Marine Pollution Bulletin 194 (2023) 115406

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

The variable influence of anthropogenic noise on summer season coastal underwater soundscapes near a port and marine reserve

Samara M. Haver[a,b,*], Joseph Haxel[c], Robert P. Dziak[d], Lauren Roche[a], Haru Matsumoto[e], Christa Hvidsten[f], Leigh G. Torres[g]

[a] Cooperative Institute for Marine Ecosystems and Resources Studies, Oregon State University, United States of America
[b] Department of Fisheries, Wildlife, and Conservation Sciences, Oregon State University, United States of America
[c] Pacific Northwest National Laboratory, Coastal Sciences Division, United States of America
[d] NOAA Pacific Marine Environmental Laboratory, United States of America
[e] Living Ocean Systems, United States of America
[f] Texas A&M University, United States of America
[g] Geospatial Ecology of Marine Megafauna Lab, Marine Mammal Institute, Department of Fisheries, Wildlife, and Conservation Sciences, Oregon State University, United States of America

ARTICLE INFO

Keywords:
Passive acoustic monitoring
Soundscapes
Marine protected areas
Ocean noise
Bioacoustics
Whales

ABSTRACT

Monitoring soundscapes is essential for assessing environmental conditions for soniferous species, yet little is known about sound levels and contributors in Oregon coastal regions. From 2017 to 2021, during June–September, two hydrophones were deployed near Newport, Oregon to sample 10–13,000 Hz underwater sound. One hydrophone was deployed near the Port of Newport in a high vessel activity area, and another 17 km north within a protected Marine Reserve. Vessel noise and whale vocalizations were detected at both sites, but whales were recorded on more days at the Marine Reserve. Median sound levels in frequencies related to noise from various vessel types and sizes (50 – 4,000 Hz) were up to 6 dB higher at the Port of Newport, with greater diel variability compared to the Marine Reserve. In addition to documenting summer season conditions in Oregon waters, these results exemplify how underwater soundscapes can differ over short distances depending on anthropogenic activity.

1. Introduction

Marine acoustic environments are important for marine mammals and other soniferous species that rely on sound for survival and reproduction. In addition to biological sounds, noise generated by anthropogenic sources and natural physical processes constitute a soundscape. Soundscapes can be described both objectively with metrics that measure sound, as well as subjectively according to listener perception of sound in the environment (Francis and Barber, 2013). The life history of marine animals, including mammals, fish, and invertebrates can be impacted by each species' perception of various sound sources and how an individual animal may rely on sound to forage, communicate, and/or avoid predators (Erbe et al., 2019; Popper and Hawkins, 2019). Beyond animal conservation, ocean sound conditions are also considered intrinsically valuable and are included as an essential ocean variable for monitoring by the Global Ocean Observing System (Tyack et al., 2018).

To date, most research on the negative effects of low-frequency ocean noise on marine mammal health and behavior has focused jointly on large mysticete whales and deep-water offshore environments that are most heavily impacted by large commercial shipping vessels and other anthropogenic noise related to industrial activities (Castellote et al., 2012; Rolland et al., 2012; Thode et al., 2020). The low-frequency acoustic communication range of large mysticete whales overlaps with sound generated by anthropogenic sound sources that are prevalent near large container ports (e.g., Shanghai [China], Rotterdam [Netherlands], or Los Angeles [United States of America]), as well as the major oceanic shipping routes that link them (Erbe et al., 2019; National Research Council, 2003; Richardson et al., 1995). Additionally, in deep-water environments (>500 m depth), noise from shipping vessels and other anthropogenic sources can propagate tens to hundreds of kilometers from the source to areas with higher densities of marine mammals (Gassmann et al., 2017; Haver et al., 2020). However, anthropogenic

---

* Corresponding author at: Cooperative Institute for Marine Ecosystems and Resources Studies, Oregon State University, United States of America.
E-mail address: samara.haver@noaa.gov (S.M. Haver).

https://doi.org/10.1016/j.marpolbul.2023.115406
Received 17 July 2023; Accepted 7 August 2023
Available online 25 August 2023

noise from vessel traffic can also influence sound levels in smaller ports with fewer cargo shipping vessels but consistent recreational vessel activity (Carome et al., 2022; Hermannsen et al., 2019). Many studies that have described soundscape conditions in marine mammal habitats where smaller vessels are more likely to dominate the soundscape have focused on semi-enclosed and federally managed areas in the United States of America (U.S.A.) such as Glacier Bay National Park, the Salish Sea, and Stellwagen Bank National Marine Sanctuary (Cholewiak et al., 2018; Cominelli et al., 2018; Fournet et al., 2018; Gabriele et al., 2018; Marley et al., 2017).

In contrast, few research efforts have described soundscape conditions in the nearshore, shallow environment (<50 m) along the outer coast of the Pacific Northwest (U.S.A.), including anthropogenic noise sources and the acoustic presence of mysticete whales and other marine species (e.g., Dahlheim, 1987; Peavey Reeves, 2021). It is challenging to collect long-term passive acoustic monitoring data in this region for many reasons, including high-energy ocean conditions and dynamic bottom substrates for stationary instruments. However, for resource management and conservation, it is important to characterize these soundscapes to establish baseline conditions and monitor changes over time. Specifically, the Oregon Coast is home to multiple economically important fisheries, year-round tourism, and is also an important habitat for protected marine species that include mammals, fish, and invertebrates. Previous documentation of acoustic conditions in Oregon marine soundscapes was focused on frequencies below 1 kHz (Haxel et al., 2013) in advance of marine renewable energy deployments. In this paper we aim to build on these initial observations of central Oregon coast low-frequency soundscape conditions to identify sound sources and describe the acoustic habitat for marine animals, including mammals, fish, and invertebrates. To our knowledge, this work is the first effort to characterize the nearshore soundscape of the Oregon Coast, and thus these results provide important information for managers and policy makers to use in decision making related to animal and habitat conservation.

A subgroup of the Eastern North Pacific (ENP) population of gray whales (*Eschrichtius robustus*), called the Pacific Coast Feeding Group (PCFG), forages seasonally (June 1 to Nov 30) off the Pacific Northwest coast in nearshore coastal habitats that intersect with increasing human activities (Calambokidis et al., 2019, 2002; Lemos et al., 2022; Sullivan and Torres, 2018). The PCFG show high site fidelity to the region, with strong foraging habitat preference for rocky reef habitat (Calambokidis and Perez, 2017; Hildebrand et al., 2022) that is also utilized by nearshore fishermen, and thus is of high interest for research and monitoring to minimize threats to this small (~212 individuals; Harris et al., 2022) subgroup of whales. Recent research within Oregon waters documented correlations between variable levels of ocean noise and vessel traffic with fecal glucocorticoid metabolite concentrations in PCFG gray whales, a physiological indicator of stress response (Lemos et al., 2022). Additionally, the density and distribution of Western North Pacific gray whales foraging in coastal waters of Russia decreased in response to increased exposure levels from vessel noise and seismic surveys (Gailey et al., 2022). This work highlights the importance of characterizing the variability in nearshore ocean soundscapes where gray whales forage to inform management decisions to mitigate impacts.

Our study closely examines the variability and sources of noise in the coastal waters of central Oregon using data collected over five years (2017–2021) from two hydrophones that were deployed in habitat frequently used by PCFG gray whales (Lemos et al., 2022) and with similar conditions (e.g., bottom substrate, bathymetry, and temperature profile) for sound propagation and natural physical sounds. However, the two sites are exposed to distinctly different patterns of nearshore anthropogenic activity. One hydrophone was deployed near the Port of Newport coastline (2.4 km SW of the Newport jetty tips), which is characterized by high vessel activity and associated levels of anthropogenic noise. The second hydrophone was deployed 17 km to the north of the Port of Newport and 0.80 km to the west of Otter Rock Marine Reserve, an area more influenced by natural underwater sound processes due to management of anthropogenic activities. Otter Rock Marine Reserve is one of five nearshore marine protected areas managed by the Oregon Department of Fish and Wildlife (ODFW, 2022). Public access and research at each Oregon Marine Reserve is specific to each location, but none permit any fishing or extraction activities.

Our study builds on initial observations of the low-frequency soundscape near the port of Newport that examined passive acoustic data sampled over the summer period from three years (2016–2018; Lemos et al., 2022). Through expanded comparison of five years of seasonal data collection of low-frequency soundscape conditions at two Oregon coast hydrophone deployment sites, this study provides important information about sound levels and trends along the Oregon coast. Long-term acoustic monitoring of Pacific Northwest coastal soundscapes is valuable for comparison to other coastal marine protected areas and port environments to provide information about conditions to managers and policy makers, as well as for ongoing research on habitat conditions for PCFG gray whales and other acoustically sensitive marine animals that occupy these nearshore regions.

2. Methods

2.1. Passive acoustic data collection

From 2017 to 2021, during the summer and early fall, two passive acoustic autonomous underwater hydrophone (AUH; Haxel et al., 2013) platforms were installed near Newport, Oregon as part of research effort to document noise from vessel traffic and other anthropogenic activities as potential stressors to gray whales and other acoustically sensitive marine species. One AUH was positioned just south of the entrance to Newport harbor (2.4 km from Newport jetty tips) at 44.59 N, −124.10 W, and the other was deployed 17 km to the north of Newport harbor at 44.76 N, −124.09 W, 0.80 km outside of Otter Rock Marine Reserve (Fig. 1). Both AUHs consisted of a single calibrated omni-directional hydrophone (ITC model 1032), preamplifier, and 16-bit data acquisition system housed in a composite pressure case (Fox et al., 2001). Each AUH was secured to a weighted aluminum metal lander 0.5 m above the seafloor at approximately 20 m depth. An acoustic release was secured to the lander for recovery, allowing for data collection without any sea-surface expression and eventual retrieval of all AUH system components (Fig. 2a and b).

Acoustic data were recorded over five years: 2017 (June 15–October 8), 2018 (June 5–October 1), 2019 (June 28–October 1), 2020 (June 2–September 25), and 2021 (May 20–November 22). Due to a lost instrument, data collected in 2021 are only available from the Marine Reserve site. From 2017 to 2020, data were recorded at 32 kHz sample rate with a 13 kHz low-pass corner frequency to avoid aliasing, and in 2021 the sample rate was adjusted to 20 kHz with an 8 kHz corner frequency to extend the data collection period. In all years the AUHs were programmed to sample on a consistent 20 % duty cycle (first 12 min of every hour).

2.2. Quantifying sound levels

Power spectral density (PSD) sound levels (dB re 1 $\mu Pa^2/Hz$) were calculated using the hydrophone sensitivity value and pre-amplifier frequency dependent gain (Fig. 3) for each original 12-minute hourly duty-cycled passive acoustic data file (.DAT binary format) with custom MATLAB (version 2018b, Mathworks, Inc.) software. The PSD sound levels were then used to compute a single median and maximum sound level for each frequency over each 12-minute window. Variance in each 12-minute file was also calculated. The median sound level for each 12-minute file was aggregated into long-term spectral averages (LTSA) for each deployment. All available data were included in comparative LTSA calculations except for the Marine Reserve site recordings from October 9 to November 22, 2021, which were abbreviated for consistency with

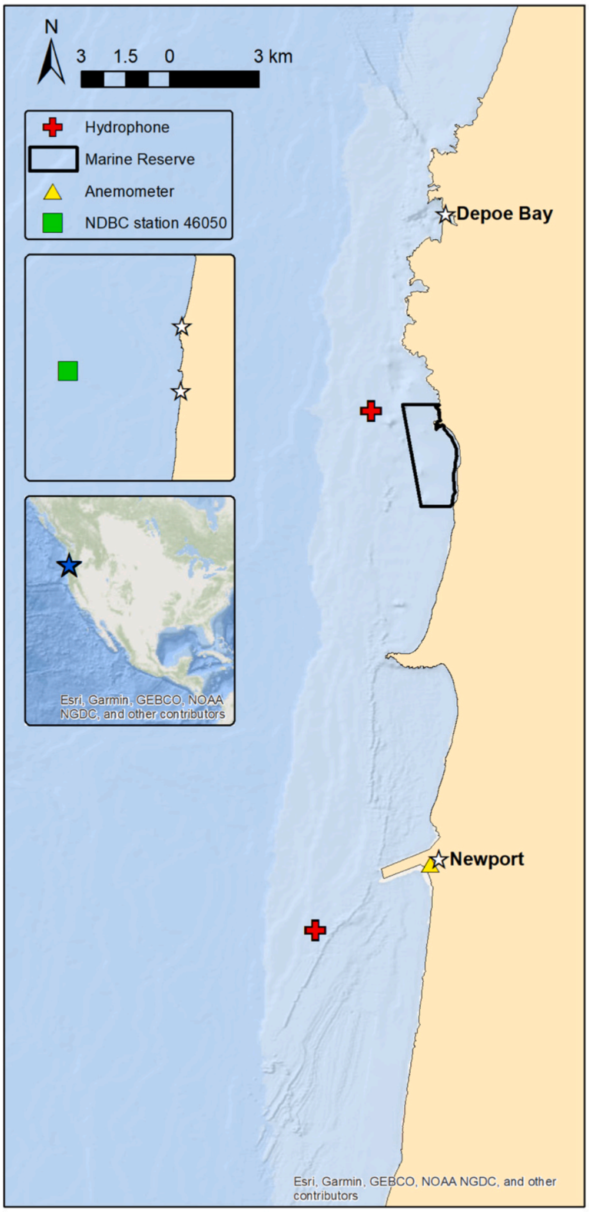

Fig. 1. Map of study area, including the Otter Rock Marine Reserve (outlined by a solid black line) and the ports of Newport and Depoe Bay. The hydrophone deployment sites are marked with red plus signs, and the location of the shore-based anemometer used to collect wind-speed data is marked by a yellow triangle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

previous years of data collection that concluded between September 25 and October 8.

Spectral probability density (SPD; Merchant et al., 2013) plots were calculated from the deployment-long LTSAs to compare the empirical probability density (EPD) of PSD sound levels observed at each site and year of data collection. Commonly occurring sound levels have higher EPD values, whereas infrequently observed sound levels are indicated by lower EPD values. EPD plots visualize the probability of PSD sound levels in each frequency, providing information about sound level variation across frequency bands and potentially indicating the presence of different sound sources. Median, 10th, and 90th percentile levels (L50, L90, L10, respectively) were also calculated for the PSD sound levels quantified for each site and year. The EPD values and percentile levels quantified for each single-frequency band and 12-min per hour time bin are also summarized over time and frequency space for the entire deployment as an overall EPD value. The overall EPD value indicates the stability of sound levels over time within the given dataset.

Median and maximum root-mean-square sound pressure levels ($\mathrm{SPL}_{\mathrm{rms}}$ dB re 1 μPa) were calculated within the 50 Hz-4 kHz frequency band in 12-minute windows (original data file length). Variance of $\mathrm{SPL}_{\mathrm{rms}}$ were also calculated over the same 12-minute window. The 50 Hz-4 kHz frequency band was selected for comparison because it captures low-frequency noise from a variety of vessel types (including commercial and recreational), and the lower frequency range of sound from wind-related environmental processes (National Research Council, 2003; Wenz, 1962). Sound levels in the 50 Hz-4 kHz are also relevant for whale and fish communication, including eastern North Pacific gray whales (Dahlheim and Castellote, 2016) and other mysticete whales that have been acoustically detected near the central Oregon coast (e.g., humpback whales; Haxel et al., 2013). Median $\mathrm{SPL}_{\mathrm{rms}}$ sound levels were averaged (mean) over the overlapping days of data collection (June 29–September 25) from 2017 to 2020 at the Port of Newport site and 2017–2021 at the Marine Reserve site to compare diel soundscape patterns between the two sites.

2.3. *Acoustic detection of discrete sound sources*

Acoustic presence of four individual species of cetaceans was investigated for all acoustic data with a combination of automated detectors and manual analysis based on species-specific vocalizations (Fig. 4). Gray whale M3 calls (Guazzo et al., 2017) and humpback whale (*Megaptera novaeangliae*) song (Au et al., 2006; Payne and McVay, 1971) were detected with generalized power-law automated detector (Helble et al., 2012; Hvidsten, 2021), while blue whale (*Balaenoptera musculus*) A and B calls (Dziak et al., 2017), and killer whale (*Orcinus orca*) vocalizations (Ford, 1987) were identified via manual verification by an experienced observer (S.M.H.) in Raven Pro software (Charif et al., 2010).

Vessel noise was identified in the passive acoustic data based on frequency characteristics (Haxel et al., 2013). Large commercial vessels are typically identifiable by sound in tonal bands with most energy concentrated below 200 Hz, but can often include focused noise in frequencies up to 1 kHz depending on the speed, size, and distance between the vessel and recorder (Gassmann et al., 2017; MacGillivray et al., 2019; Shabangu et al., 2022). Smaller vessels, including recreational and fishing types, can sometimes be distinguished from larger vessels (e.g., cargo) by engine and propeller noise above 1 kHz, as well as tonal noise bands and/or the acoustic signature of the vessels passing over or near to the hydrophone (Simard et al., 2016; Smott et al., 2018) (Fig. 4).

Acoustic determination of vessel types and individual vessel counts can be difficult, and thus we utilized visual survey data to quantify the number of vessels and distinguish vessel types at each of the study areas. Daily count of recreational vessels near each hydrophone were provided by the Oregon Department of Fisheries and Wildlife (ODFW; pers. comm to J. Haxel). Vessel counts were manually tallied from ODFW video monitoring. Recreational vessels include charters on fishing or crabbing trips and private boats, but not whale watching or research trips, including NOAA and other easily identified non-fishing vessels. Commercial fishing vessels, U.S. Coast Guard, and dredge vessels are also not included. Daily counts of recreational vessel traffic accessing Newport was compared to sound levels at the Port of Newport site (2.4 km from Newport jetty tips), and daily counts of vessel traffic at the port of Depoe Bay was compared to sound levels at the Marine Reserve site as it is the closest port to the hydrophone site (6.30 km).

2.4. *Sound contributions from wind and waves*

Surface wind generated underwater sound is a significant contributor to ambient sound levels in both deep and shallow water marine

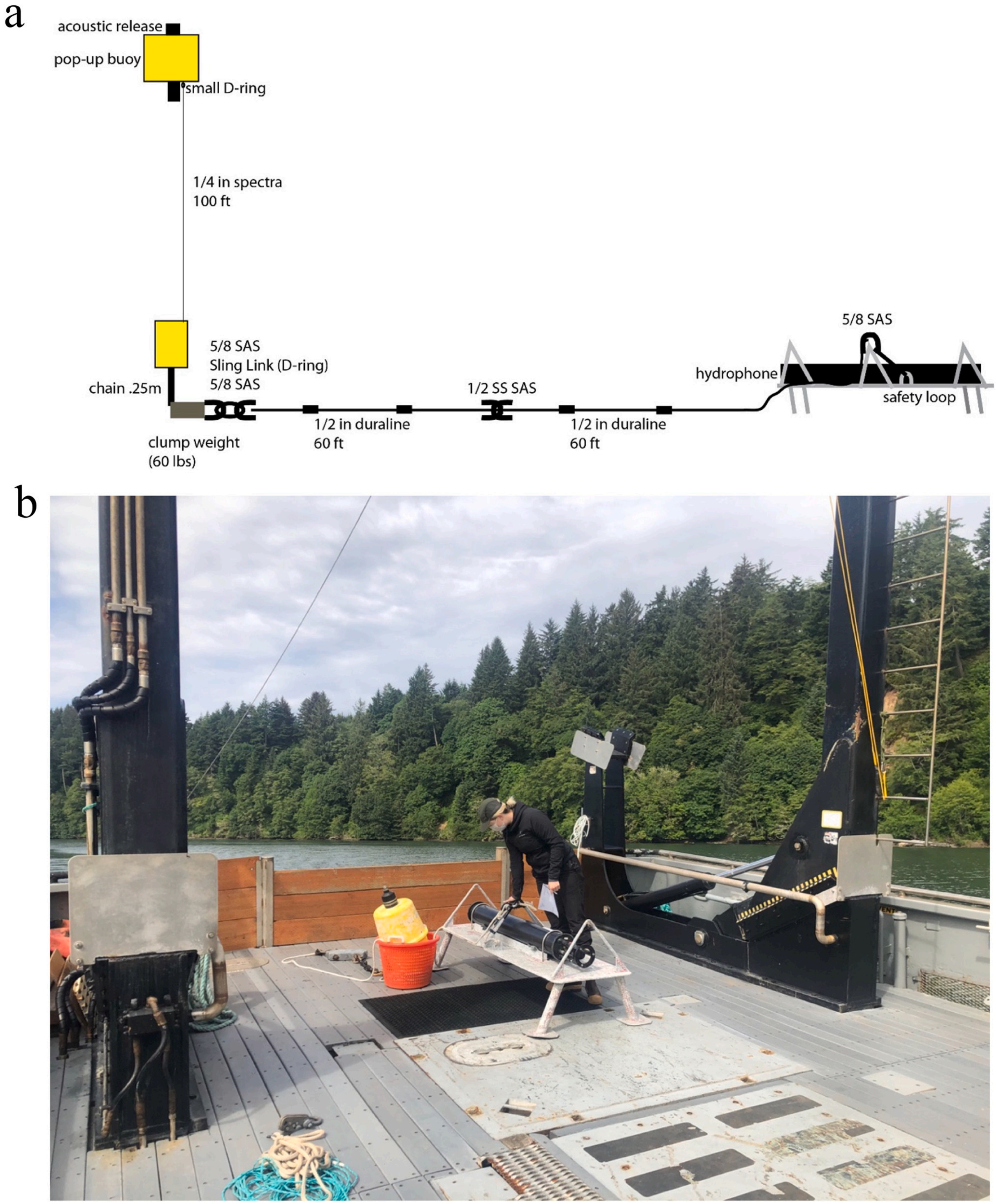

Fig. 2. a. Mooring diagram showing hydrophone and acoustic release.
b. Scientist L. Roche prepares the hydrophone (mounted on metal lander) and attached acoustic release (yellow buoy) for deployment near Newport, OR. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

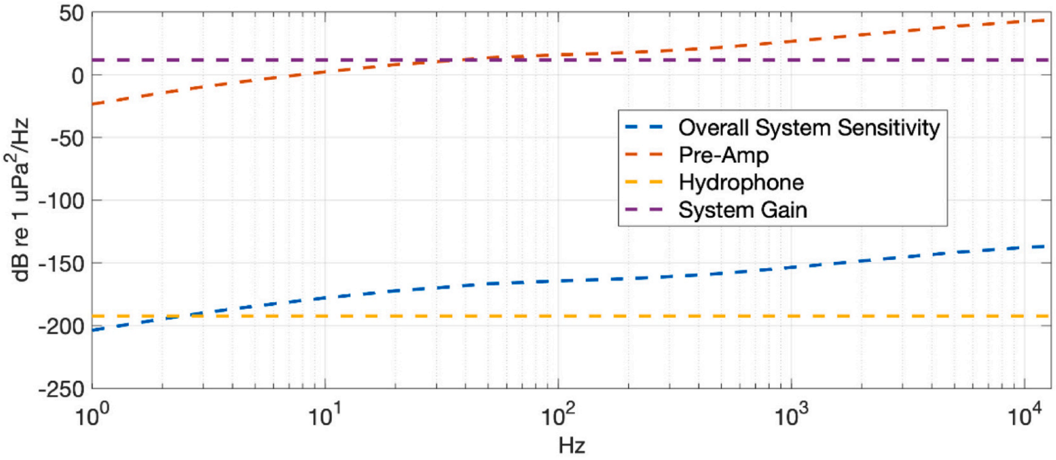

Fig. 3. Overall system sensitivity curve (blue), including frequency dependent pre-amplifier curve (red) and flat hydrophone sensitivity (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

areas over a range of frequencies from hundreds of Hz up to 20 kHz (Knudsen et al., 1948) that scales in amplitude with increasing wind speed (Carey and Evans, 2011; Hildebrand et al., 2021; Wenz, 1962; Wilson, 1983). Winds speeds were collected by an anemometer at National Data Buoy Center station NWP03[1] (US DOC/NOAA/NWS/NDBC, 1971) on the Newport jetty at the entrance to the port of Newport (Fig. 1), and were used to characterize the potential impact of rising wind speed on underwater sound levels at the Port of Newport (3.56 km distance between anemometer and hydrophone site) and Marine Reserve (~17 km from the anemometer) hydrophone stations.

Surf-generated sounds from breaking waves along the open coast are also a significant contributor to shallow water low frequency soundscapes in Oregon's nearshore waters (Haxel et al., 2013). As open ocean waves propagate from deep water toward shore, they eventually break and dissipate their energy on sand bars and rocky reef structures. Part of the turbulent dissipation is converted to acoustic energy, some of which radiates back offshore influencing shallow water soundscapes outside the surf zone (Deane, 2000; Wilson et al., 1985). Significant wave heights (Hs) used to characterize wave conditions in the study area were measured by a nearby NDBC station 46,050[2] at Stonewall Bank (Fig. 1). Observations of median sound pressure levels (50 Hz–4 kHz) were binned by Hs and time of day for the Marine Reserve and Port of Newport hydrophones to observe the influence of increasing wave heights on the acoustic conditions.

3. Results

3.1. Sound level trends

Median power spectral density (PSD) sound levels were consistently lower intensity at the Marine Reserve site compared to the Port of Newport site (Fig. 5). At the Marine Reserve, the highest sound intensities were observed in the 10 Hz–1 kHz band. In comparison, at the Port of Newport site sound intensities were consistently higher across the 10 Hz–4 kHz band, encompassing a larger range of frequencies compared to the Marine Reserve site.

The color gradient for each subplot in Fig. 6 indicates the empirical probability density (EPD) value for the SPD sound levels in all frequencies sampled in each year of data collection at the Port of Newport and the Marine Reserve site. The spread between the 10th percentile and 90th percentile of PSD sound levels is bigger at the Port of Newport site compared to the Marine Reserve, indicating that sound levels recorded at the Port of Newport were more variable compared to the Marine Reserve (Fig. 6). The increased variability at the Port of Newport site compared to the Marine Reserve is most pronounced in frequencies between 50 Hz and 4 kHz.

For each subplot, an overall EPD statistic for the deployment year and site indicates the variability of SPD sound levels across time and frequency space for the deployment dataset (warmer colors denote higher probability of consistent sound levels; Fig. 6). In general, SPD recorded at the Marine Reserve are more consistent throughout the season compared to the Port of Newport site. At the Port of Newport site, overall EPD values were steady year-to-year from 2017 to 2019 (~0.04), and then shifted to be slightly more stable throughout the season in 2020 (~0.055). At the Marine Reserve site, overall EPD values were similar across all years with the lowest overall probabilities in 2017 and 2018 (~0.06), and a slight increase in 2019 (~0.07) over all other years of data collection. At the Marine Reserve site, 2020 and 2021 EPD levels (~0.065) were slightly lower than 2019, indicating a minor increase of sound level variability. However, the 2020 and 2021 EPD were not higher than levels calculated for 2017 and 2018.

3.2. RMS frequency bands

On average, sound levels at the Marine Reserve were lower than at the Port of Newport (Figs. 5 and 6, Table 1). Additionally, at the Port of Newport a diel soundscape pattern of increased SPL_{rms} during daytime hours (Fig. 7) was detected. On many days, the highest sound levels were recorded twice daily, the first in the morning between 6:00 and 8:00 am, and a second around noon. Less predictable instances of increased SPL_{rms} were also randomly sampled in the afternoon. In comparison, at the Marine Reserve, a minimal increase of SPL_{rms} was observed around 6:00 am, but overall sound levels are consistent with random fluctuations throughout the recording period.

Throughout the annual data sampling period of June through September, median SPL_{rms} sound levels averaged over all years showed a slight decreasing trend throughout July and early August at the Port of Newport and were comparatively more stable over time at the Marine Reserve site (Fig. 8). In late August–early September peaks in median SPL_{rms} sound levels at the Port of Newport site coincide with similar sound level increases observed at the Marine Reserve site. In general, median SPL_{rms} sound levels were much less variable at the Marine Reserve compared to the Port of Newport (Fig. 8, Table 1). Additionally, sound levels at the Marine Reserve were moderately positively skewed

---

[1] https://www.ndbc.noaa.gov/station_page.php?station=nwpo3.

[2] https://www.ndbc.noaa.gov/station_page.php?station=46050.

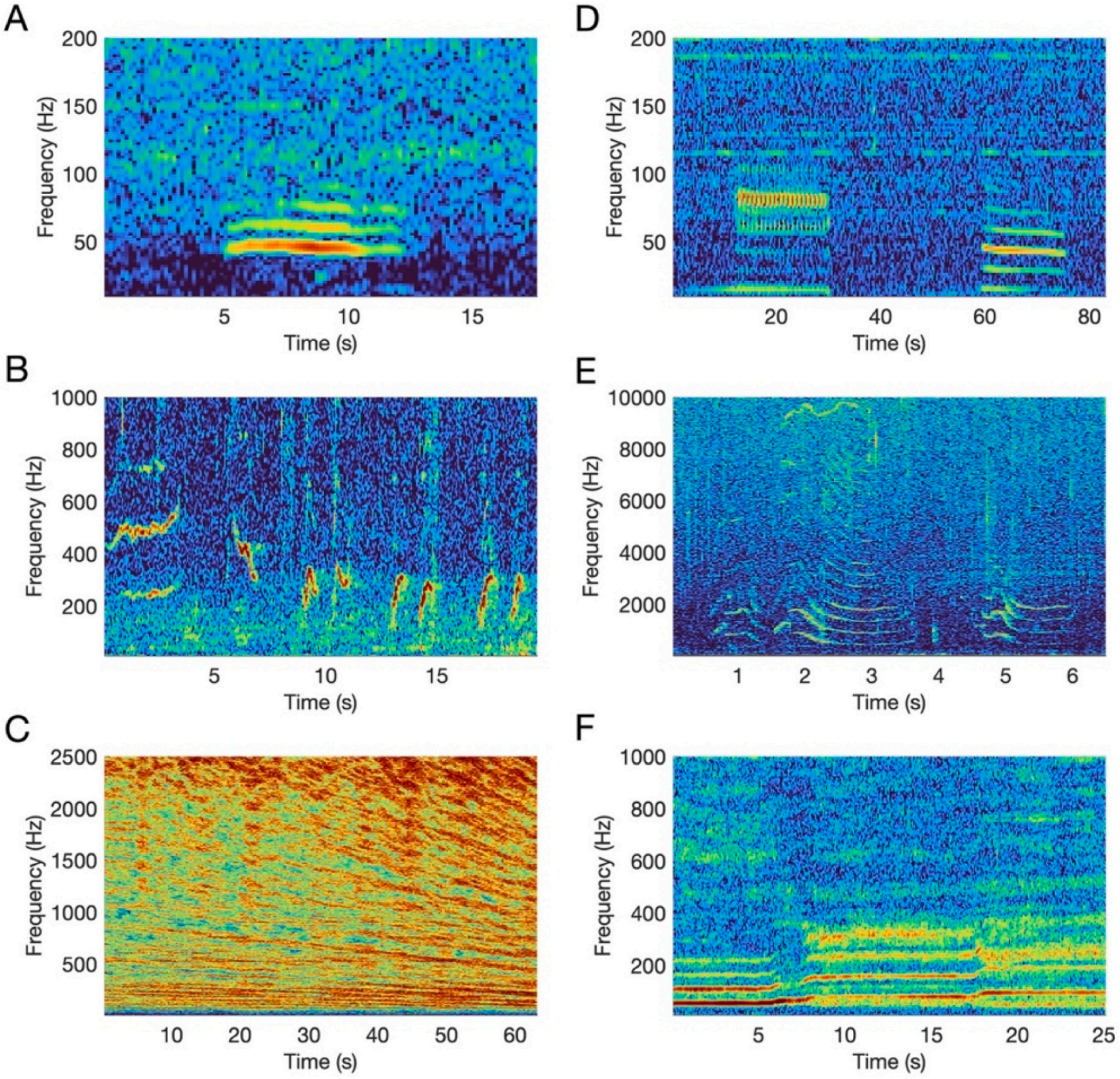

Fig. 4. Spectrograms of example sound sources recorded between 2017 and 2021 from the two hydrophones deployed off the Central Oregon coast. In all plots the intensity of the frequency is represented by color, such that warmer colors show greater magnitude. Subplots (Hann window, 50 % overlap) of individual sources show: A) Gray whale M3 (FFT 10240), B) humpback whale song (FFT 4096), C) vessel passing near hydrophone (FFT 18382), D) blue whale A and B calls (FFT 18410), E) killer whale vocalizations (FFT 2048), F) vessel engine accelerating (FFT 4603). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

in all years indicating that observed sound levels were mostly lower than the mean value with less frequent periods of elevated acoustic conditions. At the Port of Newport, sound levels were closer to a symmetrical normal distribution, suggesting a soundscape experiencing nearly equivalent periods of higher amplitude and lower amplitude conditions around the mean noise level.

3.3. *Sound sources*

3.3.1. *Vessel traffic*

Vessel noise can drive ambient sound levels and acoustic habitats for whales and other marine species (Shabangu et al., 2022). Median $\mathrm{SPL}_{\mathrm{rms}}$ sound levels (50 Hz–4 kHz) at the Marine Reserve and Port of Newport were likely affected by vessel traffic at the closest port to each site. Daily counts of recreational vessel traffic were over three times higher at the Port of Newport (mean: 102, median: 61), compared to Depoe Bay (mean: 30 median: 19). In comparison to the Marine Reserve, higher daily counts of recreational vessel traffic near the Port of Newport likely drove higher median $\mathrm{SPL}_{\mathrm{rms}}$ sound levels throughout the summer months of data collection, particularly in combination with non-recreational vessel traffic (Fig. 9). However, it is also important to note that the Port of Depoe Bay was further from the Marine Reserve hydrophone (6.30 km), while the Port of Newport hydrophone was 2.40 km from the Newport port entrance. Recreational vessels are only part of the daily vessel traffic accessing both Newport and Depoe Bay. Although not included in the vessel counts present in Fig. 9, commercial vessel traffic counts, such as for commercial fishing, as well as research missions and Coast Guard activities likely affect sound levels near the Port of Newport. Automatic information system (AIS) vessel movement data was not available for the time period overlapping with acoustic data

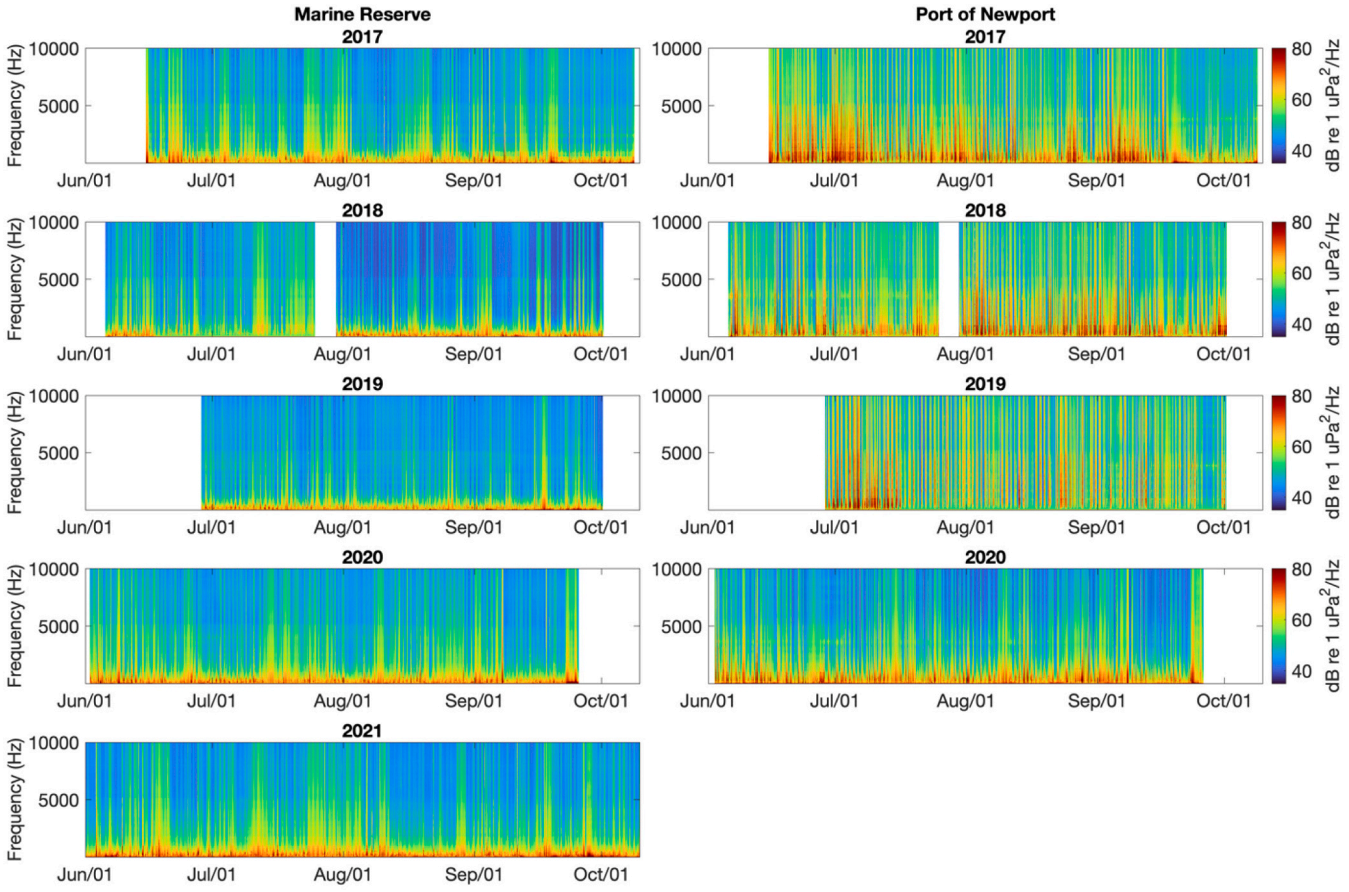

Fig. 5. Long-term spectral average (LTSA) plots of median power spectral density sound levels average over 12-minute duty-cycled recordings sampled at the top of each hour. Single frequency band sound levels are plotted by date (x-axis) and frequency (y-axis). Color (blue-green-yellow) indicates sound intensity (dB re 1 uPa^2/Hz). No data is available for the Port of Newport site in 2021 due to a lost instrument. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

collection, however grouped vessel transit counts from AIS data for 2021 show much higher annual vessel counts accessing the Port of Newport compared to Depoe Bay (Fig. S1; BOEM and NOAA, 2023).

Whale watching excursions are a larger industry in Depoe Bay compared to Newport, and consequently likely influence soundscape conditions around gray whales closest to the Marine Reserve site and general Depoe Bay region.

3.3.2. *Whale vocalizations*

Gray, humpback, and blue whale vocalizations were acoustically detected on more days at the Marine Reserve site compared to the Port of Newport site (Fig. 10). Between 2017 and 2020, gray whale vocalizations were acoustically detected on two to five days per season at the Port of Newport, and 11 to 21 days per season at the Marine Reserve. Daily acoustic presence of humpback whales followed a similar pattern to gray whales, with fewer days of detections at the Port of Newport across all years (0–6 days per season), and comparatively more at the Marine Reserve (3–9 days per season). Blue whale vocalizations were detected on the highest number of days at both sites in 2020. In 2017–2019, the number of days with blue whale vocalizations was consistent at the Marine Reserve, and more variable at the Port of Newport with 12 days with detections in 2017, only two in 2018, and none in 2019. Between 2017 and 2020, killer whale vocalizations were only detected on one day at the Port of Newport, and not once at the Marine Reserve.

3.3.3. *Wind and waves*

At wind speeds above 4 m s^{-1}, median sound pressure levels (SPL$_{rms}$) increase at both the Marine Reserve and Port of Newport hydrophone stations with rising wind speeds. The effect of wind speed on underwater sound levels is readily observed during times of the day with reduced vessel traffic from 8:00 PM–5:00 AM Pacific Daylight Time (Fig. 11). The relationship between sound levels and wind speeds is better constrained at the Marine Reserve hydrophone where vessel traffic has less of an influence. The increased scatter between sound levels plotted as a function of wind speeds at the Port of Newport indicates vessel traffic is likely a significant contributor to noise levels during the dark hours near the port of Newport.

Observations of median sound pressure levels (50 Hz–4 kHz) binned by Hs and time of day (Fig. 12) for the Marine Reserve and Port of Newport hydrophones illustrate the influence of increasing wave heights on the acoustic conditions. As wave breaking intensifies with increasing Hs, ambient sound pressure levels also rise. The influence of large waves (>3 m) on soundscape conditions is readily observed in the Marine Reserve hydrophone recordings from 2021 that extend beyond early September and into November when higher wave conditions occurred more frequently (see 2021-specific results in Fig. 9). Unfortunately, due to the loss of the Port of Newport hydrophone in 2021, similar recordings from larger wave height conditions (>3 m) are not available for the Port of Newport area. Nevertheless, as shown in Fig. 12, rising Hs conditions results in increasingly higher sound pressure levels at all hours of the day for both hydrophone stations.

The comparative influence of vessel traffic and surf sounds on

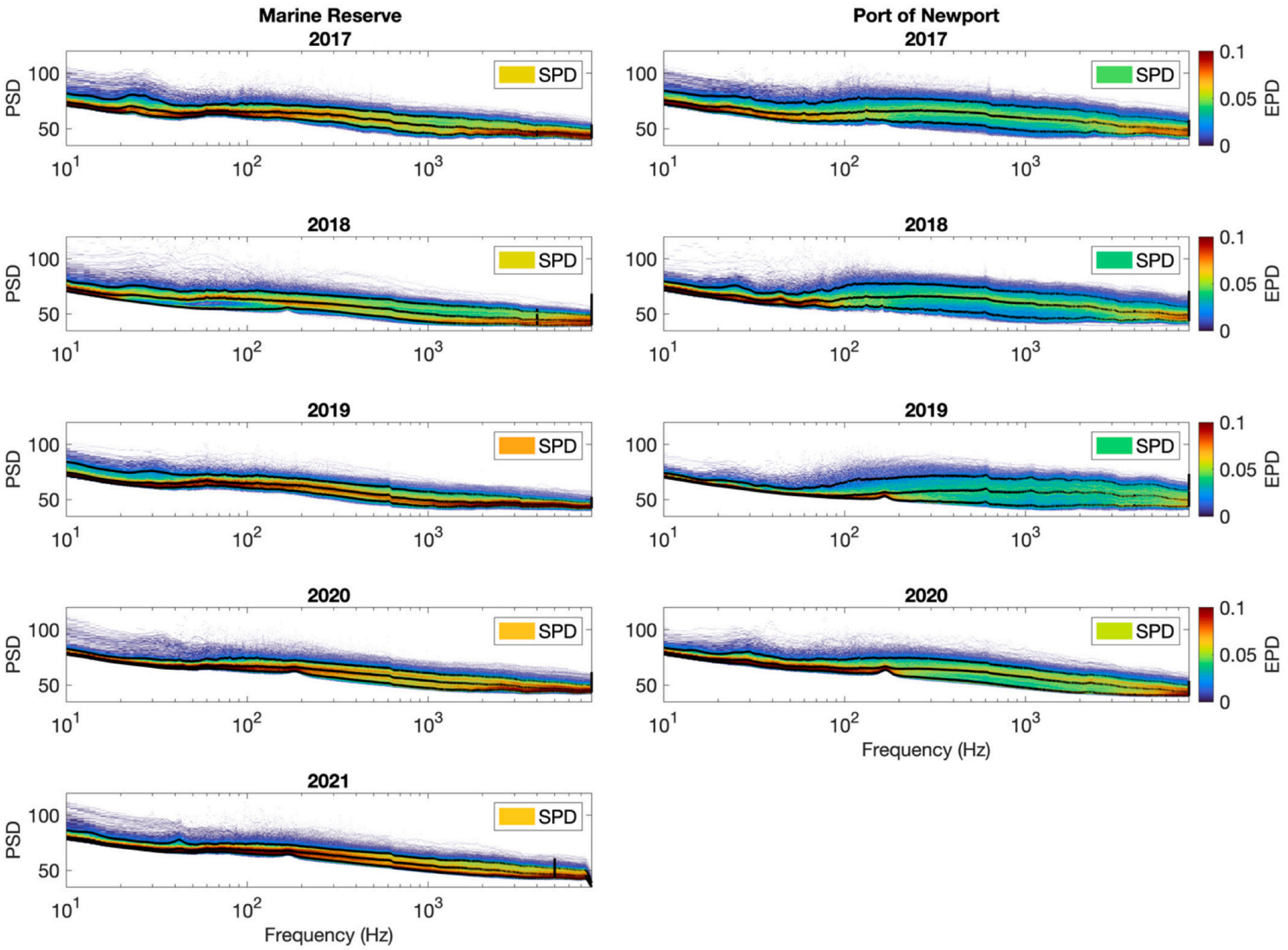

Fig. 6. Spectral probability density (SPD) plots of the distribution of sound levels (10 Hz–10 kHz) at Marine Reserve (2017–2021) and Port of Newport (2017–2020). No data is available for the Port of Newport site in 2021 due to a lost instrument. Percentile levels (10th, 50th, 90th) of power spectral densities (PSD, dB re 1 μPa2/Hz) are indicated by solid black lines. Empirical probability density (EPD) is calculated from PSD sound levels within each frequency band and indicated by z-axis color bar range of blue (lower probability) to red (higher probability). The overall probability of SPD sound level distribution consistency over time is shown in the upper right corner of each panel (corresponding to the z-axis color bar). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Median, mean, maximum, variance, and skewness statistics calculated from median sound levels (root-mean-square sound pressure levels) in the 50 Hz–4 kHz band averaged over each hour of each day between June 29 and September 25 during five years of data collection at the Marine Reserve (2017–2021) and four years of data collection at the Port of Newport (2017–2020).

	2017		2018		2019		2020		2021	
Site	Marine reserve	Newport	Marine reserve	Newport	Marine reserve	Newport	Marine reserve	Newport	Marine reserve	–
Median	92.7	96.7	90.4	96.1	90.8	93.2	93.4	94.4	94.3	–
Mean	92.8	96.8	90.7	96.1	91.1	93.4	93.7	94.7	94.6	–
Max	112.1	121.0	118.0	121.8	111.9	117.9	113.9	119.8	113.2	–
Variance	19.4	52.3	22.2	55.7	16.0	97.0	18.8	33.5	12.2	–
Skewness	0.36	0.18	0.63	0.14	0.63	0.18	0.74	0.48	0.84	–

ambient levels is also illustrated in Fig. 12. During low wave height conditions at both sites, ambient sound levels significantly increase around sunrise (e.g., 06:00 AM), are sustained throughout daylight hours, and decrease in the evening around sunset (e.g., 8:00 PM). This shift is likely driven by small vessel traffic leaving the nearby ports around sunrise and returning around sunset. As wave heights increase above Hs > 2 m, sounds from breaking waves begin to overshadow or match the effects of vessel noise, particularly at the Marine Reserve site. Meanwhile, daily maximum ambient sound levels at Port of Newport at 7 AM (likely related to peak vessel activity) are maintained throughout the range of increasing wave heights. A secondary peak in sound levels is also observed at 11 AM, potentially linked to regularly scheduled recreational fishing charter trips, which generally leave port around sunrise and return late-morning (1/2 days trips) or closer to sunset (full-day trips). As shown in the lower panels of Fig. 7, the sound level peaks are not temporally aligned with peaks in wind speeds or wave heights, but instead is likely driven by diel patterns of small vessel traffic leaving the nearby ports around sunrise and returning around sunset. Still, surf-

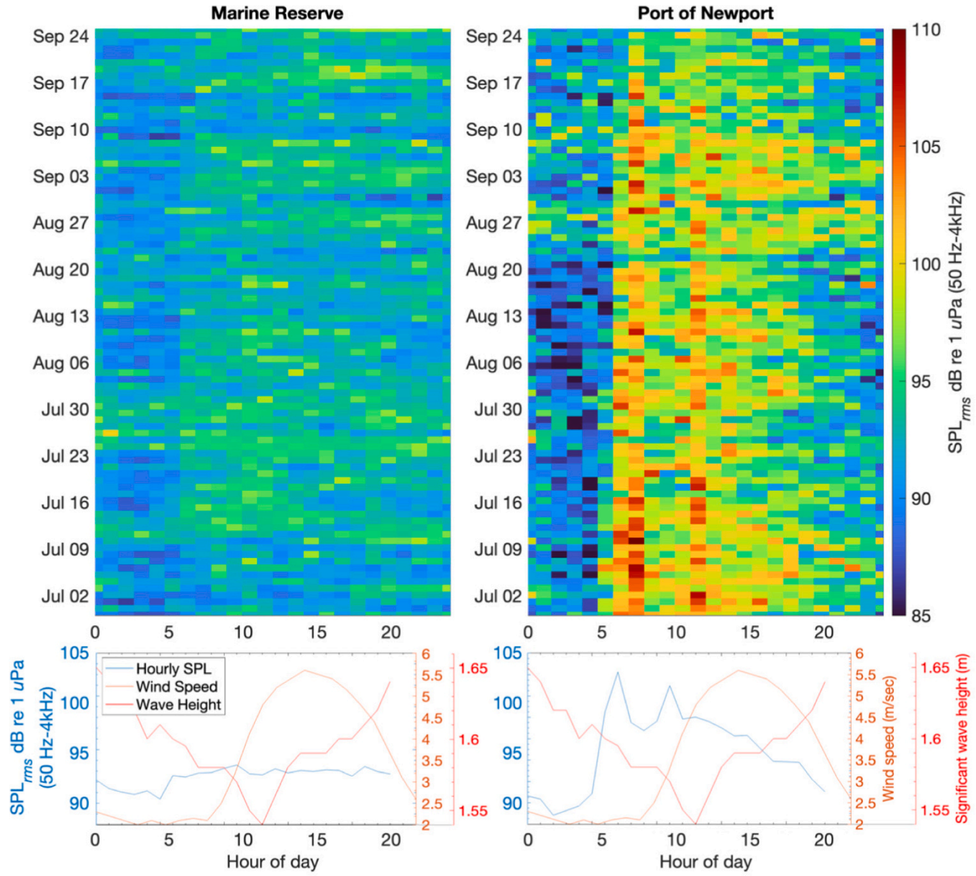

Fig. 7. Median sound levels (root-mean-square sound pressure levels) in the 50 Hz–4 kHz band for each hour of each day between June 29 and September 25 averaged over 2017–2021 at the Marine Reserve (upper left) and 2017–2020 at the Port of Newport (upper right), and hourly median noise level, hourly median wind speed from a nearby anemometer station (NWPO3), and hourly median significant wave height over the same time period averaged over all days and years at the Marine Reserve (lower left) and the Port of Newport (lower right).

generated sounds from significant wave heights >2 m can dominate the low and mid-frequency sound pressure levels of both shallow water areas despite the differences in anthropogenic activity near a port and marine reserve.

4. Discussion

Utilizing the capabilities of long-term passive acoustic monitoring, we document the sources and patterns of soundscape variation along the nearshore Oregon Coast during summer months of June to September. We found that vessel activity drove large differences between the two hydrophone recording sites, which were deployed just 17 km apart. These results demonstrate soundscape variation over relatively fine scales as a function of human activity patterns, as well as the physical environment of each deployment site (e.g., bottom substrate, bathymetry, and temperature profile) which affects sound propagation (Vagle et al., 2021). Our findings are important for management and conservation because the Oregon coast is an important foraging area and migratory corridor for multiple species of large whales, and demonstrates the potential for increased ocean noise to degrade habitat quality. The results of this analysis and baseline characterizations of the soundscape provide novel information that can be used by managers and policy makers to support ecosystem management of nearshore coastal soundscapes in the Pacific Northwest. For example, voluntary vessel speed reduction programs have been successful in decreasing low-frequency vessel noise near port cities that overlap with important whale habitat (Burnham et al., 2021; Findlay et al., 2023; MacGillivray et al., 2019; Zobell et al., 2021).

4.1. *Presence of vessel noise distinguishes hydrophone sites*

The soundscape conditions at the Port of Newport and Marine Reserve hydrophone locations were driven by each specific deployment location, particularly related to surrounding vessel activity and resulting anthropogenic noise pollution. At the Port of Newport, the hydrophone was deployed 2.40 km from the Newport jetty tips, the entrance for fishing, recreational, and other vessels accessing the port. Although the Marine Reserve hydrophone was deployed only 17 km away, it was positioned 0.80 km outside of the Otter Rock Marine Reserve where anthropogenic activities are strictly managed to promote conservation. Our analysis of five years of passive acoustic monitoring at the Port of Newport site revealed both higher vessel presence (counts) and anthropogenic noise levels compared to the Marine Reserve site. In contrast, the less intense and variable sound levels at the Marine Reserve site in this analysis are likely reflective of comparatively less vessel activity. Although wind can also be a significant sound source, we did not perceive an obvious relationship between diel sound levels and wind speed patterns at the Port of Newport site (Fig. 7). Instead, we found vessels to be the primary driver of diel sound level variation, which aligns with the results of Lemos et al., 2022. Alternatively, surf-generated sounds from nearby breaking waves with significant wave heights >2 m are shown to contribute substantially to sound pressure levels in both the Port of Newport and Marine Reserve areas. In the more naturally influenced Marine Reserve site, sound levels rise consistently with increasing wave heights and remain high throughout all hours of the day despite diel variations of nearby vessel activities. Whereas the port area of Newport, a more anthropogenically influenced marine area, maintains consistent daily peaks in sound pressure levels that coincide with high vessel activity regardless of elevated wave height conditions (Fig. 12). Similarly, after reaching a threshold of 4 m s^{-1}, wind speeds

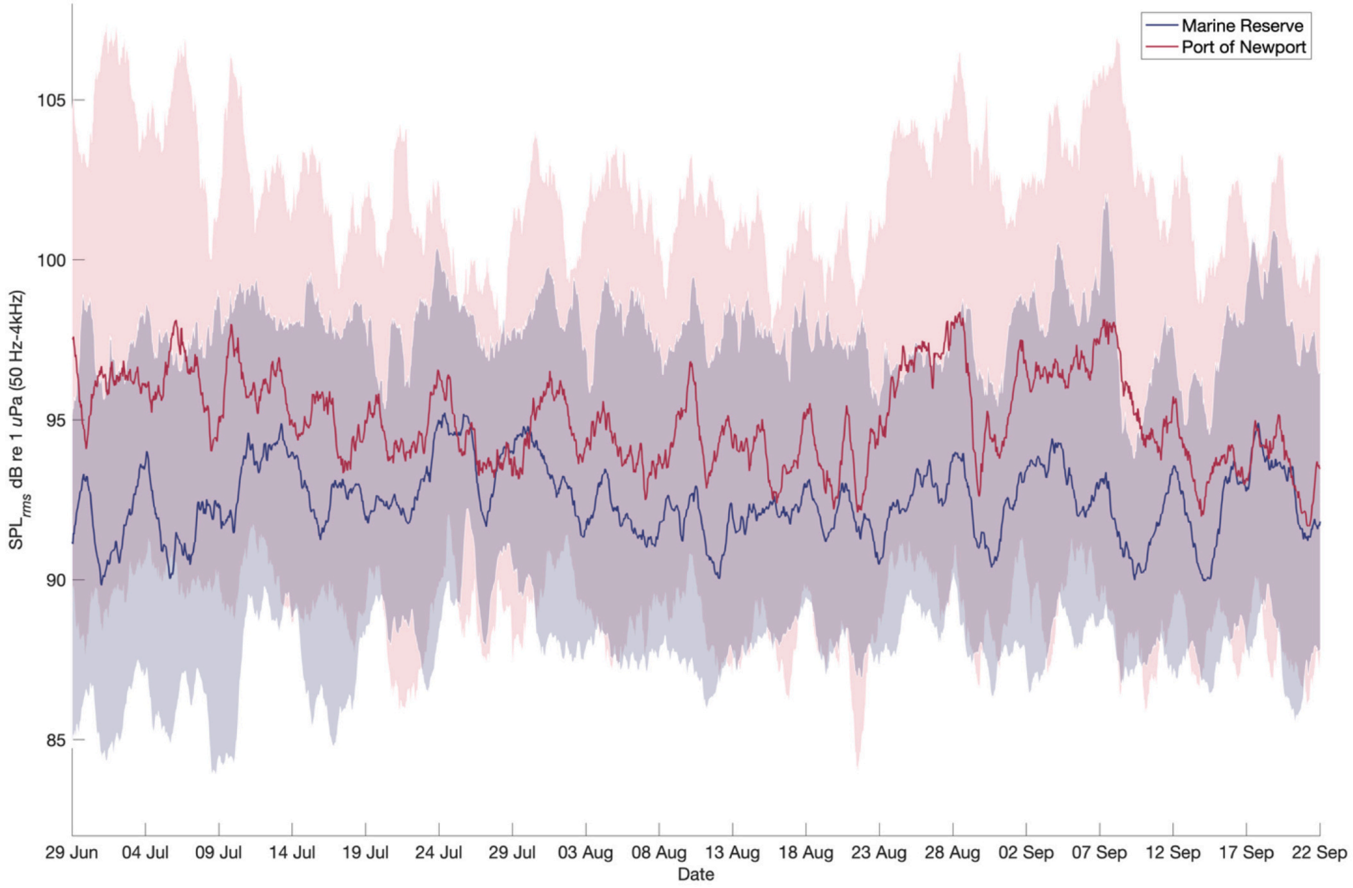

Fig. 8. 48-hour smoothed median (solid color lines) and 10th and 90th percentiles (boundaries of filled semi-transparent areas) hourly root-mean-square sound pressure levels in the 50 Hz–4 kHz band between June 29 and September 25 averaged over four years of data collection (2017–2020) at the Marine Reserve (blue) and the Port of Newport (red). The 10th and 90th percentile levels are plotted as filled areas to show averaged variability of sound levels throughout the season. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

have significantly more influence on sound levels at the natural Marine Reserve site in comparison to the port influenced Newport area (Fig. 11).

Daily patterns of vessel activity near the Port of Newport hydrophone drive twice-daily spikes in median sound levels, while comparatively reduced and less predictable vessel activity near the Marine Reserve does not result in any consistent diel patterns in the ambient soundscape. We compared counts of recreational vessel traffic to ambient sound levels to visualize the relationship between vessel traffic and ambient noise conditions (Fig. 9). However, commercial vessel traffic accessing Newport, OR is also likely a prominent sound source at the Port of Newport hydrophone. Comparable counts of commercial vessel traffic were not available for this descriptive comparison, and thus recreational vessel counts were compared to sound levels as a proxy to approximate the difference in vessel activity at the closest port to each hydrophone. Future work could consider the impact of other vessel types, including commercial fishing, whale watch, U.S. Coast Guard, and research.

During the annual June to September data sampling period, median SPL$_{\mathrm{rms}}$ sound levels averaged over all years were observed to be more variable over time at the Port of Newport in comparison to Marine Reserve median SPL$_{\mathrm{rms}}$ sound levels (Figs. 7 and 8). The 10th percentile of sound levels at both sites is more similar than the 90th percentiles, indicating that the quietest conditions (10th percentile) at both sites are relatively comparable, but that high intensity sound levels were consistently more common at the Port of Newport site (Fig. 8). This trend is likely related to seasonal patterns of vessel activity near each hydrophone. Daily recreational vessel traffic near the Marine Reserve is less compared to Port of Newport, and median SPL$_{\mathrm{rms}}$ sound levels at the Marine Reserve are also more stable than at the Port of Newport (Figs. 9 and 7). The closest port to Otter Rock Marine Reserve is Depoe Bay, a popular destination for whale watching, and the annual data sampling period between June and September is aligned with the peak season for tourism and whale watching on the central Oregon coast. Meanwhile, vessel activity near the Port of Newport is likely to also include more fishing and other forms of recreational and commercial vessel traffic. For example, in 2019, nearly twice as many fishing trips departed out of Newport compared to Depoe Bay (The Research Group, LLC, 2021). Thus, it is expected that the combined impact of overall increased vessel activity at Newport, including seasonal and/or annual pattern shifts, is more readily apparent in the long-term median SPL$_{\mathrm{rms}}$ 50 Hz–4 kHz sound levels quantified for this comparison.

Our sampling time period overlapped with the COVID-19 pandemic and societal restrictions on public leisure activities (e.g., travel, shopping, dining) in the summer of 2020. Although a comprehensive analysis of the overall impact of the pandemic on the central Oregon coast is outside of the scope of this study, we did observe that at the Port of Newport site overall soundscape conditions were less variable in 2020 compared to previous years of data collection (Fig. 6). This potentially indicates that the magnitude of vessel activity that likely drove soundscape conditions at the Port of Newport to fluctuate from quieter to noisier on a daily basis in 2017–2019 was slightly diminished in 2020. Meanwhile at the Marine Reserve site, sound level variability in 2020

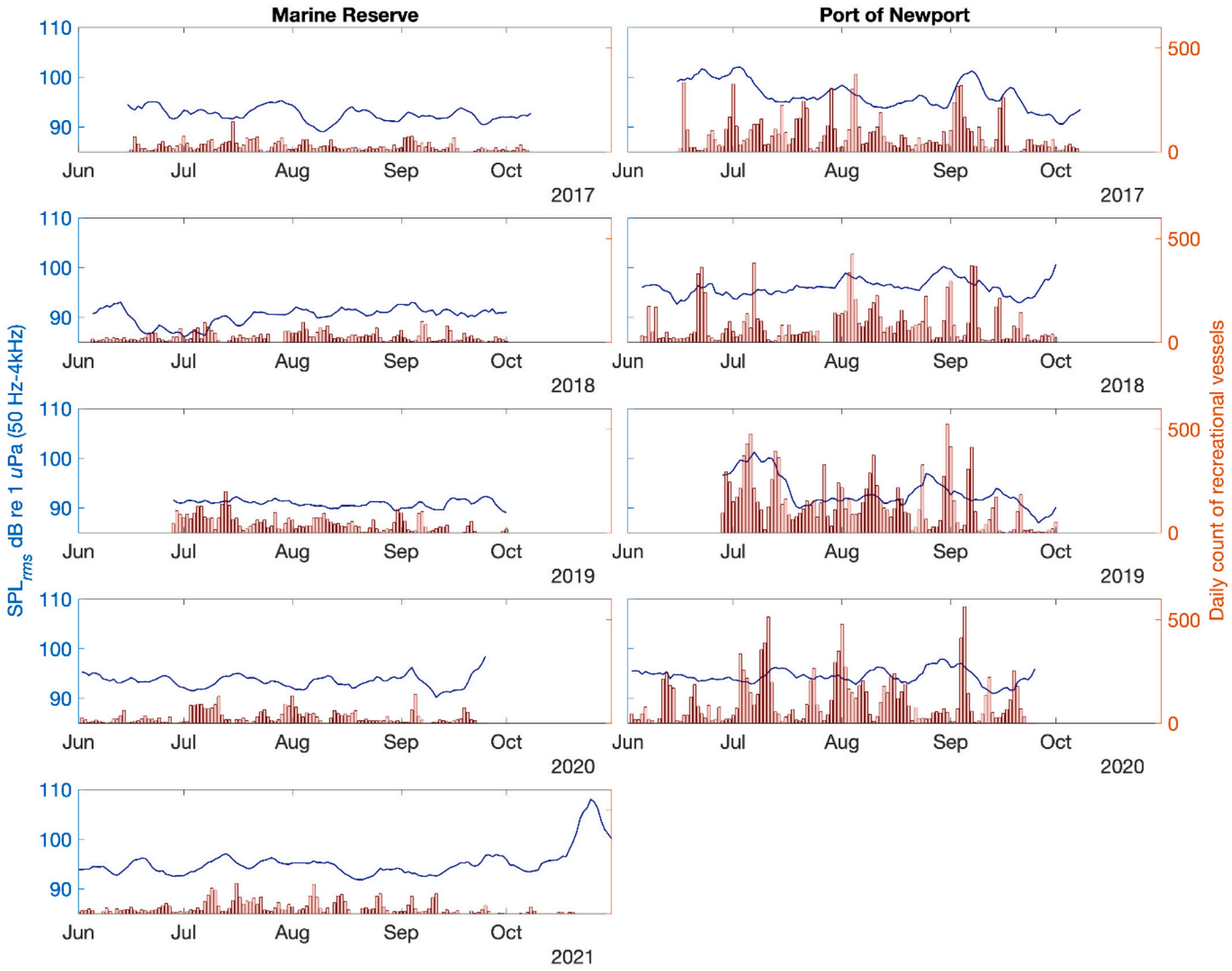

Fig. 9. 7-day smoothed median hourly sound levels (root-mean-square sound pressure levels) in the 50 Hz–4 kHz band (left y-axis, blue line) paired with bar plot of daily recreational vessel counts at the nearest port (Depoe Bay and Newport) for all days of acoustic data collection between 2017 and 2021 at the Marine Reserve and Port of Newport. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and 2021 were slightly lower than 2019, indicating that the pandemic may not have had a meaningful impact on the soundscape of Otter Rock Marine Reserve. As the port of Depoe Bay and the Marine Reserve are mostly trafficked by recreational (including charter fishing) and whale watching vessels, and Newport is a much larger commercial port, our data suggest that COVID-19 pandemic may have had a larger impact on commercial vessel activities, while recreational boating and whale watching were less impacted by public health restrictions.

4.2. *Acoustic habitat conditions for gray whales*

Presence of vessel noise at the Port of Newport hydrophone likely impacted acoustic detections of baleen whale vocalizations, especially the gray whale M3 call-type which contains the most energy at ~50 Hz and thus can be masked by vessel noise occurring in overlapping frequencies (Burnham and Duffus, 2019a; Guazzo et al., 2017). In comparison, the comparatively greater number of days that gray whale vocalizations were detected at the Marine Reserve site is likely related to a combination of drivers. It is possible that more gray whales are using the Marine Reserve area and therefore we detected more vocalizations; however gray whales were observed in generally equivalent distribution between the two hydrophone areas during daytime field observations over the sampling years (L. Torres, pers. comm). Alternatively, we may have detected fewer vocalizations at the Port of Newport hydrophone because the whales were not vocalizing or if their vocalizations were masked by higher intensity sound sources.

Although the blue, fin, and humpback whale vocalizations detected in this analysis are longer in duration and not as narrowband as the M3 gray whale call type (and thus may have been less likely to be masked by other sound sources in the acoustic data), these mysticetes may also employ behavioral strategies of reduced calling or leave an area in the presence of increased vessel noise (Richardson et al., 1995). It is also important to note that the study area is not the primary habitat for blue, fin, or humpback whales in the Oregon region (Derville et al., 2022), but it is for gray whales (Lemos et al., 2022). While other species may be more able to leave the study area seeking higher quality acoustic habitats (Pack et al., 2022; Sprogis et al., 2023), gray whales utilize these coastal environments for seasonal foraging and may exhibit a greater tolerance for noise conditions to meet more urgent foraging needs (Forney et al., 2017). As discussed in Lemos et al., 2022, the exposure to vessel noise leads to physiological consequences that may specifically impact gray whales in this specific environment and time of year (late spring to early fall).

Given the relatively short distance between the hydrophones (17 km)

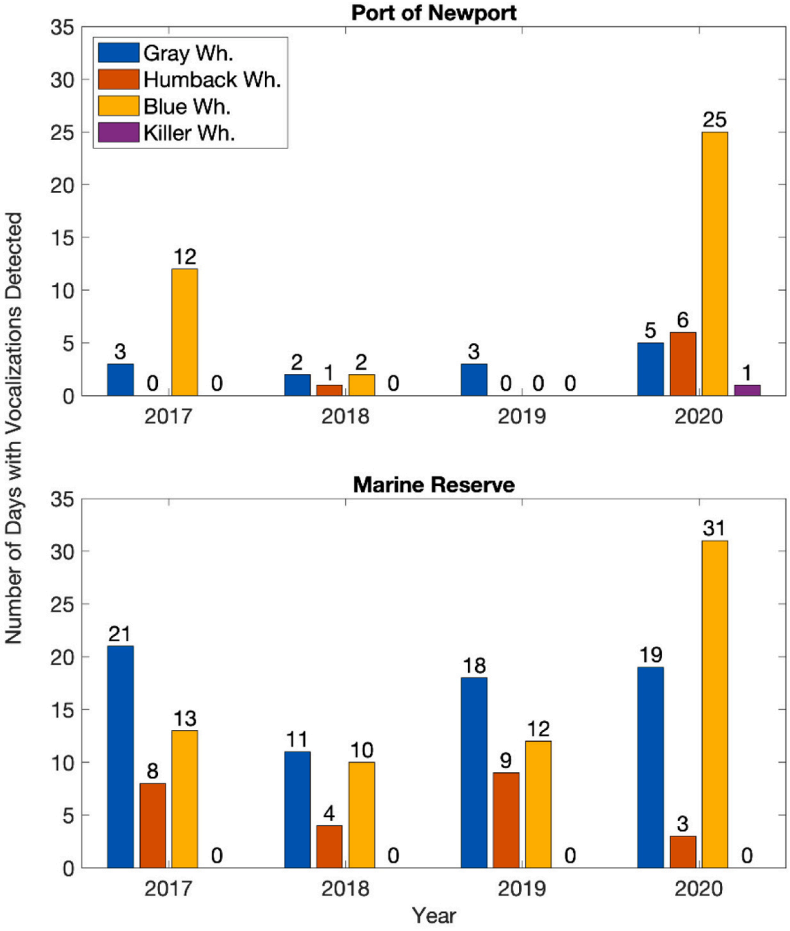

Fig. 10. Daily acoustic detections of gray, humpback, blue, and killer whale vocalizations at the Port of Newport and Marine Reserve in 2017–2020.

it is more likely that ambient conditions at the Marine Reserve hydrophone were more favorable for acoustic detection of the low-frequency whale vocalizations. Vocalizing animals may have also capitalized on quieter ambient conditions near the Marine Reserve by limiting communication near the Port of Newport where it would have been more energetically expensive to vocalize at a higher intensity to compete with other sound sources (Burnham and Duffus, 2019a; Dahlheim and Castellote, 2016). Although we only detected a single day with killer whale vocalizations in 2020, it is possible that killer whales were present near the Port of Newport area on other days and in other years, triggering nearby gray whales to cease vocalization behavior to be more cryptic from their predator (Burnham and Duffus, 2019b; Cummings and Thompson, 1971).

Finally, although it is possible that low-frequency high-energy vocalizations from any of the whale species analyzed here (especially blue and fin whales) could propagate the 17 km distance between the hydrophones, acoustic masking from vessel activity and propagation energy loss within the shallow (20–50 m) water coastal environment are likely additional factors that contributed to fewer acoustic detections of whale vocalizations at the Port of Newport hydrophone.

4.3. Implications for protected species monitoring

As well as providing important information about acoustic habitats for PCFG gray whales, this multi-year soundscape analysis establishes baseline acoustic conditions in coastal Oregon. Comparatively, in neighboring California and Washington states, long-term passive acoustic and marine mammal monitoring efforts have been active for many years (McDonald et al., 2008; Rice et al., 2021). While this study was limited to two hydrophone locations, the five years of data collection provides novel information about underwater soundscape conditions in nearshore waters in the Pacific Northwest. In future research, this passive acoustic dataset could also be utilized in coordinated efforts to monitor species along West Coast migratory corridors as has been done for blue and fin whales in Washington and California (Pearson et al., 2023).

The acoustic diversity between the two sites in this comparison demonstrates how acoustic conditions and underwater noise pollution can differ over short distances in coastal environments. During June to September, vessel activity near the Port of Newport hydrophone increased sound levels, while restrictions on fishing within Otter Rock Marine Reserve likely decreased vessel activity, and therefore sound levels, at that site. Although Otter Rock Marine Reserve is not specifically managed for noise pollution, our results demonstrate that restricting the overlap of anthropogenic activities and marine species habitats can have a dramatic impact on the soundscape. Preserving quieter ambient conditions at Otter Rock Marine Reserve may provide important habitat for foraging gray whales and other acoustically sensitive species (Williams et al., 2015). Further analysis of these long-term passive acoustic monitoring data could compare soundscape conditions in Otter Rock Marine Reserve to other nearshore marine protected areas (e.g., National Marine Sanctuaries and National Parks) and offer an opportunity to compare state and federal management strategies.

Much like other coastal marine protected areas, Otter Rock Marine

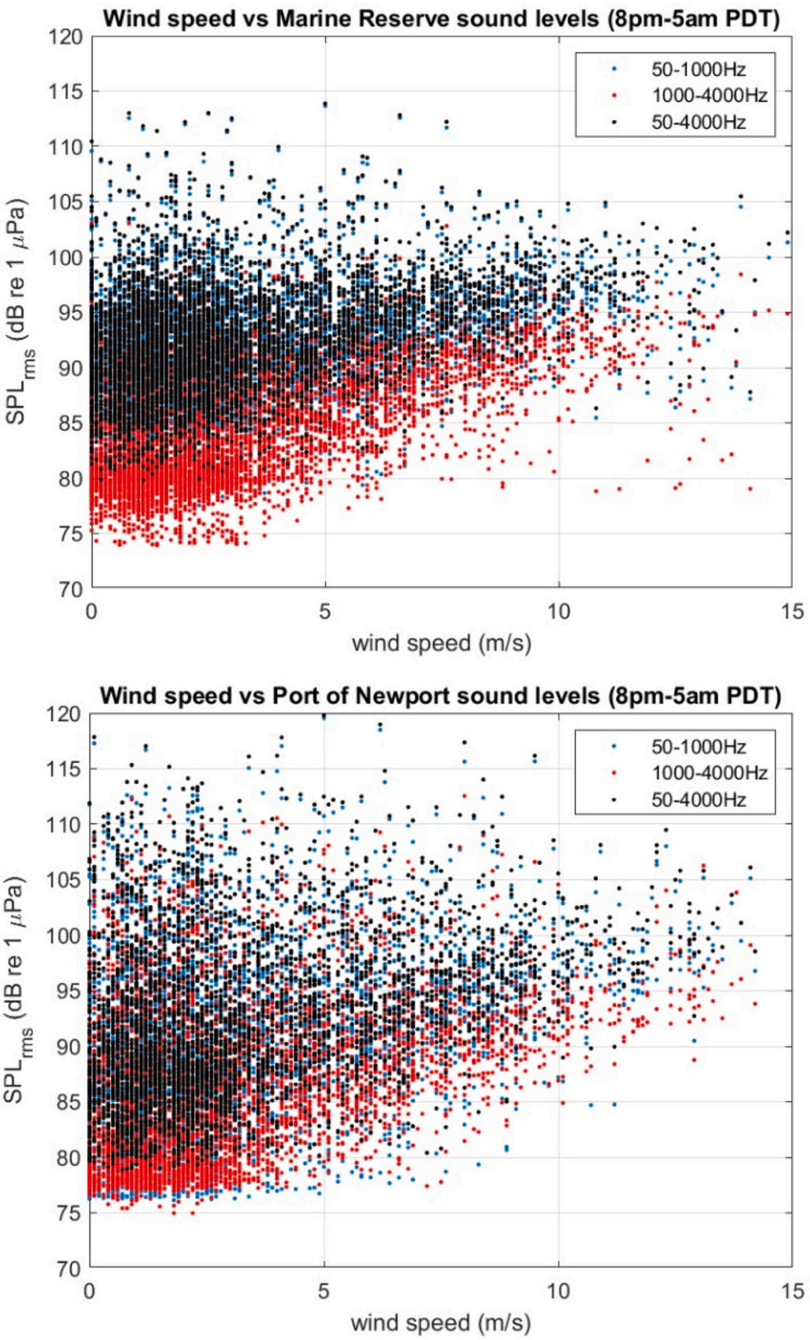

Fig. 11. Wind speeds recorded at the anemometer at the Port of Newport entrance compared with recorded underwater median sound pressure levels (50 Hz–4 kHz) at the Port of Newport and Marine Reserve hydrophones from 8 pm to 5 am PDT (low vessel traffic period).

Reserve is a tourism destination for whale watching and recreation during summer months. The designation and restrictions of the marine reserve are important management tools to protect the habitat for marine animals, including the soundscape. Combined with efforts to understand cetacean health and behavior in varying ambient soundscape conditions, research in environments where certain anthropogenetic sound sources are restricted can provide important information about potential impact of specific sound sources on acoustic habitats.

Given that soundscape conditions can be considerably different across small spatial and temporal distances, sampling across a range of nearby environments is important for understanding conditions for sensitive species with high site fidelity and low mobility (e.g., foraging gray whales, invertebrates, and fish spawning grounds). Information provided by passive acoustic monitoring surveys can be used to inform conservation and management of protected species, commercially valuable fisheries, and overall health of marine ecosystems. Noise pollution can be pervasive in marine environments, and thus it is important to preserve or improve existing conditions in "quieter" areas by maintaining successful management efforts (Hatch and Fristrup, 2009).

Increasing human activities in coastal regions around the world, including Oregon, include the potential for increased noise related to offshore renewable energies and other "blue economy" priorities. However, unlike other ocean pollutants, noise mitigation does not involve lingering clean-up and directed management efforts can have immediate impacts. Long-term monitoring of important habitats for

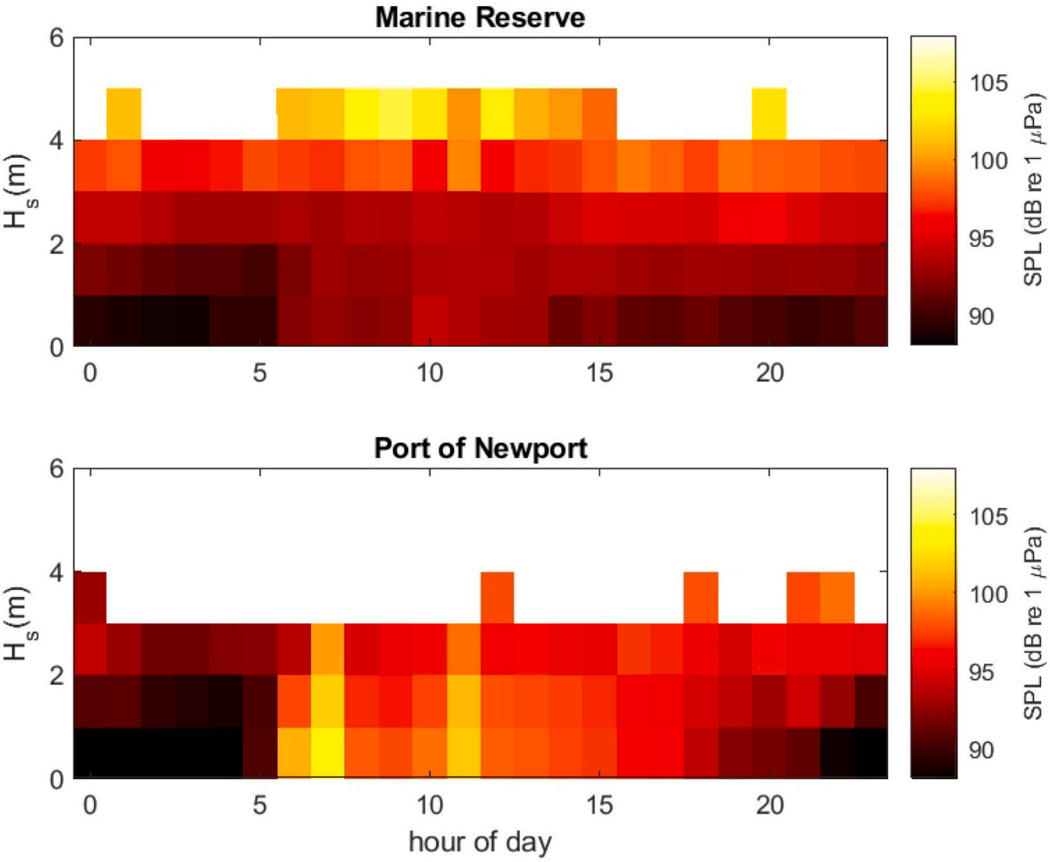

Fig. 12. Underwater median sound pressure levels (50 Hz–4 kHz) at the Port of Newport and Marine Reserve hydrophones binned by significant wave heights (H_s) and the hour of the day. A minimum of 10 observations was required for inclusion of each bin. Sound pressure is indicated by the color bar range increasing from dark red to bright yellow. White grid cells indicate no data. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

protected species, like the research effort described here, can provide ongoing information about the sources and patterns of noise pollution. Coupled with concurrent studies to understand the potential impacts of noise on sensitive species, we can provide information to manage soundscape conditions and direct conservation efforts toward mitigation strategies to protect sensitive species and important conservation areas.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2023.115406.

CRediT authorship contribution statement

Project conceptualization and funding acquisition: J.H.H., R.P.D., L.G.T.; Project administration; J.H.H., L.G.T.: Resources; R.P.D. Data collection: J.H.H., L.R., R.P.D.; Data analysis and synthesis: S.M.H., J.H.H.; Visualization: S.M.H, J.H.H.; Writing - original draft: S.M.H., J.H.H., L.G.T.; Writing - review & editing: All Authors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors thank the many crew members and captains of the research vessels, Pacific Storm, Elakha, Kalipi, Pacific Surveyor, and Gracie Lynn (Oregon Coast Aquarium) for assistance with field operations. Vessel traffic data was provided by the Oregon Department of Fish and Wildlife. This project was supported by the Office of Naval Research Marine Mammals and Biology Program (grant number: N00014-20-1-2760), the NOAA National Marine Fisheries Service Office of Science and Technology Ocean Acoustics Program (2016 and 2017; 50-27), the Oregon State University Marine Mammal Institute, NOAA Pacific Marine Environmental Laboratory, the U.S. Department of Energy, and Oregon Sea Grant Program Development funds (2018; RECO-40-PD). This is PMEL contribution #5527.

References

Au, W.W.L., Pack, A.A., Lammers, M.O., Herman, L.M., Deakos, M.H., Andrews, K., 2006. Acoustic properties of humpback whale songs. J. Acous. Soc. Am. 120, 1103–1110. https://doi.org/10.1121/1.2211547.

Bureau of Ocean Energy Management (BOEM), National Oceanic and Atmospheric Administration (NOAA). 2021 vessel transit counts. Retrieved 6.26.23 from. marinecadastre.gov/data.

Burnham, R.E., Duffus, D.A., 2019a. Gray whale calling response to altered soundscapes drive by whale watching activities in a foraging area. J. Ocean Technol. 14, 85–106.

Burnham, R.E., Duffus, D.A., 2019b. Acoustic predator-prey reaction: gray whales' (*Eschrichtius robustus*) acoustic response to killer whales (*Orcinus orca*). Aquat. Mamm. 45, 340–348. https://doi.org/10.1578/AM.45.3.2019.340.

Burnham, R.E., Vagle, S., O'Neill, C., Trounce, K., 2021. The efficacy of management measures to reduce vessel noise in critical habitat of southern resident killer whales in the Salish Sea. Front. Mar. Sci. 8.

Calambokidis, J., Perez, A., 2017. Sightings and Follow-up of Mothers and Calves in the PCFG and Implications for Internal Recruitment.

Calambokidis, J., Darling, J.D., Deecke, V., Gearin, P., Gosho, M., Megill, W., Tombach, C.M., Goley, D., Toropova, C., Gisborne, B., 2002. Abundance, Range and Movements of a Feeding Aggregation of Gray Whales (*Eschrichtius robustus*) From California to Southeastern Alaska in 1998.

Calambokidis, J., Laake, J., Perez, A., 2019. Updated Analysis of Abundance and Population Structure of Seasonal Gray Whales in the Pacific Northwest, 1996–2017. NOAA, Seattle, WA.

Carey, W.M., Evans, R.B., 2011. Ocean Ambient Noise: Measurement and Theory. Springer, New York. https://doi.org/10.1007/978-1-4419-7832-5.

Carome, W., Rayment, W., Slooten, E., Bowman, M.H., Dawson, S.M., 2022. Vessel traffic influences distribution of Aotearoa New Zealand's endemic dolphin (Cephalorhynchus hectori). Mar. Mammal 39 (2), 626–647.

Castellote, M., Clark, C.W., Lammers, M.O., 2012. Acoustic and behavioural changes by fin whales *(Balaenoptera physalus)* in response to shipping and airgun noise. Biol. Conserv. 147, 115–122. https://doi.org/10.1016/j.biocon.2011.12.021.

Charif, R., Waack, A., Strickman, L., 2010. Raven Pro 1.4 User's Manual.

Cholewiak, D., Clark, C.W., Ponirakis, D., Frankel, A., Hatch, L.T., Risch, D., Stanistreet, J.E., Thompson, M., Vu, E., Parijs, S.M.V., 2018. Communicating amidst the noise: modeling the aggregate influence of ambient and vessel noise on baleen whale communication space in a national marine sanctuary Danielle. Endanger. Species Res. 36, 59–75. https://doi.org/10.3354/esr00875.

Cominelli, S., Devillers, R., Yurk, H., MacGillivray, A., McWhinnie, L., Canessa, R., 2018. Noise exposure from commercial shipping for the southern resident killer whale population. Mar. Pollut. Bull. 136, 177–200. https://doi.org/10.1016/j.marpolbul.2018.08.050.

Cummings, W.C., Thompson, P., 1971. Gray whales, Eschrichtius robustus, avoid the underwater sounds of killer whales, Orcinus orca|Tethys. Fish. Bull. 69, 525–530.

Dahlheim, M.E., 1987. Bio-acoustics of the Gray Whale (Eschrichtius robustus). University of British Columbia. https://doi.org/10.14288/1.0097975.

Dahlheim, M., Castellote, M., 2016. Changes in the acoustic behavior of gray whales Eschrichtius robustus in response to noise. Endanger. Species Res. 31, 227–242. https://doi.org/10.3354/esr00759.

Deane, G.B., 2000. Long time-base observations of surf noise. J. Acous. Soc. Am. 107, 758–770. https://doi.org/10.1121/1.428259.

Derville, S., Barlow, D.R., Hayslip, C., Torres, L.G., 2022. Seasonal, annual, and decadal distribution of three rorqual whale species relative to dynamic ocean conditions off Oregon, USA. Front. Mar. Sci. 9.

Dziak, R.P., Haxel, J.H., Lau, T.-K., Heimlich, S., Caplan-Auerbach, J., Mellinger, D.K., Matsumoto, H., Mate, B., 2017. A pulsed-air model of blue whale B call vocalizations. Sci. Rep. 7, 9122. https://doi.org/10.1038/s41598-017-09423-7.

Erbe, C., Marley, S.A., Schoeman, R.P., Smith, J.N., Trigg, L.E., Embling, C.B., 2019. The effects of ship noise on marine mammals—a review. Front. Mar. Sci. 6, 1–21. https://doi.org/10.3389/fmars.2019.00606.

Findlay, C.R., Rojano-Doñate, L., Tougaard, J., Johnson, M.P., Madsen, P.T., 2023. Small reductions in cargo vessel speed substantially reduce noise impacts to marine mammals. Sci. Adv. 9, eadf2987 https://doi.org/10.1126/sciadv.adf2987.

Ford, J.K.B., 1987. A catalogue of underwater calls produced by killer whales (Orcinus orca) in British Columbia. In: Canadian Data Report of Fish and Aquatic Science, vol. 633, pp. 1–165.

Forney, K.A., Southall, B.L., Slooten, E., Dawson, S., Read, A.J., Baird, R.W., Brownell, R. L., 2017. Nowhere to go: noise impact assessments for marine mammal populations with high site fidelity. Endanger. Species Res. 32, 391–413.

Fournet, M.E.H., Matthews, L.P., Gabriele, C., Haver, S., Mellinger, D., Klinck, H., 2018. Humpback whales Megaptera novaeangliae alter calling behavior in response to natural sounds and vessel noise. Mar. Ecol. Prog. Ser. 607, 251–268. https://doi.org/10.3354/meps12784.

Fox, C.G., Matsumoto, H., Lau, T.-K.A., 2001. Monitoring Pacific Ocean seismicity from an autonomous hydrophone array. J. Geophys. Res. 106, 4183–4206. https://doi.org/10.1029/2000JB900404.

Francis, C.D., Barber, J.R., 2013. A framework for understanding noise impacts on wildlife: an urgent conservation priority. Front. Ecol. Environ. 11, 305–313. https://doi.org/10.1890/120183.

Gabriele, C.M., Ponirakis, D.W., Clark, C.W., Womble, J.N., Vanselow, P.B.S., 2018. Underwater acoustic ecology metrics in an Alaska marine protected area reveal marine mammal communication masking and management alternatives. Front. Mar. Sci. 5, 1–17. https://doi.org/10.3389/fmars.2018.00270.

Gailey, G., Zykov, M., Sychenko, O., Rutenko, A., Blanchard, A.L., Aerts, L., Melton, R.H., 2022. Gray whale density during seismic surveys near their Sakhalin feeding ground. Environ. Monit. Assess. 194, 739. https://doi.org/10.1007/s10661-022-10025-8.

Gassmann, M., Wiggins, S.M., Hildebrand, J.A., 2017. Deep-water measurements of container ship radiated noise signatures and directionality. J. Acous. Soc. Am. 142, 1563–1574. https://doi.org/10.1121/1.5001063.

Guazzo, R.A., Helble, T.A., D'Spain, G.L., Weller, D.W., Wiggins, S.M., Hildebrand, J.A., 2017. Migratory behavior of eastern North Pacific gray whales tracked using a hydrophone array. PLoS One 12, 1–30. https://doi.org/10.1371/journal.pone.0185585.

Harris, J., Calambokidis, J., Perez, A., Mahoney, P.J., 2022. Recent Trends in the Abundance of Seasonal Gray Whales (*Eschrichtius robustus*) in the Pacific Northwest, 1996-2020 (No. AFSC Processed Rep. 2022-05). Alaska Fisheries Science Center, NOAA National Marine Fisheries Service, Seattle, WA.

Hatch, L.T., Fristrup, K.M., 2009. No barrier at the boundaries: implementing regional frameworks for noise management in protected natural areas. Mar. Ecol. Prog. Ser. 395, 223–244. https://doi.org/10.3354/meps07945.

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., Mellinger, D.K., Oestreich, W.K., Roche, L., Ryan, J., Van Parijs, S.M., 2020. Seasonal trends and primary contributors to the low-frequency soundscape of the Cordell Bank National Marine Sanctuary. J. Acous. Soc. Am. 148, 845–858. https://doi.org/10.1121/10.0001726.

Haxel, J.H., Dziak, R.P., Matsumoto, H., 2013. Observations of shallow water marine ambient sound: the low frequency underwater soundscape of the central Oregon coast. J. Acous. Soc. Am. 133, 2586–2596. https://doi.org/10.1121/1.4796132.

Helble, T.A., Ierley, G.R., D'Spain, G.L., Roch, M.A., Hildebrand, J.A., 2012. A generalized power-law detection algorithm for humpback whale vocalizations. J. Acous. Soc. Am. 131, 2682–2699. https://doi.org/10.1121/1.3685790.

Hermannsen, L., Mikkelsen, L., Tougaard, J., Beedholm, K., Johnson, M., Madsen, P.T., 2019. Recreational vessels without Automatic Identification System (AIS) dominate anthropogenic noise contributions to a shallow water soundscape. Sci. Rep. 9, 15477. https://doi.org/10.1038/s41598-019-51222-9.

Hildebrand, J.A., Frasier, K.E., Baumann-Pickering, S., Wiggins, S.M., 2021. An empirical model for wind-generated ocean noise. J. Acous. Soc. Am. 149, 4516–4533. https://doi.org/10.1121/10.0005430.

Hildebrand, L., Sullivan, F., Orben, R., Derville, S., Torres, L., 2022. Trade-offs in prey quantity and quality in gray whale foraging. Mar. Ecol. Prog. Ser. 695, 189–201. https://doi.org/10.3354/meps14115.

Hvidsten, C.I., 2021. Gray Whale Detection Through Passive Acoustic Monitoring Near PacWave, Department of Energy, Office of Science's Science Undergraduate Laboratory Internship Program. Pacific Northwest National Laboratory, Richland, WA.

Knudsen, V., Alford, R.S., Emling, J.W., 1948. Underwater ambient noise. J. Mar. Res. 410–429.

Lemos, L.S., Haxel, J.H., Olsen, A., Burnett, J.D., Smith, A., Chandler, T.E., Nieukirk, S.L., Larson, S.E., Hunt, K.E., Torres, L.G., 2022. Effects of vessel traffic and ocean noise on gray whale stress hormones. Sci. Rep. 12, 18580. https://doi.org/10.1038/s41598-022-14510-5.

MacGillivray, A.O., Li, Z., Hannay, D.E., Trounce, K.B., Robinson, O.M., 2019. Slowing deep-sea commercial vessels reduces underwater radiated noise. J. Acous. Soc. Am. 146, 340–351. https://doi.org/10.1121/1.5116140.

Marley, S., Salgado Kent, C., Erbe, C., Thiele, D., 2017. A tale of two soundscapes: comparing the acoustic characteristics of urban versus pristine coastal dolphin habitats in Western Australia. Acoust. Aust. 45 https://doi.org/10.1007/s40857-017-0106-7.

McDonald, M.A., Hildebrand, J.A., Wiggins, S.M., 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, 1985–1992. https://doi.org/10.1121/1.4929899.

Merchant, N.D., Barton, T.R., Thompson, P.M., Pirotta, E., Dakin, D.T., Dorocicz, J., 2013. Spectral probability density as a tool for ambient noise analysis. J. Acous. Soc. Am. 133, EL262–EL267. https://doi.org/10.1121/1.4794934.

National Research Council, 2003. Ocean Noise and Marine Mammals. National Academies Press, Washington, DC.

ODFW, 2022. Marine Reserves Program Synthesis Report: 2009–2021. Oregon Department of Fish and Wildlife, Newport, Oregon.

Pack, A.A., Waterman, J.O., Craig, A.S., 2022. Diurnal increases in depths of humpback whale (Megaptera novaeangliae) mother-calf pods off West Maui, Hawai'i: a response to vessels? Mar. Mammal Sci. 38, 1340–1356. https://doi.org/10.1111/mms.12926.

Payne, R.S., McVay, S., 1971. Songs of humpback whales. Science 173, 585–597.

Pearson, E.J., Oestreich, W.K., Ryan, J.P., Haver, S.M., Gedamke, J., Dziak, R.P., Wall, C. C., 2023. Widespread passive acoustic monitoring reveals spatio-temporal patterns of blue and fin whale song vocalizations in the Northeast Pacific Ocean. Front. Remote Sens. 4.

Peavey Reeves, L.E., 2021. United in Song: Finding Common Ground to Protect Humpback Whales. NOAA Office of National Marine Sanctuaries.

Popper, A.N., Hawkins, A.D., 2019. An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. J. Fish Biol. 94, 692–713. https://doi.org/10.1111/jfb.13948.

Rice, A., Debich, A.J., Širović, A., Oleson, E.M., Trickey, J.S., Varga, L.M., Wiggins, S.M., Hildebrand, J.A., Baumann-Pickering, S., 2021. Cetacean occurrence offshore of Washington from long-term passive acoustic monitoring. Mar. Biol. 168, 1–22. https://doi.org/10.1007/s00227-021-03941-9.

Richardson, W.J., Greene, C.R., Malme, C.I., Thomson, D.H., 1995. Marine Mammals and Noise. Academic Press, San Diego.

Rolland, R.M., Parks, S.E., Hunt, K.E., Castellote, M., Corkeron, P.J., Nowacek, D.P., Wasser, S.K., Kraus, S.D., 2012. Evidence that ship noise increases stress in right whales. Proc. R. Soc. B Biol. Sci. 279, 2363–2368. https://doi.org/10.1098/rspb.2011.2429.

Shabangu, F.W., Yemane, D., Best, G., Estabrook, B.J., 2022. Acoustic detectability of whales amidst underwater noise off the west coast of South Africa. Mar. Pollut. Bull. 184, 114122 https://doi.org/10.1016/j.marpolbul.2022.114122.

Simard, P., Wall, K.R., Mann, D.A., Wall, C.C., Stallings, C.D., 2016. Quantification of boat visitation rates at artificial and natural reefs in the eastern Gulf of Mexico using acoustic recorders. PLoS One 11, e0160695. https://doi.org/10.1371/journal.pone.0160695.

Smott, S., Monczak, A., Miller, M.E., Montie, E.W., 2018. Boat noise in an estuarine soundscape – a potential risk on the acoustic communication and reproduction of soniferous fish in the May River, South Carolina. Mar. Pollut. Bull. 133, 246–260. https://doi.org/10.1016/j.marpolbul.2018.05.016.

Sprogis, K.R., Holman, D., Arranz, P., Christiansen, F., 2023. Effects of whale-watching activities on southern right whales in Encounter Bay, South Australia. Mar. Policy 150, 105525. https://doi.org/10.1016/j.marpol.2023.105525.

Sullivan, F.A., Torres, L.G., 2018. Assessment of vessel disturbance to gray whales to inform sustainable ecotourism. J. Wildl. Manag. 82, 896–905. https://doi.org/10.1002/jwmg.21462.

The Research Group, LLC, 2021. Fishing Industry Economic Activity Trends in the Newport, Oregon Area, Update 2019. Prepared for Midwater Trawlers Cooperative and Lincoln County Board of Commissioners.

Thode, A.M., Blackwell, S.B., Conrad, A.S., Kim, K.H., Marques, T., Thomas, L., Oedekoven, C.S., Harris, D., Bröker, K., 2020. Roaring and repetition: how bowhead whales adjust their call density and source level (Lombard effect) in the presence of natural and seismic airgun survey noise. J. Acous. Soc. Am. 147, 2061–2080. https://doi.org/10.1121/10.0000935.

Tyack, P.L., Costa, D.P., Allain, V., Erbe, C., 2018. Ocean sound. Essential ocean variables (EOV) for biology and ecosystems. URL. https://www.goosocean.org/components/com_oe/oe.php?task=download&id=40209&version=1.0&lang=1&format=15. (Accessed 24 October 2018).

US DOC/NOAA/NWS/NDBC, 1971. Meteorological and Oceanographic Data Collected From the National Data Buoy Center Coastal-Marine Automated Network (C-MAN) and Moored (Weather) Buoys. Station NWPO3 (44.613N 124.067W) - Newport, OR.

Vagle, S., Burnham, R.E., Neill, C.O., Yurk, H., 2021. Variability in Anthropogenic Underwater Noise Due to Bathymetry and Sound Speed Characteristics.

Wenz, G.M., 1962. Acoustic ambient noise in the ocean: spectra and sources. J. Acous. Soc. Am. 34, 1936–1956. https://doi.org/10.1121/1.1909155.

Williams, R., Erbe, C., Ashe, E., Clark, C.W., 2015. Quiet(er) marine protected areas. Mar. Pollut. Bull. 100, 154–161. https://doi.org/10.1016/j.marpolbul.2015.09.012.

Wilson, J.H., 1983. Wind-generated noise modeling. J. Acous. Soc. Am. 73, 211–216. https://doi.org/10.1121/1.388841.

Wilson, O.B., Wolf, S.N., Ingenito, F., 1985. Measurements of acoustic ambient noise in shallow water due to breaking surf. J. Acous. Soc. Am. 78, 190–195. https://doi.org/10.1121/1.392557.

Zobell, V.M., Frasier, K.E., Morten, J.A., Hastings, S.P., Reeves, L.E.P., Wiggins, S.M., Hildebrand, J.A., 2021. Underwater noise mitigation in the Santa Barbara Channel through incentive - based vessel speed reduction. Sci. Rep. 1–12. https://doi.org/10.1038/s41598-021-96506-1.