Investigating Boat Noise in Wellfleet Harbor, MA

By

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Executive Summary

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Context:

Sound plays an important role in marine environments, but growing anthropogenic noise levels in the oceans threaten marine animals' ability to utilize essential sound signals. Anthropogenic sources of underwater noise pollution include military sonar for detecting submarines, use of explosives and seismic airgun arrays during oil and gas development, and shipping traffic from commercial vessel activity. Underwater noise pollution can harm cetaceans in three ways: by causing physical injury to the animal, by masking biological important sounds in the environment, and by provoking behavioral changes.

Research Framework:

My research was part of a larger project, which aims to establish a Passive acoustic monitoring (PAM) system to detect cetacean vocalizations within and around Wellfleet Harbor in addition to possible acoustic disturbances from vessel noise. The broader study, part of research conducted by Dr. Laela Sayigh at WHOI, will attempt to determine if the vocalizations recorded can be utilized to predict mass stranding events and aid in the mitigation of such events. For my project, I analyzed recordings from the harbor to determine presence of boat noise and ascertain the potential for masking.

Methods:

I made underwater recordings in Wellfleet Harbor, MA from 22 April, 2014 to 23 July, 2014. I analyzed the files to determine boat noise occurrence and characteristics. I compared these results to those form dolphin vocalizations present in the recordings.

Results:

Overall, boat noise occurred in 32% of all recordings. Boat noise occurrences exhibited a significant trend with deployment period, day/night cycle stage, and tidal cycle stage. For boat noise: mean Center Frequency = 1447 (±141.9) Hz, 5% Frequency = 209 (± 141.9 Hz), 95% Frequency (± 6135.1) Hz, and mean Average Power = 22.8 (±3.3) dB. For dolphin vocalizations: mean Center Frequency was 10195.3 (± 924.6) Hz, mean 5% Frequency was 6591.8 (±1020.6) Hz, mean 95% Frequency was 15234.4 (±852.3) Hz and mean Average Power = 28.2 (±2.7) dB. In addition, I found anecdotal evidence of masking of dolphin vocalizations by boat noise.

Ultimately, I concluded that boat presence occurred frequency in Wellfleet Harbor, MA (~1/3 of the time). Boat noise occurrences followed expected day/night cycle patterns, but not expected tidal cycle patterns. Boat noise characteristics varied with deployment period, day/night cycle, and tidal cycle the observed patterns are unlikely to impact the current WHOI project. Boise noise frequency parameters, however, show some overlap with anecdotal dolphin vocalizations and could present problems for detection. I advised project managers at WHOI to adopt a precautionary approach when taking the next steps in the project, and made the following recommendations:

- Create a boat noise filter: The filters would reduce the influence of noise and allow researchers to detect dolphins among the boat noise.
- Conduct longer-term recordings of boat noise: A yearlong study would provide sufficient time to chronicle the various tidal, seasonal, and biological cycles in the harbor and see if significant patterns emerge.
- Conduct visual surveys of boats: Pairing acoustic data with visual surveys could provide a clearer picture of the situation within Wellfleet Harbor.
- Conduct visual surveys of dolphins: Visual data would help support the acoustic data and could establish linkages between anthropogenic noises and marine mammal behavioral responses.

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Commonly Used Acronyms:

CZMA: Coastal Zone Management Act of 1972

EIS: Environmental Impact Statement

ESA: Endangered Species Act of 1973

MMPA: Marine Mammal Protection Act of 1972

MP: Master's Project

MSE: Mass Stranding Event

NEPA: National Environmental Policy Act of 1970

NMFS: National Marine Fisheries Service

NOAA: National Oceanic and Atmospheric Administration

NRDC: Natural Resources Defense Council

OPS: Optimum Sustainable Population

PAM: Passive Acoustic Monitoring

UNP: Underwater Noise Pollution

WHOI: Woods Hole Oceanographic Institution

1. Overview

For my Master's Project (MP), I analyzed underwater recordings from Wellfleet Harbor, MA, collected during my summer internship at Woods Hole Oceanographic Institution (WHOI) using a Sound Trap and DMON recording devices. The goals of the analysis were to characterize boat noise, discern any relationship between boat noise occurrence/characteristics and tidal and day/night cycles, and determine if boat noise would interfere with WHOI researchers' ability to detect dolphins in the area during the development of a passive acoustic monitoring (PAM) project.

2. Introduction

a. Role of Sound in the Environment

Sound plays an essential role in marine environments. In terrestrial systems, visual cues often dominate life, making light the important factor. However, light waves attenuate quickly in water while sound travels well and can cover extensive distances (Jasny, 2005). Consequently, except for shallow areas where light permeates, such as a coral reef, or in situations where bioluminescence is utilized sound provides a more reliable source of information than light. Marine organisms have developed various uses for sound, such as passively listening for prey, finding or attracting mates, actively hunting prey using echolocation, navigating, and communicating over long distances (National Research Council, 2005).

b. Underwater Noise Pollution

Growing anthropogenic noise levels in the oceans threaten marine animals' ability to utilize these essential sound signals. In some regions, man-made noise levels have increased nearly 10 dB re: 1 $\mu Pa^2/Hz$ from 10-80Hz and 5-6 dB re: 1 $\mu Pa^2/Hz$ for frequencies >100Hz over the last half-century (McDonald et al., 2008). Anthropogenic activities can generate noises as loud as 299 dB (peak, assumed re: 1μPA SPL), levels reached during ship shock trials (10,000 lb. TNT) (Jasny et al., 2005). Since the decibel measuring system is logarithmic, a change of 10 decibels indicates the higher decibel sound actually generates 10 times more sound energy than the lower decibel sound. Consequently, sounds measuring 100 dB (assumed re: 1μPA SPL) are 10,000 times more intense than those at 60 dB (assumed re: 1μPA SPL) (Oceana Airgun Testing) (Huelsenbeck and Wood, 2013). With these large scale changes in noise level come potentially large-scale impacts on marine species that could affect economically important species, ecologically important species, and charismatic megafauna. Importantly, impacts of underwater noise pollution (UNP) could vary with a number of factors, such as climate change exacerbating UNP, introducing a degree of uncertainty (Brewer and Keith, 2009).

c. Sources of Underwater Noise Pollution

Sources of UNP include a number of different human activities. Firstly, military sonar for detecting enemy vessels emits sounds at different frequencies, with volumes around 235 dB (effective, assumed re: 1μPA SPL) (Jasny et al., 2005). The military employs sonar to detect enemy vessels, particularly submarines, as part of their national defense plan and training. Sonar works by creating waves sound, usually referred to as "pings," which hit the hulls of vessels, creating an echo detectable by hydrophones (Jasny et al., 2005). Different types of sonar produce different frequencies of sound, intended to detect various vessels at different ranges. The two main types of sonar include Low Frequency Active (LFA): long-rang surveillance sonar, and Anti-Submarine Warfare (ASW): shorter-range sonar (Hildebrand, 2009).

The use of explosives and seismic airgun arrays during oil and gas development exploration creates noise at various frequencies and can reach 235-259 dB (effective peak, assumed re: 1μPA SPL) (Jasny et al., 2005). When exploring for offshore oil deposits, ships tow arrays of airguns, which release pressurized air that creates a sound wave. When the sound wave encounters the seabed some energy is absorbed, however, some also bounces back to the surface carrying information about seabed formation and potential oil deposits. These airguns usually fire every 10 seconds, 24 hours a day, for periods lasting days or more (Huesenbeck and Wood, 2013).

Shipping traffic ranges from 160 to 192 dB re: 1 μPa @1m, depending on the size of the ship (Hildebrand, 2009). Similarly, fishing vessels and other small to mid-sized boats also produce noise, such as a sound generated by fishing trawlers. The main sources of noise from ships and boats are cavitation associated with propeller rotation, onboard machinery, and the engine. In particular, cavitation is the leading contributor from shipping to underwater noise pollution (Hildebrand, 2009). Cavitation occurs when the moving propeller blades create rapid changes in pressure, which promotes bubble formation. These bubbles implode and create a shockwave. Shipping and boat noise contribute the most to global underwater noise, due to the ubiquitous nature and sheer volume of shipping traffic (Hildebrand, 2009).

d. Impacts of Underwater Noise Pollution

Underwater noise pollution can harm cetaceans in three ways: by causing physical injury to the animal, by masking biological important sounds in the environment, and by provoking behavioral changes (Jasny, 2005). Examples of physical impacts include brain hemorrhaging, hearing loss, and stress that can impact the immune system and reproductive health of animals (Jasny, 2005). Physical impacts also include Temporary Threshold Shifts (TTS), i.e. auditory fatigue or temporary hearing loss, and Permanent Threshold Shifts (PTS), i.e. permanent hearing loss (National Research Council, 2005). For example, in 2005, Fernandez et al. released the findings from their investigation of the recent stranding of 14 beaked whales in the Canary Islands. These strandings began 4 hours after mid-frequency sonar exercises commenced nearby. The scientists found the evidence of brain hemorrhage and decompression sickness, or nitrogen supersaturation, in the blood. The scientists postulated that the decompression sickness could have resulted from either abnormal diving behavior or the sonar lowering the threshold for formation of nitrogen gas bubble nulcei in the animals' tissue. The whales would have ascended too quickly for safety, causing gas nuclei to expand resulting in nitrogen supersaturation. Research has also linked shipping noise to the production of stress hormones (glococorticoids) in North Atlantic right whales (*Eubalaena glacialis)* (Rolland et al., 2012). Chronic exposure to these hormones suppresses the immune system, growth, and reproduction and high levels of stress hormones can predict a high chance of individual mortality.

Underwater noise pollution can also mask biologically important sounds. Masking occurs when the perception of one sound is affected by the presence of another. In an environment with increased nose, animals risk missing essential signals among the cacophony of man-mad noise, resulting in potential harm to animals as they struggle to locate food when passively listening (Jasny, 2005). Increased sound pollution inhibits cetaceans' ability to hear signals from conspecifics as well, which carry important information relevant to their social structure, such as location of mates. For example, killer whales living in highly social family groups, which have developed their own regional "dialects," characterized by specialized calls (Deecke et al., 2000). Studies have found that in areas with increased UNP, these orcas have trouble hearing one another and will begin making longer calls in an attempt to reach pod-mates over the noise (Foote et al., 2004). Models of UNP's potential impacts on orca auditory systems have even revealed that UNP could result in hearing-loss in orcas, which would greatly impact their ability to survive and thrive (Ebre, 2002). Also, humpback whales have exhibited vocalization changes in response to low frequency sonar, increasing the length of their mating songs by 29%, possible to "compensate for acoustic interference" (Miller et al., 2000).

Underwater Noise Pollution has already resulted in documented behavioral changes. In response to both simulated and actual navy sonar, Blainville's beaked whales exhibited avoidance behavior and stopped echolocating for prey (Tyack et al., 2011). The animals abandoned their deep-dive foraging efforts and moved away from the source of the sonar, remaining at the edge of the area until the completion of the sonar activities, at which point they returned to their foraging grounds over the course of 2-3 days. Anecdotal evidence suggests that shipping noise might disrupt foraging behaviors of Cuvier's beaked whales (*Ziphius cavirostris*), an odontocete (Soto et al., 2006). Bryant et al. (1985) suggested that commercial shipping noise prompted California gray whales to temporarily abandon Laguana Geurrero Negro, a lagoon in Baja California, Mexico. In addition, Bejder et al. (2006) found that relative abundance of bottlenose dolphins (*Tursiops sp.*) declined in Shark Bay, Australia after years of exposure to increasing levels of shipping traffic, suggesting some animals have abandoned the harbor in order to avoid exposure to the increasing noise levels.

e. Domestic Legal Background

The Marine Mammal Protection Act (MMPA), established in 1972 and amended in 1994, protects marine mammals within the United States jurisdiction from human activities (MMPA, 16U.S.C. § e seq., 1973). This law mandates that these species must not fall below an Optimum Sustainable Population (OSP), which is determined based on best available scientific information of species population structure and calculations of expected population growth and carrying capacity. The act classifies species with populations below the OPS as "depleted," at which point certain protections kick in to reduce the "incidental take" to a level approaching a rate of 0 mortalities and injuries per year. "Take" is defined as to "harass, hunt capture, ill or collect, or attempt to harass, hunt, capture, kill or collect" a member of a protected species. "Incidental take" refers to any accidental taking of small numbers of marine mammals (MMPA, 16U.S.C. § e seq., 1973). The MMPA also specifies two levels of "harassment", with level A referring to act that have the potential to injure or kill marine mammals and level B to any actions that might "disturb a marine mammal" or population of animals through" meaningful disruption of biologically significant activity" (MMPA, 16U.S.C. § e seq., 1973). The National Research Council has clarified "Biologically significant" as meaning an action that "affects the ability of animal to grow, survive, and reproduce" (National Research Council, 2005). The National Marine Fisheries Service (NMFS) must review activities that could potentially result in an accidental take and determine the activities will have "negligible impact" before issuing a permit (National Research Council, 2005).

The Endangered Species Act (ESA), established in 1973, protects threatened and endangered species and the ecosystems on which they depend (Endangered Species Act, 16

U.S.C.A. § e seq., 1973). Decisions to place species on either list rely solely on the Best Science Available (BSA); once on the list, again, certain protections apply in addition to mandates to rebuild the species' populations. Section 9, or the 'Prohibited Acts' section, of the ESA makes the unauthorized "taking" of listed species illegal (Endangered Species Act, 16 U.S.C.A. § e seq., 1973). Under the ESA, "take" is defined as "to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or attempt to engage in any such conduct" and threatened or endangered species (Endangered Species Act, 16 U.S.C.A. § e seq., 1973). The Act defines an "Endangered" species as any species "in danger of extinction throughout all or a significant portion of its range", while "threatened" species include those "likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range" (§ 1532). These provisions make this act somewhat stronger than the MMPA (Reiser et al., 2013).

The National Environmental Policy Act (NEPA) of 1970 ensures the Federal government takes into account environmental concerns during decision-making by mandating that the NMFS review any marine mammal 'takes' before granting a take permit to a Federal agency (National Environmental Policy Act of 1969, 42 U.S.C.A. § et seq., 1970). Consequently, a Federal agency must issue an Environmental Impact Statement (EIS) estimating the potential harm to the species resulting form that activity. The EIS must address the two types of harassment in the estimations, Level A and Level B. Level A harassment is defined in this act as any "act that injures or has potential to injure", while Level B harassment includes any activity that disturbs or likely to disturb by causing change in natural behavior patterns" National Environmental Policy Act of 1969, 42 U.S.C.A. § et seq., 1970. NMFS must then determine that the EIS sufficiently addresses the possible impacts on marine mammals and the resulting takes would again have a "negligible impact" on the species before allowing the issuance of a take permit. While the MMPA, ESA, and NEPA play the key roles in permitting takes of marine mammals, Federal agencies must also consider another regulation before carrying out any potentially harmful activity.

The Coastal Zone Management Act (CZMA) of 1972 partners the federal and state levels of government in preserving coastal waters by providing federal funding to states in order to encourage them to develop coastal programs (Coastal Zone Management Act of 1972, 16 U.S.C.A. § et seq., 1972). The law intends "to preserve, protect, develop, and where possible, to restore" coastal zone areas and their resources, "giving full consideration ecological" values (Coastal Zone Management Act of 1972, 16 U.S.C.A. § et seq., 1972). The National Oceanic and Atmospheric Administration (NOAA) administers the CZMA and helps to ensure that "Each Federal agency activity within or outside the coastal zone that affects any land or water use or natural resources of the coastal zone shall be carried out in a manner which is consistent to the maximum extent practicable"(Coastal Zone Management Act of 1972, 16 U.S.C.A. § et seq., 1972). However, the act does allow the President to "upon written request from the Secretary, exempt from compliance those elements of the Federal agency activity that are found … to be inconsistent with an approved State program" (Coastal Zone Management Act of 1972, 16 U.S.C.A. § et seq., 1972). Thus, the law encourages and allows states to develop their own programs to conserve and protect species such as cetaceans at-risk from UNP and requires the Federal government to comply with these state regulations.

Litigation surrounding underwater noise issues has resulted in a hodge-podge of outcomes, with different agencies held to different standards. The Supreme Court Case

Winter v. the Natural Resources Defense Council (NRDC) set the main precedent regarding military exceptions from cetacean take requirements. The NRDC sought an injunction against mid-frequency sonar use by the Navy off the coast of California. Initially, the District Court of California granted a preliminary injunction, on the basis that Naval sonar activity in that area violated NEPA, the ESA, and the CZMA due to inconsistencies with California's Coastal Zone Management Plan. Despite an appeal, the Court of Appeals agreed with the District Court's issuance of a preliminary injunction, though they decided a broad ban overly restricted the Navy and adjusted the injunction to allow for Navy sonar activities which compliance with certain mitigation measures. At this point, President Bush granted an exemption to the CZMA. After subsequent back and forth between courts, the case came before the US Supreme Court, who reversed the injunction on the grounds that "forcing the Navy to deploy an inadequately trained antisubmarine force jeopardizes the safety of the fleet " (Winter v NRDC, 555 U.S. 7, 2008). The case exempted Navy sonar activities from the ESA, MMPA, and CZMA restrictions on takes, but required the Navy submit an EIS as directed under NEPA. However, a recent case in Hawaii could result in more restrictions concerning Navy sonar. The NRDC and Conservation Council for Hawaii filed a complaint against NMFS, claiming the agency did not establish "negligible impact" of Navy sonar activities in the waters surrounding Hawaii. The Federal judge determined that NMFS had approved the Navy EIS, which included thousands of Level A takes of marine mammals, without proper support for its decision (McAvoy, 2015).

The 2013 court case Jewell v NRDC set the precedent for protections from noise resulting from oil and gas exploration, including seismic airgun activity. The NRDC and several other conservation groups filed a complaint claiming the Department of the

Interior, headed by Ms. Jewell, had violated the MMPA and ESA when it failed to submit an EIS for marine mammal takes resulting from seismic activities in the Gulf of Mexico. A district court in Louisiana ruled in favor of the NRDC and expanded protections for cetaceans (NRDC, 2013). Examples of new protections include prohibiting seismic airgun testing in biologically sensitive areas in addition to temporal restrictions during important times, such as bottlenose calving season (NRDC, 2013).

3. Research Framework

My research was part of a larger project, which aims to establish a passive acoustic monitoring (PAM) system to detect cetacean vocalizations within and around Wellfleet Harbor in addition to possible acoustic disturbances from vessel noise, which might contribute to the stranding events. The broader study, part of research conducted by Dr. Laela Sayigh at WHOI, will attempt to determine if the vocalizations recorded can be utilized to predict mass stranding events and aid in the mitigation of such events. For my project, I analyzed recordings to determine presence of boat noise and ascertain the potential for masking.

a. Mass Stranding Events

Mass stranding events (MSEs), instances when large numbers of cetaceans strand together, are not fully understood. A recent study examining stranding in Cape Cod have found that while disease was the leading cause of death (37%) a large portion of the cases were classified as "Mass stranding with no significant findings" (31% of cases) (Bogomolni et al., 2010). For that 31%, the researchers did not detect any health issues with the animals unrelated to what the animals incurred upon stranding. These findings suggest that a large number of animals involved in mass stranding are healthy individuals.

One possible cause of mass standings is disturbance from anthropogenic sound pollutions sources, such as shipping noise or sonar. Owing to the prevalence of ships in the world's oceans, shipping noise generated by ship propulsion systems presents a rather large problem (Hildebrand, 2009). In fact, in certain regions shipping noise is nearly solely responsible for increases in noise level (McDonald et al., 2008).

b. What is Passive Acoustic Monitoring?

Observing marine mammals can be challenging as not only do these animals spend very little time at the surface where human-made observations are possible, but also the marine environment itself presents problems concerning equipment longevity and other experimental logistics (Marques et al., 2009; Sousa-Lima et al., 2013). Several methods exist for remotely tracking organisms, utilizing either active or passive techniques (Bradford et al., 2011). Active systems transmit some sort of signal, which 'echos' or reflects off targets and then return to the receiver or systems (Heupel et al., 2005). Examples include LIDAR, radar, and sonar. With passive techniques, conversely, equipment does not emit signals and instead records signals emitted or reflected 'naturally' (Sousa-Lima et al., 2013). Examples include the radiometer and spectrometer. An emerging form of passive remote sensing is Passive Acoustic Monitoring (PAM). Currently, both passive and active acoustic monitoring systems are available. Recently, however, researchers have been relying more and more on passive systems, both due to reduced costs and greater automation (Sousa-Lima et al., 2013).

Passive acoustic monitoring relies on underwater hydrophones placed strategically to record animal vocalizations, which can be used to determine behavior and localize the organisms (Sousa-Lima et al., 2013). They are considered 'passive' systems since they do not emit any signals, but simply record sounds present in the surrounding environment. There are several types of PAM systems; however, these can be categorized broadly as either mobile or stationary. Mobile arrays are often towed by ships and can accompany visual transect line surveys (Dudzinski et al., 2010). These devices can be utilized over a greater spatial scale than stationary systems, but have trade-offs associated with human effort and cost (Dudzinski et al., 2010). Mobile arrays typically require more human labor and thus more cost. Stationary arrays, on the other hand, generally cover more restricted areas, as the spatial scale of arrays is constricted by financial and equipment limitations (Dudzinski et al., 2010). However, these systems can be left alone in remote areas and require only occasional human labor inputs after the initial deployment phase. The more autonomous nature of the stationary recorders provides advantages to studies with extended temporal-scales. In addition, these systems are often cheaper to utilize due to the decreased human effort (Dudzinski et al., 2010).

Different species vocalize at distinct frequencies, and so specialized PAM systems and calibrations can be utilized depending on the target species. Baleen whales emit low-frequency vocalizations that can propagate farther distances (Sousa-Lima et al., 2013). Consequently, arrays require fewer hydrophones to sufficiently cover a study area (Sousa-Lima et al., 2013). Odontocetes, on the other hand, produce higher frequency vocalizations that do not propagate as far, and so arrays targeting this species would need to include a greater number of hydrophones or cover a smaller spatial region (Sousa-Lima et al., 2013). Certain systems have been developed to detect species-specific calls using programmable algorithms (Sousa-Lima et al., 2013). Examples include the PAL system, EAR system, and DMON system. Odontocete calls also require “high-speed digitization”(faster generation of discrete data samples), which results in greater power and storage needs (Sousa-Lima et al., 2013). Deployment depths might also vary for different species, which would further impact the array configurations.

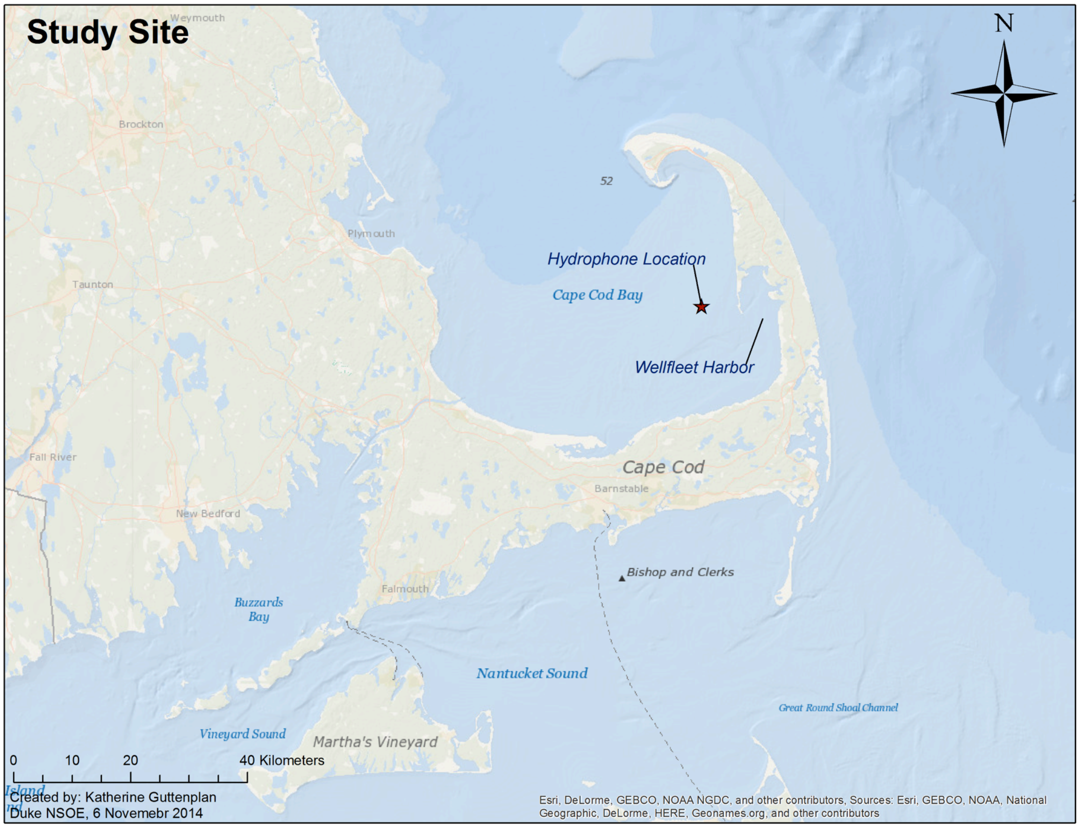
The chosen duty-schedule of an experiment will have important ramifications for data-storage necessities and capabilities, range of sounds capable of being recorded, and cost. PAM systems can record data using either a continuous or intermittent duty-cycle (Sousa-Lima et al., 2013). Continuous recording not only captures all animal vocalizations, but also the background environmental noises. Consequently, this data can provide insight into behavior and position in addition to potential interactions with the environment, including anthropogenic noise. However, continuous recording requires adequate storage for all the resulting data points, which can be extremely costly due to the price of high-capacity storage (Sousa-Lima et al., 2013). Also, these systems will often need to be larger (Sousa-Lima et al., 2013). If storage is a limiting factor, then the instruments will have to be deployed over a shorter time-period. If the goal is a season or yearlong study, this time constraint could be a problem. Systems with intermittent recording will require less storage capacity, and thus can be deployed longer. However, recording intermittently risks missing infrequent vocalizations (Sousa-Lima et al., 2013). The resulting data might also omit important background sounds. One potential solution is utilizing the species-target algorithms described above. The PAM systems will identify when target-species vocalizations are occurring and only retain these data points, cutting down on necessary storage and enabling longer deployments (Sousa-Lima et al., 2013). Again, though, data might not include important background sounds. Experimental setups must therefore carefully weigh these trade-offs in the context of study goals.

4. Methods

Study Questions: during what percentage of time does boat noise occur in Wellfleet Harbor; is that e related to patterns of tidal, day/night, and monthly cycles; does boat noise frequency and other characteristics follow tidal, day/night, or monthly cycles; and does boat noise have the potential to mask dolphin vocalizations and affect the ability of Dr. Laela Sayigh's research project to detect dolphins in the harbor.

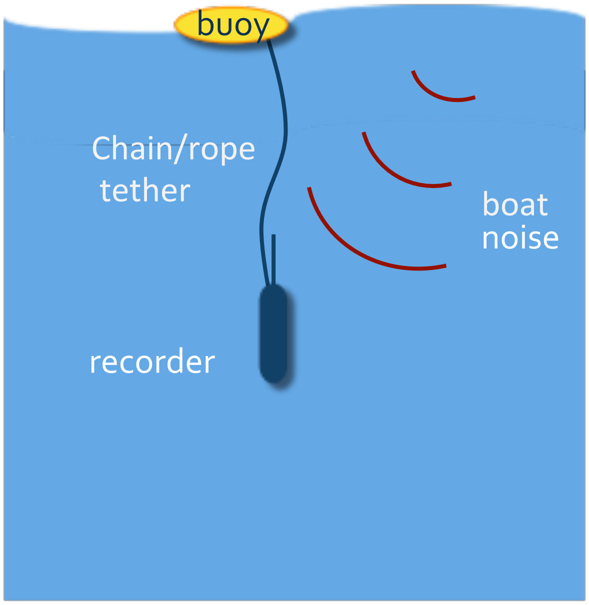
a. Study Area:

I made underwater recordings in Wellfleet Harbor, MA. The harbor is a protected region within Cape Cod Bay. This area experiences relatively large numbers of mass stranding events, making the site a suitable area for research (Sayigh et al., 2013). The exact recorder location, N41° 53.006 and W070° 07.747, lies at the mouth of the harbor near Jeremy Point and Billingsgate Island. Transportation within the harbor was graciously provided by the Wellfleet Harbormasters.



b. Deployment and Retrieval Schedule:

I spent two months at Woods Hole Oceanographic Institution assisting Dr. Sayigh with the implementation of the planned project during June and July. Dr. Sayigh and Alessandro Bocconcelli had already deployed two passive acoustic monitoring (PAM) devices, a Soundtrap and a DMON, on 22 April 2014 to record cetacean vocalizations and shipping traffic noise in the area (data collect during this first deployment herby referred to as deployment Period 1). Once I arrived at WHOI in June, I assisted Bocconcelli when these devices were retrieved on 20 May 2014 and one device, a DMON, was device deployed (data collect during this second deployment herby referred to as deployment Period 2). I again assisted Bocconcelli and Tammy L. Silva when this device was retrieved on 10 June 2014 and two devices, Soundtrap and a DMON deployed (data collect during this third deployment herby referred to as deployment Period 3). These devices were retrieved on 23 July 2014. Dr. Sayigh unpacked the audio files from all devices. Deployment setup is pictured below.



c. Recorder Set Up:

The Sound Trap recorded on a duty cycle of 5 minutes every hour with a gain of 1 dB, digital resolution of 16 bits, and sample rate of 288 kHz. The DMONs recorded on a duty cycle of 5 minutes every half hour, a gain of 13.3 dB, digital resolution of 16 bits, and sample rate of 240 kHz; however, I only utilized data collected every hour for the analysis. According to the Nyquist Theorem, sampling rate should be more than twice the highest target frequency. Consequently, samplings rates were high order to capture high-frequency odontocete vocalizations.

d. Data Preparation:

I examined all audio files using Adobe Audition 3.0 software © 2015 Adobe Systems Incorporated to determine presence (occurrence) or absence of boat noise. I also noted any dolphin vocalizations present in the recordings. I utilized a series of python scripts, with assistance from John Fay, to extract date and time data from xml files associated with the audio wav files. For Period 1, I utilized data collected by the Soundtrap while for Periods 2 and 3 I utilized data collected by the DMONs. Originally, I planned to use data from DMONS alone to achieve a more uniform data collection method; however, the data downloading process from the DMON deployed during Period 1 experienced a technical problem and thus the data was not available for any analyses.

I obtained tidal prediction and day night cycle data from NOAA in order to compare tidal cycles and day night cycles to boat noise occurrence. For each recording, I assigned a tidal stage and a day/night cycle stage. I first assigned high or low tidal stage to the hour closest to which the high or low tide occurred and then an hour on either side such that high or low tidal stage occurred in three-hour segments. I assigned recordings outside of the high or low tidal blocks either an ebb or flood designation. The tides in Wellfleet Harbor follow a semidiurnal pattern. Consequently, for any 24-hour period, I grouped recordings into two sets of generally three-hour segments: high, low, ebb, and flood. For the day/night cycle stage, I first calculated the average sunrise time of 5:31 AM and average sunset time of 7:54 PM. I assigned the hours of 5-7 AM as 'sunrise' and 7-9 PM as 'sunset' in addition to the hours of 11 AM-1 PM as noon and 11 PM- 1 AM as 'midnight'. All other recordings were assigned a value of 'other'. I randomly selected 5 files from each month for each category: high, low, ebb, flood, sunrise, noon, sunset, and midnight for analysis.

Finally, I used a high-pass order ten filter of 100Hz to filter out self-noise I detected in the files selected for analysis. The 100 Hz filter adequately reduced the influence of boat noise on the analysis while allowing for sufficient lower frequency sounds to provide a complete picture of boat noise and its potential to mask dolphin vocalizations. I used this filter on all data from all deployment periods as it seemed to adequately filter noise on all files and resulted in a more uniform treatment of data.

e. Data Analysis:

I analyzed the recordings using Raven 1.4 Pro software © 2015 Cornell University to determine the characteristics of the boat noise. If boat noise fell in the middle of the recording, I selected the ten-section section from 2:25-2:35min. If boat noise did not fall in the middle of the recording, I instead selected a 10 second section from the middle of the boat noise. I focused on the measurements of center frequency, 5% frequency, 95% frequency, and average power. Raven considers the first three measurements robust as they do not vary based on the bounds of the selection box, but instead account for the energy in the selection (Charif et al., 2010). Center frequency determines the frequency that divides the energy in a selected sound into two equal parts, such that half the energy will be below the frequency and half above it (Charif et al., 2010). It serves as a median value, rather than an average, for the selected sound. The 5% frequency measurement calculates the frequency that divides the energy of the selected sound into two parts, with 5% of the energy contained below the frequency and 95% of the energy above (Charif et al., 2010). This values essentially serves as a minimum frequency value that excludes extreme anomalies. Likewise, the 95% frequency measurement calculates the frequency that divides the energy of the selected sound into two parts, with 95% of the energy contained below the frequency and 5% of the energy above (Charif et al., 2010). This value essentially serves as a maximum frequency value that excludes extreme anomalies. Finally, the Average Power measurement averages the power, or total energy, over the frequency extent (Charif et al., 2010). Raven determines Average Power by first summing the values of the power spectrum in the selection and then dividing by the number of time-frequency bins in the selection. This is the only measurement utilized that could vary with the selection box.

I performed Poisson GLM analyses using SPSS Statistics for Mac, Version 22.0 © IBM Corp. for the following tests: Boat Noise Occurrences over Time, Boat Noise Occurrences by Day/Night Cycle, Boat Noise Occurrences by Tidal Cycle, Boat Noise Occurrences and Tidal Cycles for each time period, and Boat noise and Tidal Cycles for each time period. Finally, to extract potential overlap between data points with both a tidal stage and day/night cycle stage designation, I ran a Multivariate ANOVA investigating the influence of the independent variables Tidal Cycle Stage, Day/Night Cycle Stage, and Time Period, on the dependent variables Center Frequency, 5% Frequency, 95% Frequency, and Average Power. I performed Post Hoc multiple comparisons using Least Significant Difference (LSD).

Lastly, I used Raven software to analyze any dolphin vocalizations I found in the recordings. I determined mean Center Frequency, 5% Frequency, 95% Frequency, and Average Power for the vocalizations and compared these values to those of the boat noise.

5. Results

Occurrence Data

Overall, boat noise occurred in 32% of all recordings (see Table 1 for details; Figure 1). Occurrences of boat noise increased over time (Poisson GLM, omnibus test p-value<0.001) with each sequential time period experiencing a greater number of boat noise occurrences (parameter estimates period 1 p-value<0.001, period 2<0.001, period 3<0.001; Figure 2).

Boat noise occurrences also exhibited a significant trend over the day/night cycle (Poisson GLM, omnibus test p-value<0.001, Figure 3A), with occurrences increasing throughout the day and then decreasing during the night stages (parameter estimates for sunrise, sunset, midnight p-value<0.001 and noon p-value= 0.067). I found the same significant trend for over the day/night cycle for the first time period (Poisson GLM, omnibus test p-value<0.001), second time period (Poisson GLM, omnibus test p-value<0.001), and third time period (Poisson GLM, omnibus test p-value<0.001; Figure 4A-C).

Boat noise occurrences also exhibited a significant trend over the tidal cycle (Poisson GLM, omnibus test p-value=0.15), however only the 'ebb' category had a significant increase compared to the other tidal stages (parameter estimate for ebb p-value= 0.003; Figure 3B). I did not find a significant trend of boat noise occurrences for tidal cycle for the first time period (Poisson GLM, omnibus test p-value=2.45) or second time period (Poisson GLM, omnibus test p-value=331), but was present in the third time period (Poisson GLM, omnibus test p-value=002) with the 'ebb' stage experiencing a significant increase (parameter estimates p-value<0.001; Figure5.).

Boat Noise Characteristic Data:

Overall means for Center Frequency, 5% Frequency, and 95% Frequency were as expected, with 5% Frequency comprising the lowest frequency value, 95% frequency the highest, and Central Frequency a median value (Figure 6).

The multivariate ANOVA revealed that the effect of Period was significant (Pillai's Trace p-value=0.003), Day/Night Cycle exhibited a trend (Pillai's Trace p-value=0.092), and Tidal Cycle had no effect (Pillai's Trace p-value=0.269) (See Figures 7-10 for graphs of noise characteristics with day/night and tidal cycles). Period had a significant effect on

Average Power (p-value=0.001), but no effect on Center Frequency, 5% Frequency, or 95% Frequency (p-values>0.10). Tidal Stage had an effect on 95% Frequency (p-value=0.014), and did not significantly influence Center Frequency, 5% Frequency, or Average Power (p-value>0.10). Day/night had an effect on 95% Frequency (p-value= 0.037) and Average Power (p-value= 0.029) and no effect on either Center Frequency or 5% Frequency (p-values>0.10).

Post Hoc multiple comparisons using Least Significant Difference (LSD) revealed that Average Power was significantly lower in the first period than second or third periods (p-values<0.001). 95% Frequency was also significantly lower in the first period than the second (p-value=0.043) and the third month (p-value=0.002). Center Frequency was greater for ebb than rising tide (p-value= 0.055) and greater for high than rising tide (p-value=0.021), and there was a trend showing that values for rising were greater than for low tide (p-value=0.069). 95% Frequency was significantly higher for low than ebb tide (p-value=0.024) and rising tide (p-value=0.002). 95% Frequency was significantly higher for midnight than sunrise (p-value=0.008) and noon than sunrise (p-value= 0.005), and nearly significantly higher for sunset than sunrise (p-value=0.054). Average Power was significantly greater for midnight than sunrise (p-value=0.027), sunset than midnight (p-value=0.025), noon than sunrise (p-value=007), sunset than noon (p-value=0.006), and sunset than sunrise (p-value<0.001).

Dolphin Vocalization Data:

I found dolphin vocalizations on 10 recordings, all during the third deployment period, and was able to determine characteristics for eight (Table 2). The remaining two overlapped with boat noise, making it difficult to separate and analyze characteristics for just the vocalizations, effectively masking the vocalizations from detection. For the detections analyzed, mean Center Frequency was 10195.3 (± 924.6) Hz, mean 5% Frequency was 6591.8 (±1020.6) Hz, mean 95% Frequency was 15234.4 (±852.3) Hz, and mean Average Power was 28.2 (±2.7) dB. I compared the frequency characteristics of the boat noise and dolphin vocalizations (Figure 11) in addition to the Average Power (Figure 12). Overlap was present for the 95% Frequencies and values for Average Power were similar.

Figures:

Dataset	sunrise	noon	sunset	midnight	low	rising	ebb	high	total boat noise occurrence	total records for period
Period 1	16	47	4	0	26	42	38	37	**143**	703
Period 2	0	50	57	11	56	43	56	43	**198**	511
Period 3	0	52	58	20	70	50	95	64	**279**	696
Totals	16	149	119	31	152	135	189	144	**620**	1910

Table 1: Summary of Boat Occurrence Results. Occurrences are given for Tidal Stage and Day Night Cycle for each time period. Total boat records for each period indicates the total number of recordings for that time period, including those without an occurrence of boat noise.

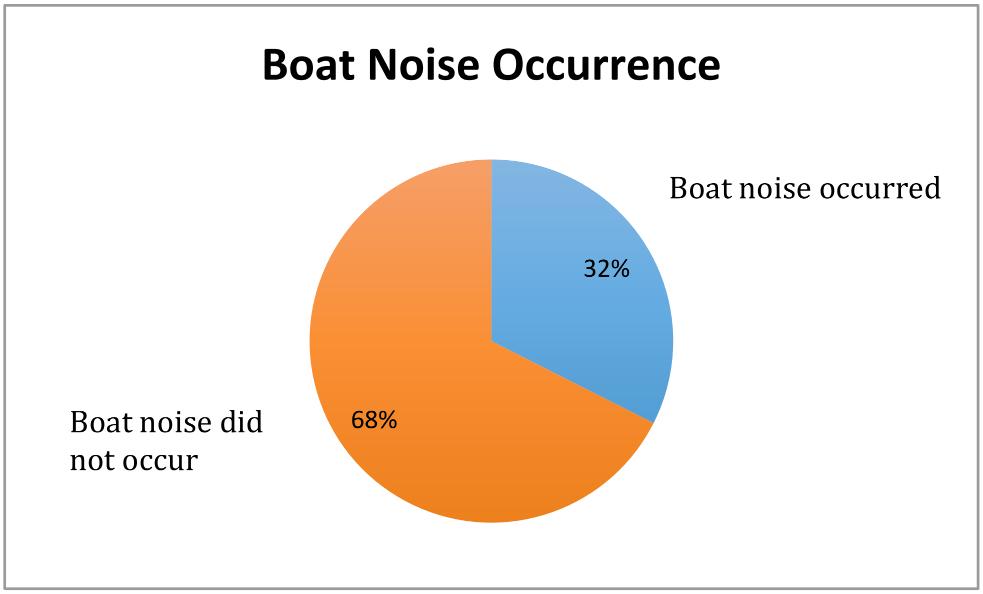


Figure 1: Boat noise occurrence. Boat noise presence or absence was noted for each recording. When a boat was detected, the recording was assigned a binary value of 1. Recordings in which no boats were detected received a binary value of 0. Boat noise occurred at least once in 32% of recordings.

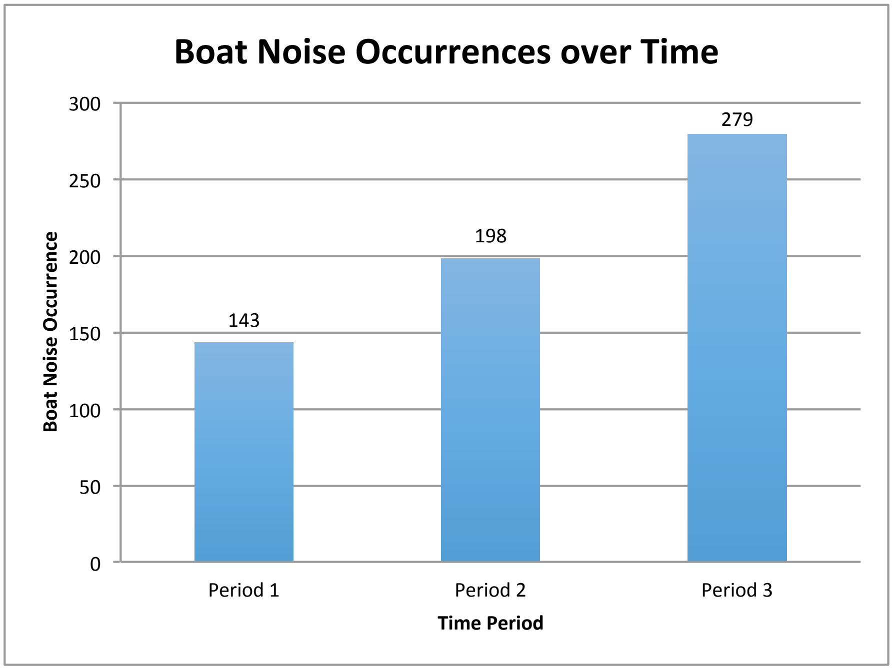


Figure 2: Boat noise occurrence during each deployment period. Occurrences of boat noise increased over time (Poisson GLM, omnibus test p-value<0.001) with each sequential time period experiences a greater number of boat noise occurrences (parameter estimates period 1(deployed 22 April, 2014) p-value<0.001, period 2 (deployed 20 May, 2014) p-value <0.001, period 3 (deployed 10 June, 2014) p-value<0.001).

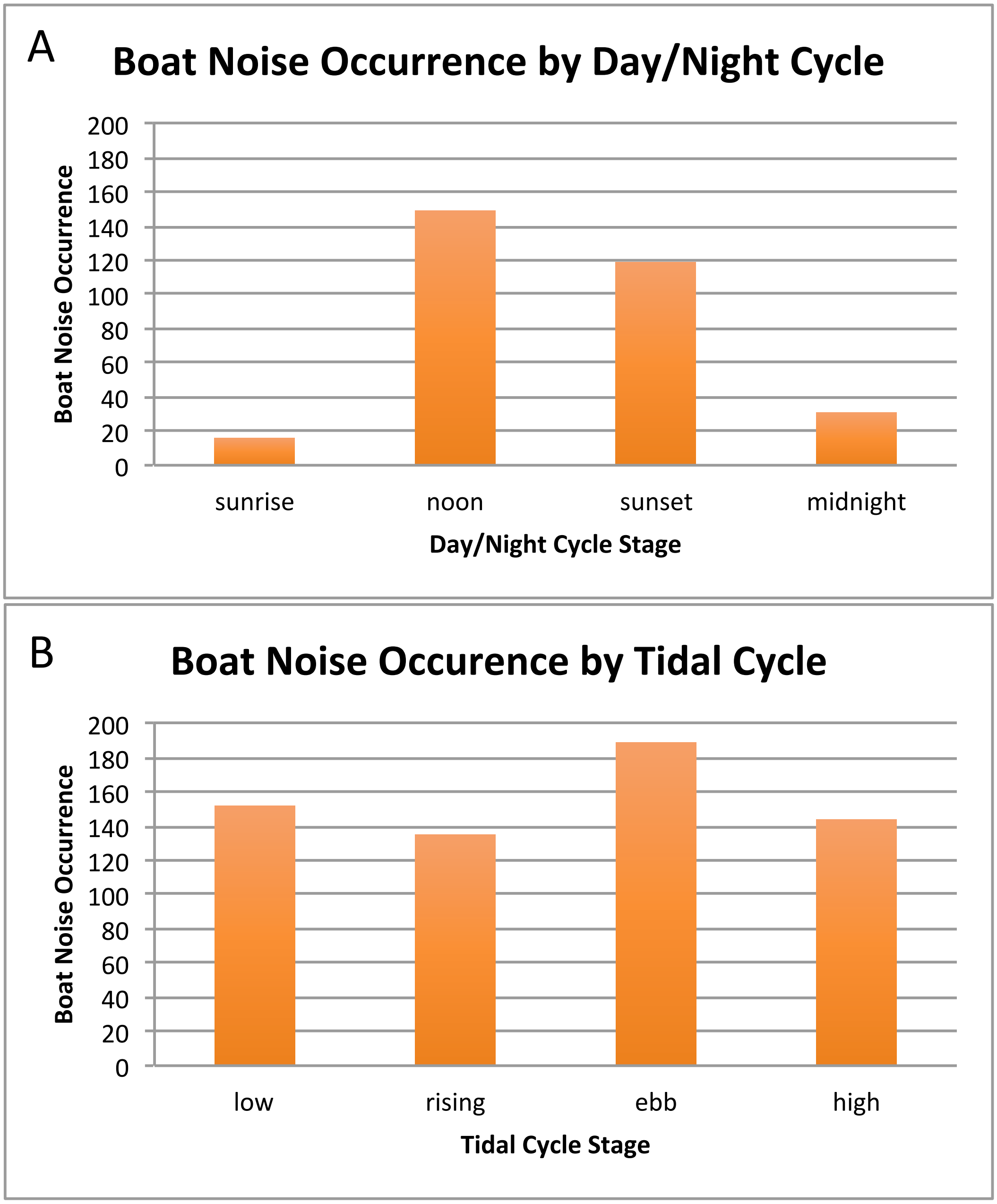


Figure 3: Boat Noise Occurrence compared to Day/Night Cycle Stage (A) and Tidal Stage (B). Boat noise occurrences exhibited a significant trend over the day/night cycle (Poisson GLM, omnibus test p-value<0.001), with occurrences increasing throughout the day and then decreasing during the night stages (parameter estimates for sunrise, sunset, midnight p-value<0.001 and noon p-value= 0.067). Boat noise occurrences also exhibited a significant trend over the tidal cycle (Poisson GLM, omnibus test p-value=0.15), however only the 'ebb' category had a significant increase compared to the other tidal stages (parameter estimate for ebb p-value= 0.003).

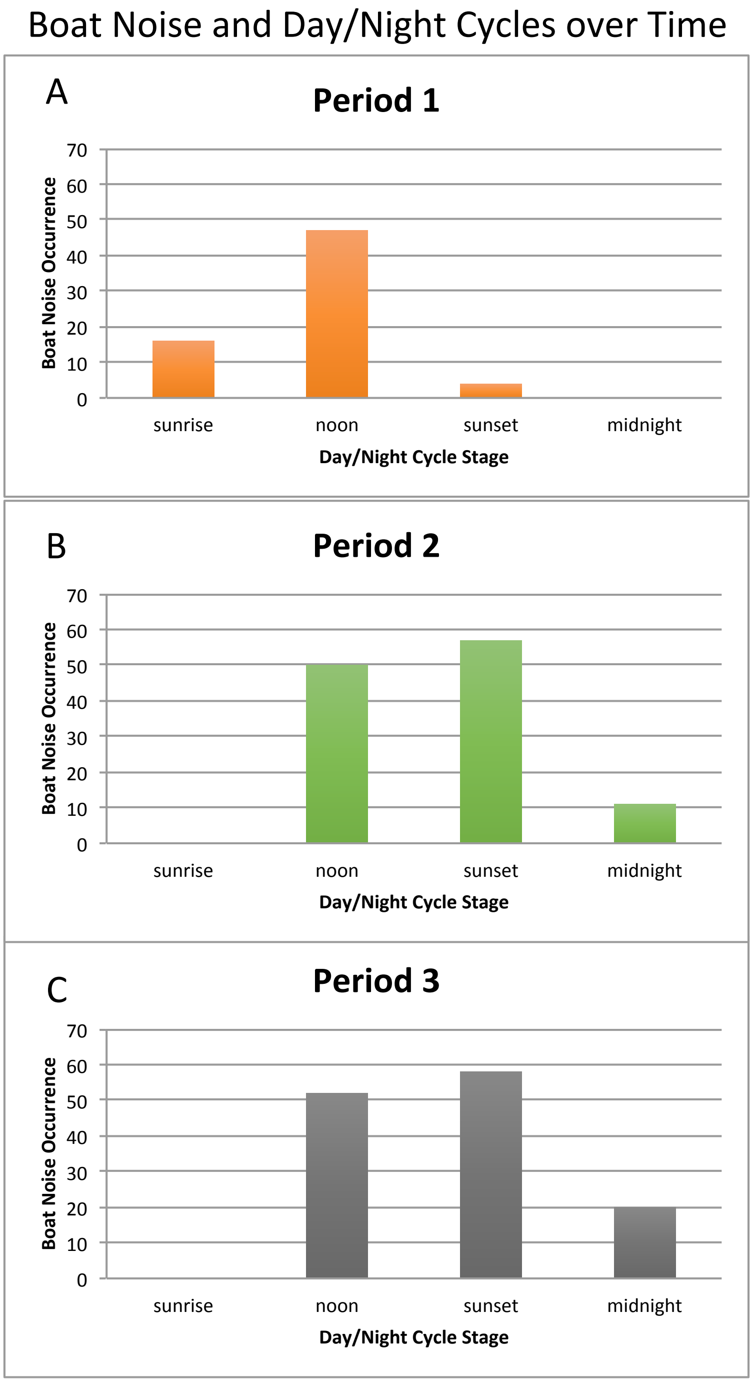


Figure 4: Boat noise occurrence compared to day/night cycle stage for each deployment period. Boat noise occurrences also exhibited a significant trend for over the day/night cycle for the first time period (Poisson GLM, omnibus test p-value<0.001), second time period (Poisson GLM, omnibus test p-value<0.001), and third time period (Poisson GLM, omnibus test p-value<0.001)

Boat Noise and Tidal Cycles Over Time

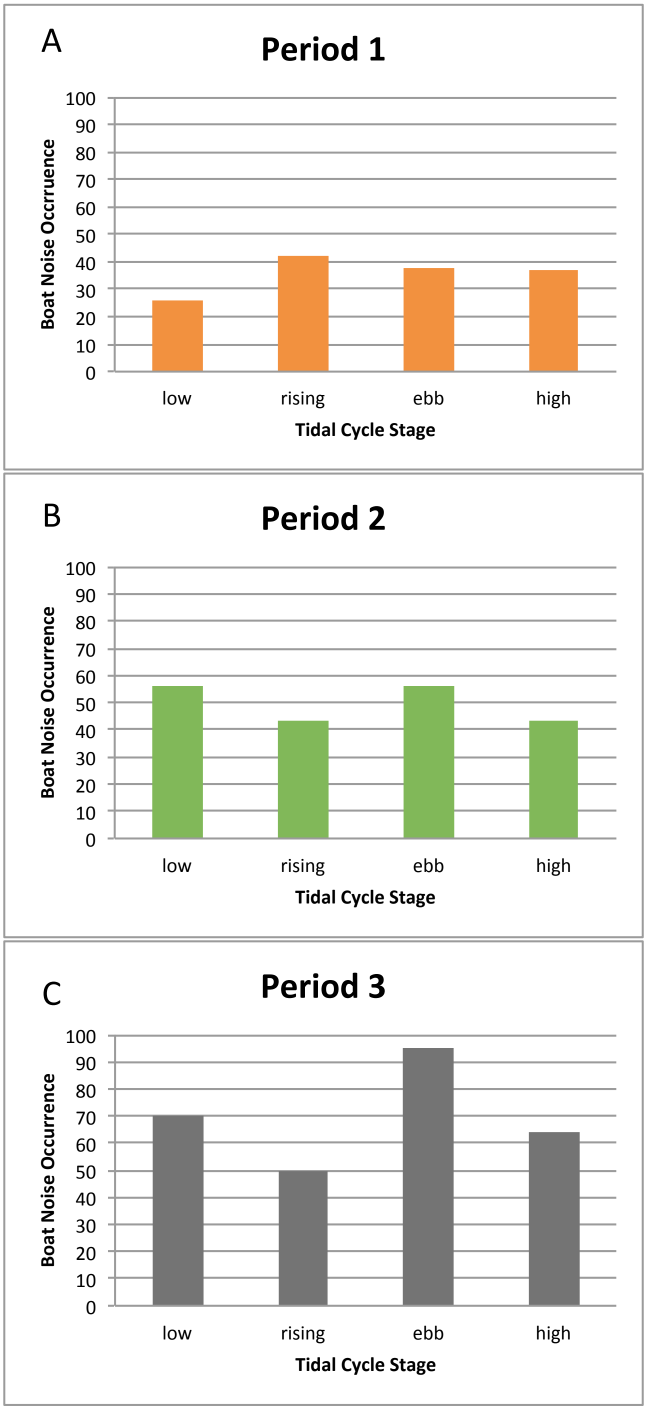


Figure 5: Boat noise occurrence compared to tidal cycle stage for each deployment period. Boat noise occurrences also exhibited a significant trend over the tidal cycle (Poisson GLM, omnibus test p-value=0.15), however only the 'ebb' category had a significant increase compared to the other tidal stages (parameter estimate for ebb p-value= 0.003).

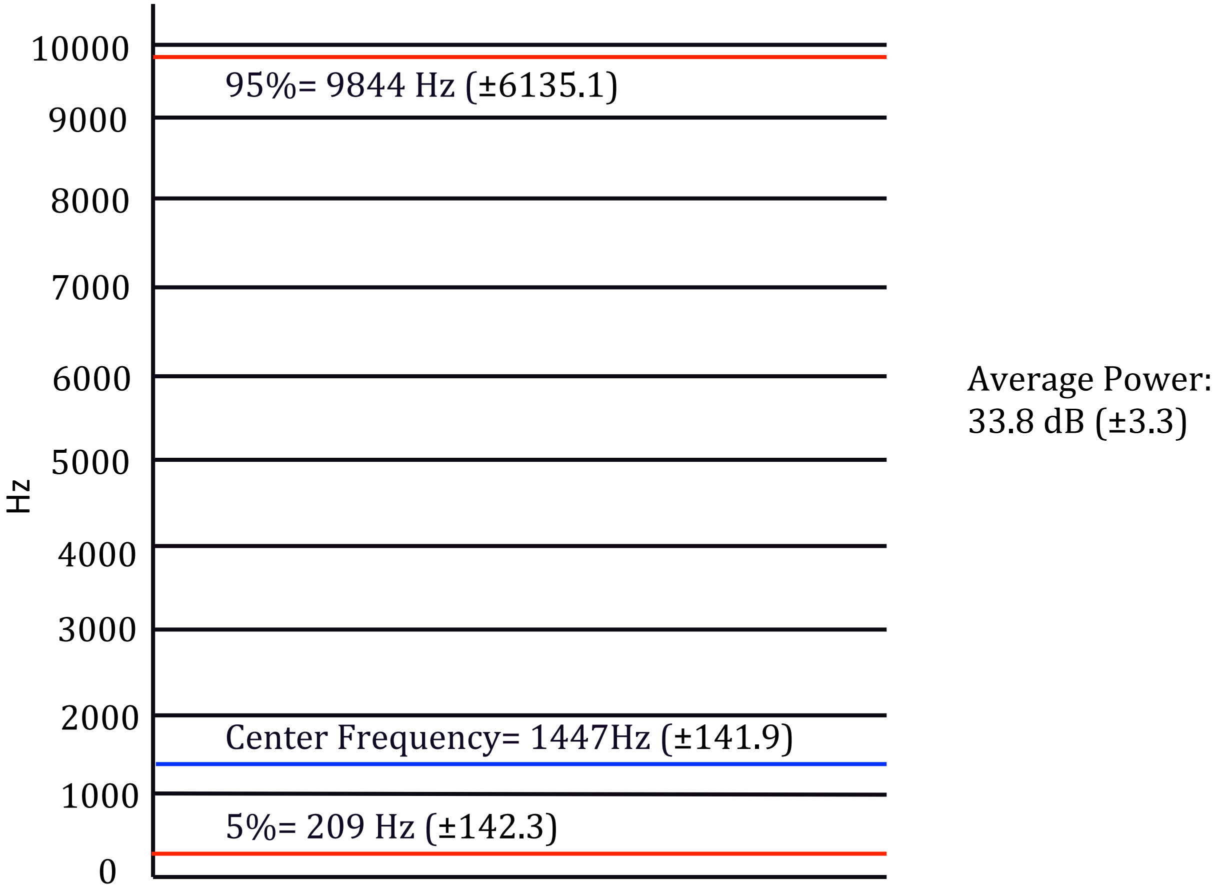


Figure 6: Overall means for Center Frequency, 5% Frequency, and 95% Frequency were as expected, with 5% Frequency comprising the lowest frequency value, 95% frequency the highest, and Central Frequency a median value. Mean Average Power was calculated by averaging the Average Power values for each boat noise analyzed. Raven determines Average Power by first summing the values of the power spectrum in the selection and then dividing by the number of time-frequency bins in the selection.

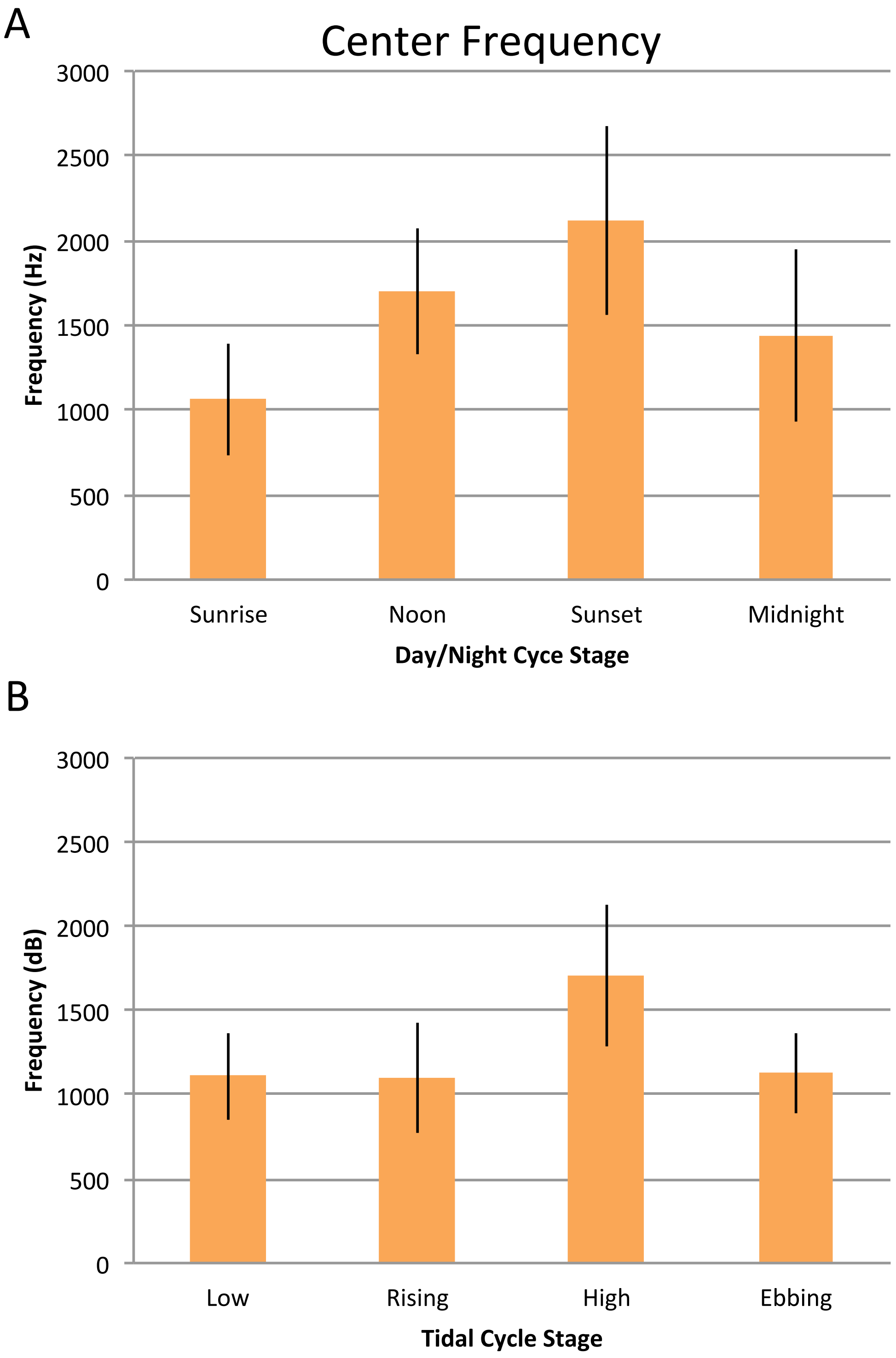


Figure 7: Center Frequency compared to Day/night Cycle Stage (A) and Tidal Cycle Stage (B). Multivariate ANOVA revealed Day/Night Cycle exhibited a trend (Pillai's Trace p-value=0.092) and Tidal Cycle had no effect (Pillai's Trace p-value=0.269). Bars represent standard error.

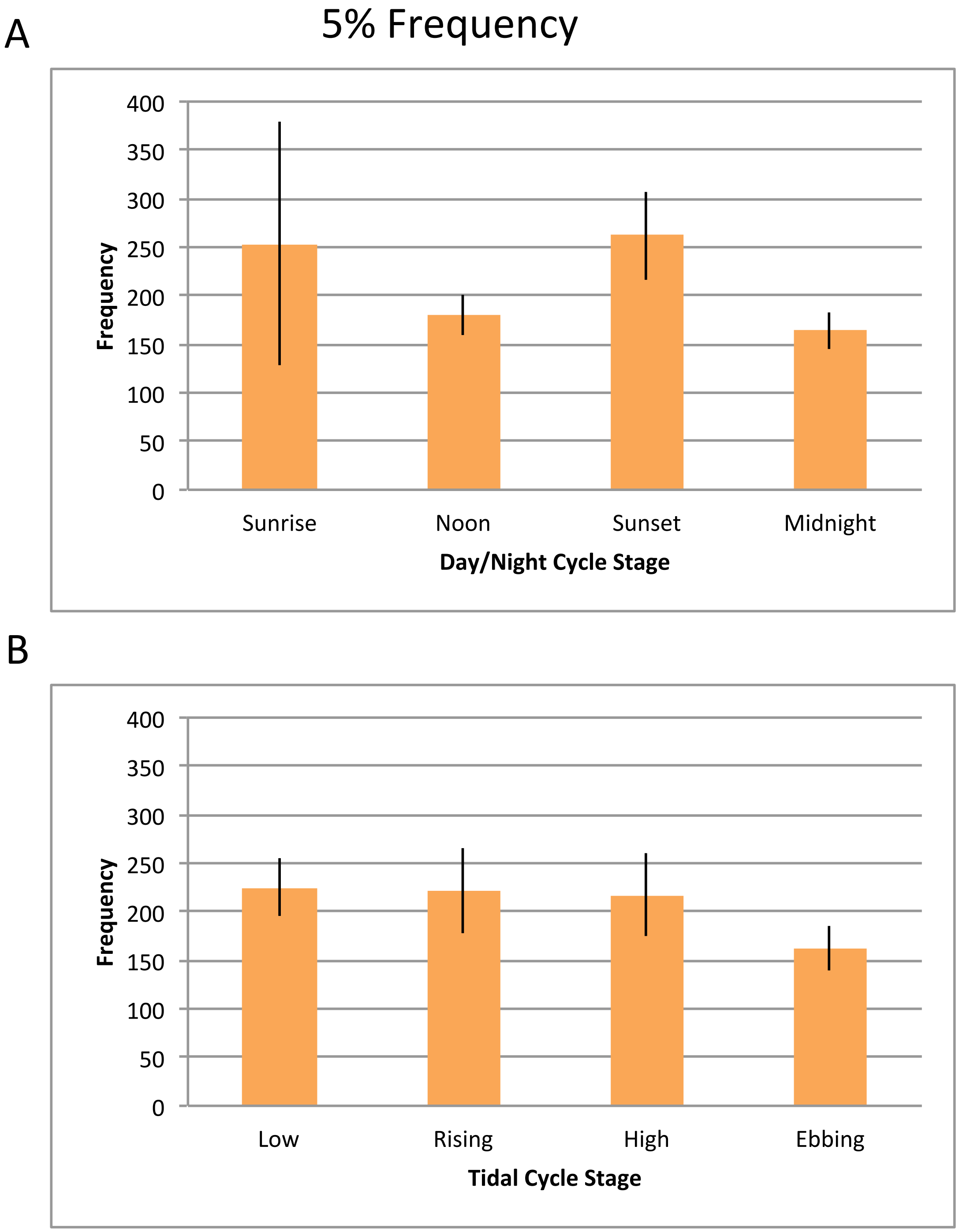


Figure 8: 5% Frequency compared to Day/night Cycle Stage (A) and Tidal Cycle Stage (B). Day/Night stage did not have an effect on 5% Frequency (MANOVA, p-value>0.5). Tidal cycle also did not have a significant effect on 5% Frequency (MANOVA, p-value>0.5). Bars represent standard error.

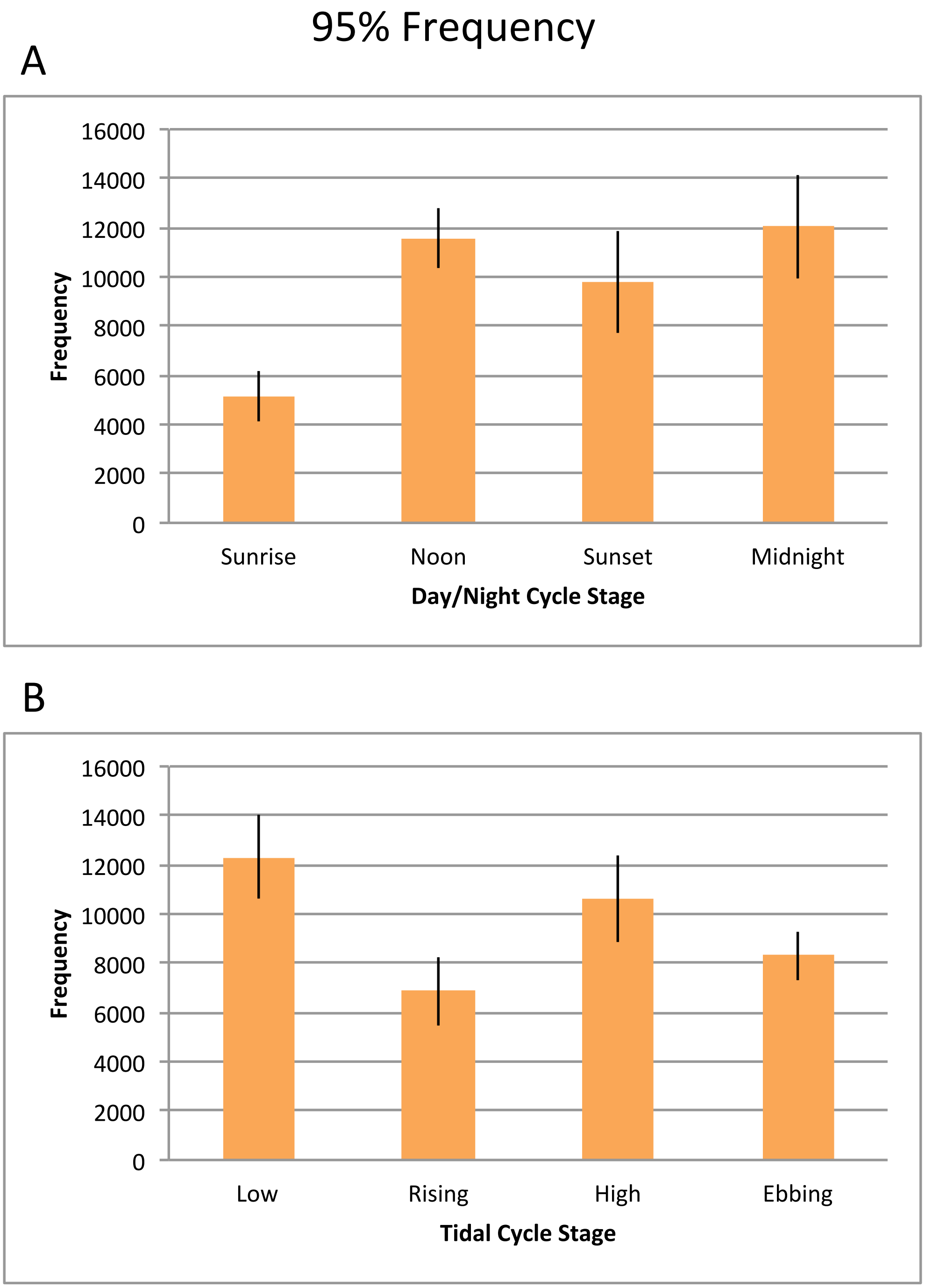


Figure 9: 95% Frequency compared to Day/night Cycle Stage (A) and Tidal Cycle Stage (B). Day/night cycle stage had an effect on 95% Frequency (MANOVA, p-value= 0.037) and Tidal Cycle stage had an effect on 95% Frequency (MANOVA, p-value=0.014). LSD tests revealed 95% Frequency was significantly higher for midnight than sunrise (p-value=0.008) and noon than sunrise (p-value= 0.005), and nearly significantly higher for sunset than sunrise (p-value=0.054). 95% Frequency was significantly higher for low than ebb tide (p-value=0.024) and rising tide (p-value=0.002). Bars represent standard error.

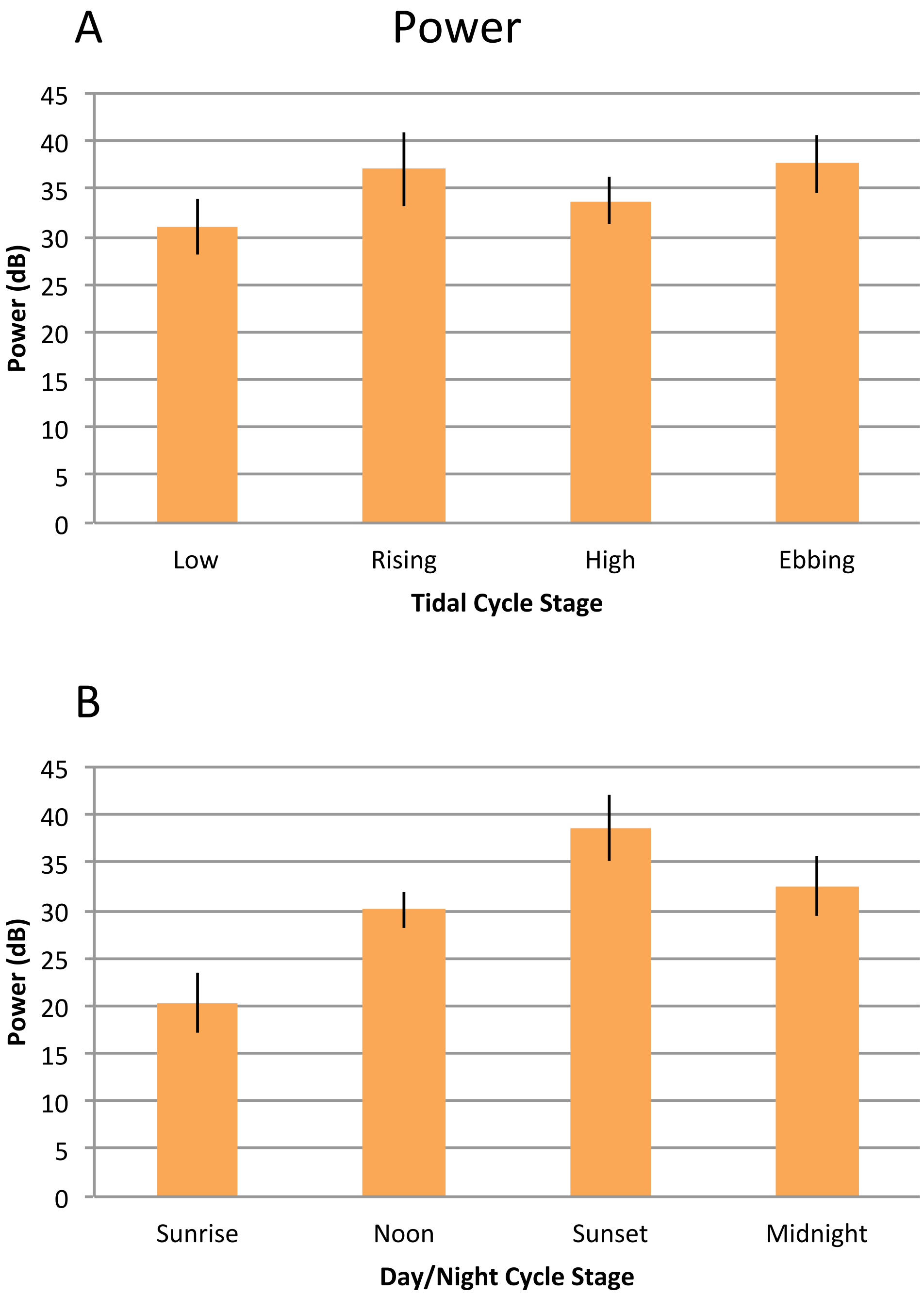


Figure 10: Average Power compared to Day/night Cycle Stage (B) and Tidal Cycle Stage (A). Day/night Cycle stage had an affect on Average Power (MANOVA, p-value=0.029) but Tidal Cycle stage had no effect on Average Power (p-value>0.05). According to Post Hoc LSD tests, Average Power was significantly greater for midnight than sunrise (p-value=0.027), sunset than midnight (p-value=0.025), noon than sunrise (p-value=007), sunset than noon (p-value=0.006), and sunset than sunrise (p-value<0.001). Bars represent standard error.

File	Center Frequency (Hz)	5% Frequency (Hz)	95% Frequency (Hz)	Avg Power (dB)
354	7500.0	4335.9	12070.3	24.0
362	10664.1	6796.9	16875.0	21.8
374	10546.9	7031.2	16289.1	30.0
375	15703.1	13242.2	19453.1	22.3
1334	7500.0	4101.6	14648.4	45.3
1335	9140.6	5859.4	13476.6	27.3
1336	9375.0	6562.5	13007.8	26.1
1345	Masked by boat so unable to separate characteristics of dolphin vocalization			
1346	Masked by boat so unable to separate characteristics of dolphin vocalization			
1347	11132.8	4804.7	16054.7	29.0
Average	10195.3 (± 924.6)	6591.8 (±1020.6)	15234.4 (±852.3)	28.2 (±2.7)

Table 2: Summary of dolphin vocalization characteristics from dolphins detected in Wellfleet Harbor. All vocalizations were detected during the third deployment period. Mean Center Frequency was 10195.3 (± 924.6) Hz, mean 5% Frequency was 6591.8 (±1020.6) Hz, mean 95% Frequency was 15234.4 (±852.3) Hz, and mean Average Power was 28.2 (±2.7) dB.

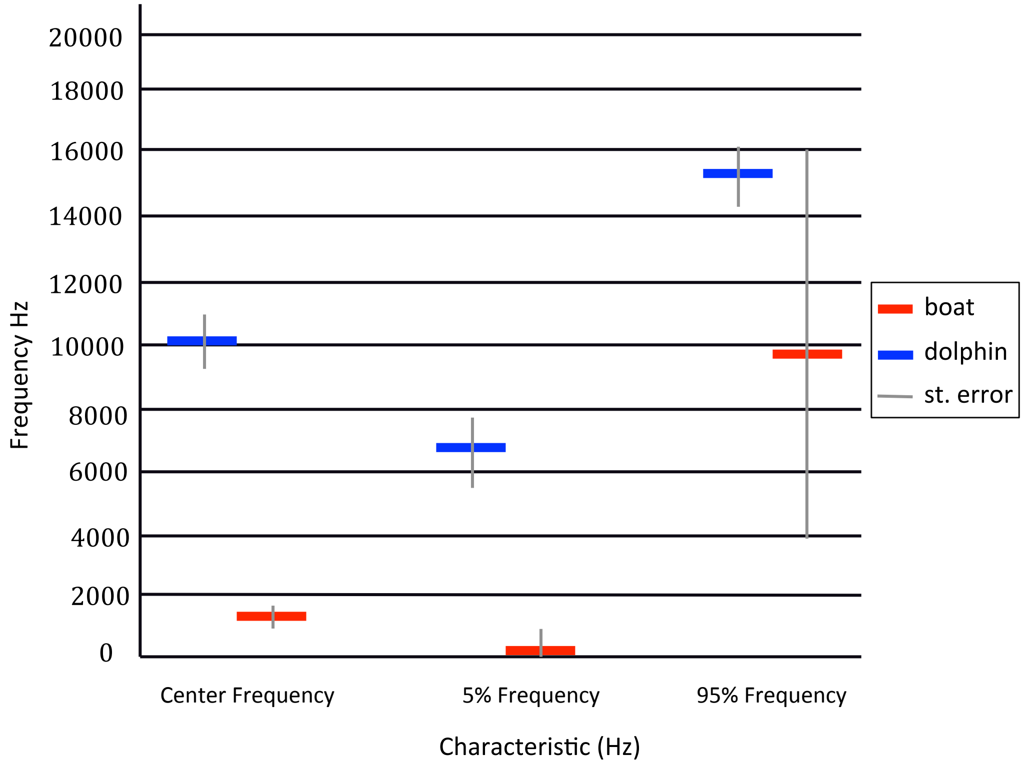


Figure 11: Center Frequency, 5% Frequency, and 95% Frequency for dolphins and boats, error bars depicts standard error. For boat noise: mean Center Frequency = 1447 (±141.9) Hz, 5% Frequency = 209 (± 141.9 Hz), and 95% Frequency (± 6135.1) Hz. For dolphin vocalizations: mean Center Frequency was 10195.3 (± 924.6) Hz, mean 5% Frequency was 6591.8 (±1020.6) Hz, mean 95% Frequency was 15234.4 (±852.3) Hz.

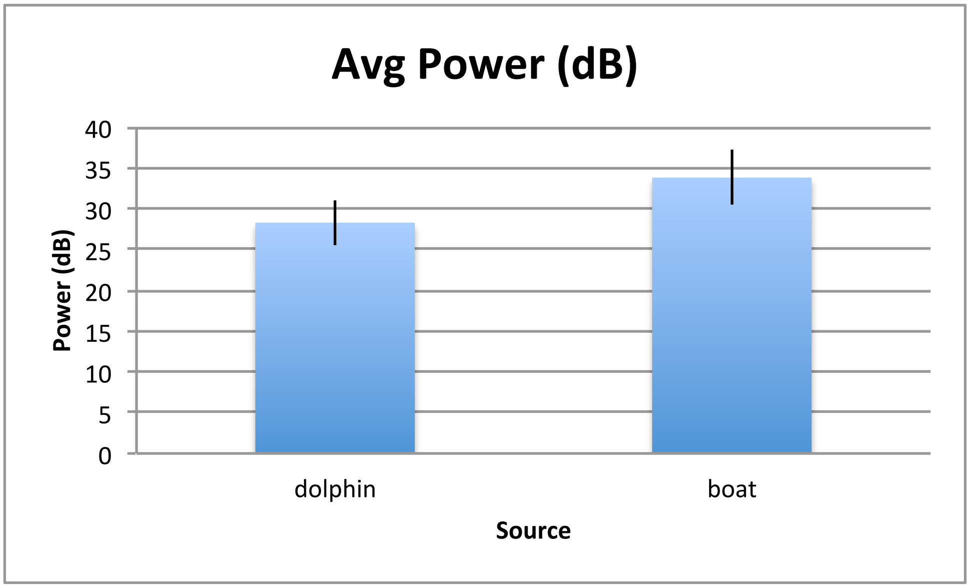


Figure 12: Average Power comparison between dolphin vocalizations and boat noise. For boat noise: mean Average Power = 22.8 (±3.3) dB and for dolphins: mean Average Power = 28.2 (±2.7) dB. Bars represent standard error.

6. Discussion

As part of larger project led by Dr. Laela Sayigh of Woods Hole Oceanographic Institute to design a PAM system in Wellfleet Harbor, MA, I investigated incidence of boat noise in the harbor from recordings made from April 22-July 23, 2015. My study sought to determine how frequently boat noise occurred in the harbor, what characteristics that boat noise possessed, and whether boat noise occurrence or characteristics followed deployment period, day/night cycle, or tidal cycle patterns. I found boat noise occurred in 33% recordings. These occurrences followed day/night cycles patterns, with more occurrences during the day, and a small tidal trend, with somewhat more occurrences during ebb tide. In addition, I analyzed boat noise characteristics and found a mean central frequency of 1447Hz (+ 141.9), a 5% Frequency of 209 Hz (+142.3), a 95% frequency of 9844 Hz (+ 6135.1), and an Average Power of 33.8 dB (+3.3).

Boat Noise Occurrence:

Based on onsite observations and initial data inspections made during the summer, I realized boat occurrence in Wellfleet Harbor was greater than I had anticipated. The data supported this supposition, with one-third of all files containing at least one instance of boat noise. A study conducted by Pirotta et al. (2015) to assess the impacts of boat noise on bottlenose dolphin foraging using PAM only detected boat noise in 5% of recordings made over a 101 day period. However, the study area in question focused on two narrow channels along the Scottish coast, which experiences a mix of commercial vessels such as tanker ship and leisure boat traffic (Pirotta et al., 2015). Wellfleet Harbor, on the other hand, is a protected region within a bay that experiences mostly local fishing and tourist boat traffic, which could explain the variance between study results. A different study conducted by Henry and Hammill (2001) to determine the impact of boats on seal activity detected found that during their 43-day study, 27 experienced disturbance by a boat, 27.8% of which were motorized vessels. The methods for this study also varied greatly from my own, as data was collected visually. Researchers also only noted boat presence when that boat was visually confirmed disturbing a seal.

I predicted boat noise occurrence would increase with each deployment period, as periods later in the summer would overlap with the main tourism season for Cape Cod. As predicted, boat noise occurrence did increase significantly between deployment periods. It is possible the increase reflects an increase in the number of boat trips made by existing users, rather than an increase in the overall number of users. However, observations made by the Wellfleet harbormasters, Dr. Laela Sayigh, Alex Bocconcelli, fellow WHOI interns, and myself support the conclusion that the increasing amount of boat noise is most likely a result of increasing tourist boat traffic as vacationers flock to the Cape during the summer months.

In addition, I had anticipated boat noise occurrence would follow day/night patterns, with more boat noise occurring during daylight periods. Daylight allows for easier and safer navigation. The local fishermen of Wellfleet might venture out during night hours to set traps, nets, and lines or to beat rivals to prime fishing spots. Oyster fishermen in particular have utilized the harbor many decades (Kirby, 2004). However, other users, especially summer vacationers who are less familiar with the harbor utilize the harbor during the day. The data did in fact reveal that boat occurrences increased from sunrise to noon, then decrease between noon and sunset and between sunset and midnight. These findings are consistent with those of Haviland-Howell et al. (2007), who utilized PAM to monitor boat noise near Wilmington, NC. The researchers found that boat traffic varied significantly with day/night cycles, with boat activity generally increasing over the course of the day, peaking in the mid-afternoon, and then decreasing in the evening.

I also expected tidal cycles to influence boat noise occurrences in Wellfleet Harbor, with fewer boat noise occurrences during low tide. I based by hypothesis on observations made by the Wellfleet harbormasters, Dr. Laela Sayigh, Alex Bocconcelli, and myself of the impact of low tide on the water levels with the harbor. Deployments for data collection were not possible during low tide as there was insufficient water for boats to leave the harbor. According to the harbormasters, it is common for low tide to restrict movement of boats. In fact, during a trip to make visual observations of the harbor, I witnessed automobiles driving on the exposed seabed several hundred meters from shore. Therefore, I expected that with fewer boats able to leave and enter the harbor at low tide, fewer boats would pass near the recorder at the mouth of the harbor. In addition, during my initial inspections of the data I heard what I believed to be seagulls on the recording, suggesting the recorders were either exposed or in shallow enough water to pick up sounds in the air, indicating water levels were quite low. However, while the boat noise occurrence data exhibited a tidal trend, ebb tide was the only stage that significantly differed from the other stages, with a greater number of occurrences. One explanation for this result is that more boats moved either away from the harbor to avoid low tide or headed back to dock before low tide prevents passage. However, without visual data to lend credence to these speculations, it is impossible to ascertain the true underlying driver of the observed increase.

Boat Noise Characteristics:

As stated above, mean values for Center Frequency, 5% Frequency, and 95% Frequency were within expectations for small fishing and recreational boats. The spectral characteristics revealed the majority of the noise produced was of a lower frequency and spread across a range of frequencies rather than following a frequency modulated pattern. Other studies have found that small boats typically emit sound in the lower portion of the frequency spectrum, <2000Hz, with broadband frequency characteristics (Picciulin et al., 2008; Pirotta et al., 2015).

Several explanations could account for the effect of period on Average Power and 95% Frequency, in which Period 1 exhibited significantly lower values than in Period 2 or 3. Firstly, as described above, the groups that utilize Wellfleet Harbor for boating activities vary over the season. These fishermen, other locals, and vacationers might have employed different types of vessels that created different noises with varying power. However, I cannot rule out the possibility that the differences resulted from the different recorder utilized during the first deployment period.

Tidal stage had an effect on 95% Frequency, which was greater during low tide than rising and ebb tides. Tidal stage also exhibited a trend with Center Frequency, which was greater during ebb and high than rising tide and nearly greater during rising than low. Despite the significant differences, the results do no indicate any pattern that would suggest a uniform cause for all the differences. While the trend with Center Frequency seems to suggest an increase towards high then decrease with ebb until bottoming at low, the fact that 95% Frequency was actually greater during low is inconsistent with this pattern. The mostly likely explanation is that these differences, while significant, are noise and not attributable to a single, determinable cause. Haviland-Howell et al. (2007) did not detect a significant influence of tide on boat frequency or noise level. However, they only considered high tide relative to all other tidal stages, not high, low, ebb, and rising compared with one another, and so could have missed potential trends. Background noise levels can fluctuate with tide, and has been found to peak during period of slack tide (high or low tide), rather than during ebb or rising tide in regions with high tidal flow (Willis et al., 2013). It is possible the background noise levels added to the boat noise and contributed to the overall tidal pattern. Unfortunately, I did not have sufficient time to examine background noise levels in relation to tidal cycles for this dataset, and so cannot make conclusions about the underlying impetus of the trend.

As for Day/Night cycle effects on boat noise characteristics, the most interesting pattern I detected was that Average Power increased throughout the day, reaching its peak at sunset before declining towards its minimum at sunrise. Haviland-Howell et al. (2007) also found that the mean pressure levels received, or noise levels, by their recorders also were significantly higher during the day. These patterns could reflect a conscious choice by boaters in the area to try to keep noise levels down during nighttime hours or could a shift in the types of boats that are present in the harbor throughout the day.

Dolphin Vocalization Data:

A key concern for this project was potential masking of dolphin vocalizations by boats, which could interfere with the detection system. The overlap with boat noise, which made it difficult to separate and analyze characteristics for just the vocalizations, effectively masked the vocalizations from detection from my perspective. This was the first indication that potential masking might occur as a result of the boat noise. However, these incidents were anecdotal and by no mean definitive proof that the boat noise in Wellfleet Harbor would interfere with dolphin detection and/or communication between or among dolphins.

To further explore the possibility of masking, I compared the frequency characteristics and Average Power means from my boat noise data to that of the dolphin vocalizations. The frequency parameters for dolphins were consist with those documented in other studies (Caldwell et al., 1990; Janick et al., 1994; Esch et al., 2009). While still not a statistically powerful result owing to the paucity of dolphin vocalization samples, the comparison can still facilitate understanding of the relationship between boat noise and dolphin vocalizations. Center Frequency and 5% Frequency for the dolphin vocalizations are well out of range of the boat noise counterparts, but overlap does occur for the 95% Frequency values. The 95% Frequency range of boat noise also overlaps with the other two parameters from the dolphin vocalizations, suggesting that the higher frequency end of the boat noise could present a problem for detection. Still, frequency alone does not determine if interference can occur. Even if overlap occurs, if the dolphin vocalizations have significantly more energy than the boat overlapping boat noise, the system could still detect them.

When I compared the Average Power (again not a significant result) I found similar values for both dolphins and boats. Since decibels are logarithmic, a few decibels can have a large effect, though, and boat noise had slightly higher values. This is complicated by the fact that the Average Power represents the average for the entire spectral rang of the noise, but not all of that energy occurs in the region of spectral overlap. Remember, Center Frequency is the frequency that separates the energy of the sound into two segments. Since the mean Center Frequency for boat noise occurs far below the parameters of the vocalizations, the overlap can at most contain half of the total energy of the sound. This fact makes establishing a masking effect difficult. Despite these difficulties, I can attest to at least three instances on 2 separate recordings in which the presence of boat noise impeded my perception of dolphin vocalizations. Normally, I could easily distinguish dolphin vocalizations both visibly, as in Figure 13 below, and audibly when listening to a recording. In the spectrograms with boat sounds, the noise visibly overlapped dolphin vocalizations, which audibly interfered with my ability to hear the dolphin (Figure 14). Importantly, I had trouble separating the vocalizations from the boat noise when analyzing sound parameters in Raven, which suggests a detector might encounter similar issues. This interference has implications for the current WHOI dolphin detection project, which might encounter problems detecting dolphins amidst boat noise.

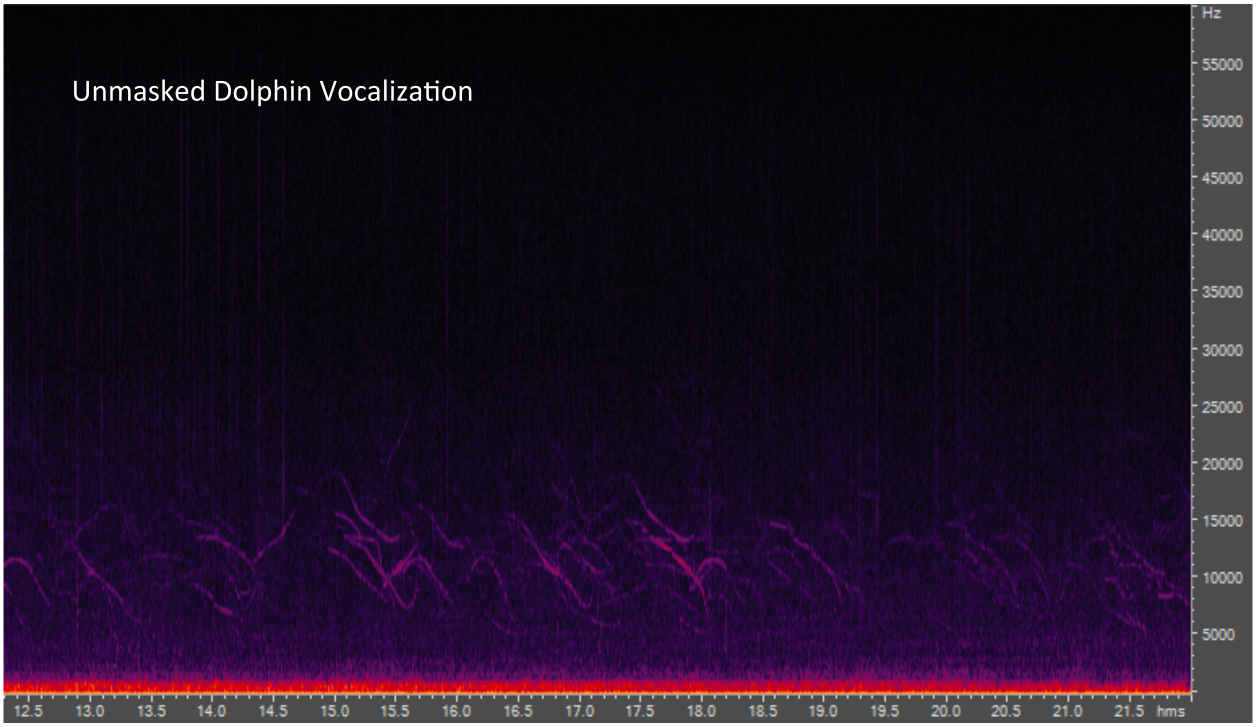


Figure 13: Example of dolphin vocalizations recorded during the third period of data collection.

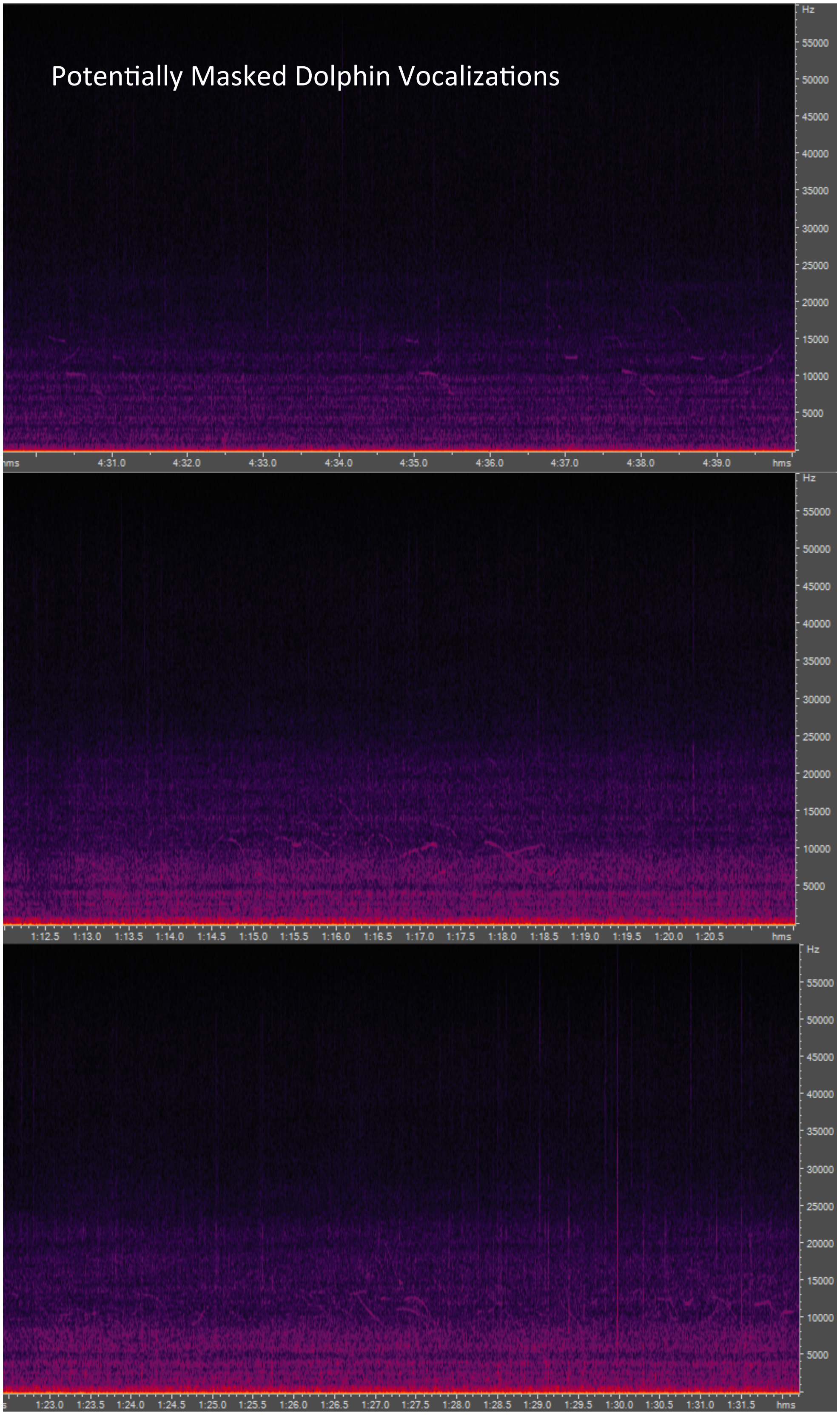


Figure 14: Several examples of dolphin vocalizations (unidentified species) potentially masked by boat noise. All three incidents occurred during the third period of data collection.

Establishing that the boat noise in the area could disturb the dolphins or mask their vocalizations from one another presents an even trickier problem. Firstly, the fact that the boat noise inhibited my ability to hear the vocalizations does not indicate that the same will hold true for a dolphin. The hearing ranges of humans and dolphins differ. The human range extends from 0.064-16 kHz, while the bottlenose dolphin range extends from 0.075-150 kHz, for example (Dehnhardt, 2002). A study must demonstrate that the noise in question has interfered with the perception of the dolphin, and confirming any disturbance utilizing audio data alone presents a challenge. In 2014, Pirotta et al. who found boat presence led to a reduction in foraging activities of bottlenose dolphins, incorporated both audio and visual data in their analysis. Haviland-Howell et al. (2007), who concluded that boat noise in Wilmington could represent a source of acoustic harassment for bottlenose dolphins and may impact communication, also combined video and audio data. Audio data can not only provide confirmation for conclusion made based on acoustics data, but can also fill in important gaps, such as which types of boats generated which sounds. This information can facilitate decision-making processes concerning next research steps or management options.

Furthermore, other factors may influence animal behavior and confuse results. For instance, researchers have found that the physical presence of boats themselves can disturb dolphins (Pirotta et al., 2014). Distinguishing the influence of harassment from boat presence as opposed to boat noise introduces further complexities in establishing a direct chain of cause and effect. The context in which the boat noise occurs also matters. For example, prior exposure to certain sounds can influences an animal's response (Thompson et al., 2013). Also, environmental conditions could further influence behavior, such that the same stimulus might instigate different responses under a variety of conditions (Pirotta et al., 2014).

Suggestions for Next Steps:

While the study did not provide definite confirmation of boat noise masking dolphin vocalizations, analysis indicated a potential overlap of boat noise and dolphin vocalization frequencies. Anecdotal evidence suggests boat noise will interfere with the ability of researchers to detect dolphins in Wellfleet Harbor. Consequently, I recommend the Wellfleet project take a precautionary approach regarding boat noise. With this approach in mind, I have listed several possible next steps for the research project.

Create boat noise filter

During discussions with Dr. Laela Sayigh, she proposed the possibility of creating boat noise filters for the dolphin detector. The filters would reduce the influence of noise and allow researchers to detect dolphins among the boat noise. Given the prevalence of boats in the area and the potential overlapping frequencies, I think project managers should proceed with developing the filters.

Conduct longer-term recordings of boat noise

While the ultimate goal of the WHOI project is to detect dolphins, after reviewing boat noise occurrence and noise characteristics, I believe the boat noise situation in Wellfleet merits a longer-term survey project of its own. The types of vessels present in Wellfleet Harbor will likely vary over the year, with more vacationers' leisure craft present during the time of my study relative to the rest of the year. The types of fishing vessels present in the harbor may also vary throughout the year depending on season fishing shifts. In addition, anecdotal observations made by Dr. Sayigh suggest that dolphin appear in the harbor more frequently in early spring, and so understanding what types of boats are present in the harbor at that time is important. Researchers could utilize the planned PAM system to conduct the study by programming the majority of recorders to detect dolphin noise and allowing a remaining one or two recorders to track general noise in the harbor including boat noise. A yearlong study would provide sufficient time to chronicle the various tidal, seasonal, and biological cycles in the harbor and see if significant patterns emerge.

Conduct visual surveys of boats

As mentioned before, acoustic data has limitations that make establishing direct cause and effect problematic. Paring acoustic data with visual surveys could provide a clearer picture of the situation within Wellfleet Harbor. Other studies have implemented this methodology and been able to come to more definitive conclusions about boat presence, noise, and potential impacts on marine animals (Pirotta et al., 2014; Haviland-Howell et al., 2007). The issue of marine mammal responses to boat presence and noise could have relevance not only for the project in Wellfleet, but could advance general knowledge of marine mammals and anthropogenic noise.

Conduct visual surveys of dolphins

In order to determine if boat presence and noise have an impact on dolphin behavior, researchers will need to pair the acoustic data collected by the PAM system with visual survey data of dolphins. Again, visual data helps support acoustic data and establishing linkages between anthropogenic noises and marine mammal behavioral responses. Surveys should examine dolphin behavior relative to boat noise, while keeping in mind the general context in which the behaviors occur. As shown by Haviland-Howell et al. (2007), these methods can produce relatively conclusive results.

Conclusions:

Boat presence occurs frequency in Wellfleet Harbor, MA (~1/3 of the time). Boat noise occurrences follow expected day/night cycle patterns, but not expected tidal cycle patterns. Boat noise varies with deployment period, day/night cycle, and tidal cycle but the observed patterns are unlikely to impact current WHOI project. Boise noise frequency parameters, however, reveal some overlap with anecdotal dolphin vocalizations and could present problems for detection. Adopting a precautionary approach, project managers in WHOI should create boat noise filters for their detectors, conduct longer-term studies of boat noise in the harbor, pair the acoustic data with visual surveys of boats, and explore dolphin behavior in response to boat presence and noise utilizing a combination of acoustics and visual methods.

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