	5	5	5
Target species	blue and fin whales	humpback and minke whales	beaked, sperm, and killer whales; dolphins

To examine biophony in detail during a one week period, recordings from 25 – 31 October 2015 were analyzed interactively using the PAMGUARD software [15,16], including detectors for clicks, whistles and moans [17,18]. Analyses were separated into frequency ranges above and below 500 Hz. For the low frequency band, original 256 kHz data were decimated to 1 kHz, and baleen whale vocalizations were detected by visual inspection of LTSA plots generated by PAMGUARD (not Triton results described above for the long-term analyses). For the high-frequency band, which includes toothed whale and delphinid vocalizations, detector modules for clicks and whistles were applied to original 256 kHz data, and automated results were checked by visual inspection. Start and end times of all detections were recorded, and species identification was attempted manually based on waveform and spectrogram plots. For unidentified detections, if the signal was too faint to distinguish from ambient noise, the detection was not used. Summary of results was based on defining vocalization events as the presence of marine mammal vocalizations with less than 10 minutes between detections, and then quantifying the percentage of the total time containing vocalization events.

Examination of geophony focused on wind and rain. To examine sound variation due to wind, power spectral density at 2 kHz was extracted from the mid-frequency range LTSA results (Table I) and compared to wind speed measured at NDBC station 46042, located 25 km WNW of MARS (36°47'29" N 122°27'6" W). Hourly wind data were interpolated to the 5-second time reference of LTSA results, so that the influence of transient sounds on this relationship would be evident. Observational results were compared with theoretical predications using values extracted from Wenz curves [19,20] computed for a range of wind speeds.

Examination of anthrophony focused on two common noise sources, vessel traffic and fishery explosions. To characterize noise from a typical vessel transit near the hydrophone, an example was selected from early in the recording period (3 August 2015), based on examination of LTSA plots. For this example results from all three LTSA computations (Table I) were subset to non-overlapping frequency ranges and combined to produce a spectrogram spanning the full frequency range (0 to 128 kHz). To characterize noise originating from the offshore shipping lanes (Fig. 1), we examined recordings from 30 – 31 December 2015, when the largest container vessel to dock in a US port, the CMA CGM *Benjamin Franklin*, first transited along the west coast between the ports of LA and Oakland, passing by Monterey Bay. To characterize noise from a fishery explosion, an example was selected from early in the recording period (3 August 2015), and its signal was represented as waveform and spectrogram.

III. RESULTS

The results are organized as follows. In section A, an overview of low-frequency (0–1 kHz) variability is presented using the first 10 months of recordings. In section B, biophony is examined using low-frequency LTSA results and human-expert analyses of the full frequency range that can be analyzed from the recordings (0–128 kHz). In section C, geophony is examined for the cases of long-term variation in wind and short-term variation due to a rain squall. In section D, anthrophony is examined for the cases of near and far vessel traffic, and fishery explosions.

A. Overview of low-frequency LTSA results

Monthly LTSA results reveal modulation of the soundscape on seasonal and diel time scales (Fig. 2). Most of the variations occur below 100 Hz. The most energetic features are bands of high power spectral density at specific frequencies, for example three dominant frequency bands (centered at 15, 29 and 44 Hz) during August through October 2015, transitioning to one dominant band (centered at 21 Hz) during November – December 2015. Diel variations are also indicated in these bands. For example, the 44 Hz band during September exhibited 6% variation about the daily mean, and the 21 Hz band during November exhibited 8% variation about the daily mean. These signals are of biological origin and illustrate the dominance of biophony in this low frequency range. They are examined in relation to species' vocalizations in the next section. A second feature evident in all months is the occurrence of clouds of enhanced sound energy near midnight and midday, largely within the frequency range of 10 to 100 Hz. The clouds are broader in frequency range than the bands and do not persist throughout the day as the narrower bands do. There is some indication of seasonal modulation in the timing of the midday cloud, becoming later during winter (Fig. 2). The origin of these features has not yet been examined.

B. Biophony

The relatively high-energy bands in the LTSA results (Fig. 2) correspond with vocalizations of baleen whales. The three bands that were most energetic during August through October 2015 were centered at 15, 29 and 44 Hz (Fig. 2). Averaging across these months and the full daily cycle clearly defines these peaks (Fig. 3a), which are caused by blue whale vocalizations (B calls) and associated harmonics (Fig. 3b). Additionally, a more subtle peak centered at 80 Hz is indicative

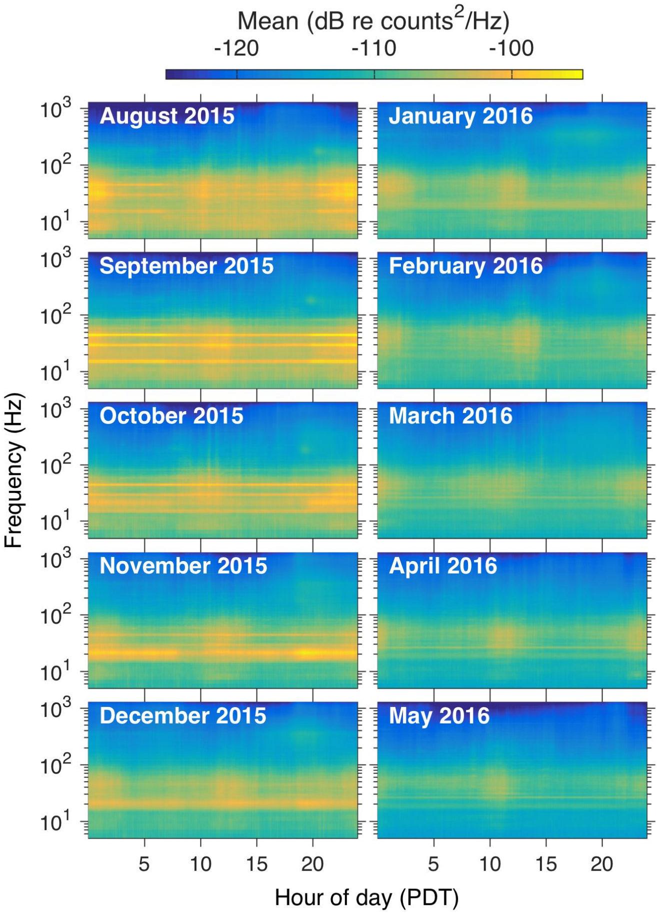

Fig. 2. Mean daily soundscape variations from low-frequency LTSA power spectral density (Table I) for the first 10 months of hydrophone data.

of another type of blue whale vocalization (A calls, Figure 3a). The band that was most energetic during November 2015 through January 2016 was centered at 21 Hz (Fig. 2). Averaging across these months and the full daily cycle clearly defines this peak (Fig. 3a), which is caused by fin whale vocalizations (Fig. 3c). While seasonal variation in the dominant baleen whale vocalization frequencies is pronounced, temporal overlap is also clear – evident as the blue whale peaks at 29 and 44 Hz coincident with the fin whale peak at 21 Hz in the November 2015 through January 2016 mean (Fig. 3a and corresponding LTSA results in Fig. 2).

Over the 7-day period analyzed by a human expert, vocalization events occupied 86% of the 168 hours (Table II). The percentage of time for which low frequency vocalization events were detected (79%) was greater than that for high frequency (55%). The majority of the low frequency detections were of blue whales (B calls), fin whales and humpback whales, often vocalizing concurrently. With clicks and whistles, it is more difficult to identify the species vocalizing. However the detection of clicks and whistles indicates the animal was relatively near the hydrophone because their high-frequency energy cannot travel far; for example delphinid clicks travel 1–2 km [21-23]. Two events of beaked whale clicks were identified. The 92.18 hours of high-frequency detections came from 34 events of clicks and whistles, with an average event length of 2.71 hours. Nine events were longer than 5 hours, and two were longer than 10 hours with continuous clicking and/or whistling.

At the high-frequency end of biophony are a great variety of odontocetes clicks. As described in the introduction, beaked whales are of particular interest, and reliable identification of their clicks is essential. An example of a beaked whale click is shown in Fig. 4, exhibiting peak energy centered at ~ 32 kHz, a duration of ~ 0.3 milliseconds, and 18 zero crossings. Beyond the challenges of positive identification inherent in the biological signal (variation in click attributes within a species, overlap of click attributes among odontocetes, variations in

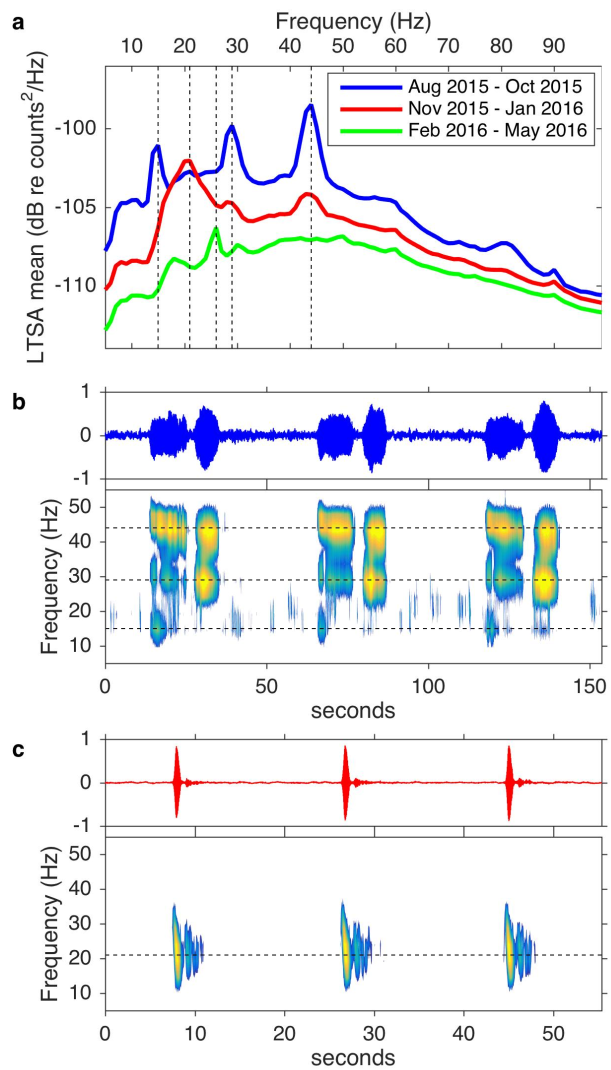

Fig. 3. Biophony: seasonal change in low-frequency vocalization energy. (a) Seasonal averaged LTSA spectra, computed from selected months of LTSA results (Figure 2). Months were grouped (legend) based on similarity of dominant patterns. (b) Example waveform and spectrogram plots of blue whale vocalizations (B calls and harmonics) causing the August – October peaks at 15, 29 and 44 Hz. (c) Example waveform and spectrogram plots of fin whale vocalizations causing the November – January peak at 21 Hz. MARS recordings in (b) and (c) were low-pass filtered with a 100 Hz cutoff and normalized for representing the waveform and spectrogram. Dashed lines in the spectrograms of (b) and (c) correspond with those defined in (a).

signal due to variations in distance and orientation of the source relative to the hydrophone), analysis is complicated by high-frequency noise originating from the MARS node (Fig. 4). We cannot yet definitively identify the species associated with this click, however its attributes are consistent with prior identifications of beaked whale clicks in recordings from deep water off Point Sur [11,13]. Methods development is presently underway, including reducing influence of MARS noise, and comparison of detectors developed for PAMGUARD with emerging wavelet-based detection and classification.

TABLE II. BIOPHONY DURING 25 – 31 OCTOBER 2015

Frequency range (Hz)	Detections (hours, % of total)
0 – 128,000	144.25, 86%
0 – 500	132.17, 79%
500 – 128,000	92.18, 55%

C. Geophony

The first 10 months of LTSA results for the mid-frequency range (Table I) show a clear relationship to wind speed (Fig. 5). Power spectral density at 2 kHz followed Wenz curve predictions for wind speeds above ~ 5 m/s. The narrowing envelope of sound levels toward higher wind speeds is determined by an increasing sound level minimum, and it indicates the increasing influence of wind-driven processes as a sound source. Under the umbrella of surface roughness, the processes by which wind generates sound include wave breaking (whitecaps), cavitation, flow noise, and generation of an interacting wave spectrum by wind turbulence at the air-sea interface [20]. Below wind speeds of ~ 5 m/s, other sources of sound dominate, including local transient sound sources and distant shipping noise, and the Wenz curve is not predictive (Fig. 5).

The sensitivity of deep-water acoustic signals to surface physical phenomena is also shown by the passage of a rain squall over the MARS site (Fig. 6). Passage of a squall was suggested by observations of the real-time spectrogram on 21 March 2016, as rising broadband signal below ~ 50 kHz, and brief (~ 2 minute) periods of maximum signal (Fig. 6a, maxima between 22:40 and 22:50). Examination of weather radar showed that a squall had recently passed over the hydrophone during its eastward movement (Fig. 6b; image time indicated in Fig. 6a).

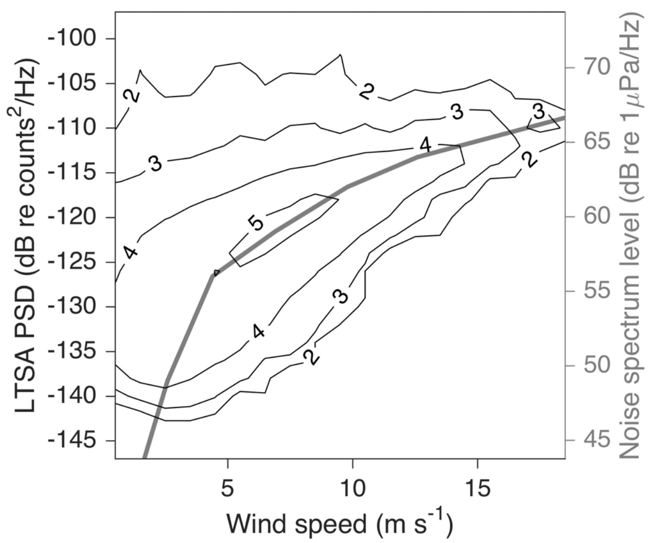

Fig. 5. Geophony: wind influenced sound. Relationship between wind speed measured at NDBC Station 46042 (36°47'29" N 122°27'6" W, 25 km WNW of MARS) and 2 kHz sound levels quantified by LTSA power spectral density of MARS hydrophone data. Contours are $\log_{10}$ (number of observations). The thick gray line is the Wenz curve estimate at 2 kHz.

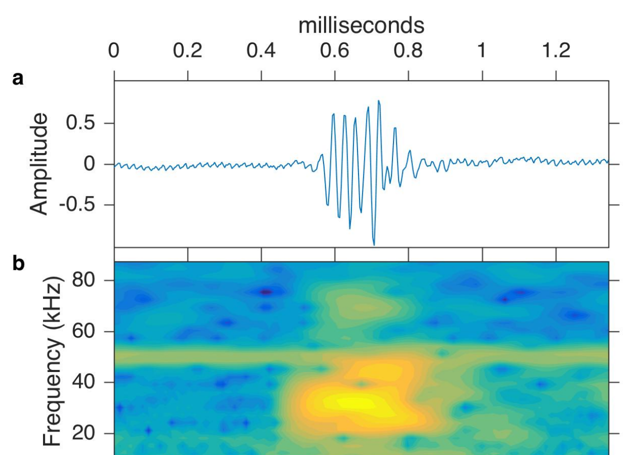

Fig. 4. Biophony: example of a beaked whale click detected on 28 October 2015, within a period of increased beaked whale click detections. (a) Waveform represented as normalized amplitude. (b) Spectrogram computed with nfft = 85, overlap = 95, and Hanning window; represented as relative spectral level. The continuous signal centered near 50 kHz is due to noise from the MARS power system.

Both of these sources of geophony originate at the surface and tend to travel more vertically and direct path [20]. Thus, in contrast to seismic sources of geophony, they represent more specifically the local soundscape.

D. Anthrophony

Sounds of local vessel transits and operations of vessel machinery are clearly discernible in listening to the MARS recordings. A typical local vessel transit shows a number of features (Fig. 7): (1) The sound impacts a large frequency range (~ 20 Hz to 50 kHz). (2) The sound begins in mid range (~ 500 Hz to 15 kHz) and spreads to higher and lower frequencies as the vessel approaches the hydrophone. (3) Departure mirrors approach, and the affected frequency range correspondingly narrows. The broadband energy suggests a smaller vessel, and fishery explosions detected this same day suggest that this example transit may represent a fishing vessel, however we cannot specifically match this sound to vessel type. The example, selected at random, suggests a quieter background after the vessel transit than before (Fig. 7). The many examples of local vessel transits will allow us to examine and statistically evaluate this suggested pattern.

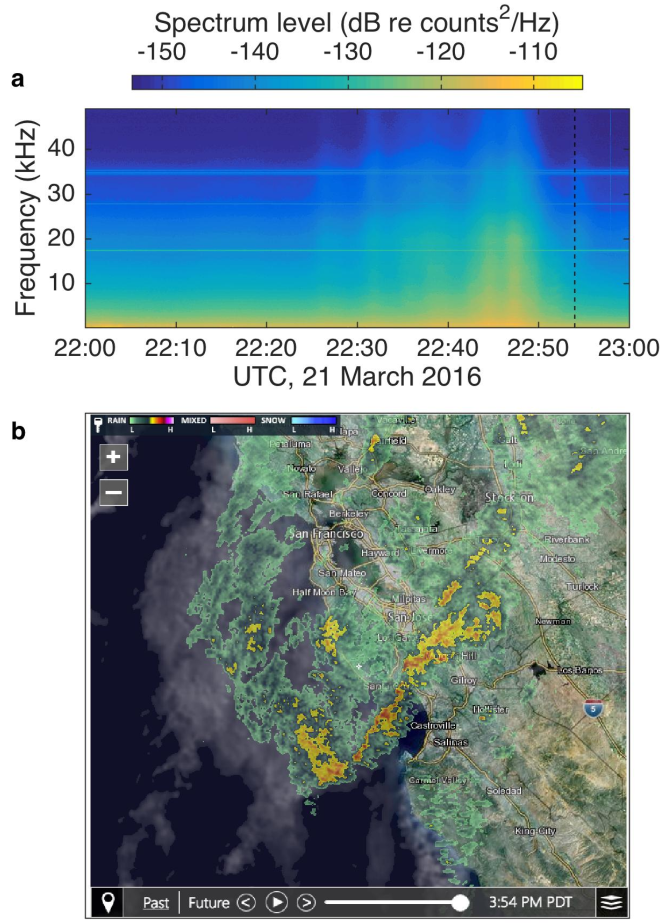

Fig. 6. Geophony: acoustic detection of a rain squall. (a) LTSA during one hour on 21 March 2016. (b) Weather radar image shows the squall line having passed over of the MARS location (image time indicated by the dashed line in (a). The squall moved west to east.

Distant noise originating from the offshore shipping lanes (Fig. 1) is also of interest. Massive container vessels recently built have the potential to reduce noise from commercial shipping operations, by reducing the number of ships required to transport goods, and by design for quieter operation. The CMA CGM *Benjamin Franklin* is the largest container vessel to dock in a US port, and its maiden voyage along the US west coast occurred as the ship transited between the ports of LA and Oakland on 30 – 31 December 2015. This transit passed by the MARS hydrophone, and its very low frequency sound (< 1 Hz) was detected (Fig. 8). This frequency is below the lower limit of the hydrophone's bandwidth (10 Hz), however diminished response at lower frequencies is recorded. Production of sound at these low frequencies is consistent with the size and rotation rate of the vessel propeller as it transited at approximately half of its maximum speed [24]. Ecologically, the striking feature of this recording is that the vessel noise was well below the frequency range of fin whale vocalizations (Fig. 8), presumably minimizing direct interference with animal communication.

The final example of anthrophony is a fishery explosion. These distinct sounds were noticed shortly following

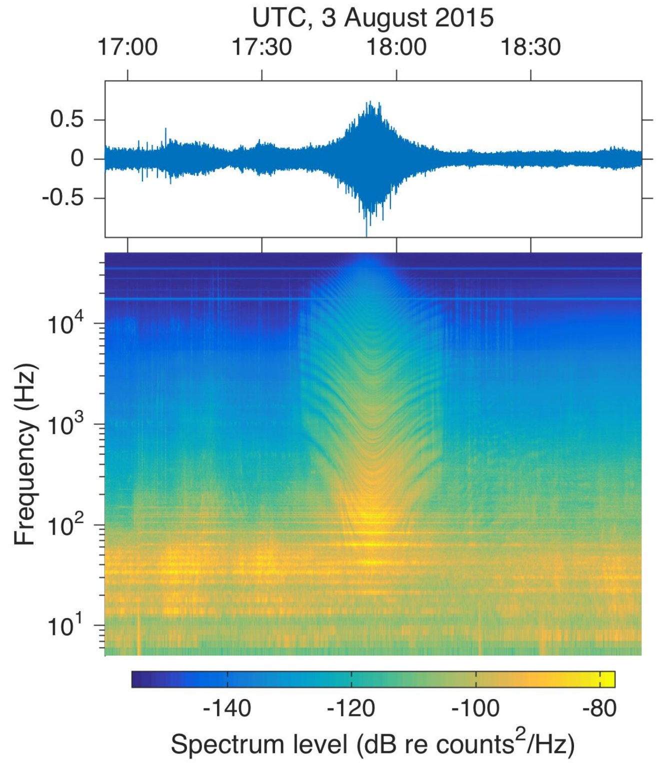

Fig. 7. Anthrophony: a typical boat transit detected by the hydrophone, represented as normalized waveform (top) and LTSA power spectral density (bottom).

deployment of the hydrophone and were later confirmed to be explosions detonated underwater during squid fishery operations (A. Meyer Loebbecke and S. Baumann-Pickering, Scripps Institution of Oceanography, personal communication). The intention of these detonations is to deter interference in fishing operations by curious and hungry pinnipeds (seals, sea lions). The sudden nature of the sound is pronounced in both the waveform and spectrogram representations (Fig. 9). The intensity is accurately represented relative to background in the waveform plot of the unfiltered recording. During the hour from which this example was taken, beginning at 11:00 on 3 August 2015 (UTC), nine such explosions were detected. Temporal variations in the occurrence of explosions are being examined with the first six months of recordings (A. Meyer Loebbecke and S. Baumann-Pickering, Scripps).

IV. Summary and Discussion

In the vast and largely dark ocean, sound is an essential dimension of life, used by animals in diverse ways to navigate, communicate, and forage. Sound is thus also an essential dimension of ocean stewardship. As environments in which stewardship efforts are focused, the National Marine Sanctuaries are ideal places in which to further our scientific knowledge of soundscapes, as a basis for informed management. Toward this purpose, the recent deployment of a hydrophone on a cabled observatory in the heart of Monterey Bay National Marine Sanctuary represents a unique and effective scientific resource. The continuity of this data stream supports more complete examination of the soundscape than is

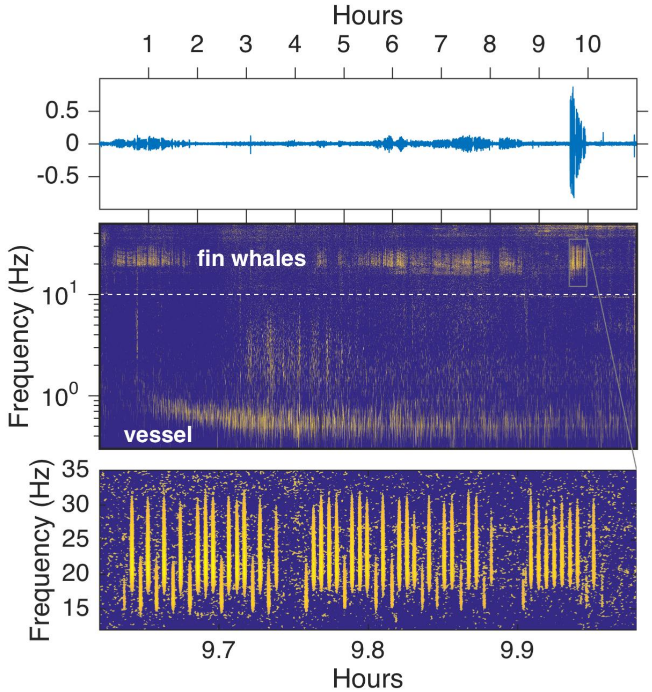

Fig. 8. Anthrophony: acoustic detection of distant shipping noise, specifically from the largest container vessel to dock in a US port, the CMA CGM *Benjamin Franklin*. The vessel transited offshore of the MARS hydrophone (Figure 1) during its first passage between the Ports of Los Angeles and Oakland. The start time of this recording is 30 December 2015 23:00 PST. Shown are waveform (top), the log of power spectral density (middle), and a zoom on the period of most active fin whale vocalization (bottom, domain delineated by the box in the middle panel). In the middle panel, the dashed line marks the low end of the range for the hydrophone's bandwidth specification.

possible from stand-alone deployments. Real-time data flow to shore introduces possibilities for event detection and response, for not only biological research, but also marine operations. For example, acoustic signals from a malfunctioning system moored on the bottom of Monterey Canyon were detected in February 2016, and this motivated deployment of an autonomous surface glider to communicate with the system and remotely diagnose and repair the problem. For more effective biological research, real-time knowledge of variations in vocalizations can be used to detect periods of enhanced animal activity, which can in turn motivate complementary research and monitoring efforts such as visual surveys and tagging.

Research results from this new source of passive acoustic monitoring reveal great complexity within this deep-water marine soundscape. The sensitivity of passive acoustic sensing, and therefore its great utility, were emphasized by the clear signals of wind and rain originating from processes occurring at the ocean surface, 900 m above the hydrophone. Seasonal variation was evident in the dominant sources of biophony during the fall to winter transition – from blue whales to fin whales – and these sources of biophony dominated mean patterns in the soundscape at low frequencies. The richness of biophony was further represented by expert analysis of a single week of data, in which sound events from marine mammals occupied 86% of the time. The recordings also reveal dimensions of anthrophony, such as vessel noise from near to far sources and explosives detonated underwater. The complex intersections of anthrophony and marine life are very important to understand and manage.

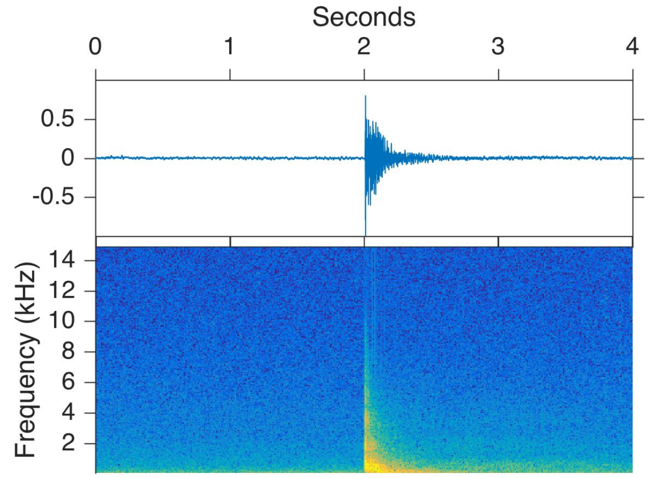

Fig. 9. Anthrophony: acoustic detection of a fishery explosion ('seal bomb'), represented as waveform (top) and the log of power spectral density (bottom).

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