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## Introduction

### Soundscapes

Sound serves as the main sensory input for many species in the ocean. Since sound travels over four times faster in water than in air and can carry information over far distances (Urick 1983), the use of sound has evolved as a critical component of communication, navigation, and foraging for many invertebrates, fishes, and cetaceans (Duarte et al. 2021). Under the right conditions, sounds can travel across ocean basins (Miksis-Olds, Martin, and Tyack 2018).

The total collection of sounds in an environment is called a soundscape, and these sources of sound are grouped into three broad categories: biophonies, sound produced by animals like cetaceans, fishes, and invertebrates; geophonies, natural sounds like rain, wind, and earthquakes; and anthropophonies, human-made sounds from shipping vessels, sonar, and oceanographic survey activities (Miksis-Olds, Martin, and Tyack 2018; Duarte et al. 2021). Every region of the ocean experiences high spatio-temporal variation in sound levels and sources based on traits such as properties of water, organism diversity, human activities, and bathymetry (André et al. 2011). Because of their unique sound signatures, ocean soundscapes can be characterized, measured, and monitored as indicators of ecosystem health or species diversity (Radford et al. 2010; Pijanowski et al. 2011; Haver et al. 2019; Weiss et al. 2021).

When noise levels reach higher than normal levels, organisms can be negatively impacted. Invertebrates and fishes may experience stunted development, elevated stress responses, and physical injuries (L. Weilgart 2018), while cetaceans’ behavior, calling patterns, physiology and stress levels, and ability to locate prey or conspecifics are impacted (L. S. Weilgart 2007). Sensitivities and responses to noise can vary among species and even individuals (Kunc, McLaughlin, and Schmidt 2016). While terrestrial ecosystem-level effects have been well-documented (Francis et al. 2012; Shannon et al. 2016; Buxton et al. 2017), effects within aquatic ecosystems require further studies (Kunc, McLaughlin, and Schmidt 2016).

Ocean noise pollution is among the anthropogenic changes that have recently grown to concerning levels (Tyack 2008; Hildebrand 2009). The global ambient noise in the ocean is estimated to have increased by 12 decibels in the last few decades and has a close correlation to global economic trends (Frisk 2012). Ships have been increasing in terms of gross tonnage and fleet size (Hildebrand 2009) and now account for over 80% of the global trade, with an estimated 1.4% expected annual increase in shipping through 2027 (UNCTAD 2022). Commercial shipping now accounts for most of the low-frequency anthropogenic noise in the ocean (Hildebrand 2009).

These noise-generating activities are categorized as either incidental or deliberate (Chou et al. 2021; Chahouri, Elouahmani, and Ouchene 2022). Deliberate activities such as active sonar pingers, resource extraction from the seabed, seismic surveys, and echosounders intentionally produce sound to measure an area and can utilize both high and low frequencies (Duarte et al. 2021). Incidental activities like dredging, offshore development, and shipping produce sound as a by-product (Hawkins and Popper 2017; Southall et al. 2017). Anthropogenic noise can further be characterized by the frequency and duration of the sound. For example, shipping occurs in all oceans and produces a continuous, low-frequency (<200 Hz) sound that travels far distances (Hildebrand 2009). Sonar for military surveillance or research such as seafloor mapping produces mid-frequency sounds, but attenuates quicker, therefore impacting a smaller acoustic space (Hildebrand 2009; Richardson et al. 2013). Noise has been shown to propagate differently based on static features like bathymetry and depth (Richardson et al. 2013; Vagle et al. 2021), as well as dynamic variables like temperature, salinity, and pH from a changing climate (Kunc, McLaughlin, and Schmidt 2016; Affatati, Scaini, and Salon 2022).

As soniferous animals, cetaceans have varying levels of sensitivity and vulnerability to certain types of noise. Generally, mysticetes are more affected by low-frequency noise produced by large shipping vessels (Southall et al. 2017). Odontocetes produce and detect mid- to high-frequency sounds and are more likely to interfere with human activities at these frequencies. These generalizations appear to have exceptions, as odontocete species like beaked whales have shown avoidance behaviors in response to broadband and low frequency vessel noise (Aguilar Soto et al. 2006; Pirotta et al. 2012). It remains uncertain how short-term effects of chronic or acute noise pollution for cetaceans translates into long-term or population level changes. New et al. (2013) suggest enough exposure can cause beaked whales to cease foraging and eventually lower reproduction rates.

### Beaked Whales and Sperm Whales

Beaked whales (family *Ziphiidae)* are a group of 24 species and among the least understood cetaceans and deepest divers in the ocean. They regularly dive for over an hour to depths greater than 800 meters, sometimes exceeding three hours and 2000 meters, followed by only a few minutes on the surface (Tyack et al. 2006; Baird et al. 2006). Their preference for deep water, coupled with a low-profile body makes them nearly invisible on the surface, so very little is known about them with visual observations (Awbery 2022). Much of what is known comes from strandings and stomach content analysis (West et al. 2017). Even when sighting events occur, they risk misidentification due to the paucity of data of morphological variations in some species (Aguilar de Soto et al. 2017). Tagging studies prove useful, but it is often difficult to acquire a sizable dataset (Baird et al. 2006; Tyack et al. 2006; Baird 2008).

Beaked whales are known to be exceptionally sensitive to noise (Hooker et al. 2019). There are several documented cases of naval mid-frequency active sonar (MFAS) activities coinciding with mass stranding events by beaked whales (Fernández et al. 2005; L. S. Weilgart 2007; DeRuiter et al. 2013; Bernaldo de Quiros et al. 2019; Simonis, Brownell, et al. 2020; Stanistreet et al. 2022). The same physiological adaptations that allow for extreme diving are observed to increase their decompression risk when they alter their behavior in response to noise (Kvadsheim et al. 2012; Fahlman et al. 2014). Furthermore, these responses vary based on the individuals’ age, sex, past experience with noise, or current activity (L. S. Weilgart 2007).

Despite their visually cryptic nature, their sound signals are very well-described, down to the species level (Baumann-Pickering et al. 2013; Baumann-Pickering et al. 2014). Beaked whales produce clicks, pulses, and buzzes during foraging below 500 meters of depth (Tyack et al. 2006). Increased acoustic surveys reported in the literature have detected new vocalization patterns globally (Manzano-Roth et al. 2023), with notable temporal patterns emerging (Yamada et al. 2019).

Sperm whales (*Physeter macrocephalus*) also occupy deep ocean habitats, but their dive depths and times are reduced in comparison. Sperm whales have been known to dive regularly between 400-600 meters and often over 1000 meters (Watkins et al. 1993; Amano and Yoshioka 2003; Awbery 2022). They also appear to have more acoustic tolerance than beaked whales (Madsen et al. 2002; P. J. O. Miller et al. 2009; Winsor, Irvine, and Mate 2017; Patrick J. O. Miller et al. 2022). While avoidance responses in sperm whales have been recorded following MFAS events (Sivle et al. 2012; Curé et al. 2013; Stanistreet et al. 2022) and seismic survey pulses (Madsen et al. 2002) , and can range from minor (Isojunno et al. 2022) to moderate (Isojunno et al. 2016) in severity, the circumstances surrounding the noise exposure is not well understood.

Sperm whales also emit series of targeted clicks when socializing (Marcoux, Whitehead, and Rendell 2006; Fais et al. 2015) and foraging (Fais et al. 2016), but it’s unlikely they debilitate their prey with their vocalizations as previously hypothesized (Norris and Harvey 1972). More is known about sperm whales than beaked whales as they spend more time on the surface, lending themselves to better detection during visual surveys.

Several studies to date have documented specific effects of acoustic interference from human activity in beaked and sperm whales. Intense noise events can affect behavior through habitat displacement, time and effort fleeing spent instead of foraging, and communication and echolocation click disruption (Aguilar Soto et al. 2006; DeRuiter et al. 2013; Cholewiak et al. 2017; Falcone et al. 2017; Joyce et al. 2020; Stanistreet et al. 2022); cause physiological harm like hearing loss, tissue damage, and elevated stress levels (Cox et al. 2006; Hooker et al. 2019) even up to 100 km away (Falcone et al. 2017); and mask signals for communication (Erbe et al. 2014), environmental cues (Duarte et al. 2021), or mating (L. S. Weilgart 2007).

Under the Marine Mammal Protection Act, these species are federally protected, and several receive addition protection under the Endangered Species Act due to a vulnerable or endangered conservation status (Taylor et al., n.d.), but some remain listed as “data deficient” by the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species (Pitman and Brownell, n.d., 2020). The latter designation has been scrutinized for not eliciting the same conservation urgency as species whose populations are well-documented (Parsons 2016), therefore emphasizing the need for population and abundance studies of these species.

### Passive Acoustic Monitoring

Passive acoustic monitoring (PAM) is a tool that allows researchers to record and listen to the soundscape. It is also an ideal method for assessing habitat use and improving species distribution models of visually cryptic cetaceans like beaked whales and sperm whales that are more likely to be heard than seen (Fleishman et al. 2023), live relatively far offshore (Robbins et al. 2022), and have low-density populations (Hildebrand et al. 2015; Hooker et al. 2019; Arranz et al. 2023).

Passive acoustic recorders come in two forms: fixed or mobile, each better suited to a certain ecological application. A mobile (towed or free drifting) buoy is either towed behind a vessel or moves autonomously with the currents for days or weeks at a time. It captures the dynamic nature of sound over a large spatial area, especially in deep and less studied parts of the ocean, making it ideal for detecting offshore or mobile species. Bottom-mounted recorders allow for greater temporal coverage and are often used when studying specific regions or known habitats of study species (Nosal and Frazer 2007; Marques et al. 2012; Jarvis et al. 2022).

The benefits of using PAM over visual surveys include use during night hours or through inclement weather, lower cost to charter and little experience needed to conduct a survey (Johnson, Soto, and Madsen 2009; Fleishman et al. 2023). The trade-offs include costly equipment or deployment, high data/battery storage requirements, uncertain chance of return, limited spatial coverage for fixed recorders, and limited temporal coverage for mobile recorders. Even with experienced acousticians, noisy detections can obfuscate number of individuals or species detected and distance or direction from recorder for species with large call ranges such as sperm whales (Barlow and Gisiner 2005; Mellinger et al. 2007).

### Automatic Identification System

Automatic Identification System (AIS) is a mandatory vessel tracking system for vessels over 300 gross tons to aid in position communication and safe navigation (Federal Register 2003). While not originally intended for use in research, it has become a valuable resource for vessel traffic data, especially in studying effects of vessel strikes (Reimer et al. 2016; Greig et al. 2020) and noise pollution (Aguilar Soto et al. 2006; Erbe et al. 2014) on cetaceans. Because ships are abundant throughout the study area due to major U.S. ports, AIS was included in this study to investigate patterns of co-occurrence between vessels and whales and sound levels in those moments. Previous studies have separated vessel and anthropogenic noise from ambient soundscape based on known spectral signatures, frequency bands, and percentiles (Haver et al. 2020; Weiss et al. 2021). The inclusion of AIS to soundscape metrics in this study provides fine-scale evaluation of sound and source.

### Laws and Regulations

While there is consensus that anthropogenic noise in the ocean is increasing, policies that aim to mitigate chronic noise are generally lacking. This is due to knowledge gaps regarding the long-term and cumulative effects of noise on certain species (Markus and Sánchez 2018). International and regional efforts are underway (see Chou et al. (2021)) but are not fully complete. Within the European Union, the Marine Strategy Framework Directive establishes a directive about environmental regulation on marine noise, specifically requiring member states to adopt strategies in compliance with threshold values for impulsive and continuous noise (“Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 Establishing a Framework for Community Action in the Field of Marine Environmental Policy (Marine Strategy Framework Directive) (Text with EEA Relevance)” 2008; Borsani, J.F. et al. 2023). Some studies have independently tested these threshold values (Sebastianutto et al. 2015; Garrett et al. 2016; Haver et al. 2021) or used them as guidelines in their study (Mustonen et al. 2019). The National Oceanic and Atmospheric Administration (NOAA) has developed an Ocean Noise Strategy Roadmap, an agency-wise approach to mitigating both chronic and acute effects of noise exposure to animals (NOAA 2018). Within it, the authors agree upon impairment thresholds for mid-frequency cetaceans (NOAA 2018). Because chronic effects are not fully understood, they remain to be regulated. The International Maritime Organization (IMO) has also been addressing noise pollution from commercial vessels through quieter ship design (International Maritime Organization 2014). Updates to their 2014 guidelines are set to be finalized by January 2024. Finally, Canada has launched a Quiet Vessel Initiative and is expected to publish a Ocean Noise Strategy for underwater noise management in 2023 (Breeze et al. 2022).

### Research Objective

With anthropogenic noise-generating activities on the rise, global oceanic sound levels are expected to increase. Noise is a form of habitat degradation, so there is a need for research on a large spatial scale to understand how these highly mobile animals overlap in space and time with human activities and how they’re affected (Erbe et al. 2014; Haver et al. 2019; Hooker et al. 2019). Acquiring information on these federally protected and acoustically sensitive species is challenging, but certain PAM techniques can be well-suited for this type of research. Logistical difficulties associated with offshore research and low-density populations of visually cryptic deep diving whales have created a paucity of data in the California Current Ecosystem. This research provides a step towards understanding soundscape variation in the area and beaked and sperm whale distributions and their acoustic environment.

The purpose of this study is to characterize the spatial and temporal acoustic variability of beaked and sperm whale habitat in the California Current Ecosystem using soundscape metrics, environmental variables, and AIS. We determine significant predictors of whale presence for each species with the use of Random Forest models and generalized additive models and provide explicit sources for noise-generating human activities through overlay of large vessel activity.

## Methods

### Study Area

The California Current Ecosystem (CCE) is a highly productive and complex ecosystem that contains one proposed and five current national marine sanctuaries (Office of National Marine Sanctuaries, n.d.), supports several wild fisheries (Field and Francis 2006), and is home to nineteen protected whale species (NOAA Fisheries, n.d.). The 1,141,800 km2 area extends along the US’ Economic Exclusion Zone from southern Canada to northern Mexico and is a characterized by deep canyons and a continental shelf (Barlow and Forney 2007; Barlow et al. 2009). Characteristic of the area are upwelling events that carry nutrients to the surface and drive primary productivity, creating an ideal habitat where whales’ prey are found (Ryther 1969). The year 2018 was characterized in the CCE with slightly warmer than average sea surface temperatures as the recent El-Nino and marine heatwave events were ending (Harvey et al., n.d.). Because this area has high economic value and natural ecological activity, it’s a well-managed and well-researched area (Peña and Bograd 2007; Coleman 2008; Oldach et al. 2022).

In 2021, California, Washington, and Oregon ranked 3rd, 5th, and 23rd in most trafficked U.S. waterways, respectively (United States Army Corps of Engineers [USACE] 2018). Between vessel activity like fishing, shipping and naval exercises in California alone, there is notable overlap of anthropogenic presence with important habitat for protected species. Furthermore, the future development of offshore wind turbines off of Morro Bay and Humboldt, California are expected to be noise-producing activities during construction and operation, increasing sound levels in those regions (Madsen et al. 2006; Cooperman et al. 2022).

### Data Collection and Processing

Acoustic detections were collected as part of the 2018 California Current Ecosystem Survey (CCES) by the Southwest Fisheries Science Center (SWFSC). Twenty-three free drifting buoys (numbered 1-23) were deployed at varying times between July and November in the offshore waters of the study area. These buoys contained two satellite geo-locators above water to monitor GPS information and two hydrophones at depth attached by a 150-meter line. They collected a total of 1910 hours of data. SWFSC detected and classified acoustic detections in PAMGuard to species level as per methods mentioned in Simonis, Trickey, et al. (2020).

Acoustic data were duty-cycled, with most buoys sampling at a rate of 18 minutes off and 2 minutes on. The SWFSC team analyzed the data and detected echolocation pulses produced by beaked and sperm whales. These were classified by peak frequency and spectral signature and identified to the species level (see Simonis, Trickey, et al. (2020) for details on this survey and Rand, Wood, and Oswald (2022) for duty-cycle study). Soundscape metrics were binned by peak frequency into low, medium, high frequency bands, along with the 1, 5, 10, 25, 75, 95, and 99 percentile distribution from each metric.

Soundscape metrics were rounded to the nearest 20 minutes (:00, :20, :40) and converted to the UTC time zone. These metrics include third-octave level (TOL) bands from 63 to 20,000 Hz and broadband (20-24,000 Hz) metrics. Several TOL levels were chosen as proxies to vessel or sonar frequencies. Whale detection timestamps were rounded to nearest 20 minutes based on start time to align with the soundscape metrics. A separate column was created as a common join field that contained nearest timestamp in UTC to that of buoy tracks (see below). Two types of beaked whale detections (species code *?BW* and *?BWC*) were removed from analysis as the species was unknown. Buoy tracks were similarly rounded to nearest 20 minutes. Seven buoys (1,2,3,5,6,9,11) were lost at sea and two buoys had corrupted data (4,17) so these were removed from the analysis. Buoys 14 and 15 were the same and therefore consolidated to 14. These three preliminary datasets were joined together based on a common buoy number (column “station”) and time field column “UTC”). Whale detections (column “Wpresence”) were reduced to binary data for absence/presence and all other fields of that dataset were eliminated.

### Environmental Data

Possible environmental and oceanographic predictors of cetacean habitat were extracted from the NOAA Environmental Research Division Data Access Program (ERDDAP) server ((https://coastwatch.pfeg.noaa.gov/erddap/) and Hybrid Coordinate Ocean Model (HYCOM) using the *matchEnvData* function in R package *PAMmisc*. Six modeled variables at depth (mixed layer depth, mixed layer temperature, temperature at 400m, thermocline temperature, thermocline depth, salinity at 400m) were calculated using a formula from McCullough et al. (2021). Such variables are especially important to incorporate as it better reflects the deep environment that beaked and sperm whales are known to inhabit. Distance to slope and bathymetric slope were calculated from a bathymetry TIF acquired from the General Bathymetric Chart of the Oceans (GEBCO).

### Modeling

We used a Random Forest (RF) model in R (R Core Team, 2023) using the package () to identify most important environmental or acoustic predictors for beaked and sperm whales. A separate model was run for each species. We built generalized additive models in R using the package *mcgv* to relate beaked and sperm whale detections to an environmental or acoustic variable.

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