JASA ARTICLE

Climatic and economic fluctuations revealed by decadal ocean soundscapes[a)]

Vanessa M. ZoBell,[b)] Natalie Posdaljian, Kieran L. Lenssen, Sean M. Wiggins, John A. Hildebrand, Simone Baumann-Pickering, and Kaitlin E. Frasier
Scripps Institution of Oceanography, University of California San Diego, La Jolla, California 92037, USA

ABSTRACT:
Decadal variations of ocean soundscapes are intricately linked to large-scale climatic and economic fluctuations. This study draws on over 15 years of acoustic recordings at six sites within the Southern California Bight, investigating interannual, seasonal, and diel variations. By examining acoustic energy from fin and blue whales along with sounds from ships and wind, we identified changes in soundscape over time and space. This study reveals that sound levels associated with both biological and non-biological sound sources varied seasonally and correlated with large-scale climatic patterns and long-term oceanographic fluctuations. Baleen whale sound levels before, during, and after a marine heatwave were assessed; sound levels decreased in southern sites and increased in northern sites adjacent to the California Current, underscoring the potential for range shifts and habitat compression during warm years for these species. Ship-generated sound levels at high-traffic sites reflected economic events such as recessions, labor shortages and negotiations, and changes to port activities. Marine soundscapes offer an approach to assess the ocean's condition amid ongoing climatic and economic fluctuations.
 https://doi.org/10.1121/10.0036778

(Received 22 December 2024; revised 21 March 2025; accepted 9 May 2025; published online 5 June 2025)

[Editor: Lauren A. Freeman] Pages: 4233–4251

I. INTRODUCTION

Ocean soundscapes exhibit temporal and spatial variations influenced by sounds originating from marine organisms, human activities, and natural physical sources such as wind and earthquakes (Duarte *et al.*, 2021). These variations offer valuable insights into the marine ecosystems' responses to climate change, changes in human activities, and extreme temperature anomalies. Acoustic monitoring of ocean sounds at particular locations, or soundscape analysis, enables the investigation of short- (hours to days), medium- (weeks to months), and long-term (multiple years) changes in the underwater sound environment (Krumpel *et al.*, 2021; McDonald *et al.*, 2006; McDonald *et al.*, 2008; McKenna *et al.*, 2012; Ryan *et al.*, 2021). While previous studies, spanning months to a few years, have described biological sounds, such as baleen whale calls, anthropogenic sounds such as ship traffic, and weather-related sounds, such as wind patterns, these studies have primarily focused on seasonal and diel patterns (Bittencourt *et al.*, 2020; Haver *et al.*, 2021; McKenna *et al.*, 2024; Merkens *et al.*, 2021). However, longer-term acoustic sensing is needed to document and interpret year-to-year changes. Decadal sensing of the ocean can reveal the influences of multi-year climatic cycles, like the Pacific Decadal Oscillation (Zhang and Levitus, 1997; Seger and Miksis-Olds, 2020), which influence biological and human activities. Socio-economic drivers, such as economic growth, recessions, and regulatory frameworks, further contribute to variability in ocean soundscapes by shaping patterns of human behavior (McKenna *et al.*, 2012). With millions of sound sources adding to the acoustic environment, interpreting individual sound sources can be challenging. Identifying and characterizing the acoustic signatures over time offers deeper insight into the ecological health of marine environments amid ongoing changes in oceanic conditions (Pijanowski *et al.*, 2011).

Decade-long, multi-site passive acoustic time series provide essential context for interpreting soundscape variability at each site and between sites (Miksis-Olds *et al.*, 2013; Miksis-Olds and Nichols, 2016). In this study, we examine over 60 cumulative years of acoustic recordings collected from six sites in the Southern California Bight (SCB) from 2008 to 2023. This region, known for its high biodiversity, economic activity, and intense maritime traffic, offers a unique opportunity for studying long-term variability in ocean soundscapes (Dailey *et al.*, 1993; UNCTAD, 2022). This work advances our understanding of increasingly popular soundscape analysis by selecting frequency bands of interest associated with well-known signals across time series of over a decade. Our study reveals biological signals from baleen whales dominating the soundscape seasonally in regions with minimal human activity. Climatic events, like El Niño and the Pacific Decadal Oscillation, contributed to the variation in these biological signals. In contrast, regions with higher human activity reflect

[a)]This paper is part of a special issue on Climate Change: How the Sound of the Planet Reflects the Health of the Planet.
[b)]Email: vmzobell@ucsd.edu

historical economic fluctuations within their soundscapes. Soundscape analysis provides an effective approach for examining extensive acoustic datasets, enabling the identification of trends in biological, anthropogenic, and geophysical sound sources, as well as their variations in response to fluctuating ocean conditions.

II. METHODS

A. Data collection

Passive acoustic monitoring was conducted in the Southern California Bight (SCB) from 2008 to 2023 using High-frequency Acoustic Recording Packages (HARPs) (Wiggins and Hildebrand, 2007) at six sites (Fig. 1, Table I). At each site, HARPs were moored on the seafloor with a calibrated hydrophone suspended approximately 8–18 m above the seafloor. Select hydrophones were calibrated at the U.S. Navy's Transducer Evaluation Center facility in San Diego, California. Hydrophones had an average sensitivity of –153 dB re 1 V/μPa and gain that ranged from 27 to 43 dB (Hildebrand *et al.*, 2021). HARPs sampled at either 200 or 320 kHz with 16-bit quantization. The instruments recorded continuously with the exception of a few early deployments between 2008 and 2010 when three different duty cycle regimes were used. At site B (311 days) and site C (360 days), two deployments each operated on a 5/7 duty cycle (5 min recording every 7 min interval), while another two deployments at these sites operated on a 5/10 duty cycle. At site SN (379 days), one deployment utilized a 5/35 duty cycle.

Intermittent gaps between deployments occurred due to servicing schedules, limitations of battery life, and data storage capacity (Table I). Water depths varied across sites, ranging from around 580 m (B) to 1320 m (E). At these sites, sediment primarily consists of organic matter and clay in the basins, silty clay on the slopes, and fine sand on the shelf, as described in ZoBell *et al.* (2024). Recording days at each site ranged from 1908 to 5368 days (Table I), accumulating a total of 23 507 days (~64 years) of data across six sites for

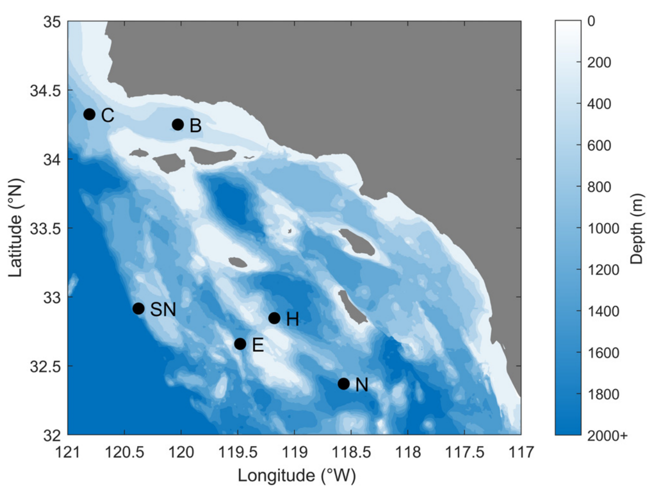

FIG. 1. Map of HARP monitoring locations in the Southern California Bight.

analysis. Notably, SN and E have large recording gaps due to their early period of occupation from 2008 to 2010 followed by a prolonged hiatus, as recording focus shifted to other locations.

B. Signal processing and sound level calculation

The recordings were decimated to a 2 kHz sample rate to enhance the efficiency for analyzing low-frequency signals. Decimation involves applying a 1 kHz low-pass filter forward and backward to prevent time shifts, followed by resampling at the lower rate. Each data set was used to construct sequential sound pressure spectrums with 1 Hz frequency and 5 s temporal resolution using the Welch method (Welch, 1967), followed by conversion to decibels (dB) and application of the calibrated instrument transfer function. For each recording, individual full-instrument transfer functions were created and used to account for signal conditioning electronics, hydrophone sensor(s) frequency response, and additional anti-aliasing filtering used during analog-to-digital signal conversion.

During recording, HARPs transferred data from RAM to hard drive storage in 75 s increments. To avoid instrument self-noise during the disk write process, we computed five sequential 5 s sound pressure spectrum level measurements from the 25 s in the middle of each 75 s segment. Hourly averaged sound pressure spectra were computed from these 5 s averages, excluding partial hours.

Sound pressure spectrum levels from each site were assessed hourly for data quality. Where present, tones in the original spectrograms were examined to determine if they were instrument self-noise; if so, they were removed. Noise from nearby seafloor electrical cables were also seen at certain sites and removed. Low-frequency hydrophone cable strumming caused by subsurface ocean currents and often correlated with ocean tides was apparent at certain sites, causing high-amplitude, low-frequency humming. Hours affected by instrument cable strumming were identified and excluded. Hourly, daily, and monthly sound pressure spectrum level densities were computed from cleaned hourly spectra and averaging and arranged sequentially to create long spectrograms (LSGs).

C. Ambient sound sources

Biological and non-biological sound sources were investigated by computing sound levels across specific frequency bands. LSGs provided broader context for band level interpretations. LSGs were first visually analyzed to identify frequencies that were associated with previously characterized sound sources. Biological bands included frequencies in which fin whale and blue whale calling activity was dominant. The fin whale 20-Hz call and the blue whale B call were prevalent and were targeted for this study. Sound levels in the 18–25 Hz range were selected as a proxy for the 20-Hz calls of fin whales. Similarly, sound levels in the 40–48 Hz range were chosen to represent blue whale B calls, as this frequency range encompasses the third harmonic of

TABLE I. Summary of HARPs in the Southern California Bight from 2008 to 2023. Recording effort includes site abbreviation, latitude (N), longitude (W), depth in meters, recording start (MM/DD/YYYY), recording end (MM/DD/YYYY), and total number of recording days.

Site	Latitude (N)	Longitude (W)	Depth (m)	Recording Start	Recording End	Recording Days
C	34°19.3	120°48.0	770	02/12/2008	08/05/2023	4367
B	34°15.1	120°01.6	580	02/14/2008	09/19/2023	5005
SN	32°54.9	120°22.5	1100	05/18/2009	04/17/2023	1908
H	32°51.4	119°09.0	1100	06/04/2008	04/17/2023	5368
E	32°39.5	119°29.0	1320	08/03/2008	07/03/2023	2366
N	32°22.1	118°33.9	1270	01/14/2009	04/18/2023	4493
					Total	23 507

the B call. The first and second harmonics were not targeted because they could be obscured by the 20-Hz fin whale calls, which tend to dominate the lower frequency band when present. However, in the absence of fin whale 20-Hz calls, blue whale calls often can be observed at these low frequencies. Non-biological sound level bands included frequencies in which wind and ships were prevalent. The 63-Hz one-third octave levels (TOL) were used to capture the influence of ship sounds, as ship noise tends to have higher amplitudes at low frequencies, and 63 Hz experiences minimal frequency overlap with marine mammal calls. Wind is a broadband sound source and can modulate levels from several Hz to tens of kHz. Within the 1000 Hz limit in this study, the 800-Hz TOL is least contaminated by other contributing sources and hence most representative of the influence of wind (Hildebrand, 2009; Wenz, 1962). Across the frequency bands of interest, each hourly sound pressure spectrum was summed in linear space from the start frequency to the end frequency of the band, adjusted for bandwidth by dividing by the length of the bandwidth, and converted back to logarithmic space to achieve mean-squared sound pressure levels (SPLs) in units dB re 1 μPa^2.

Throughout this paper, band sound pressure levels will be referred to as fin whale sound levels, blue whale sound levels, ship sound levels, and wind sound levels, recognizing that each band encompasses sources beyond its primary signal of interest. Contaminations from sound sources beyond the signal of interest are addressed in the discussion. Additional sound sources, such as fish choruses and humpback whale songs were intermittently present and visible within the LSGs. Because these sound sources spanned a wide frequency band, had low overall sound levels, and were entangled in frequency with each other and other signals such as radiated noise from vessels and sounds from weather, these signals were not extracted in band levels and were not analyzed in this soundscape analysis. More discussion on the limitations of soundscape analysis for sound sources with these features is documented in the discussion. Band levels were computed for all six sites, with select sites used for statistical analyses.

D. Climatic ocean variables

To understand the relationship between trends identified in the ocean soundscape and greater climatic patterns, several key variables were investigated. The Pacific Decadal Oscillation (PDO) is a long-term (20–30 year) oceanographic fluctuation in the North Pacific, reflecting persistent changes in Pacific climate variability (Zhang and Levitus, 1997). The PDO index is a sea surface height anomaly pattern and was used to identify "cool/negative" and "warm/positive" phases throughout the recording period (Zhang, 1996). The PDO index was obtained from the Tokyo Climate Center—Climate Prediction Division database, with data represented in monthly time intervals (Tokyo Climate Center, 2024).

The El Niño Southern Oscillation (ENSO) was analyzed to assess how climatic variations in the Pacific and the global tropics that persist on the 6 to 18 month time scales influence ocean soundscapes (Rasmussen and Wallace, 1983). The Oceanic Niño Index (ONI) was used as the ENSO related climate output. The ONI is the average sea surface temperature in the Niño 3.4 region (120°W to 170°W) over three-month periods. Monthly ONI values were extracted from NOAA's National Weather Service Climate Prediction Center (National Weather Service Climate Prediction Center, 2024).

Finally, the North Pacific Gyre Oscillation (NPGO) was extracted from the NOAA Weather Service to understand how climate patterns related to the second prominent mode of sea surface height variability in the Northeast Pacific may influence sound levels. The NPGO climate pattern is associated with interannual and decadal variations of salinity, nutrient upwelling, and chlorophyll-a in the Northeast Pacific (Di Lorenzo *et al.*, 2008).

E. Wind speed

Wind speeds used in this study were obtained from the Cross-Calibrated Multi-Platform (CCMP) (Ricciardulli 2022) as previously described by Hildebrand *et al.* (2021). In summary, the data provide a wind vector, which focuses on wind speeds at a 10 m altitude with a temporal resolution of 6 h. The CCMP model data are spatially resolved at a 0.25-degree grid, and the wind data from the nearest grid point to each HARP site were extracted to analyze potential relationships between the acoustic data and wind patterns. Sound from rain occurs at higher frequencies (4–21 kHz), and was not analyzed in this study (Nystuen *et al.*, 1993).

F. Vessel presence

Automatic Identification System (AIS) provides vessel spatiotemporal data which were downloaded and analyzed from Marine Cadastre (Marine Cadastre, 2024) to calculate daily unique Maritime Mobile Service Identities (MMSI) at each site. A 25 km radius around each recorder site was applied to filter ships within the average listening range of the acoustic instruments to explore the extent at which local vessels influence non-biological sound levels. Since propeller cavitation is the primary source of vessel noise, non-moving vessels were excluded from the analysis. Prior to 2015, fishing vessels were not required to be equipped with an AIS transmitting antenna, resulting in significantly fewer unique MMSIs within 25 km of each site during this period. To investigate contributions of sound from ships, given the limited information on fishing vessels, only cargo ships and tankers were analyzed using the AIS data. The proportion of unique MMSIs attributed to cargo ships and tankers varied across regions, ranging from 44% (SOCAL N) to 79% (SOCAL SN). From 2009 to 2014, cargo ships and tankers were identified by type codes 70 through 89. For the period from 2015 through 2023, cargo ships and tankers were identified with type codes 70 through 89, 1004, 1016, 1017, and 1024.

G. Statistical analysis

To identify different patterns within the data, median sound levels were computed in dB space at various temporal resolutions, and associated variables were investigated to identify relationships. Median SPLs were computed across daily and monthly intervals from the original hourly SPLs to elucidate interannual, seasonal, and diel patterns. The results are presented starting from the longest time scale (interannual) to emphasize overarching trends, and progressing to the shortest time scale (diel) to showcase more nuanced patterns.

1. Interannual

To identify interannual patterns for fin whale and blue whale sound levels, the daily median SPLs were de-seasoned to capture long-term trends spanning greater than one year. De-seasoning involved fitting a fourth-degree polynomial model to the daily SPLs for each biological band at each site. The fitted model was subtracted from the observed data to create a seasonally adjusted daily time series of sound levels. The adjusted time series was then normalized to values between –1 and 1, since the de-seasoned sound levels no longer represented the measured values in dB re 1 μPa^2. Since the climatic variables were binned by month, the median monthly sound levels were calculated for comparison. A 12-month moving median was calculated for the normalized monthly sound levels to compare with the PDO values. Linear least squares regression was used to fit first-order polynomials to each of the normalized monthly sound levels as a function of PDO, ONI, and NPGO. The slope and variance explained (r^2) were computed for the sound levels for each site and explanatory variable.

A similar approach was employed to analyze patterns in ship and wind sound levels. No de-seasoning adjustments were applied to the non-biological bands, as these levels were found to be less influenced by seasonal changes. For ship noise analysis, the daily sound levels were fitted to a first-order polynomial as a function of unique daily cargo/tanker counts. For wind noise, the daily sound levels were fitted as a function of daily median wind speed (m/s).

2. Seasonal

To understand how the seasonality of sound levels changed over time, the median for each month and year was computed. Median monthly sound levels were also computed to identify specific months where sound levels peaked and dipped. The data were also categorized by season, with winter represented by January, February, March; spring as April, May, June; summer as July, August, September; and fall as October, November, and December. Seasonally binned spectra from 15 Hz to 1 kHz were computed and visualized as box plots for ship and wind sound levels.

3. Diel

Diel patterns were analyzed using recordings from a single month per site and frequency band. To minimize the influence of seasonal variations that could obscure potential diel signals, the month with the highest median sound level for each frequency band at each site was selected. For the selected month, median hourly sound levels were computed from 0 to 23 h (UTC).

III. RESULTS

The soundscapes at all six sites were examined for influence from biological and non-biological sound sources by analyzing the long-term spectrograms and frequency bands of interest. Additionally, a subset of sites were used to investigate patterns between sound levels and ancillary data.

A. Biological sound levels

1. Interannual patterns

Interannual soundscape variability influenced by blue and fin whale vocalizations, exhibited both shared characteristics across sites and site-specific differences. (Fig. 2, Suppl. 1, 2). Sites C, E, H, and N were selected for further biological investigation as they represented a variation in acoustic environment and anthropogenic activity.

Fin whale 20-Hz pulses and blue whale B call third-harmonics were apparent in Sites C, H, E, and N LSGs with varying intensities (Fig. 2). Humpback calling and fish choruses were seen at sites E, H, and N, with lower intensities. Both fin and blue whale sound levels showed a clear seasonal pattern with peaks in summer/fall for blue whales and fall/winter for fin whales. At sites H and N fin and blue whale sound levels were higher from the beginning of the recording effort until 2015. In late 2014, a change in fin and blue whale sound levels occurred at site C, H, and N, which coincided with the onset of a severe marine heat wave (MHW) (Fig. 2). Fin and blue whale levels remained lower from 2015 until 2018, and began to rise again in 2018 through the end of the recording effort. A decline in the blue

https://doi.org/10.1121/10.0036778

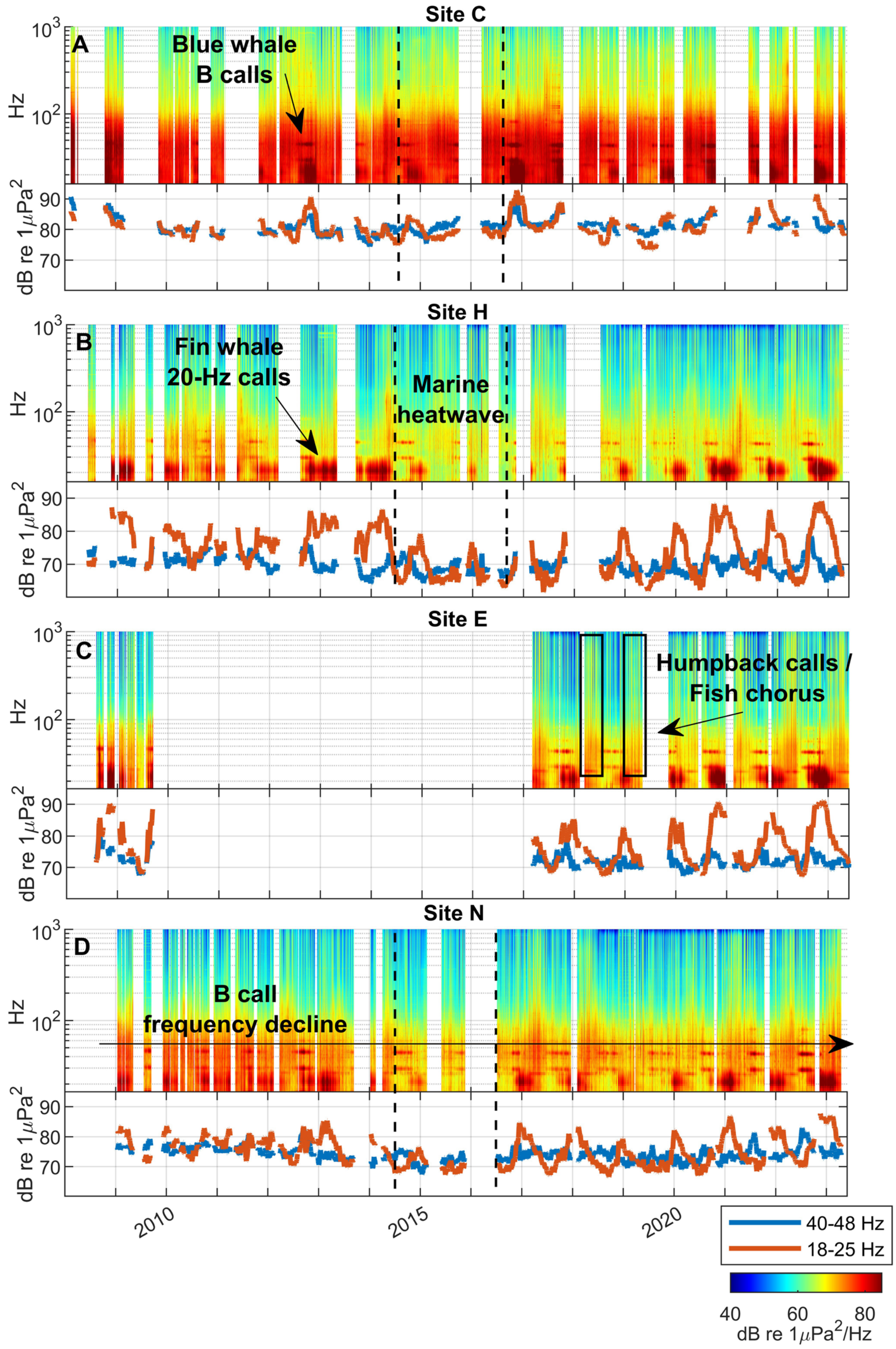

FIG. 2. Long spectrograms and time series of sound pressure levels of biological sound sources with a 10 day moving average at four monitoring sites: C, H, E and N. Annotations show blue whale B third harmonic call tone, fin whale 20-Hz calls, the 2014-2016 Marine Heatwave (MHW), humpback whale and fish chorus events, and the long-term blue b call frequency decline. Below the site spectrograms, red lines show band sound pressure levels associated with fin whale calls (18–25 Hz) and blue lines show band sound pressure levels associated with blue whale B third harmonic calls (40–48 Hz).

whale B call frequency is apparent over time, with peak frequency starting at approximately 47 Hz in 2009 and ending at approximately 42 Hz in 2023 [Fig. 2(D)].

The time series of the PDO index in relation to the 12-month moving average time series of normalized fin whale associated SPLs indicated an anti-correlation (Fig. 3). During the cool phase from 2009 through 2014 normalized fin whale sound levels at sites H, E, and N were above 0. The switch to the warm phase in 2014 was associated with fin whale sound levels dropping at sites N and H, and remaining below 0 until

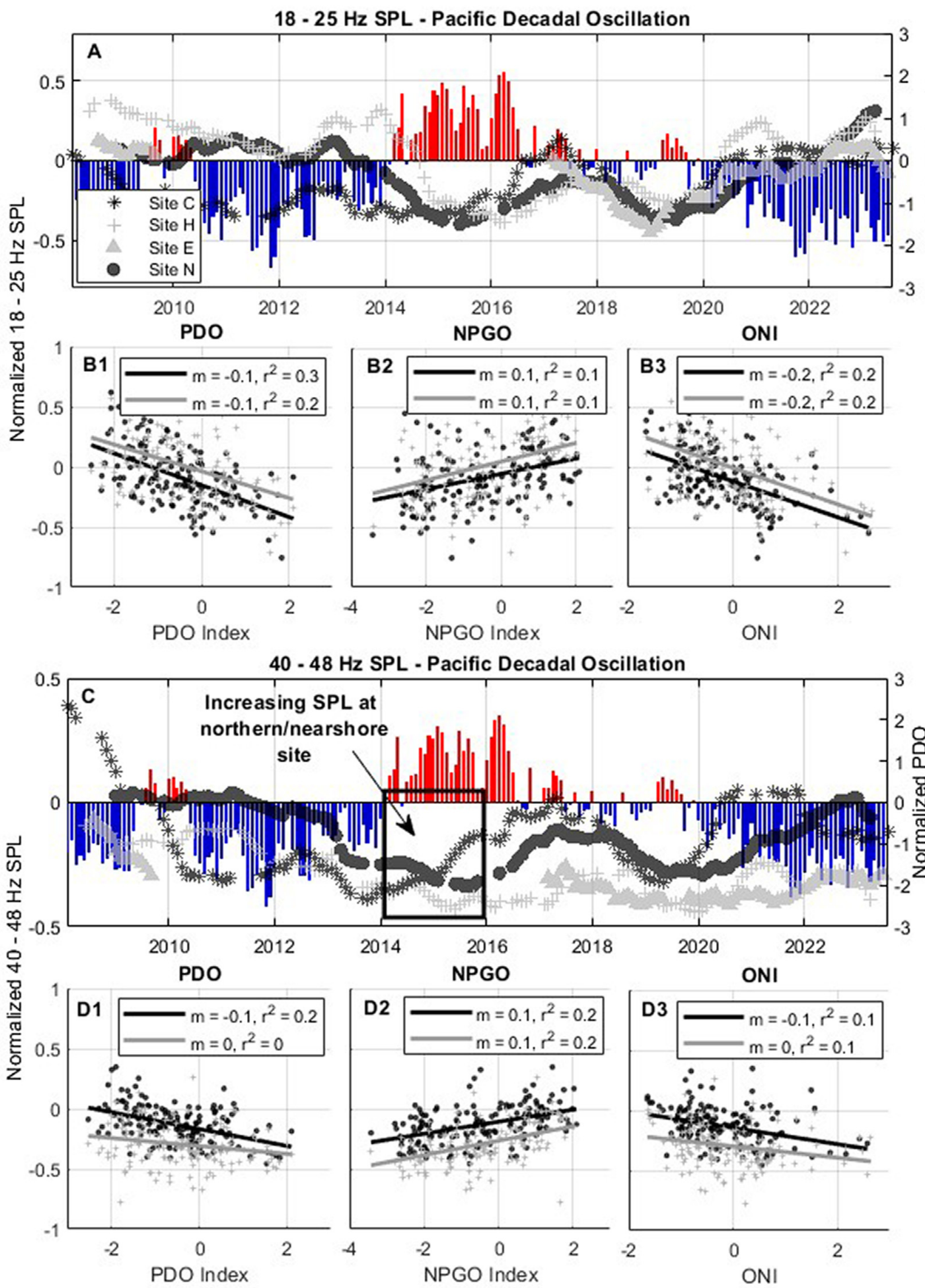

FIG. 3. Interannual oscillations of biological band sound pressure levels (SPL) for four sites in Southern California: C, H, E, and N. Subplots show fin whale 20-Hz call (A) and blue whale B call third harmonic (C) associated SPL (points) in relation to the Pacific Decadal Oscillation (PDO; blue and red bars) at sites C (black asterisk), H (gray cross), E (gray triangle), and N (black circle). Linear regressions for normalized fin whale (B1)–(B3) and blue whale (D1)–(D3) SPL and PDO, North Pacific Gyre Oscillation (NPGO), and Oceanic Niño Index (ONI) show varying slopes and degrees of explanatory power for sites N (black) and H (gray). Site C did not have a strong relationship with these variables. Regression analysis was not completed at site E due to a large gap in the time series.

steadily increasing from the end of 2019 through the end of the recording period, with fluctuations in between. Fin whale sound levels at site C remained below zero with a decreasing trend until the end of 2014, in which it started to slowly increase and peak in 2017. Following the end of the warm phase in 2017, fin whale sound levels decreased at site C through 2019, then increased again and began to level out from 2020 through 2023. Monthly fin whale sound levels were negatively associated with the PDO, with higher fin whale sound levels during negative PDO indices and lower fin whale sound levels during positive PDO indices [Fig. 3(B1)]. The steepest negative slope and highest variance explained for fin whale sound levels and PDO was at site N ($m=-0.1$, $r^2=0.30$), while site C showed little to no relationship ($m=0.0$, $r^2=0.0$). Monthly fin whale sound levels were positively associated with the NPGO for all sites, with higher fin whale sound levels during positive NPGO indices and lower fin whale sound levels during negative indices [Fig. 3(B2)]. The slope and variance explained was the highest for site N ($m=0.1$, $r^2=0.10$), with site C showing no relationship ($m=0.0$, $r^2=0.0$). Like the PDO, monthly fin whale sound levels and the ONI were negatively associated for all sites, with higher fin whale sound levels associated with negative ONI values and lower fin whale sound levels associated with positive ONI values [Fig. 3(B3)]. The slope and variance explained for site N showed the greatest relationship ($m=-0.2$, $r^2=0.20$) with the lowest relationship found at site C ($m=-0.1$, $r^2=0.20$).

Blue whale sound levels showed some differences in trends in comparison to fin whale sound levels [Fig. 3(C)]. Blue whale sound levels steadily decreased at sites H and N from the beginning of the recording effort until 2016, rose during the neutral PDO phase, dropped again in late 2019 during a warm phase, and then steadily increased from 2020 to the end of the recording period. The blue whale sound levels at site C steadily declined from 2008 till 2015 where it rose throughout the warm phase until 2017 [Fig. 3(C)]. During the neutral phase it began to decrease and then rose again in 2019. Site H blue whale sound levels mirrored the same patterns as site N, with lower overall levels and flatter responses to the warm and cool PDO phases. The relationship between blue whale sound levels and climate indices mirrored the patterns of the fin whale sound levels with lower association in slope and variance explained by the climatic variables [Figs. 3(D1)–3(D3)]. PDO and blue whale sound levels were negatively associated with the steepest slope and variance explained at site N ($m=-0.1$, $r^2=0.20$), while site C had the lowest variance explained and a zero slope [$m=0.0$, $r^2=0.03$, Fig. 3(D1)]. Blue whale sound levels were positively associated with NPGO for sites N and H ($m=0.1$, $r^2=0.20$) while site C had a zero slope and zero variance explained. Blue whale sound levels were negatively associated with ONI at each site, with the steepest negative slope and variance explained at site N [$m=-0.1$, $r^2=0.10$, Fig. 3(D3)], and lowest for site C ($m=-0.1$, $r^2=0.05$).

2. Seasonal patterns

Seasonal patterns for the biological sound levels were present at each site. The month with maximum intensity for the biological sound levels differed depending on the site (Fig. 4). Maximum sound levels for fin whale associated band levels were earliest for the most northern site (C, October) and latest for the most southern site (N, January). Sites H and E had maximum fin whale sound levels during October and November, respectively. Full median spectra over each season show peaks in frequencies associated with fin whale 20-Hz calls and blue whale B calls [Figs. 4(A4)–4(D4)]. Fin whale 20-Hz calls produced a peak in the fall (C, H, E) and in the winter (H, E, N).

Blue whale sound levels peaked 3–4 months before fin whale sound levels at sites N and H (Figs. 2, 4), and peaked during the same month at site C. The average monthly blue whale sound levels peaked in August for sites H, E, and N, and October for site C. The monthly blue whale sound levels were highest for site C and lowest at site H. The full seasonal spectra show increases in frequencies associated with blue whale B calls, although the SPLs do not reach the amplitudes of the fin whale sound levels [Figs. 4(A4)–4(D4)]. Blue whale B calling shows a third harmonic at ~43 Hz for summer and fall at all sites.

3. Diel patterns

Diel patterns for the fin and blue whale sound levels were investigated and appeared to reflect the diel pattern of ship traffic rather than whale calling behavior at sites C and N [Figs. 5(A), 5(B) compared with Fig. 5(C)]. There were only minimal changes (<2 dB) associated with the hour of day, at sites H, E, and N. The slightly larger range at site C is likely caused by nearby shipping, with range values of 3.0 dB (18–25 Hz) and 4.5 dB (40–48 Hz).

B. Non-biological sound levels

Non-biological sound levels were investigated in two bands of interest. A 63-Hz TOL was analyzed as a proxy for ship sound levels, and an 800-Hz TOL band was analyzed as a proxy for wind sound levels. Ambient sound levels were explored at sites C, B, SN, and N.

1. Interannual patterns

Ship sound levels displayed varying patterns depending on the site. Ship and wind sound levels were highest at sites C and SN and lowest at sites B and N (Fig. 6). At sites C and B, ship sound levels were the highest pre-2009, and dropped dramatically at the beginning of 2010. Ship sound levels gradually increased from 2010 through the end of the recording effort, but did not reach pre-2009 sound levels. Sites SN and N did not reflect these changes but rather displayed highest ship sound levels pre-2015 with a decrease in the middle of 2015. Ship sound levels gradually rose from 2016 through the end of the recording effort at sites SN and N (Fig. 6).

The relationship between ship sound levels and unique tanker and cargo ship counts was investigated to determine which soundscapes reflected nearby vessel traffic (Fig. 7). The daily ship sound levels at sites C, B, SN, and N all had a positive relationship with daily tanker and cargo ship counts [Figs. 7(B1)–7(B4)]. Site N had the highest positive slope ($m=0.78$), and site B had the highest variance explained ($r^2=0.42$). Site SN had the lowest positive slope and variance explained ($m=0.31$, $r^2=0.05$).

The relationship between sound levels and wind speed were investigated over the duration of the recording time series for each site (Fig. 7). Peaks in wind speed reflected peaks in wind sound levels across the 13-year time series at

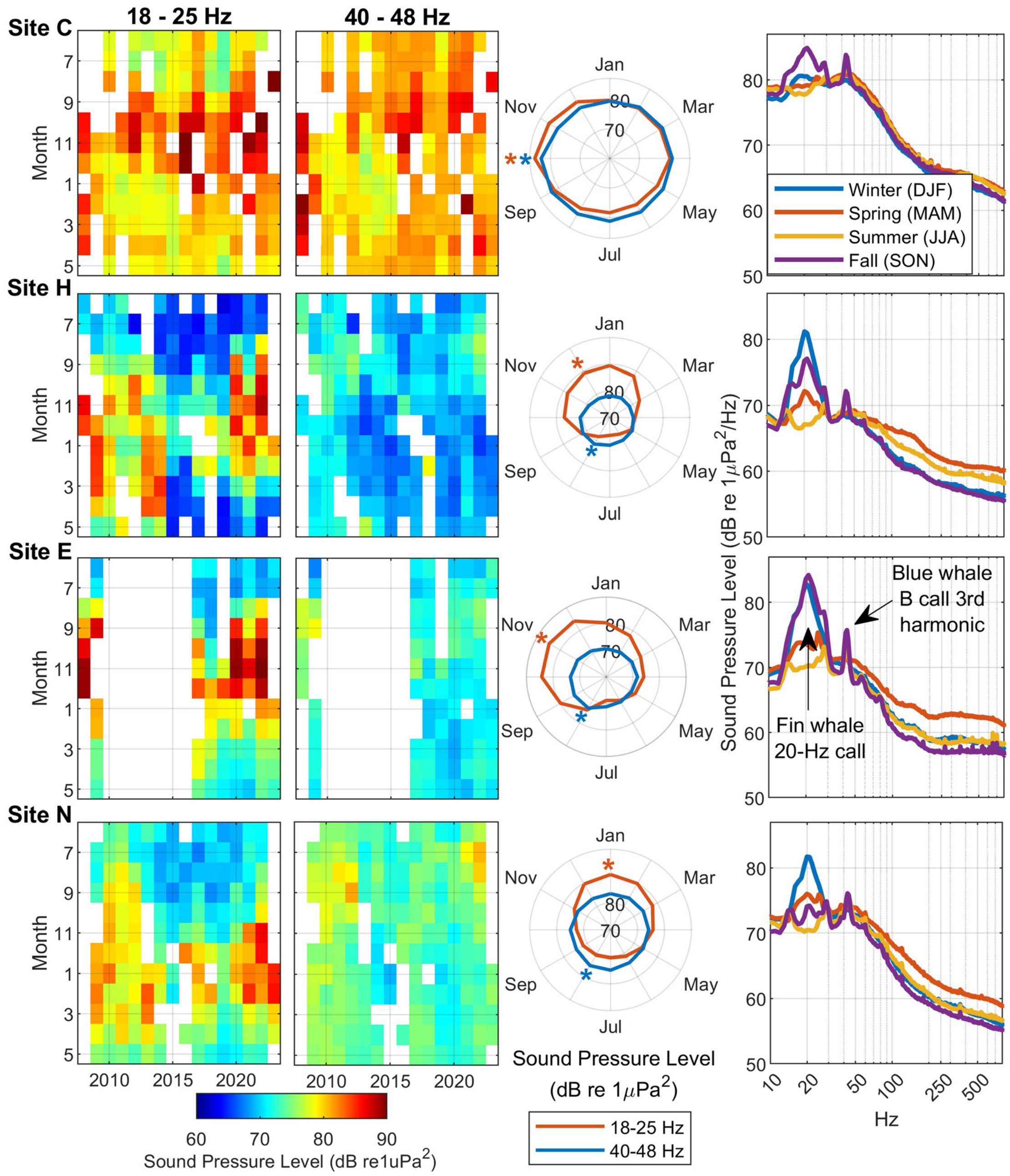

FIG. 4. Median seasonal sound levels associated with biological bands of interest at four sites (C, H, E, and N). Fin whale 20-Hz calls (18–25 Hz) and blue whale B call third harmonic (40–48 Hz) monthly sound pressure levels showed variation in intensity across sites throughout the time series. Asterisks indicate the maximum monthly sound levels for both bands (A3)–(D3). Acoustic energy associated with fin whale 20-Hz and blue whale B calls were identifiable seasonally in full spectra (A4)–(D4).

site N, with the highest associated peak during the spring of 2022 [Fig. 7(C)]. Wind sound levels at all sites increased as wind speed increased from 0 to 10 m/s, and started to flatten out above 10 m/s [Figs. 7(D1)–7(D4)].

2. Seasonal patterns

Seasonal patterns for non-biological sound levels were present at each site with varying degrees of intensity. Monthly median sound levels were computed to further investigate the seasonality of ship and wind sound levels (Fig. 8). On average, maximum ship sound levels occurred in the spring with sites C and N in April, site B in May, and site SN in March [Figs. 8(A3)–8(D3)]. Spring had the highest median ship sound levels and fall reflected the lowest levels at sites C, B, and N [Figs. 8(A4)–8(D4)]. Site SN had the highest median ship sound levels during winter, and the lowest median ship sound levels in summer.

The maximum monthly wind sound levels also occurred in spring, with sites B, SN, and N in May, and site C in April [Fig. 8(A5)–8(D5)]. Site C had the highest monthly wind sound levels and site B had the lowest monthly wind sound levels. At all sites, fall had the lowest median wind sound levels.

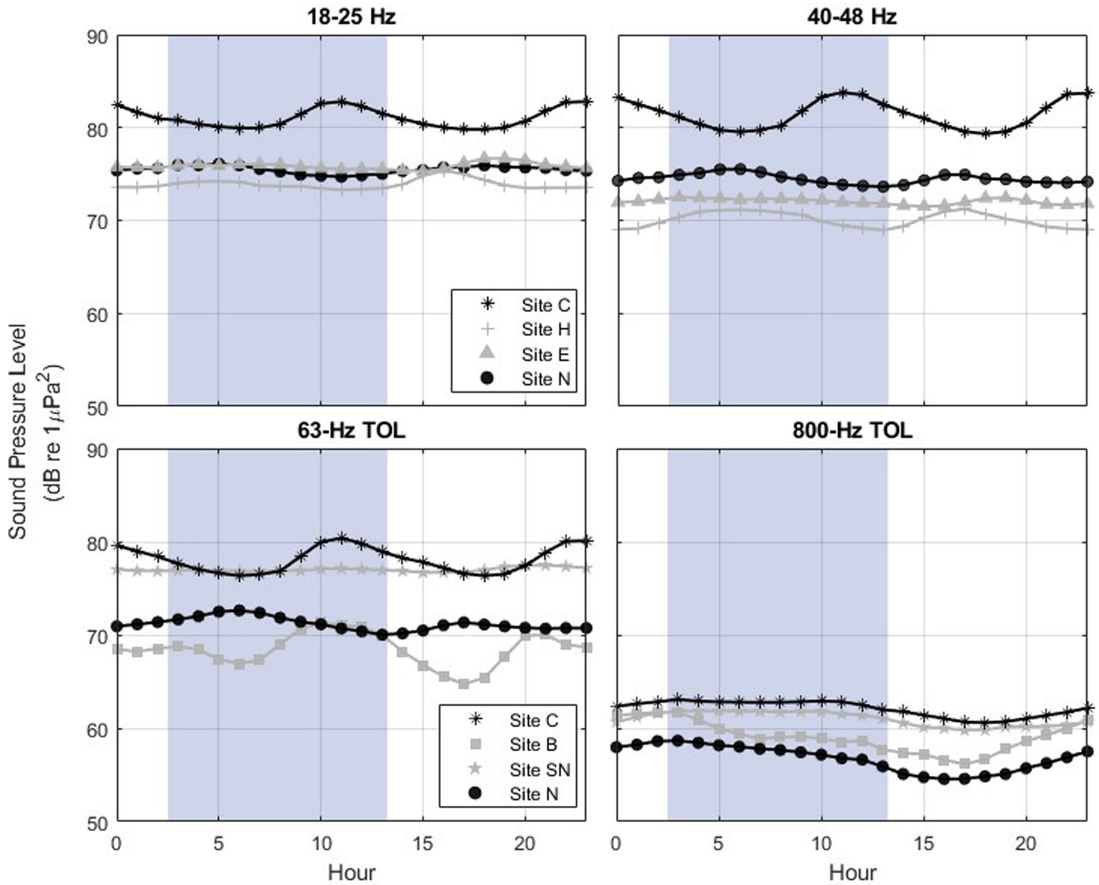

FIG. 5. Median hourly (UTC) sound pressure levels (SPL) during the month of maximum SPL for each frequency band of interest. Fin whale 20-Hz call band (18–25 Hz) and blue whale B call third harmonic band (40–49 Hz) SPLs are shown for sites C (black asterisk), H (gray cross), E (gray triangle), and N (black circle). Ship noise (63-Hz one-third octave level) and wind noise (800-Hz one-third octave level) are shown for sites C (black asterisk), B (gray square), SN (gray star), and N (black circle). Nighttime hours are shaded in blue.

3. Diel patterns

Diel patterns for ship and wind sound levels were investigated at sites C, B, SN, and N. Ship sound levels had the highest range of 6.6 dB across hours of day at site B, with peaks at 10:00 UTC and 21:00 UTC [Fig. 5(C)]. Site C had a similar pattern with ship sound levels peaking at 12:00 UTC and 00:00 UTC, with a range of 4.0 dB across hours. Sites N and SN did not mirror this trend and were relatively unvarying across hours of the day. Ranges across hours for ship sound levels were 2.6 and 0.8 dB and peaked at 6:00 and 22:00 UTC for sites N and SN, respectively [Fig. 5(C)].

Wind sound levels showed a similar pattern across sites, with higher sound levels during the hours of night and lower sound levels in the morning [Fig. 5(D)]. Maximum wind sound levels occurred between the hours of 3:00 and 6:00 UTC across the sites. Minimum sound levels occurred at the hour 18:00 at site B, 17:00 for site N, 19:00 for site SN and site C [Fig. 5(D)].

IV. DISCUSSION

Acoustic sound levels were processed for over a decade of acoustic data at six sites to analyze long-term trends of biological and non-biological acoustic sound levels. Biological sound levels included frequencies for fin whale 20-Hz calls and blue whale B calls. Non-biological sound levels included frequencies associated with ship and wind-driven sounds. A variety of patterns were revealed for sound levels in relation to long-term climatic cycles, economic events, seasonality, and diel patterns. Some findings from this study provide new insights, while others supported previous research, reinforcing existing knowledge of acoustic variability in the Southern California and Northeastern Pacific region. Additionally, the findings provide evidence that this approach can be a valuable tool for studying these patterns over long time scales. In general, soundscape analyses provide insights into ecological and anthropogenic activity in the Southern California Bight; however, shortcomings of soundscape analysis, such as contamination of sound levels of interest from non-target sound sources, are apparent.

A. New insights

1. Interannual variability in biological bands

a. Geographical influences on acoustic activity. Interannual biological patterns and their associations with climatic ocean indices were examined at four sites. Sites H and N had the lowest sound levels for the biological bands

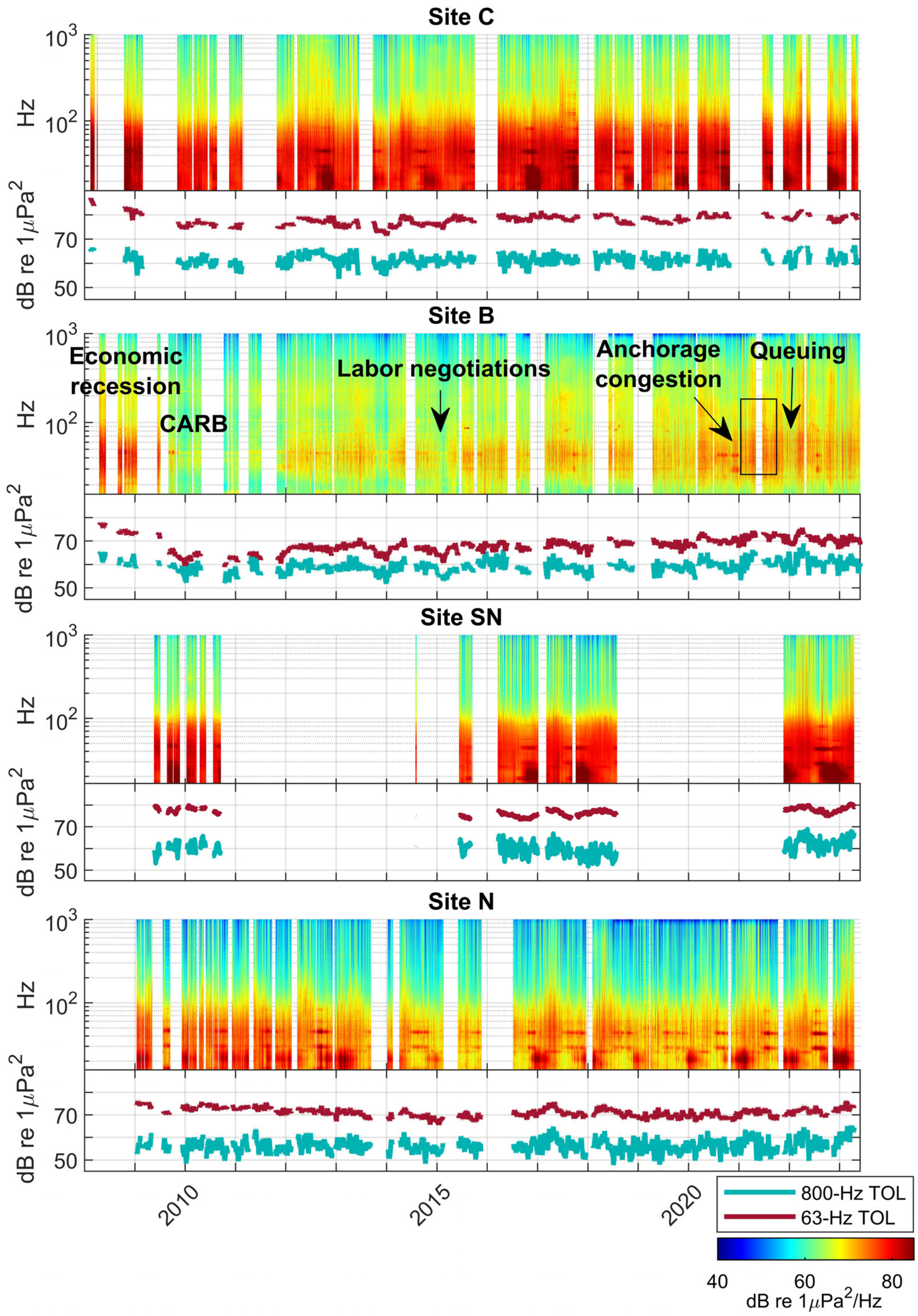

FIG. 6. Long spectral averages and time series of sound pressure levels with a 10 day moving average of non-biological sound of interest at four sites: C, B, SN, and N. Burgundy lines show sound levels associated with ships (63-Hz one-third octave level, or TOL) and teal lines show sound levels associated with wind (800-Hz TOL). CARB (California Air Resources Board) marks the start of the Vessel Fuel Rule.

while site C had the highest. The geographic positioning of these sites likely influenced these differences in acoustic activity. Site C is situated on the western-facing slope, enhancing detection ranges (22 432 km^2) for fin and blue whales throughout offshore Southern California and the entire northeastern Pacific (Širović *et al.*, 2015). In contrast, site H is on an eastern-facing slope of a marine canyon, shrinking the detection range (19 316 km^2) and blocking fin and blue whale acoustic signals from propagating to the hydrophone beyond the immediate basin region, reducing sound levels and biological activity recorded at this site (Širović *et al.*, 2015). Sound levels in the fin whale band exceeded sound levels in the blue whale band at sites H and N, likely due to the higher overall fin whale density at those

https://doi.org/10.1121/10.0036778

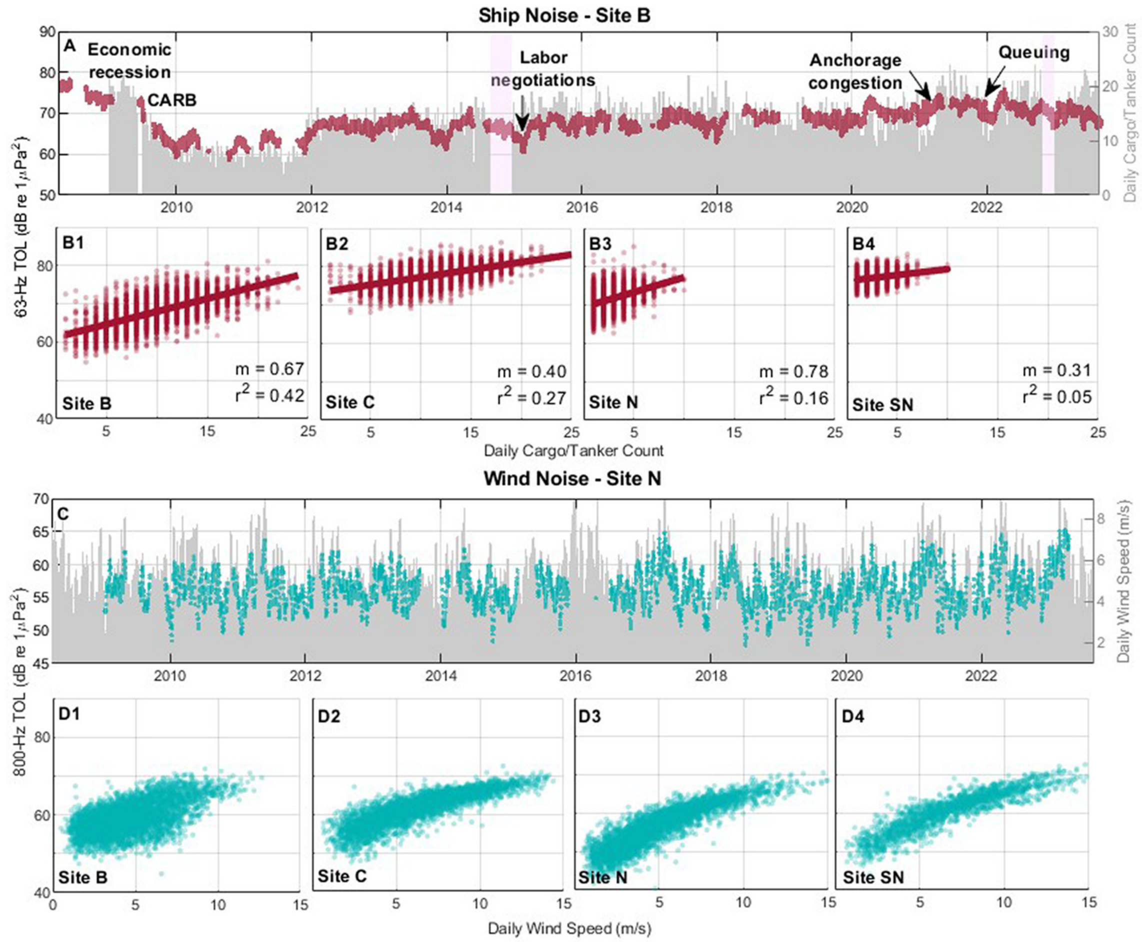

FIG. 7. Interannual oscillations of non-biological sound pressure levels (SPLs) for four sites: B, C, N, and SN. Subplots show ship sound levels in relation to daily vessel count at site B, pink shaded bars indicate periods of time with no or erroneous AIS data (A). Linear regressions for ship sound levels (B1)–(B4) show varying slopes and degrees of explanatory power. Subplot C shows sound levels in relation to wind speed at site N (C). Wind sound levels with daily wind speed (D1)–(D4) display a non-linear relationship.

sites compared to blue whales at these locations (Campbell *et al.*, 2015; Giddings, 2022; Širović *et al.*, 2015). Fin whales also exhibit slightly higher source levels for 20-Hz calls (177.9 dB re 1 μPa^2/Hz @ 1 m at 21 Hz) compared to blue whale B calls (171 dB re 1 μPa^2/Hz @ 1 m at 44 Hz), allowing the 20-Hz calls to reach farther distances (Širović *et al.*, 2007; Thode *et al.*, 2000).

Increased sound levels in the fin and blue whale bands at site C could be due to a combination of effects. First, the higher sound levels could be the result of higher fin whale density within the listening range of the recording devices (Becker *et al.*, 2022), where the summation of sound levels of overlapping calls create higher sound levels within the 20-Hz call band. Second, the increase could be a result from the combined effects of ship noise contaminating these biological bands of interest, through the summation of ship sound and whale sound. Third, the increased levels could be due to the Lombard effect, the rise in call amplitude in response to increasing ambient noise level (Lombard, 1911; Zollinger and Brumm, 2011). The Lombard effect has been documented for various cetacean species, including humpback, minke, and North Atlantic right whales (Guazzo *et al.*, 2020; Helble *et al.*, 2020; Parks *et al.*, 2011). The increased blue and fin whale levels were documented at the site with the highest non-biological background noise conditions in this study. In order to determine the Lombard effect for blue and fin whales, source levels would need to be modeled from the sound pressure levels of individual detected calls, taking into account the background noise levels at the time of the call. With anthropogenic noise impacts on marine mammals being of high concern, the Lombard effect should be verified for these two species to understand how, when, and where cetaceans in Southern California are being affected by anthropogenic noise.

b. Marine heatwave (MHW) effects on biological bands and sound propagation. Beyond geographic influences, climatic variability also played a role in interannual differences associated with the biological band metrics. In late 2014, a change in fin and blue whale sound levels occurred at site C, H, and N, which coincided with a severe MHW in the Pacific and a shift to a positive phase of the PDO (Fewings and Brown, 2019; Johnson *et al.*, 2020). The PDO is known to intensify MHWs, making them longer, stronger, and more frequent off the Northeast Pacific coast under a positive PDO scenario (Frölicher *et al.*, 2018; Ren *et al.*,

https://doi.org/10.1121/10.0036778

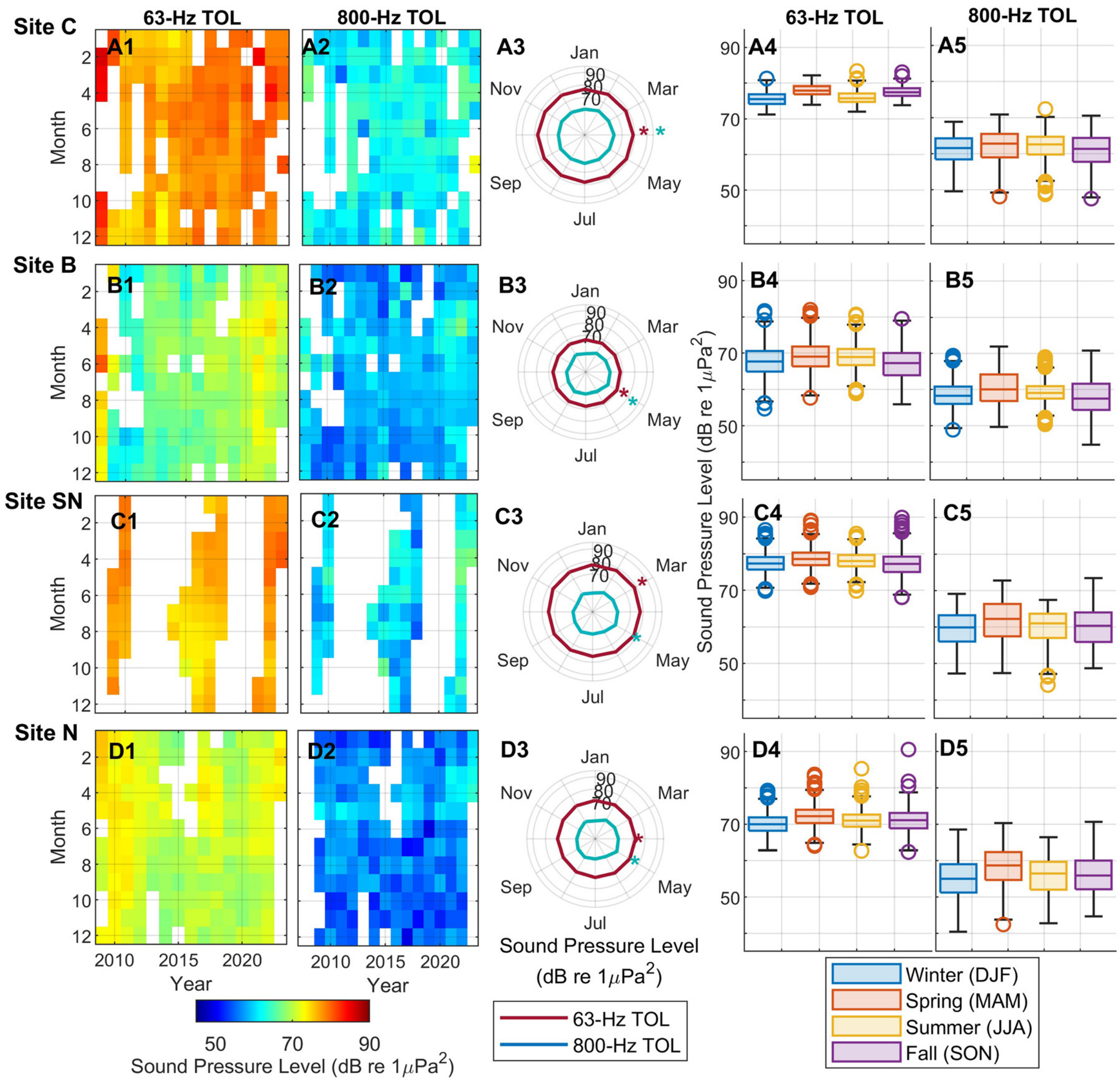

FIG. 8. Seasonal sound levels associated with ship sound (63-Hz one-third octave level, or TOL) and wind sound (800-Hz TOL). Both peak mainly during the spring season, although these peaks are minimal.

2023). During historical MHW events, warmer sea surface temperatures led to northward shifts in zooplankton, fish larvae, and juvenile fishes (Cavole *et al.*, 2016; Lea and Rosenblatt, 2000). Humpback whales and possibly other marine mammals follow these prey shifts, concentrating closer to the coast where productive upwelling persisted (Santora *et al.*, 2020). Soundscapes at these three sites reflected those shifts, with increases in fin and blue whale sound levels at the more northern and nearshore site (site C), and decreases in sound levels at southern, offshore sites (sites N and H). Site C is situated 300 and 220 km north of sites N and H, respectively, and over 100 km closer to shore within productive coastal upwelling waters.

Additionally, the MHW likely altered sound propagation in Southern California waters due to warmer seawater. Increased warming of seawater can increase the speed and attenuation of these signals, potentially reducing the distance sound travels. Increased warming at the sea surface may also create a steeper thermocline, creating downward refraction of acoustic signals produced at the surface, potentially increasing the detection of the signals from HARPs that are moored on the seafloor (Lynch *et al.*, 2018). Propagation modeling with temperature, salinity, and depth profiles from the marine heatwave years in comparison to the non-marine heatwave years may be investigated in future studies to determine the effects of MHW, and warming in general, on ocean soundscapes (Lynch *et al.*, 2018; Širović *et al.*, 2007).

From 2008 to 2017, researchers documented an early arrival of blue whale D calls, while B calls showed no changes at several acoustic monitoring sites in the Southern California Bight (Szesciorka *et al.*, 2020). Our study highlights the persistence of the effects of the marine heatwave for multiple years after 2015, suggesting that extending the analysis beyond 2017 could provide insights into whether this early arrival trend is ongoing or has reversed. Additionally, B and D calls were grouped across all recording sites within Channel Islands and Southern California. As

https://doi.org/10.1121/10.0036778

seen in our analysis, changes to the presence and timing of blue whale B call activity can vary by site, suggesting that a site and region specific analysis is needed to understand how the animals are changing spatiotemporal patterns with increased warming and MHW intensity.

c. Relationship between baleen whale sound levels and climatic indices. Fin and blue whale sound levels at the three sites showed a negative correlation with PDO and ONI and a positive correlation with NPGO, which is comparable to studies with blue and fin whale tagging efforts in the Southern California region (Lagerquist *et al.*, 2024). Decreased PDO and ONI typically indicate cooler phases, corresponding to months and years with high levels of upwelling and prey productivity within the Southern California region (Chhak and Di Lorenzo, 2007). Among the sites, site N exhibited the greatest variance explained by the climatic indices whereas site C showed the lowest. Despite its western-facing slope toward the Pacific, site C faces significant noise pollution from container ships that transit on the southbound shipping lane approximately 8 km away from the site. Similar patterns have been observed in other areas along the U.S. West Coast, such as Cordell Bank National Marine Sanctuary, where vessel noise was a dominant year-round contributor to the low-frequency soundscape, overlapping significantly with fin and blue whale vocalizations (Haver *et al.*, 2020). Ship noise may be potentially masking biological sounds or reducing biological activity, or both. This likely contributes to the lower variance explained by climate indices for fin and blue whale sound levels at this site. The lower variance explained was also seen for the blue whale associated sound levels in comparison to fin whale sound levels. It is important to note that the lower variance explained in the blue whale sound levels compared to the fin whale sound levels is not necessarily because there is a lesser association, but because there are fewer blue whales calling and the source levels are lower, making soundscape metrics between the two species difficult to compare. Detecting individual calls, in addition to soundscape analyses, may be helpful in determining the association between blue whale acoustic presence and various environmental variables.

2. Economic drivers of ship sound variability

a. Influence of economic events on ship sound levels. Ship sound levels largely reflected the volatility and cyclicity of maritime traffic patterns, which are shaped by factors such as holidays and U.S. consumer spending. Sites B and C are located adjacent to the traffic separation scheme that supports ship transits to the Port of Los Angeles and Long Beach, the central gateway for international trade in the Western Hemisphere (United Nations Conference on Trade and Development (UNCTAD): Navigating Stormy Waters, 2022). These sites showed the highest variance explained by over 40% and 20%, respectively. Sites N and H had far fewer vessels, resulting in lower variance explained in ship sound levels attributed to vessel count. Ship sound levels have not reached the pre-recession sound levels, as shipping line bankruptcies led to major mergers and acquisitions among large carriers, and international shipping markets in general remained sluggish (Gu *et al.*, 2020; Notteboom *et al.*, 2021). While the failure of shipping sound levels to reach pre-recession levels is largely attributed to these economic factors, advancements in quieter ship designs and noise-reduction technologies may also play a role (McKenna *et al.*, 2024; ZoBell *et al.*, 2021; ZoBell *et al.*, 2023; ZoBell *et al.*, 2024). However, these technologies are not yet widely adopted across the industry. Documenting changes in ocean noise as such operations and technologies improve and become more widespread will be important for understanding their long-term impact.

Strikes, negotiations, and walkouts taken by the International Longshore and Warehouse Union (ILWU) can also be seen within the vessel counts and ship sound levels specifically within late 2014 and early 2015, when dock worker contract discussions ensued (Bradley, 2016). During COVID-19 pandemic, shifts in the demand of consumer goods and disruptions in the global supply chain were reflected in vessel presence in the San Pedro Bay Port Complex (Vukić and Lai, 2022). While ship counts decreased at certain times, this was offset by increases in loitering, congestion, and dwell time (Vukić and Lai, 2022). Sound levels remained comparable to previous years during the same months, followed by an increase in sound levels due to anchorage congestion. Although the acute anchorage congestion led to high levels of ships within the 25 km radius in this study, the vessels were moving very slowly or not at all, leading to slightly higher sound levels than average, but not extending to sound levels from pre-financial crisis. In mid-November 2021, a queuing system was implemented along the west coast where ships were advised to wait outside of a designated Safety and Air Quality area that extends150 miles west and 50 miles north and south of the port to be assigned a berth to unload cargo (Vukić and Lai, 2022). The system along the West Coast drastically reduced ship count in December 2021, leading to a dip in ship sound levels. Vessel count was used as a proxy for vessel activity in our study, but it does not take into account what operating conditions the vessels are undergoing, and some operations may contribute to higher sound levels than others. Future analysis could expand operations and vessel types considered in their study to achieve a more comprehensive understanding of vessel activity effects on the soundscape.

b. Seasonal and diel patterns of ship noise in relation to maritime operations. Seasonal trends in non-biological sound levels were less pronounced than with the biological sound levels. Overall, ship sound levels peaked in the spring season across sites, with peak months ranging from March to May. During January and February, many factories in Asia close for a couple of weeks for Lunar New Year celebrations, reducing transits to the west coast (Zhao *et al.*, 2022). Imports resume to normal growth in the spring and increase even more when distributors are restocking inventories for the shopping season that peaks in July and late-summer (Smith *et al.*, 2023).

In terms of diel patterns, early morning hours of 3:00 to 5:00 PST mark the morning rush-hour for cargo ships to arrive at the Port of Los Angeles for the longshoreman to start handling cargo by 7:00 PST (Batz, 2024). Longshoremen finish their shifts around 18:00 PST, creating an afternoon rush hour starting at a broader time span of 14:00 to 18:00 PST, where most cargo ships are departing POLA (Batz, 2024). Ships transit at different speeds in different areas of the channel. Established in 2001, the POLA vessel speed reduction program (VSR) advises vessels to voluntarily reduce their speed to 12 kn within 40 NM of the port. Within the POLA precautionary zone, there is a mandatory VSR program for ships to transit 12 kn. Within the inner harbor, vessels are required to transit no more than 6 kn. In addition to POLA VSR programs, the Blue Whales and Blue Skies voluntary VSR program (est. 2014) advises vessels that are 300 GT or larger to transit at 10 kn from May through December (Morten *et al.*, 2022). Sites C and B are approximately 120 NM and 90 NM from POLA. Taking this into consideration, a ship departing POLA at the end of the morning and evening rush hour on the northbound shipping lane would reach site B 14:00 PST and 3:00 PST (10:00 UTC and 21:00 UTC), which are the times of the sound level peaks in the diel analysis. With farther distance away from POLA and outside of some of the VSR regions, a ship planning to arrive at POLA at the start of the rush hour on the southbound shipping lane would pass site C at 5:00 AM and 17:00 PST (12:00 UTC and 00:00 UTC), creating the peaks seen in the diel analysis. Overall, the longshoreman daily schedules mirror peaks in ship noise diel patterns for the sites adjacent to busy shipping lanes (sites B and C).

B. Supported results: Biological bands

1. Interannual

Patterns of acoustic behavior for blue and fin whales have been extensively studied in the Southern California region, and many of the findings, both from detected calls and soundscape analyses, align with the results of this study. For example, long-term spectrogram analysis revealed a decline in the peak frequency of blue whale B calls. Since the 1960s, the frequency of blue whale calls has been decreasing (McDonald *et al.*, 2009) at a rate of 0.27 Hz per year, with a slowing of the rate in more recent years (Rice *et al.*, 2022). Previous studies have typically relied on detecting individual calls (McDonald *et al.*, 2009; Rice *et al.*, 2022) through manual or automated detection methods. In contrast, our study identified a decline in frequency directly from the soundscape, without detecting individual calls, highlighting an additional analysis possible through soundscape analysis.

While soundscape analyses provided valuable insights, certain call types could not be fully captured by this method. For instance, additional biological sound presence was observed in the long spectrograms, notably from humpback whale song and fish choruses. These sounds first appeared in the LSG as high amplitudes across a wide frequency range during the spring months. By examining data with higher temporal resolution, humpback whale calls and fish choruses were identified during these months (supplementary material Figs. 4 and 5). The wide frequency range and variability of humpback whale calls is attributed to the lower received levels across this band within the LSGs. Variable calls, when averaged over an hour or day, dilute the energy across the range of frequencies. Additionally, humpback whale calls have a lower rms source level compared to blue and fin whale calls of 173 dB re 1 μPa^2 (150–1000 Hz), resulting in lower received levels at the recording devices (Guazzo *et al.*, 2020). Fish choruses are a relatively new area of passive acoustic research in Southern California, and some of the choruses identified in Southern California acoustic datasets are yet to be characterized. The fish choruses observed in this study were consistent with the unidentified fish chorus centered at 110 Hz seen in spectrograms in Kim *et al.* (2023) but also included some previously unrecognized choruses. These choruses exhibited low received levels and were intermittent across days, suggesting that the deep sensor locations may be detecting choruses from distant areas or that these sensors are not located in optimal habitat for fish chorusing. Call detections for these species, or a higher temporal resolution in soundscape analyses, will be necessary to fully understand the interannual trends of these species (Ryan *et al.*, 2025).

2. Seasonal

Seasonal patterns of biological sound levels were investigated by examining monthly peaks across years, median monthly peaks for all years combined, and median sound levels per season. Fin whale and blue whale sound levels displayed seasonal partitioning, with blue whale sound levels peaking in the summer and fall seasons, and fin whale sound levels peaking in the fall and winter, consistent with studies in the California Current Ecosystem for these species (Ryan *et al.*, 2025). Previous studies using manual and automated detections of 20-Hz fin whale calls and blue whale B and D calls in the Southern California region have also documented similar seasonal partitioning between these species which may allow for less competition both in acoustic and ecological space (Irvine *et al.*, 2019; Oleson *et al.*, 2007; Širović *et al.*, 2015; Vu, 2015). A study using a similar soundscape analysis approach observed the same seasonal partitioning of baleen whale calls in the Cordell Bank National Marine Sanctuary, further supporting the consistency of these seasonal patterns across the region (Haver *et al.*, 2020).

Blue whale seasonal patterns in Southern California have been studied extensively by detecting B and D calls to understand seasonal presence in time and space (Krumpel *et al.*, 2021; Oleson *et al.*, 2007; Širović *et al.*, 2015; Szesciorka *et al.*, 2020; Wiggins *et al.*, 2005). Blue whales occupy their feeding grounds in the Southern California

Bight from late May through November (Burtenshaw *et al.*, 2004; Calambokidis *et al.*, 1990; Lagerquist *et al.*, 2024; Mate *et al.*, 1999; Szesciorka *et al.*, 2020). It is believed that these whales begin producing B calls at the end of their foraging period in Southern California for a few months before departing for their likely mating grounds in the Costa Rica Dome region. This migration is associated with a peak in energy within the 40–48 Hz frequency band during the summer and fall months (Mate *et al.*, 1999; Širović *et al.*, 2015; Wiggins *et al.*, 2005). Spatially, blue whale sound levels peaked in summer for sites H, E, and N and fall for site C, indicating a northward shift in distribution throughout that time period as whales presumably extended their range towards the Oregon/Washington coast, covering their feeding ground before leaving the region and migrating southward to their breeding grounds (Bailey *et al.*, 2009; Burtenshaw *et al.*, 2004; Trickey *et al.*, 2015; Vu, 2015).

Fin whales, in contrast, are present in the Southern California area year-round, with some hypotheses of complex within-area migration (Mizroch *et al.*, 2009; Širović *et al.*, 2015; Vu, 2015). They displayed increased 20-Hz calls during fall and winter at H, E, and N and fall at site C which does not match their visually active periods in summer and fall while they are producing 40-Hz calls, in much lower quantities, suggesting individual 20-Hz calling rates rise as the reproductive season nears (Giddings, 2022; Širović *et al.*, 2013; Vu, 2015).

Long-term spectrogram analysis revealed a seasonal variation in the spectral frequency of blue whale calls. Each year, the frequency content of calls initially peaked in the summer/fall and then gradually decreased throughout the calling season. This has been described for multiple blue whale populations (Gavrilov *et al.*, 2011; Gavrilov *et al.*, 2012; Leroy *et al.*, 2018; Miksis-Olds *et al.*, 2018; Miller *et al.*, 2014; Rice *et al.*, 2022; Širović *et al.*, 2016). Several hypotheses exist for this intra-annual pattern including changes in whale behavior, particularly body condition or blubber thickness, seasonal changes in dive behavior, the Doppler effect, and short-term changes in the ambient noise (Gavrilov *et al.*, 2011; Gavrilov *et al.*, 2012; Miller *et al.*, 2014; Leroy *et al.*, 2018).

3. Diel

Previous studies in the region have identified a diel calling pattern in blue whales and fin whales, peaking during twilight periods and dark phases, correlating with diel patterns observed in their primary prey, krill (Friedlaender *et al.*, 2015; Keen *et al.*, 2019; Stafford *et al.*, 2005; Wiggins *et al.*, 2005). Fin and blue whale associated band levels did not reflect notable diel patterns, except for at sites B and C. The diel call patterns at these sites appeared to directly reflect the diel patterns of ship sound levels. Additional foraging call types, such as D calls, are unlikely to cause this pattern due to their variability and short duration. At an hourly scale, ship sound appears to obscure biological patterns, underscoring the challenges of using this type of analysis to discern fine-scale biological behaviors in the presence of anthropogenic noise contamination.

C. Supported results: Non-biological bands

1. Interannual

Historical economic and port events were reflected within the ship sound levels for sites B and C. The months in the beginning of the 2008–2009 financial crisis showed peak sound levels in the Santa Barbara Channel, mirroring past results from this site and time period (McKenna *et al.*, 2012). The crisis generated a surplus of cargo capacity, as the world cargo shipping demand in Twenty-Foot Equivalent Unit (TEU), a standard measure of cargo capacity based on a 20-foot shipping container, fell by 12.4% in 2009 (Notteboom *et al.*, 2021). The sudden decline in mid-2009 and 2010 aligns with the spike in vessel layup, with 508 ships (totaling 1.3×10^6 TEU) taken out of service in February 2010 (Notteboom *et al.*, 2021). The ship sound levels have gradually increased over time since the trough in 2010, with a spike in January 2012 from recession recovery and a growth in U.S. imports by 5.8% [Port of Los Angeles (POLA), 2012]. In addition to the financial crisis, in 2009 the California Air Resources Board (CARB) enacted the Vessel Fuel Rule, prescribing specific fuel content requirements for vessels traveling in interstate waters (Easterbrooks, 2013). This ruling required ships to use low-sulfur emitting fuels within 24 nm of the coast, ultimately leading ships to transit farther offshore, reducing sound within the Santa Barbara Channel (McKenna *et al.*, 2012).

At sites farther away from shipping lanes, sound levels may mirror additional anthropogenic sources. In this study, site SN had less overall vessel activity, but the sound levels within the ship sound band were comparable to site C. However, the variance explained by ship count was less than 16%. This is likely due to additional anthropogenic sound sources contributing to the soundscape, in addition to the site being situated on the western-facing slope of a basin, thereby receiving sound sources from the entire Pacific. Site SN lies adjacent to a navy testing range where incidental harassment from missile launching is authorized and active sonar testing occurs (McDonald *et al.*, 2008; United States Department of Commerce, 2021), which is likely the cause of increased anthropogenic noise at this site beyond ship noise. Site N is also likely exposed to fishing vessel sounds, which was not incorporated into this analysis, because AIS antennas on fishing vessels were not required pre-2015. Seal bomb use by fisherman has been documented at site N to detract pinnipeds from fishing effort (Krumpel *et al.*, 2021). From 2005 to 2016, site N had 35% of days present with seal bombs, which likely contributed to the low-frequency (<1 kHz) anthropogenic noise at this site (Krumpel *et al.*, 2021).

In addition to ship sound levels, interannual wind sound levels were studied in relation to wind speeds. Wind sound levels showed a clear relationship with wind speed across the time series for all sites. At wind speeds below 4 m/s, where surface wave and turbulence interactions dominate, a flatter slope and greater variability in the relationship between wind sound levels and wind speeds was observed. At sites C, H, and N there was a stronger relationship with increases in wind speed (>6 m/s), when the source may include bubble oscillations (Hildebrand *et al.*, 2021). Site B had the most scatter and lowest wind speeds compared to the other sites, likely due the sheltered location of the site by the Channel Islands, creating overall lower interactions with wind speed and wind sound levels.

2. Seasonal

In terms of geophysical sound, seasonal and geographic variability of wind patterns over the Southern California Bight were reflected in our findings. Wind sound levels peaked in spring and dipped in the fall for all sites, with the highest monthly levels seen at sites C and SN and the lowest at site B. Site C is located offshore of Point Conception where strong winds persist while site B is sheltered in the eastern Santa Barbara Channel and experiences weaker winds (Caldwell *et al.*, 1986; Dorman and Winant, 2000; Andrew *et al.*, 2011). During the spring and summer, offshore and near Point Conception, winds are consistently vigorous and sustained due to the influence of the North Pacific high and southwest thermal low, in contrast to the generally light and offshore-directed winds observed near the coast in the Southern California Bight (Winant and Dorman, 1997).

3. Diel

Wind-related sound levels exhibit a distinct daily pattern, driven by temperature gradients between land and sea. In the afternoon, higher sound levels are observed as the land heats up faster than the sea, creating a temperature gradient that causes cool air to move from the sea to the land, thereby increasing wind speed (Hughes *et al.*, 2007). In contrast, sound levels are lowest in the morning when the temperature difference between land and sea equalizes, leading to a significant reduction in wind speed.

D. Uncertainties and future directions

The ocean is a dynamic, fluid medium that undergoes a multitude of simultaneous chemical, physical, biological, and anthropogenic interactions. Even with multi-point acoustic sensing for timespans of over a decade, using, understanding, and predicting soundscape trends and patterns remains difficult, especially in the face of altered conditions with climate change. Climatic oscillations, such as PDO, ENSO, and NPGO, operate over interannual and decadal timespans. Our time series captured the pre-, during, and post-phases of a marine heatwave that had persistent effects on biological sound sources across multiple sites for years thereafter. Notably, these effects varied by location, showing the need for spatial analysis across many point sources to understand the impacts of these climatic events. As marine heatwaves become more frequent and prolonged, documenting marine mammal displacement through soundscape analysis becomes increasingly critical (Alksne *et al.*, 2024; Frölicher *et al.*, 2018; Ren *et al.*, 2023). Capturing additional marine heatwaves in the acoustic datasets may glean insights into whether marine organisms are shifting closer to shore or northward, towards regions that mirror their cooler, historical home ranges. Similarly, the PDO spatial pattern was calculated using data from 1950 to 1993. With the increase in marine heatwaves, the energetic modes of the North Pacific have fundamentally changed, rendering the PDO less reliable as a metric in the context of climate change (Werb and Rudnick, 2023). This necessitates exploring additional metrics or recalibrating existing ones to accurately reflect climate-driven alterations. Given the PDO's 20–30 year timespan, extending soundscape monitoring at these sites for decades to come will be essential to explore patterns and trends across longer cycles.

Our study focused on acoustic monitoring in the Southern California Bight, which had an abundance of marine mammal sounds, as well as geophysical and anthropogenic activity. Soundscape analysis was performed by targeting certain frequency bands that were associated with biological, anthropogenic, and geophysical sound sources of interest. Trends and oscillations were apparent, noting the potential for soundscape analysis as a tool to study ocean health. However, shortcomings were also apparent, with contamination of sound levels from non-target noise, creating differences in intensities that were not associated with the sound sources of interest. This should be considered a caveat of soundscape analysis, especially in regions associated with anthropogenic noise, or comparing soundscape metrics in regions with differing acoustic environments.

Expanding the spatial and temporal scope of our study beyond this region will allow for identification of widespread trends across ocean basins, taxa, and human impacts, providing valuable insights into ongoing changes in the global ocean. We recommend that the time series developed in this study be extended into the future through ongoing monitoring efforts to comprehensively assess changes in space and time amidst evolving ocean conditions.

V. CONCLUSION

In conclusion, this comprehensive study of long-term acoustic data spanning over 60 cumulative years from 2008 to 2023 across six sites reveals intricate patterns in biological and non-biological sound levels across multiple sites in the Southern California Bight. Our soundscape analysis uncovers significant oscillations influenced by climatic cycles, economic events, seasonal changes, and diel patterns, and documents both the strengths and weaknesses of using soundscape metrics to determine ocean health.

Biological sound levels associated with fin and blue whale calls exhibit distinct seasonal and interannual variations and underscore the sensitivity of whale vocalizations to major climatic events, such as the marine heatwave, and shifts in ocean-atmosphere climate variability, such as the Pacific Decadal Oscillation. The decline in frequency of blue whale calls revealed by the soundscape analysis suggests a potential shift in population dynamics or habitat use over time. These findings contribute valuable insights into long-term trends that may inform conservation efforts and management strategies for these species.

Non-biological sound levels associated with ship and wind sounds reflect the volatility of maritime traffic patterns and seasonal variations in wind speeds. This study notes significant influences of economic activities, such as the 2008–2009 financial crisis and subsequent regulatory changes, on ship sound levels within the region. Additionally, wind sound patterns exhibit clear seasonal trends linked to regional wind patterns and local environmental conditions.

This study displays the strengths and shortcomings of soundscape analyses for long-term acoustic datasets, which can provide a nuanced understanding of ecological dynamics by capturing both large-scale and subtle shifts over time. By examining acoustic data spanning decades, researchers gain insights into the cumulative impacts of human activities, climate variability, and climate change on marine ecosystems. Integrating soundscape analysis into long-term monitoring frameworks can enhance our ability for managing anthropogenic impacts, developing sustainable practices in marine spatial planning, and preserving marine biodiversity and ecosystem health in the face of ongoing global changes.

SUPPLEMENTARY MATERIAL

See the supplementary material for long spectrograms and band levels at all sites, along with examples of humpback whale song and fish choruses.

ACKNOWLEDGMENTS

This project required vast support from technicians, ship crew, data experts, and members of the Scripps Marine Bioacoustics Research Collaborative both past and present. We would like to thank Ryan Griswold, John Hurwitz, and Bruce Thayre, for leading the maintenance, recovery, and deployment of the acoustic sensors used in this work. A special thanks to Erin O'Neill and Shelby Bloom for processing the raw acoustic data for this analysis. We would like to thank the crew of the R/V Shearwater, R/V Beyster, and R/V Robert Gordon Sproul for supporting our science missions over the past decade. The funding for this research was provided by the California Marine Sanctuary Foundation, Office of National Marine Sanctuaries, Office of Naval Research Marine Mammal and Biology Program, and the U.S. Pacific Fleet.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

DATA AVAILABILITY

Daily median sound pressure levels for all sites and bands of interest are available on dryad: https://doi.org/10.5061/dryad.nzs7h450t. Automated Identification System data is open-access and can be found at https://marinecadastre.gov/. Wind speed data is open-access and can be found at https://climatedataguide.ucar.edu/climate-data/ccmp-cross-calibrated-multi-platform-wind-vector-analysis.

Alksne, M. N., Kok, A. C. M., Agarwal, A., Frasier, K. E., and Baumann-Pickering, S. (**2024**). "Biogeographic patterns of Pacific white-sided dolphins based on long-term passive acoustic records," Divers. Distrib. **30**(9), e13903.

Andrew, R. K., Howe, B. M., and Mercer, J. A. (**2011**). "Long-time trends in ship traffic noise for four sites off the North American West Coast," J. Acoust. Soc. Am. **129**(2), 642–651.

Bailey, H., Mate, B. R., Palacios, D. M., Irvine, L., Bograd, S. J., and Costa, D. P. (**2009**). "Behavioural estimation of blue whale movements in the Northeast Pacific from state-space model analysis of satellite tracks," Endang. Species Res. **10**(1), 93–106.

Batz, J. (**2024**). (private communication).

Becker, E. A., Forney, K. A., Miller, D. L., Barlow, J., Rojas-Bracho, L., Jorge Urbán, R., and Moore, J. E. (**2022**). "Dynamic habitat models reflect interannual movement of cetaceans within the California current ecosystem," Front. Mar. Sci. **9**(May), 829523.

Bittencourt, L., Barbosa, M., Bisi, T. L., Lailson-Brito, J., and Azevedo, A. F. (**2020**). "Anthropogenic noise influences on marine soundscape variability across coastal areas," Mar. Pollut. Bull. **160**(May), 111648.

Bradley, J. (**2016**). " 'The union ruptured': Mechanization, modernization, and the international longshore and warehouse union," student thesis, University of California, Berkeley, CA.

Burtenshaw, J. C., Oleson, E. M., Hildebrand, J. A., McDonald, M. A., Andrew, R. K., Howe, B. M., and Mercer, J. A. (**2004**). "Acoustic and satellite remote sensing of blue whale seasonality and habitat in the Northeast Pacific," Deep-Sea Res. Part II: Topical Stud. Oceanogr. **51**(10-11), 967–986.

Calambokidis, J., Steiger, G. H., Cubbage, J. C., Balcomb, K. C., Ewald, C., Kruse, S., Wells, R., and Sears, R. (**1990**). "Sightings and movements of blue whales off central California 1986–88 from photo-identification of individuals," Rep. Int. Whaling Commission **12**, 343–348, available at https://www.rorqual.com/downloads/sightings-and-movements-of-blue-whales-off-central-california-1986-88-from-photo-identification-of-individuals.pdf.

Caldwell, P., Stuart, D., and Brink, K. (**1986**). "Mesoscale wind variability near point conception, California during spring 1983," J. Clim. Appl. Meteor. **25**(9), 1241–1254.

Campbell, G. S., Thomas, L., Whitaker, K., Douglas, A. B., Calambokidis, J., and Hildebrand, J. A. (**2015**). "Inter-annual and seasonal trends in cetacean distribution, density and abundance off southern California," Deep-Sea Res. Part II: Topical Stud. Oceanogr. **112**, 143–157.

Cavole, L. M., Demko, A. M., Diner, R. E., Giddings, A., Koester, I., Pagniello, C. M. L. S., Paulsen, M. L., Ramirez-Valdez, A., Schwenck, S. M., Yen, N. K., Zill, M. E., and Franks, P. J. S. (**2016**). "Biological impacts of the 2013–2015 warm-water anomaly in the northeast Pacific: Winners, losers, and the future," Oceanography **29**(2), 273–285.

Chhak, K., and Di Lorenzo, E. (**2007**). "Decadal variations in the California current upwelling cells," Geophys. Res. Lett. **34**(14), L14604, https://doi.org/10.1029/2007GL030203.

Dailey, M. D., Reish, D. J., and Anderson, J. W. (**1993**). *Ecology of the Southern California Bight: A Synthesis and Interpretation* (University of California Press, Berkley, CA).

Di Lorenzo, E., Schneider, N., Cobb, K. M., Franks, P. J. S., Chhak, K., Miller, A. J., McWilliams, J. C., Bograd, S. J., Arango, H., Curchitser, E., Powell, T. M., and Rivière, P. (**2008**). "North Pacific Gyre Oscillation links ocean climate and ecosystem change," Geophys. Res. Lett. **35**(8), 2–7, https://doi.org/10.1029/2007GL032838.

Dorman, C. E., and Winant, C. D. (**2000**). "The structure and variability of the marine atmosphere around the Santa Barbara Channel," Mon. Weather Rev. **128**(2), 261–282.

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., Erbe, C., Gordon, T. A. C., Halpern, B. S., Harding, H. R., Havlik, M. N., Meekan, M., Merchant, N. D., Miksis-Olds, J. L., Parsons, M., Predragovic, M., Radford, A. N., Radford, C. A., Simpson, S. D., Slabbekoorn, H., Staaterman, E., Van Opzeeland, I. C., Winderen, J., Zhang, X., and Juanes, F. (**2021**). "The soundscape of the Anthropocene ocean," Science **371**(6529), aba4658.

Easterbrooks, B. D. (**2013**). "Overreach on the High Seas?: Whether federal maritime law preempts California's vessel fuel rules," Pepp. L. Rev **39**(3), 645–699.
Fewings, M. R., and Brown, K. S. (**2019**). "Regional structure in the marine heat wave of summer 2015 off the western United States," Front. Mar. Sci. **6**(July 2015), 564.
Friedlaender, A. S., Goldbogen, J. A., Hazen, E. L., Calambokidis, J., and Southall, B. L. (**2015**). "Feeding performance by sympatric blue and fin whales exploiting a common prey resource," Mar. Mammal Sci. **31**(1), 345–354.
Frölicher, T. L., Fischer, E. M., and Gruber, N. (**2018**). "Marine heatwaves under global warming," Nature **560**(7718), 360–364.
Gavrilov, A. N., McCauley, R. D., and Gedamke, J. (**2012**). "Steady inter and intra-annual decrease in the vocalization frequency of Antarctic blue whales," J. Acoust. Soc. Am. **131**(6), 4476–4480.
Gavrilov, A. N., McCauley, R. D., Salgado-Kent, C., Tripovich, J., and Burton, C. (**2011**). "Vocal characteristics of pygmy blue whales and their change over time," J. Acoust. Soc. Am. **130**(6), 3651–3660.
Giddings, A. (**2022**). "Climate, circulation, chlorophyll, and cetaceans in the California current a dissertation submitted in partial satisfaction of the requirements for the degree doctor of philosophy," doctoral dissertation, University of California San Diego, San Diego, CA.
Gu, Y., Dong, X., and Chen, Z. (**2020**). "The relation between the international and China shipping markets," Res. Transp. Bus. Manage. **34**(January), 100427.
Guazzo, R. A., Helble, T. A., Alongi, G. C., Durbach, IN., Martin, C. R., Martin, S. W., and Henderson, E. E. (**2020**). "The Lombard effect in singing humpback whales: Source levels increase as ambient ocean noise levels increase," J. Acoust. Soc. Am. **148**(2), 542–555.
Haver, S. M., Adams, J. D., Hatch, L. T., Van Parijs, S. M., Dziak, R. P., Haxel, J., Heppell, S. A., McKenna, M. F., Mellinger, D. K., and Gedamke, J. (**2021**). "Large vessel activity and low-frequency underwater sound benchmarks in United States Waters," Front. Mar. Sci. **8**(November), 669528.
Haver, S. M., Rand, Z., Hatch, L. T., Lipski, D., Dziak, R. P., Gedamke, J., Haxel, J., Heppell, S. A., Jahncke, J., McKenna, M. F., and Mellinger, D. K. (**2020**). "Seasonal trends and primary contributors to the low-frequency soundscape of the Cordell Bank National Marine Sanctuary," J. Acoust. Soc. Am. **148**(2), 845–858.
Helble, T. A., Guazzo, R. A., Martin, C. R., Durbach, I. N., Alongi, G. C., Martin, S. W., Boyle, J. K., and Henderson, E. E. (**2020**). "Lombard effect: Minke whale boing call source levels vary with natural variations in ocean noise," J. Acoust. Soc. Am. **147**(2), 698–712.
Hildebrand, J. A. (**2009**). "Anthropogenic and natural sources of ambient noise in the ocean," Mar. Ecol. Prog. Ser. **395**, 5–20.
Hildebrand, J. A., Frasier, K. E., Baumann-Pickering, S., and Wiggins, S. M. (**2021**). "An empirical model for wind-generated ocean noise," J. Acoust. Soc. Am. **149**(6), 4516–4533.
Hughes, M., Hall, A., and Fovell, R. G. (**2007**). "Dynamical controls on the diurnal cycle of temperature in complex topography," Clim. Dyn. **29**(2–3), 277–292.
Irvine, L. M., Palacios, D. M., Lagerquist, B. A., and Mate, B. R. (**2019**). "Scales of blue and fin whale feeding behavior off California, USA, with implications for prey patchiness," Front. Ecol. Evol. **7**(September), 338.
Johnson, N. C., Amaya, D. J., Ding, Q., Kosaka, Y., Tokinaga, H., and Xie, S. P. (**2020**). "Multidecadal modulations of key metrics of global climate change," Global Planet. Change **188**(February), 103149.
Keen, E. M., Falcone, E. A., Andrews, R. D., and Schorr, G. S. (**2019**). "Diel dive behavior of fin whales (*Balaenoptera physalus*) in the Southern California Bight," Aquat. Mamm. **45**(2), 233–243.
Kim, E. B., Frasier, K. E., McKenna, M. F., Kok, A. C. M., Peavey Reeves, L. E., Oestreich, W. K., Arrieta, G., Wiggins, S., and Baumann-Pickering, S. (**2023**). "SoundScape learning: An automatic method for separating fish chorus in marine soundscapes," J. Acoust. Soc. Am. **153**(3), 1710–1722.
Krumpel, A., Rice, A., Frasier, K. E., Reese, F., Trickey, J. S., Simonis, A. E., Ryan, J. P., Wiggins, S. M., Denzinger, A., Schnitzler, H. U., and Baumann-Pickering, S. (**2021**). "Long-term patterns of noise from underwater explosions and their relation to fisheries in southern California," Front. Mar. Sci. **8**(December), 796849.
Lagerquist, B. A., Irvine, L. M., Follett, T. M., Ampela, K., Falcone, E. A., Schorr, G. S., Mate, B. R., and Palacios, D. M. (**2024**). "Blue and fin whale residence time and occupancy in Navy training and testing areas off the U.S. West Coast," Front. Mar. Sci. **11**(November), 1–25.
Lea, R. N., and Rosenblatt, R. H. (**2000**). "Observations on fishes associated with the 1997-98 El Niño off California," California Cooperative Oceanic Fisheries Investigations Report No. **41**(October), 117–129, available at https://www.researchgate.net/profile/Robert-Lea/publication/241576767_Observations_on_fishes_associated_with_the_1997-98_El_Nino_off_California/links/00b4952c48c683478d000000/Observations-on-fishes-associated-with-the-1997-98-El-Nino-off-California.pdf?origin=journalDetail&_tp=eyJwYWdlIjoiam91cm5hbERldGFpbCJ9.
Leroy, E. C., Royer, J. Y., Bonnel, J., and Samaran, F. (**2018**). "Long-term and seasonal changes of large whale call frequency in the southern Indian Ocean," J. Geophys. Res. Oceans **123**(11), 8568–8580, https://doi.org/10.1029/2018JC014352.
Lombard, E. (**1911**). "Le signe de televation de la voix" ("The sign of raising the voice"), Annu. Maladies Oreille Larynx Nez Pharynx **27**, 101–119, available at https://cir.nii.ac.jp/crid/1571980075029126272.
Lynch, J. F., Gawarkiewicz, G. G., Lin, Y.-T., Duda, T. F., and Newhall, A. E. (**2018**). "Ocean warming on acoustic propagation," Oceanography **31**(2), 175–181, available at https://www.jstor.org/stable/26542663.
Marine Cadastre (**2024**). "Vessel traffic," https://hub.marinecadastre.gov/pages/vesseltraffic (Last viewed 4/2/2024).
Mate, B. R., Lagerquist, B. A., and Calambokidis, J. (**1999**). "Movements of North Pacific blue whales during the feeding season off southern California and their southern fall migration," Mar. Mammal Sci. **15**(4), 1246–1257.
McDonald, M. A., Hildebrand, J. A., and Mesnick, S. (**2009**). "Worldwide decline in tonal frequencies of blue whale songs," Endang. Species Res. **9**(1), 13–21.
McDonald, M. A., Hildebrand, J. A., and Wiggins, S. M. (**2006**). "Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California," J. Acoust. Soc. Am. **120**(2), 711–718.
McDonald, M. A., Hildebrand, J. A., Wiggins, S. M., and Ross, D. (**2008**). "A 50 year comparison of ambient ocean noise near San Clemente Island: A bathymetrically complex coastal region off Southern California," J. Acoust. Soc. Am. **124**(4), 1985–1992.
McKenna, M. F., Katz, S. L., Wiggins, S. M., Ross, D., and Hildebrand, J. A. (**2012**). "A quieting ocean: Unintended consequence of a fluctuating economy," J. Acoust. Soc. Am. **132**(3), EL169–EL175.
McKenna, M. F., Rowell, T. J., Margolina, T., Baumann-Pickering, S., Solsona-Berga, A., Adams, J. D., Joseph, J., Kim, E. B., Kok, A. C. M., Kügler, A., Lammers, M. O., Merkens, K., Reeves, L. P., Southall, B. L., Stimpert, A. K., Barkowski, J., Thompson, M. A., Van Parijs, S., Wall, C. C., Zang, E. J., and Hatch, L. T. (**2024**). "Understanding vessel noise across a network of marine protected areas," Environ. Monit. Assess. **196**(4), 369.
Merkens, K., Baumann-Pickering, S., Ziegenhorn, M. A., Trickey, J. S., Allen, A. N., and Oleson, E. M. (**2021**). "Characterizing the long-term, wide-band and deep-water soundscape off Hawai'i," Front. Mar. Sci. **8**(November), 752231.
Miksis-Olds, J. L., Bradley, D. L., and Maggie Niu, X. (**2013**). "Decadal trends in Indian Ocean ambient sound," J. Acoust. Soc. Am. **134**(5), 3464–3475.
Miksis-Olds, J. L., and Nichols, S. M. (**2016**). "Is low frequency ocean sound increasing globally?," J. Acoust. Soc. Am. **139**(1), 501–511.
Miksis-Olds, J. L., Nieukirk, S. L., and Harris, D. V. (**2018**). "Two unit analysis of Sri Lankan pygmy blue whale song over a decade," J. Acoust. Soc. Am. **144**(6), 3618–3626.
Miller, B. S., Leaper, R., Calderan, S., and Gedamke, J. (**2014**). "Red shift, blue shift: Investigating doppler shifts, blubber thickness, and migration as explanations of seasonal variation in the tonality of antarctic blue whale song," PLoS One **9**(9), e107740.
Mizroch, S. A., Rice, D. W., Zwiefelhofer, D., Waite, J., and Perryman, W. L. (**2009**). "Distribution and movements of fin whales in the North Pacific Ocean," Mammal Rev. **39**(3), 193–227.
Morten, J., Freedman, R., Adams, J. D., Wilson, J., Rubinstein, A., and Hastings, S. (**2022**). "Evaluating adherence with voluntary slow speed initiatives to protect endangered whales," Front. Mar. Sci. **9**(February), 833206.
National Weather Service Climate Prediction Center (**2024**). "El Nino—Southern Oscillation (ENSO)," https://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml (Last viewed 12/15/2023).

Notteboom, T., Pallis, T., and Rodrigue, J. P. (**2021**). "Disruptions and resilience in global container shipping and ports: The COVID-19 pandemic versus the 2008–2009 financial crisis," in *Maritime Economics and Logistics* (Macmillan, Palgrave, UK), Vol. 23, Issue 2.
Nystuen, J. A., McGlothin, C. C., and Cook, M. S. (**1993**). "The underwater sound generated by heavy rainfall," J. Acoust. Soc. Am. **93**(6), 3169–3177.
Oleson, E. M., Wiggins, S. M., and Hildebrand, J. A. (**2007**). "Temporal separation of blue whale call types on a southern California feeding ground," Anim. Behav. **74**(4), 881–894.
Parks, S. E., Johnson, M., Nowacek, D., and Tyack, P. L. (**2011**). "Individual right whales call louder in increased environmental noise," Biol. Lett. **7**(1), 33–35.
Pijanowski, B. C., Farina, A., Gage, S. H., Dumyahn, S. L., and Krause, B. L. (**2011**). "What is soundscape ecology? An introduction and overview of an emerging new science," Landscape Ecol. **26**(9), 1213–1232.
Port of Los Angeles (POLA) (**2012**). "Port of Los Angeles container statistics for 2012," https://www.portoflosangeles.org/business/statistics/container-statistics/historical-teu-statistics-2012 (Last viewed 3/4/2024).
Rasmusson, E. M., and Wallace, J. M. (**1983**). "Meteorological aspects of the El Nino/southern oscillation," Science **222**(4629), 1195–1202.
Ren, X., Liu, W., Capotondi, A., Amaya, D. J., and Holbrook, N. J. (**2023**). "The Pacific Decadal Oscillation modulated marine heatwaves in the Northeast Pacific during past decades," Commun. Earth Environ. **4**(1), 218.
Ricciardulli, L. (**2022**). "The climate data guide: CCMP: Cross-calibrated multi-platform wind vector analysis," available at https://climatedataguide.ucar.edu/climate-data/ccmp-cross-calibrated-multi-platform-wind-vector-analysis (Last viewed 5/10/2024).
Rice, A., Širović, A., Hildebrand, J. A., Wood, M., Carbaugh-Rutland, A., and Baumann-Pickering, S. (**2022**). "Update on frequency decline of Northeast Pacific blue whale (*Balaenoptera musculus*) calls," PLoS One **17**(4 April), e0266469.
Ryan, J. P., Joseph, J. E., Margolina, T., Hatch, L. T., Azzara, A., Reyes, A., Southall, B. L., DeVogelaere, A., Peavey Reeves, L. E., Zhang, Y., Cline, D. E., Jones, B., McGill, P., Baumann-Pickering, S., and Stimpert, A. K. (**2021**). "Reduction of low-frequency vessel noise in Monterey Bay National Marine Sanctuary during the COVID-19 pandemic," Front. Mar. Sci. **8**(June 2020), 656566.
Ryan, J. P., Oestreich, W. K., Benoit-Bird, K. J., Waluk, C. M., Rueda, C. A., Cline, D. E., Zhang, Y., Cheeseman, T., Calambokidis, J., Fahlbusch, J. A., Barkowski, J., Fleming, A. H., Turner Tomaszewicz, C. N., Santora, J. A., Margolina, T., Joseph, J. E., Friedlaender, A. S., and Goldbogen, J. A. (**2025**). "Audible changes in marine trophic ecology: Baleen whale song tracks foraging conditions in the eastern North Pacific," PLoS One **20**(2 February), e0318624.
Santora, J., Mantua, N., Schroeder, I., Field, J., Hazen, E., Bograd, S., Sydeman, W., Wells, B., Calambokidis, J., Saez, L., Lawson, D., and Forney, K. A. (**2020**). "Habitat compression and ecosystem shifts as potential links between marine heatwave and record whale entanglements," Nat. Commun. **11**(1), 536.
Seger, K. D., and Miksis-Olds, J. L. (**2020**). "A decade of marine mammal acoustical presence and habitat preference in the Bering Sea," Polar Biol. **43**(10), 1549–1569.
Širović, A., Hildebrand, J. A., and Wiggins, S. M. (**2007**). "Blue and fin whale call source levels and propagation range in the Southern Ocean," J. Acoust. Soc. Am. **122**(2), 1208–1215.
Širović, A., Rice, A., Chou, E., Hildebrand, J. A., Wiggins, S. M., and Roch, M. A. (**2015**). "Seven years of blue and fin whale call abundance in the Southern California Bight," Endang. Species Res. **28**(1), 61–76.
Širović, A., Varga, L. M., and Oleson, E. M. (**2016**). "Long-term trends in ambient and anthropogenic noise in central and western Pacific Ocean," Proc. Mtgs. Acoust. **27**(1), 040001.
Širović, A., Williams, L. N., Kerosky, S. M., Wiggins, S. M., and Hildebrand, J. A. (**2013**). "Temporal separation of two fin whale call types across the eastern North Pacific," Mar. Biol. **160**(1), 47–57.
Smith, D., Bingham, P., Hackett, D., and Smith, J. (**2023**). "Multiperspective analysis of pandemic impacts on U.S. import trade: What happened, and why?," Transp. Res. Rec. **2677**(2), 50–61.
Stafford, K. M., Moore, S. E., and Fox, C. G. (**2005**). "Diel variation in blue whale calls recorded in the eastern tropical Pacific," Animal Behav. **69**(4), 951–958.
Szesciorka, A. R., Ballance, L. T., Širović, A., Rice, A., Ohman, M. D., Hildebrand, J. A., and Franks, P. J. S. (**2020**). "Timing is everything: Drivers of interannual variability in blue whale migration," Sci. Rep. **10**(1), 1–9.
Thode, A. M., D'Spain, G. L., and Kuperman, W. A. (**2000**). "Matched-field processing, geoacoustic inversion, and source signature recovery of blue whale vocalizations," J. Acoust. Soc. Am. **107**(3), 1286–1300.
Tokyo Climate Center (**2024**). "Pacific Decadal Oscillation (PDO) index," https://ds.data.jma.go.jp/tcc/tcc/products/elnino/decadal/pdo.html (Last viewed 3/4/2024)
Trickey, J., Baumann-Pickering, S., Sirovic, A., Hildebrand, J., Brewer, A., Herbert, S., Rice, A., Thayre, B., and Wiggins, S. (**2015**). "Passive acoustic monitoring for marine mammals in the Northwest Training Range Complex July 2013–April 2014," MPL technical memorandum No. MPS-TM 557, Marine Physical Laboratory, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA.
UNCTAD (**2022**). *Navigating Stormy Waters* (United Nations Conference on Trade and Development, Geneva, Switzerland).
United States Department of Commerce (**2021**). "Incidental harassment authorization," National Marine Fisheries Service.
Vu, E. (**2015**). "Habitat use of calling baleen whales in the Southern California current ecosystem," Ph.D. dissertation, University of California, San Diego, CA.
Vukić, L., and Lai, K. (**2022**). "Acute port congestion and emissions exceedances as an impact of COVID-19 outcome: The case of San Pedro Bay ports," J. Shipp. Trade **7**(1), 25.
Welch, P. D. (**1967**). "The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms," IEEE Trans. Audio Electroacoust. **15**, 70–73.
Wenz, G. M. (**1962**). "Acoustic ambient noise in the ocean: Spectra and sources," J. Acoust. Soc. Am. **34**(12), 1936–1956.
Werb, B. E., and Rudnick, D. L. (**2023**). "Remarkable changes in the dominant modes of north Pacific sea surface temperature," Geophys. Res. Lett. **50**(4), e2022GL101078, https://doi.org/10.1029/2022GL101078.
Wiggins, S. M., and Hildebrand, J. A. (**2007**). "High-frequency Acoustic Recording Package (HARP) for broad-band, long-term marine mammal monitoring," in *2007 Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies*.
Wiggins, S. M., Oleson, E. M., McDonald, M. A., and Hildebrand, J. A. (**2005**). "Blue Whale (*Balaenoptera musculus*) diel call patterns offshore of southern California," Aquat. Mamm. **31**(2), 161–168.
Winant, C. D., and Dorman, C. E. (**1997**). "Seasonal patterns of surface wind stress and heat flux over the Southern California Bight," J. Geophys. Res. Oceans **102**(C3), 5641–5653, https://doi.org/10.1029/96JC02801.
Zhang, R. H., and Levitus, S. (**1997**). "Structure and cycle of decadal variability of upper-ocean temperature in the North Pacific," J. Clim. **10**(4), 710–727.
Zhang, Y. (**1996**). "An observational study of atmosphere-ocean interactions in the Northern oceans on interannual and interdecadal time-scales," Ph.D. dissertation, University of Washington, Seatle, WA.
Zhao, H. M., He, H. D., Lu, K. F., Han, X. L., Ding, Y., and Peng, Z.-R. (**2022**). "Measuring the impact of an exogenous factor: An exponential smoothing model of the response of shipping to COVID-19," Transp. Policy **118**, 91–100.
ZoBell, V. M., Frasier, K. E., Morten, J. A., Hastings, S. P., Peavey Reeves, L. E., Wiggins, S. M., and Hildebrand, J. A. (**2021**). "Underwater noise mitigation in the Santa Barbara Channel through incentive-based vessel speed reduction," Sci. Rep. **11**(1), 18391.
ZoBell, V. M., Gassmann, M., Kindberg, L. B., Wiggins, S. M., Hildebrand, J. A., and Frasier, K. E. (**2023**). "Retrofit-induced changes in the radiated noise and monopole source levels of container ships," PLoS One **18**(3), e0282677.
ZoBell, V. M., Hildebrand, J. A., and Frasier, K. E. (**2024**). "Assessing approaches for ship noise reduction within critical whale habitat," J. Acoust. Soc. Am. **156**(5), 3534–3544.
Zollinger, S. A., and Brumm, H. (**2011**). "The Lombard effect," Curr. Biol. **21**(16), R614–R615.