JASA ARTICLE

Seasonal trends and primary contributors to the low-frequency soundscape of the Cordell Bank National Marine Sanctuary[a)]

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ABSTRACT:
Passive acoustic monitoring of ocean soundscapes can provide information on ecosystem status for those tasked with protecting marine resources. In 2015, the National Oceanic and Atmospheric Administration (NOAA) established a long-term, continuous, low-frequency (10 Hz–2 kHz) passive acoustic monitoring site in the Cordell Bank National Marine Sanctuary (CBNMS), located offshore of the central United States of America (U.S.) west coast, near San Francisco, CA. The California Current flows southward along the coast in this area, supporting a diverse community of marine animals, including several baleen whale species. Acoustic data analysis revealed that both large vessels and vocalizing baleen whales contribute to the ambient soundscape of the CBNMS. Sound levels fluctuated by month with the highest levels in the fall and lowest levels in the summer. Throughout the year, very low-frequency (10–100 Hz) sound levels were most variable. Vessels and whales overlap in their contributions to ambient sound levels within this range, although vessel contributions were more omnipresent, while seasonal peaks were associated with vocalizing whales. This characterization of low-frequency ambient sound levels in the CBNMS establishes initial baselines for an important component of this site's underwater soundscape. Standardized monitoring of soundscapes directly supports NOAA's ability to evaluate and report on conditions within national marine sanctuaries.

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I. INTRODUCTION

The soundscape of an underwater environment is composed of acoustic contributions from biotic and abiotic natural sources, and often also includes sounds generated by anthropogenic activities; these latter sources may be harmful to sound-sensitive species (Erbe *et al.*, 2019; Popper and Hawkins, 2019; Williams *et al.*, 2015). Passive acoustic

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monitoring is a noninvasive and relatively economical method for observing a soundscape over extended durations (Sousa-Lima, 2013). Data collected through long-term passive acoustic monitoring efforts can provide critical information about the status of an ecosystem and help record changes over time to inform those tasked with protecting marine resources (Buxton *et al.*, 2019; Hatch *et al.*, 2016; Van Parijs *et al.*, 2015).

In the United States of America (U.S.), the National Oceanic and Atmospheric Administration (NOAA) manages 14 national marine sanctuaries and 2 national marine monuments located throughout the U.S. Exclusive Economic Zone, which extends 200 nautical miles from the coast. The guiding legislation for the NOAA Office of National Marine Sanctuaries (NMS) is the National Marine Sanctuary Act, which mandates, among other things, "comprehensive and coordinated conservation and management of these marine areas, and activities affecting them…" and that the sanctuaries are to "maintain the natural biological communities in the national marine sanctuaries, and to protect, and, where appropriate, restore and enhance natural habitats, populations, and ecological processes" (National Marine Sanctuaries Act, 2000).

The Cordell Bank National Marine Sanctuary (CBNMS; Fig. 1) is one of five national marine sanctuaries in the northeast Pacific along the west coast of the contiguous U.S. CBNMS borders the central-western boundary of the Greater Farallones NMS, which is adjacent to the Monterey Bay NMS to the south. The CBNMS is located on the continental shelf and slope and is geographically exposed to the deep-open ocean (Fig. 1). Within the CBNMS, the Cordell Bank (42 sq mi) rises to 35 m beneath the surface and is surrounded by soft sediment on the shelf and a steep drop to the west (NOAA, 2014). The Cordell Bank comprises approximately one-third of the total area of the CBNMS. The prevailing California Current flows southward along the coast in this area, and the annual upwelling of nutrient-rich deep ocean water supports the sanctuary's rich biological community of fishes, invertebrates, sea birds, and marine mammals (Office of National Marine Sanctuaries, 2009). Many of the marine species in the CBNMS can detect and utilize sound for communication; however, marine mammals are of particular interest because of their known soniferous behavior (and, thus, detectability via passive acoustic monitoring), their frequency range overlaps with anthropogenic sound sources, and they are the target of conservation efforts within many sanctuaries (Gedamke *et al.*, 2016; Hatch and Fristrup, 2009). The CBNMS provides habitat for endangered populations of blue (*Balaenoptera musculus*) and fin

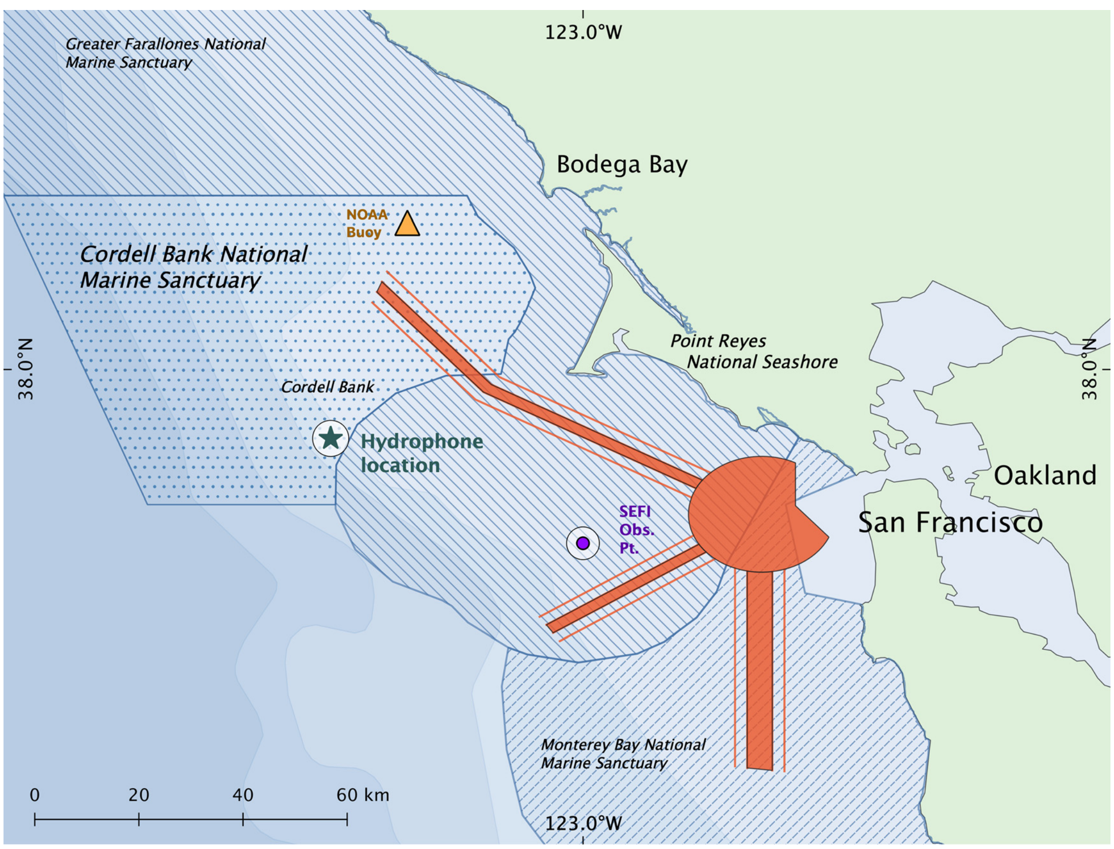

FIG. 1. (Color online) Map of hydrophone location (star) within the Cordell Bank National Marine Sanctuary (CBNMS; dot filled outline) and surrounding area, including San Francisco Bay Area traffic separation scheme shipping lanes (opaque orange circle and lines), the Greater Farallones National Marine Sanctuary (NMS; solid diagonal line fill), and the Monterey Bay NMS (dashed diagonal line fill). The Southeast Farallon Islands (SEFI) land-based surveys were conducted from an island lighthouse marked by the purple dot. Wind data were collected by NOAA Station 46013 (filled triangle). Gradient shading in water (light to dark) indicates bathymetric contours at 200 m, 1000 m, 2000 m, 3000 m, and 4000 m.

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(*Balaenoptera physalus*) whales and federally protected humpback whales (*Megaptera novaeangliae*; Gill *et al.*, 2007; Scales *et al.*, 2017). Gray whales (*Eschrichtius robustus*) are also common in the region (Guazzo *et al.*, 2017). These soniferous cetaceans rely on low-frequency sound for basic life functions of feeding, navigation, and reproduction.

Broadly, large cetaceans are threatened by anthropogenic activity in the form of ship strikes, entanglement, and increased noise (Frankel and Gabriele, 2017). Anthropogenic noise can impact whales in a number of ways, including hearing loss, masking, and behavioral changes (Blair *et al.*, 2016; Castellote *et al.*, 2012; Clark *et al.*, 2009; Fournet *et al.*, 2018; Melcón *et al.*, 2012; Parks *et al.*, 2016; Richardson *et al.*, 1995). San Francisco Bay is home to large global shipping ports, including the ports of Oakland and San Francisco (Moore *et al.*, 2018), which are accessed by shipping lanes that pass through all three national marine sanctuaries in the area. Therefore, noise from the ships that use these ports likely impacts cetaceans in all three sanctuaries. A traffic separation scheme has been in place in the San Francisco Bay Area since 1973 and was modified in 2013, primarily to increase mariner safety but also to reduce the overlap of known whale hot spots and ship traffic; however, this reduced overlap between vessels and marine mammals in the CBNMS still poses a threat to marine mammals (NOAA, 2014). The CBNMS is exposed to noise radiated not only from the San Francisco traffic separation scheme shipping lanes but also from regional offshore traffic transiting in deeper waters along the U.S. west coast.

Under certain environmental conditions, the sound velocity structure of the water column can create conditions favorable for the efficient propagation of low-frequency vessel sounds to areas outside of the traffic separation scheme, potentially degrading whale habitat in other areas of the sanctuaries. Historical underwater recordings from this area have been compared to more recent data showing that sound levels have increased in the North Pacific since the 1960s (Andrew *et al.*, 2010; Chapman and Price, 2011). These increases in low-frequency ambient sound levels may be positively correlated with economic growth via the expansion of commercial shipping (Frisk, 2012; McKenna *et al.*, 2012a) as an increasing number of larger and faster ships have been linked to increased ambient noise levels (McDonald *et al.*, 2006a). The commercial shipping lanes in and around the CBNMS experience minimal seasonal and diel variability in traffic density (Jensen *et al.*, 2015). Although many previous studies have documented ambient and vessel-related noise near the port of Los Angeles (McDonald *et al.*, 2006a, 2008; McKenna *et al.*, 2012b; Redfern *et al.*, 2017), no studies have specifically sought to document sound levels in the CBNMS.

Baseline monitoring of underwater sound levels in the CBNMS supports the ability of marine sanctuary managers to characterize and track long-term changes in the soundscape. Monitoring underwater soundscapes across biologically important areas in U.S. waters is a priority for NOAA, including priority acoustic habitats within national marine sanctuaries that are affected by noise, such as the CBNMS (Ferguson *et al.*, 2015; Gedamke *et al.*, 2016; Hatch *et al.*, 2016). Additionally, acoustic monitoring and soundscape research are specifically identified as priority activities in the CBNMS management plan (NOAA, 2014). Current CBNMS objectives related to sound include acoustic monitoring of ambient sound in the sanctuary, assessing the sources and effects of anthropogenic activities on marine organisms and ecosystem health, and developing management activities to conserve sanctuary resources. To support these management priorities, it is necessary to understand the relative inputs to the sanctuary soundscape and any spatial or temporal patterns of sounds. Additionally, the potential effects of these sounds on species of concern must be assessed (Cordell Bank National Marine Sanctuary, 2014).

Soundscape monitoring in the CBNMS is achieved through one of the 12 stations included in the NOAA/National Park Service Noise Reference Station (NRS) network. The NRS network was established in 2014 in an effort to document current baseline levels and sources of ambient sound in U.S. waters using calibrated autonomous underwater hydrophone moorings (Haver *et al.*, 2018). The NRS in the CBNMS is the first effort to document soundscape conditions in the sanctuary, and data collected support the NOAA Office of National Marine Sanctuaries' goal of NMS system-wide comparative measurements. Continued passive acoustic monitoring in the CBNMS provides data to support NOAA's efforts to characterize the soundscape, including the relative presence of animals and activities that make sounds and assess the overall status of ambient noise as a stressor affecting the condition of the sanctuary as prescribed in the CBNMS management plan (NOAA, 2014).

Guided by the scientific needs of the NOAA Office of National Marine Sanctuaries' managers of protected marine resources, here, we document the underwater soundscape of the CBNMS during the first deployment of the NRS hydrophone mooring between October 2015 and October 2017. Specifically, we quantify baseline measurements of ambient sound levels, assess seasonal sound level differences, and document the temporal variation of four highly vocal marine mammal species.

II. METHODS

A. Instrumentation

The NRS mooring was deployed in the CBNMS at 37.8° N 123.4° W at a water depth of 550 m (Fig. 1). The single passive acoustic archival hydrophone (Fox *et al.*, 2001) is housed in a titanium pressure case and suspended within the deep sound channel at 500 m (sound speed profile verified via Global Ocean Sound Speed Profile Library (GOSSPL); Barlow, 2019). The model ITC-1032 (International Transducer Corp., Santa Barbara, CA) hydrophone has a sensitivity of -192 dB re 1 V/μPa and a flat frequency response (± 1 dB) between 10 Hz and 2 kHz. The

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instrument was programmed to record continuously from October 2015 to October 2017 at a sample rate of 5 kHz with a 2 kHz low-pass cutoff frequency. Incoming signals were conditioned by a preamplifier and pre-whitening filter to maximize the dynamic range of the 16-bit acoustic data logging system (see Haver *et al.*, 2018, for additional details). In all analyses, the effect of the pre-whitening filter was removed to restore actual spectral levels.

B. Sound level measurements

Spectrum levels were calculated from raw binary files in 1 s spectral averages at a 1 Hz frequency resolution (10 Hz–2 kHz) and then averaged in hourly windows before conversion to decibels for efficient data analysis of the two-year-long continuous data set. Median (50th percentile), 1st, 5th, 10th, and 90th percentiles of 10 Hz–2 kHz power spectral densities (re 1 $\mu Pa^2/Hz$) were computed in decibels. Percentiles (also known as statistical noise levels) are computed to evaluate sound level fluctuations from both chronic and intermittent sources; for example, the 5th percentile is the sound level exceeded 95% of the time and, thus, is a measure of background sound levels, whereas the 90th percentile is the level exceeded 10% of the time, indicating sporadic peaks in sound levels. The first percentile power spectral density sound levels were calculated as a measure of the system noise floor. Two-year mean monthly narrowband sound levels were calculated from monthly median power spectral densities.

C. Historical weather records

Weather, specifically wind and rain in this climate zone, can influence the ambient soundscape (Wenz, 1962). To assess the extent to which wind speed conditions affected sound levels, wind speed measurements in the CBNMS from NOAA buoy Station 46013, located approximately 40 km from the NRS (Fig. 1), were retrieved from the NOAA National Data Buoy Center database (National Data Buoy Center, 1971), divided into 10 cm/s bins, and correlated with hourly time-aligned 500 Hz sound levels. Daily rainfall measurements were obtained from the Bodega Ocean Observing Node at the University of California Davis Bodega Marine Laboratory.[1]

D. Whale presence/absence visual analysis

Large whale surveys were conducted daily from the lighthouse on the Southeast Farallon Islands (SEFI) at an elevation of 90 m (Pyle and Gilbert, 1996), located approximately 45 km from the NRS (Fig. 1). All observations were recorded and identified down to species using 10× and 25× binoculars. Observations of surrounding waters were conducted for 1 hour per day (15 min per quadrant) when visibility was greater than 11.2 km, no low hanging fog was present, the Beaufort wind force was less than or equal to 4, and swells were less than 3 m. The daily total numbers of humpback, gray, blue, and fin whales observed in all quadrants were summed and used for analysis. Additionally, at-sea marine mammal surveys were also conducted in the CBNMS during Applied California Current Ecosystem Studies (ACCESS) cruises in May, July, and September of 2016 and 2017 from the survey vessel's flying bridge. Standardized line transect methods were used to count whales from both sides of the vessel while "on effort" in the sanctuary, which was defined as daylight hours while the vessel was underway at 10 kn (see Jahncke *et al.*, 2008, for more details on methodology). Each cruise was 6–10 days in duration, and the survey area included the CBNMS and most of the offshore regions of the Greater Farallones NMS. Results from the SEFI and ACCESS visual observation efforts were compiled into a single database, including all efforts spanning October 2015 to October 2017 (hereafter, ACCESS/SEFI data). Results were separated by platform and species monitored.

E. Whale acoustic analysis

1. Humpback whales

Using the ACCESS/SEFI data, all days of the NRS acoustic sampling that corresponded with the ACCESS/SEFI effort (322 days, which includes days with no positive visual detections of humpback whales) were manually reviewed for the presence of humpback whale vocalizations by a trained analyst using Raven Pro software (Cornell Bioacoustics Research Program, Cornell, NY). Comparisons of visual and acoustic detections included only visual on effort survey days so as not to bias results toward continuous acoustic monitoring. The analyst reviewed data for both song and non-song vocalizations, including feeding-type calls between 200 and 600 Hz (Fournet *et al.*, 2015; Stimpert *et al.*, 2011). Data were reviewed chronologically by day starting in 2015 until vocalizations were identified or the entire day elapsed (see Fig. 2 for example vocalizations). If humpback whale vocalizations were identified in the data, the time and date of the vocalizations were logged, and the observer moved ahead to the next day, corresponding to visual effort. If no vocalizations were identified in a day, an absence was recorded.

2. Gray whales

Migrating eastern North Pacific gray whales have been detected visually and acoustically near the CBNMS (Guazzo *et al.*, 2017; Lagerquist *et al.*, 2019; Pyle and Gilbert, 1996). The M3 call is the most common gray whale migratory call type and has been successfully used to localize migrating gray whales via passive acoustic monitoring. The M3 call has a source level of 156.9 dB re 1 μPa at 1 m in the 20–100 Hz bandwidth of the call and a peak frequency of 38.1 Hz (Guazzo *et al.*, 2017). The ACCESS/SEFI data were used to identify days and times of visual observations of gray whales, and the days with the highest number of gray whales sighted (>15 individuals) were reviewed first for the presence of M3 calls in order to try and increase the likelihood of detecting their vocalizations. Days with <15 individuals sighted were randomly subsampled in hourly bins to reduce processing time. All manual analysis was completed using Raven Pro software (Cornell Bioacoustics

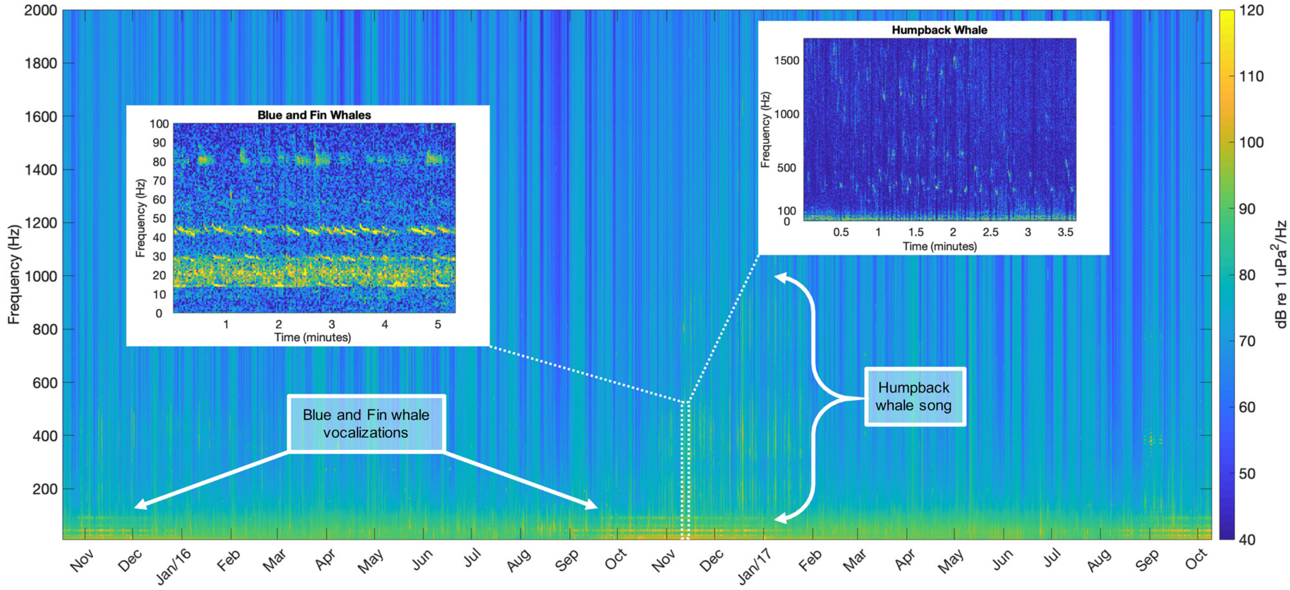

FIG. 2. (Color online) Long-term spectral average (LTSA) of passive acoustic data recorded in the CBNMS between October 2015 and October 2017. Color (blue to yellow) indicates increasing intensity of sound (dB re 1 μPa^2/Hz). Magnified spectrogram clips (inset) show example details of blue/fin whale (left) and humpback whale (right) vocalizations, represented in the time periods indicated in the LTSA.

Research Program, Cornell, NY). Although an automated detector was developed to identify gray whale M3 calls in nearby Monterey Bay (as described in Guazzo *et al.*, 2017; Helble *et al.*, 2012), our application of the algorithm to facilitate and expedite detection of M3 calls in all available acoustic data from the CBNMS was unsuccessful.

3. Blue and fin whales

Blue and fin whales in the California Current are often detected acoustically via the most prominent components of their songs—B-calls and 20 Hz "pulse" calls, respectively (McDonald *et al.*, 2006b; Watkins *et al.*, 1987). While these call types are often used to quantify acoustic presence due to their relative abundance, this abundance can create significant overlaps between individual calls, producing a "chorusing" effect (see Fig. 2 for example vocalizations). This chorusing effect, previously documented for both blue and fin whales in the California Current (Redfern *et al.*, 2017; Širović *et al.*, 2015), was present in the acoustic data collected in the present study. As a result, acoustic detection of blue and fin whales was determined via calculation of "call index" values for blue whale B-calls and fin whale 20 Hz pulses rather than individual call detection.

Building upon acoustic power methods introduced by Mellinger *et al.* (2009), Širović *et al.* (2009), Širović *et al.* (2015), and Oestreich *et al.* (2020) for fin and blue whales, both call indices were calculated as a signal-to-noise ratio between the peak and background frequencies in calibrated long-term spectral averages (LTSAs). For the blue whale B-call index, peak values were calculated as the mean across 43–44 Hz; background values were calculated as the mean of values at 37 and 50 Hz. For the fin whale pulse call index, peak values were calculated as the mean across 20–21 Hz; background values were calculated as the mean of values at 12 and 34 Hz. Call indices were calculated on both daily and monthly LTSAs in order to present results at multiple temporal scales. For the determination of acoustic presence at a daily scale, the number of days with blue whale B- and fin whale pulse call index exceeding a conservative estimate of background call index values (1.1) was recorded.

F. Vessel noise propagation

To estimate the range at which vessel noise would be detectable above ambient levels, we followed the methods of Širović *et al.* (2013) to compute the passive sonar equation and calculated average (mean and median rounded to whole number) power spectral density ambient sound levels between 10 and 100 Hz. We assumed a vessel source level of 177 dB re 1 μPa at 1 m at 41 Hz (Gassmann *et al.*, 2017), which was measured from vessels in Southern California following the current American National Standards Institute protocol for measurement of underwater sound from ships (ANSI/ASA, 2009). Transmission loss was calculated using the Phased Array System Toolbox™ in MATLAB (The MathWorks, Natick, MA) for four ranges between the NRS moorings: the center of each western entry/exit point into the traffic separation scheme (north, middle, south) and the entry/exit to the San Francisco bay (see Fig. 1).

G. Automatic Information System vessel tracking

Automatic Information System (AIS) large vessel movement tracks in the traffic separation scheme shipping lanes near the NRS hydrophone in the CBNMS from 2015 to 2017 were obtained from the U.S. Coast Guard National AIS.[2] Daily AIS tracks were imported and plotted in QGIS (version 3.4),[3] and the TimeManager plugin was utilized to quantify the daily sum of vessels transiting in the traffic

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separation scheme corresponding to each day of acoustic data from 2015 to 2017. The daily sum totals were exported to MATLAB for comparison with the acoustic data.

III. RESULTS

A. Sound level trends

Sound levels in the CBNMS varied in both the frequency and time domains throughout the year. Over the 2-year recording time period, the largest difference between the 10th and 90th percentiles of sound levels across the whole recording period (88.0 dB vs 105.3 dB for a difference of 17.3 dB at 45 Hz) and the highest monthly median sound level (November 2016; 105.9 dB at 44 Hz) were observed below 50 Hz, which was likely driven by blue whale song (B-call harmonics).

Between 50 Hz and 2 kHz, sound level variations were generally broadband. The exceptions to this consistency were the increased sound levels observed at ∼60 and ∼80 Hz from September to December, which were likely driven by blue whale vocalizations (B-call harmonics and A-calls, respectively), as well as between 200 and 500 Hz from November to January, which were driven by humpback whale song (Figs. 2 and 3). Across all frequencies between 50 Hz and 2 kHz, the lowest monthly median sound levels were recorded in August. Because blue whales began vocalizing (B-calls) in August, the lowest monthly median sound levels between 10 and 50 Hz were recorded in either June, July, or August, depending on the frequency (Fig. 3).

1. Monthly trends

Sound levels varied in an apparent seasonal pattern with the highest levels recorded in the fall/winter and the lowest levels recorded in the summer months. The highest monthly median power spectral density sound levels were recorded in October and November at approximately 15 Hz, 30 Hz, and 45 Hz, which are the fundamental frequency and harmonics of the blue whale B-call (Fig. 3). Sound levels between ∼15 and ∼30 Hz were highly variable by month throughout the year (Fig. 3). The lowest monthly median power spectral density sound levels were recorded in August at frequencies above 100 Hz (Fig. 3).

Differences between the 10th and 90th percentiles of 10 Hz–2 kHz power spectral densities were largest at frequencies below 100 Hz, which are associated with blue and fin whale vocalizations (Fig. 3). At three frequencies associated with blue whale vocalizations (15, 30, and 45 Hz), the 90th percentile sound levels were ∼15 dB higher than the 10th percentile sound levels (15.3, 14.5, and 17.2 dB, respectively). At 22 Hz, a frequency associated with fin whale vocalizations, the 90th percentile sound levels were 12 dB higher than the 10th percentile sound levels. At all frequencies between 500 Hz and 2 kHz, the 90th percentile sound levels were a minimum of 14 dB higher than the 10th percentile sound levels, likely driven by fluctuations of wind and humpback whale vocalizations.

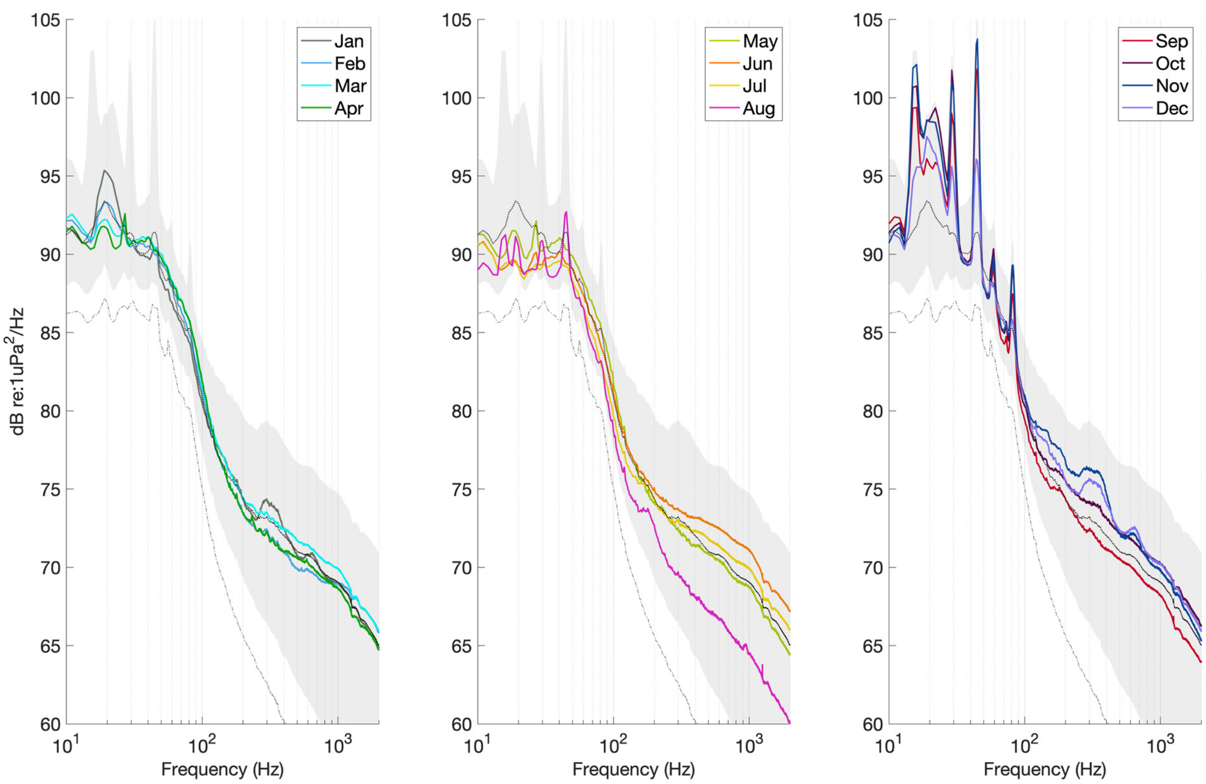

FIG. 3. (Color online) Monthly median power spectral density sound levels (mean of two-year recording) between 10 Hz and 2 kHz, colored by month and plotted by season (January–April, May–August, September–December). In each panel, the light gray background shading shows the 90th and 10th percentile power spectral density sound levels, whereas the central gray dashed line shows the median over the entire two-year recording. The system noise floor (first percentile power spectral density sound levels) is indicated by the dashed-dotted line.

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B. Weather increases ambient sound levels in some conditions

Wind noise and surface agitation increased ambient sound levels in the CBNMS. The highest measured wind speeds were in the winter (January–March; three-month mean, 4.8 m/s; maximum hourly mean, 9.9 m/s) and wind speeds were lowest in the summer (June–August; three-month mean, 3.4 m/s; maximum hourly mean, 7 m/s). At wind speeds greater than 4 m/s (∼50% of all hours sampled), the hourly mean wind speed was highly correlated ($R^2 = 0.86$) with an increase in hourly mean 500 Hz sound levels. Rainfall (collected by the Bodega Ocean Observing Node) was not found to be correlated with sound levels recorded in the CBNMS. Typically, bubble-induced rainfall sounds contribute to ambient sound in the 4–20 kHz range; however, heavy rainfall (i.e., larger bubbles) can influence ambient sound at frequencies below 2 kHz (Nystuen, 1996). It is likely that the light amounts of rainfall near the CBMNS between October 2015 and October 2017 did not influence ambient sound levels below 2 kHz.

C. Comparison of visual and passive acoustic detections of whales

Detections of vocalizations of humpback, gray, blue, and fin whales in passive acoustic data were compared to visual observations of the same species collected during SEFI field station effort and ACCESS cruises.

1. Humpback whales

Humpback whales were detected in all months between October 2015 and October 2017 in the passive acoustic data (93% of days with corresponding visual effort), and in all months except December 2015 by visual observation efforts (visual detections on 51% of on effort days; Fig. 4). In all months except July 2017, humpback whales were detected acoustically on more days than they were detected via visual observation. On only one day in July 2017, visual survey efforts detected humpback whales that were not detected in the acoustic data.

2. Gray whales

Although gray whale M3 migratory calls were anticipated to be detected in the acoustic data on the same days that visual observers identified gray whales, no M3 calls were detected in the acoustic data. The ACCESS/SEFI data were used to identify days and times of visual observations of gray whales, and those days and times were reviewed in acoustic data for the presence of M3 calls; however, no M3 calls were positively identified at any of the acoustic day/time correlates. Gray whales were primarily observed by SEFI visual observer effort in the winter and early spring (Fig. 4).

3. Blue whales

Acoustic detections of blue whale B-call song vocalizations were temporally offset from visual sightings of the

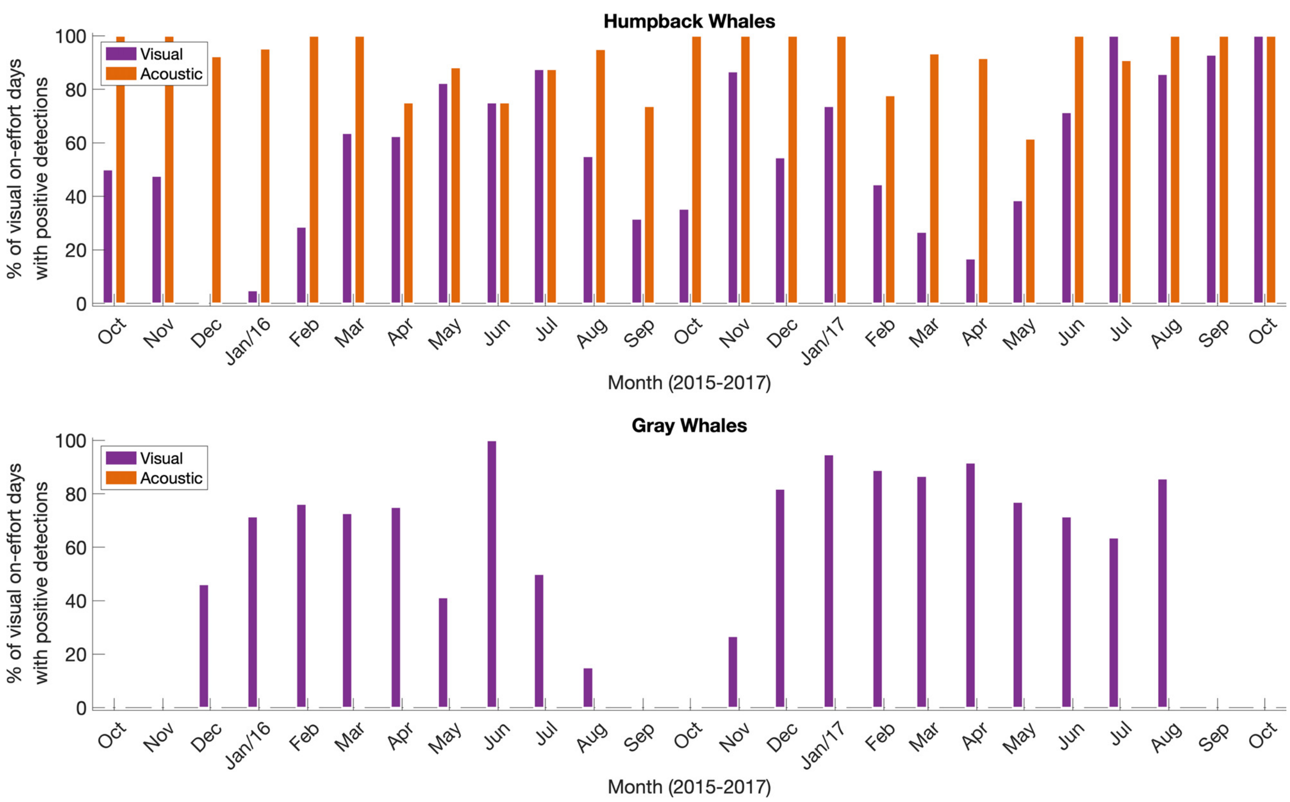

FIG. 4. (Color online) Monthly percentage of positive detections of humpback (top) and gray whale (bottom) presence via visual (purple) and acoustic (orange) methods during all on effort visual survey days between October 2015 and October 2017. Note that there were no acoustic detections of gray whales.

animals during the ACCESS cruises or at the SEFI field site. B-call vocalizations were detected in a continuous time period that began in July or August and ended in December or January, depending on the year (Fig. 5). Each year, the highest B-call index was observed in a successively earlier month (i.e., in 2015, November; in 2016, October; in 2017, September). However, due to the deployment and retrieval operations taking place in October 2015 and October 2017, the full B-call season was captured only in 2016.

4. Fin whales

Although fin whales were rarely observed in and nearby the CBNMS by the ACCESS/SEFI effort, the 20 Hz fin whale pulse sound was recorded consistently throughout the fall and winter. In all years, peak fin whale call index values were observed in the early fall and gradually decreased until March (Fig. 5). Background-level call index values suggest that no calls were detected in the late spring and early summer.

D. Low-frequency vessel noise propagation

Average (mean and median power spectral density rounded to a whole number) ambient sound levels were 88 dB re 1 $\mu Pa^2/Hz$ between 10 and 100 Hz. Range dependent transmission loss calculations revealed that low-frequency noise emanating from vessels transiting within the traffic separation scheme shipping lanes and into the San Francisco Bay would exceed average ambient sound levels by 15–20 dB, depending on vessel characteristics (vessel source levels calculated by Gassmann *et al.*, 2017). This range of signal excess would increase for larger or faster ships, such as super tankers (180 dB at 50 Hz; Carey and Evans, 2011), and would persist above ambient levels for slower or quieter ships with source levels above ~164 dB re 1 μPa at 1 m at 40 Hz (signal excess calculated in MATLAB for a 40 Hz signal propagating up to 100 km to a hydrophone at 500 m deep). Quantifying the actual physical loss is complex and varies with oceanographic conditions (e.g., temperature, salinity). Instead of providing absolute measures of vessel noise contributions, our estimates demonstrate that vessel noise originating within the traffic separation scheme shipping lanes and at points further offshore, up to at least 100 km away, will increase sound levels at the NRS mooring location within the CBNMS and, therefore, vessel noise contributes to the soundscape at this site.

E. AIS vessel tracking

Review of AIS vessel tracks between 2015 and 2017 revealed nearly daily presence of vessels accessing the San Francisco traffic separation scheme near the NRS hydrophone in the CBNMS (daily mean 21; Fig. 6). The acoustic impact of vessel traffic in the traffic separation scheme to ambient sound levels was estimated with the fifth percentile of daily sound level measurements in the 40–100 Hz band in

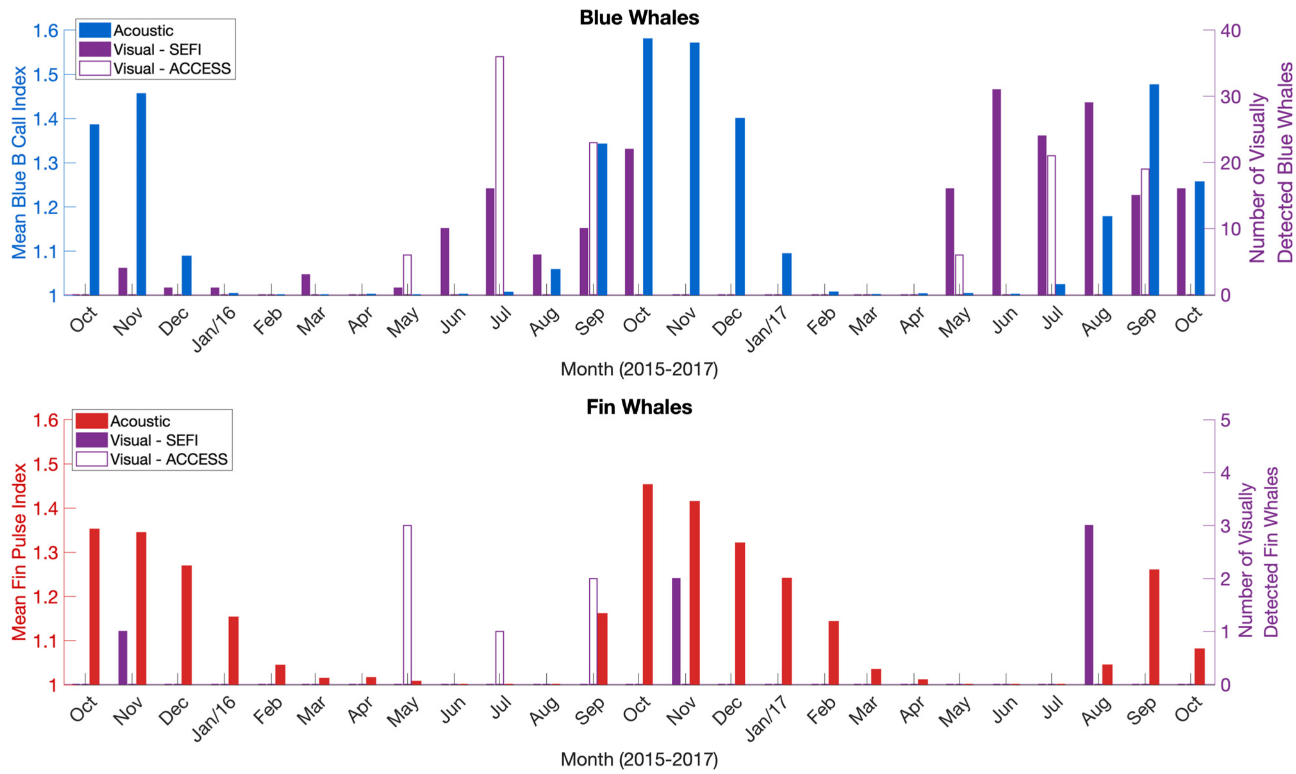

FIG. 5. (Color online) Monthly acoustic vocalization indexes (left axis) for blue whale B-call (blue bars, top) and fin whale 20 Hz pulse (red bars, bottom) alongside the monthly sum of visually detected blue and fin whales during on effort time periods (right axis) from October 2015 to October 2017. Filled purple bars represent visual observations at the SEFI field site (year-round), and open purple bars are sightings during ACCESS cruises (May, July, and September only).

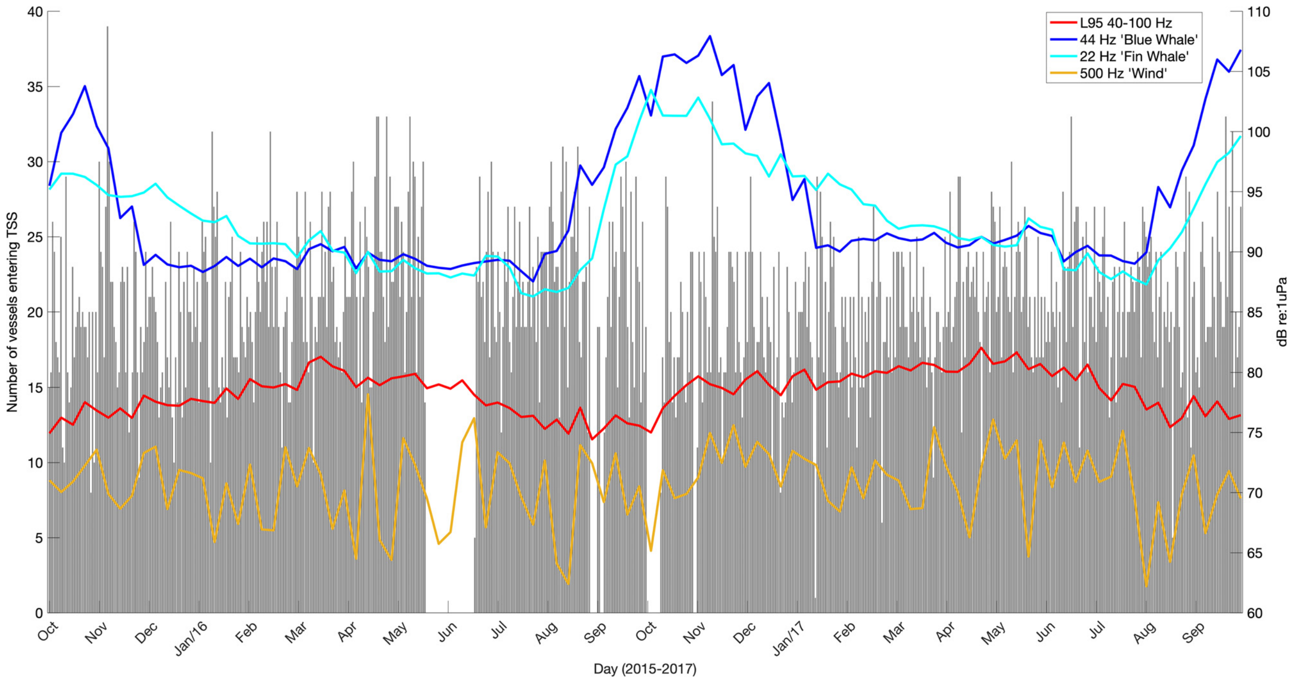

FIG. 6. (Color online) Daily sum of vessel transits (tallied by start time; gray bars, left scale). Weekly sound level measurements associated with ambient vessel noise (fifth percentile of 40–100 Hz spectrum levels, dB re 1 μPa), blue whale (44 Hz, dB re 1 μPa^2/Hz), fin whale (22 Hz, dB re 1 μPa^2/Hz), and wind (500 Hz, dB re 1 μPa^2/Hz; right scale) are superimposed. Note the data gaps in vessel transit data in 2016: June 1–30, September 8–11, October 12–19, and November 10–11.

weekly bins. Although many sound sources, including whales, drive 40–100 Hz sound levels, calculating the fifth percentile (i.e., the sound level exceeded 95% of the time) excludes some of the variability associated with episodic sound sources within those frequencies to reveal ambient sound levels driven by chronic sources. Additionally, by limiting the bandwidth to 40–100 Hz, biological (e.g., fin and blue whale song fundamental frequencies and many components of humpback whale song) and physical sound sources (e.g., wind) outside of this range are excluded from the calculation. Although the fifth percentile of weekly 40–100 Hz sound levels was not significantly correlated with the number of vessels accessing the traffic separation scheme, it was not as variable as the frequencies associated with animal vocalizations, signifying that chronic low-frequency sound sources like vessels are contributors to the sanctuary soundscape (Fig. 6).

IV. DISCUSSION

Analysis of the long-term continuous passive acoustic monitoring data collected in the CBNMS revealed that whale vocalizations and vessel traffic are primary drivers of low-frequency (<2 kHz) sound levels, and wind (or other natural abiotic sources) may increase sound levels during specific times. Temporal (monthly) variability was most apparent in the lowest end of the recorded frequencies (10–100 Hz) and related to seasonal patterns of whale acoustic behavior. Ships accessing the ports of Oakland and San Francisco were present year-round in AIS data and likely increased ambient sound levels throughout the sanctuary due to the physical environment of the CBNMS.

A. Environmental features influence the ambient soundscape

The physical environment of the CBNMS is an underlying driver of the soundscape. Combined, the oceanography (e.g., California Current upwelling), density profile, bathymetry (e.g., Bodega canyon, Cordell Bank), and bottom substrate directly influence the soundscape by facilitating sound transmission from coastal and offshore sound sources. Furthermore, upwelling also bolsters biological productivity, which makes central California a prime feeding habitat for whales, which may vocalize in the environment.

Weather is a significant source of sound in any soundscape, even in the relatively mild and temperate region of Central California. In the CBNMS, the primary source of natural abiotic sound is wind. Wind speeds as low as 4 m/s (or Beaufort force 3) are highly correlated with an increase in ambient sound levels (at lower speeds, other sound sources may mask more subtle acoustic contributions from wind). In the CBNMS, wind speeds at 4 m/s or higher were recorded at the sea surface during approximately half of the year. Although wind speeds were highly positively correlated with sound levels in the 500 Hz frequency band ($R^2 = 0.86$), high wind speeds are likely related to a broadband increase of sound levels at frequencies greater than 200 Hz (Širović *et al.*, 2013). However, in acoustic environments where many sound sources overlap in the time and frequency domains (e.g., wind, animals, and vessels), it can be difficult to extract subtle impacts of each source in the overlapping frequency ranges.

Rainfall can also be a significant contributor to underwater sound levels, but the absence of an *in situ* udometer and minimal rainfall levels recorded at a nearby shore station (Bodega Ocean Observing Node) did not provide evidence to support a relationship between rainfall and ambient sound levels below 2 kHz in the CBNMS.

Broader climate patterns may drive long-term temporal acoustic variability. For example, interannual or decadal shifts in ocean temperatures (e.g., warm water anomalies, El Niño-Southern Oscillation, the Pacific Decadal Oscillation, etc.) may affect the physical properties of underwater sound propagation or change biological features that affect the ecology of migratory and resident soniferous species in the sanctuary. Additional long-term acoustic and environmental data can be compared to these observations and used to evaluate or model the potential effects of environmental changes to the soundscape.

Finally, the central Pacific region is a geologically active area, well-known for high levels of seismic activity. The United States Geological Survey earthquake monitoring database[4] revealed that seismic events recorded between October 2015 and October 2017 in the immediate vicinity of the hydrophone in the San Francisco Bay Area (including terrestrial areas) were minor (<4.0 magnitude). Although events of this size may influence sound levels at frequencies as high as 50 Hz, because earthquake activity is a stochastic process, seismic energy does not consistently contribute to the soundscape and, thus, is likely not expressed in the monthly median power spectral density levels.

B. Whales are drivers of the temporal variability of low-frequency sound levels

Multiple species of baleen whales contribute to the CBNMS soundscape across a range of frequencies and time periods. Acoustic data were analyzed for vocalizations of humpback, gray, blue, and fin whales. Results of contemporaneous visual marine mammal surveys and passive acoustic data were not equivalent with substantial differences across the four species selected for analysis. These differences highlight the ability of passive acoustic technologies to facilitate endangered and protected species monitoring and research in varying conditions. For example, when visual observers are not on effort or when conditions may preclude detection of animals at the surface, passive acoustic monitoring can provide data about the potential presence of species-specific vocalizations. The life history of each species drives the usefulness of each sampling technique at different times (e.g., seasonality of feeding-type vs reproductive function vocalizations). As observed here, humpback whales were often detected by visual and acoustic sampling simultaneously, whereas acoustic detections of blue whales extended into fall and winter months beyond the time period when visual observers recorded their presence within the CBNMS. It is difficult to draw conclusions about gray and fin whales because gray whales were not detected acoustically, and fin whales were only seen on 6 days compared to the >300 days when they were heard (Figs. 5 and 6). However, the abundant acoustic detections of fin whales compared to few visual sightings further highlights the usefulness of passive acoustic monitoring for whale species that occur far offshore (see Calambokidis *et al.*, 2015; Scales *et al.*, 2017).

Humpback whales were acoustically detected year-round and visually in all months but one. Humpback whale vocalizations are distributed across the frequencies sampled in this study and often overlap with frequencies associated with vessel noise and weather. Thus, humpback whale vocalizations were less evident in the monthly sound level plots in comparison to the high energy narrower-band vocalizations of blue and fin whales. The central California coast region, including the CBNMS, is the largest "biologically important area" for humpback whales, and they have been observed year-round in the region, although their primary seasonal occurrence is considered to be from July to November (Calambokidis *et al.*, 2015; Ferguson *et al.*, 2015). The observed year-round presence of humpback whale vocalizations implies high use and may increase the likelihood of whale and vessel interactions, a resource protection priority for the CBNMS (see Strategy RP-2, NOAA, 2014).

Most of the temporal variability detected in the 10–100 Hz range was due to seasonal patterns of blue and fin whale vocalizations. Consistent with previous studies of fin and blue whale song seasonality in Southern California, blue whale B-calls (song) were detected between late summer and early winter, peaking in late fall, and fin whale 20-Hz vocalizations were detected throughout the fall and winter (Lewis *et al.*, 2018; Širović *et al.*, 2015; Wiggins *et al.*, 2005). However, the acoustic detections of these species are not consistent with the SEFI and ACCESS visual observation results. Specifically, blue whales were detected by visual observers primarily in the spring and summer while fin whales were rarely seen at all. This difference can possibly be attributed to environmental factors that may affect visual detection range, such as low-visibility and increased sea state, as well as whale behavior, including physical distance from shore, foraging vs transiting vs migratory behavior, and change in calling activity or type by season or behavior (e.g., social feeding-type D-calls compared to reproductive function B-calls). For example, blue whale B-call detections represent male singing behavior (reproductive function) and, thus, have a seasonal pattern that is offset from feeding behavior and D-calls (which is likely what was visually observed in the spring and summer; Oleson *et al.*, 2007; Szesciorka *et al.*, 2020). It is also possible that the first B-call singers in the late spring or summer months were masked by other ambient sounds.

The lack of blue whale sightings in the fall and winter may be related to seasonally detailed behaviors, in addition to potentially lower visibility and increased sea state. Specifically, following spring and summer feeding periods, blue whales may maintain a larger geographic distance from shore with less frequent and predictable surfacing intervals, which presumably makes them more difficult for visual observers to detect but still places them within acoustic detection range (Burtenshaw *et al.*, 2004; Irvine *et al.*, 2019). Although a comprehensive analysis of all blue whale vocalization behavior was beyond the scope of this paper, additional comparative studies may provide further evidence to link specific behaviors (e.g., feeding, migrating) to seasons and call types in and near the CBNMS.

Similarly, although gray whales were visually detected throughout the winter, spring, and summer, no migratory vocalizations (i.e., M3 calls) were detected in the acoustic data. Gray whales migrate through central California between northern feeding grounds and southern breeding grounds, usually close to shore. The M3 call has been repeatedly detected nearby in Monterey Bay (Guazzo *et al.*, 2017), and although the hydrophone was deployed offshore, we expected that M3 calls would propagate to the hydrophone location and be detected during quiet ambient noise condition periods. Although it is possible that a small number of calls were recorded in the dataset, none were positively identified on days with the highest number of visually detected gray whales. With passive acoustic monitoring, it is impossible to determine whether an animal is not detected due to behavior (not calling) or masking (calls are quieter than ambient sound). Although it was not possible to measure the propagation range of whale vocalizations in this study due to the dynamic nature of the CBNMS environment and the limitation of data collection via a single instrument, we can make assumptions based on known characteristics of the call and whale behavior. For example, the relatively low source level of the gray whale M3 call (156.9 dB re 1 μPa at 1 m; Guazzo *et al.*, 2017) likely limits the audible propagation range in this environment, and the large amount of nearby vessel traffic could more easily mask the lower frequency and source level calls. Also, gray whales can exhibit a behavioral response to exposure to vessels or other sounds associated with predators, including avoidance, change of behavior state, and change in vocalizations (Burnham and Duffus, 2019; Dahlheim and Castellote, 2016; Malme *et al.*, 1984; Sullivan and Torres, 2018; Tyack and Thomas, 2019). Thus, we cannot definitively determine a reason for the lack of M3 calls in the CBNMS dataset.

Understanding the seasonality of whale presence in the CBNMS is important for the CBNMS mission as it can directly inform management efforts to reduce ship strikes and entanglement. For example, since 2015, a voluntary vessel speed reduction program for the San Francisco traffic separation scheme shipping lanes (Fig. 1) has been implemented annually from May 1 through November 15, a date range that is based on historic visual observation data of higher whale abundances during that time period. Our results show that multiple species of endangered or threatened large whales are present throughout the winter well beyond that time period, which could inform future adaptive management efforts related to this topic.

Differences in acoustic detection of vocalizations across the four species of whales analyzed in this dataset provide species-specific baseline information for future studies. California is home to some of the largest shipping ports in the world, and the anthropogenic stressors of vessel presence and noise may influence the behavior of these large migratory whale species. Future integration of data that documents each species' behavioral response to noise may provide information that resource managers and policy makers can use to make decisions about species-specific conservation actions.

C. Vessel noise propagates into the CBNMS

The CBNMS does not provide refuge from vessel noise for marine mammals. The physical environment of a habitat is an important driver of the potential effects of anthropogenic noise, particularly low-frequency vessel noise (Redfern *et al.*, 2017). Specifically, the CBNMS is small relative to other west coast national marine sanctuaries, close to densely trafficked shipping lanes, and exposed to deep-ocean areas where low-frequency sound may travel from hundreds to thousands of kilometers away.

Mean and median band sound levels at 50 Hz and 100 Hz in the CBNMS were extracted to compare with predicted levels in Southern California whale habitats, including the Channel Islands NMS. In the CBNMS, both mean and median 50 Hz sound levels were 1 dB higher (89 dB vs 88 dB), and 100 Hz sound levels were 4 dB higher (81 dB vs 77 dB) than the levels predicted for the Southern California whale habitat (Redfern *et al.*, 2017). In both regions, these sound levels correspond with "heavy traffic" conditions (National Research Council, 2003; Wenz, 1962), which is consistent with the high vessel activity documented in the San Francisco Bay Area (Moore *et al.*, 2018). However, due to the physical location and environment of the CBNMS, restricting vessel traffic within the sanctuary for any reason would not necessarily decrease vessel-related noise there because low-frequency sound easily propagates into the sanctuary from sources outside of the boundary.

Although there are no current regulatory statutes to limit chronic noise exposure to protected species, establishing current sound level baselines facilitates assessments of potential regulatory actions that may affect ambient noise levels within the CBNMS. For example, actions to reduce ship speed may have a quieting effect on the soundscape because slower vessels are generally quieter (McKenna *et al.*, 2013), and cooperation with NOAA's request for voluntary seasonal vessel speed reduction in the San Francisco traffic separation scheme has increased from 28% of nautical miles traveled by large ships in 2015 to 45% of nautical miles traveled by large ships in 2018. Additionally, since 2018, California national marine sanctuaries, local air quality management districts in coastal California, and other partners have conducted an incentive-based program to further encourage cooperation with the slow-down request in order to improve air quality and reduce lethal ship strikes

(Mobley *et al.*, 2018). Meanwhile, other policies may increase vessel-generated sound in the CBNMS; for example, the Ocean-Going Vessel Fuel Rule resulted in some carriers approaching the San Francisco Bay Area from offshore instead of using coastal routes (Jensen *et al.*, 2015; Moore *et al.*, 2018). Continued acoustic monitoring in the CBNMS is necessary to assess changes to the ambient soundscape over time and will provide data to facilitate regulatory efforts to balance commercial needs with the conservation of protected species and environments.

V. CONCLUSION

Establishing a long-term passive acoustic monitoring program in the CBNMS helps meet the CBNMS science goals, as well as broader NOAA Office of National Marine Sanctuaries conservation research and the NOAA Ocean Noise Strategy (Gedamke *et al.*, 2016). Specifically, continuous underwater ambient sound monitoring collects data that can be analyzed to provide assessments of biological resources and anthropogenic impacts not available through existing research and monitoring programs, as well as facilitating site goals of integrating acoustic research with additional data streams (e.g., AIS vessel tracking, essential ocean variables, animal behavior studies). With these data collected in the CBNMS, as well as from the two other NRSs deployed in national marine sanctuaries along the West Coast of the U.S. (Channel Islands NMS and Olympic Coast NMS), future studies can compare the three soundscapes to assess how the similarly managed marine protected areas may be unequally affected by anthropogenic, physical, and biological sound sources and how they may change over time and in response to management actions. For example, overlapping temporal coverage of data from the Channel Islands NMS and Olympic Coast NMS will enable comparisons of the acoustic impact of events that may affect ocean soundscapes along the entirety of the west coast, such as climate fluctuations (e.g., Pacific Decadal Oscillation, El Niño-Southern Oscillation), significant seismic or volcanic activity, and the U.S. economy (McKenna *et al.*, 2012a). Cross-sanctuary comparisons will also be possible with the Monterey Bay Aquarium Research Institute (MBARI) Monterey Accelerated Research System (MARS) cabled hydrophone (36.713 N, 122.186 W) in Monterey Bay NMS (Ryan *et al.*, 2016). By investigating the sources and factors that account for the variability in these soundscapes over time and space, it may be possible to determine how place-based factors may affect each sanctuary and drive differences, as well as identify the ability of passive acoustic monitoring to detect changes in animal use, weather, and anthropogenic stress in these areas.

This first documentation of the underwater soundscape of the CBNMS establishes current baseline measurements of ambient sound, monthly sound level differences, and the temporal variation of three highly vocal marine mammal species. Collecting and analyzing data from a calibrated U.S. network of passive acoustic hydrophone moorings supports broader NOAA goals of standardized soundscape monitoring over time and compared to other protected sites, and directly supports NOAA's ability to assess habitat quality, evaluate trends, and report on conditions within national marine sanctuaries.

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