Zoë Groenewoud

Communicating in noisy waters: assessing the impact of shipping activity on blue and fin whale calling activity in the Santa Barbara Channel during Covid-19

Master's thesis in Ocean Resources
Supervisor: Ana Širović
November 2023

Master's thesis

NTNU
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ABSTRACT

This study investigated the impact of shipping activity and environmental conditions on the Northeast Pacific blue (*Balaenoptera musculus*) and fin whale (*B. physalus*) calling activity in the Santa Barbara Channel. Passive acoustic data were collected and analyzed from late November through late March for two consecutive years: 2019/20 and 2020/21, covering the beginning of the global Covid-19 pandemic, which reduced shipping activity worldwide. Presence of three blue whale call types and two fin whale call types in 15-minute windows was manually marked and number of daily ship passages was counted in the total 2892 hours of data. Additionally, remotely sensed environmental data from the study site, including measurements of sea surface height (SSH), sea surface temperature (SST), and chlorophyll a (Chl a), covering October 25 – March 25 during both 2019/20 and 2020/21 were extracted from the European Union Copernicus Marine Service Information (CMEMS) and used as a proxy for primary productivity and prey abundance. Overall, significantly fewer blue whale calls were detected in 2019/20, as well as fin whale 20 Hz-calls. Fin whale 40 Hz-calls were continuously present throughout both years, with significantly higher activity in 2019/20. There was no clear difference in shipping activity between the two years, hence no effect of reduced shipping activity as a result of Covid-19 was observed in these data. However, shipping activity was still negatively affecting the presence of blue whale B- and D-calls, as well as fin whale 20 Hz-calls. Significantly lower SST and higher Chl a values in 2020/21 compared to 2019/20 suggest higher productivity in the second year, which was characterized by a La Niña event. The significant positive relationship between Chl a and all blue whale call-types, as well as fin whale 20 Hz-calls likely explains the higher calling activity of all these call-types in 2020/21, and lower activity during the less-productive winter of 2019/20. The persistent presence of fin whale 40 Hz-calls confirms the continuous presence of some fin whale populations in the Santa Barbara Channel, whereas the annual variability of blue whale calls suggests that the timing of their occurrence could be driven by favorable environmental circumstances as they seek high densities of prey over a broad area during the foraging season. In conclusion, these findings contribute to the growing understanding of blue and fin whale acoustic activity and their response to anthropogenic noise. The results of this study raise concerns for these whale populations that seek prey-abundant areas amidst the high noise levels in the Santa Barbara Channel. Continuing research efforts to explore the impact of anthropogenic sound sources on marine fauna is essential for enabling the conservation of the underwater soundscape on which these animals depend.

Key words

Blue whales · Fin whales · Shipping activity · Whale acoustics · Santa Barbara Channel · Covid-19 · La Niña

1. INTRODUCTION

1.1 Marine soundscape

Many marine organisms require acoustic abilities to survive in the ocean. They can use sound for various purposes, such as mate selection, finding a suitable habitat, or searching for food (Au & Hastings, 2008; Simon et al., 2010; Stanley et al., 2012). For these reasons, a healthy marine ecosystem requires a healthy marine soundscape. Soundscapes can be defined as 'ambient sound in terms of its spatial, temporal, and frequency attributes, and the types of sources contributing to the sound field' (Ainslie et al., 2021). Since sound propagates more efficiently than any other form of energy underwater and is critical for many important functions across marine fauna, understanding the variation in marine soundscapes over time and space is extremely important to study the effects of sound on marine fauna (Putland et al., 2017; Urick, 1983).

1.1.1 Natural ambient sound field

The marine soundscape consists of two natural sources: biological (biotic) and geo-physical (abiotic), as well as anthropogenic (human source) sounds (Duarte et al., 2021). Biophony includes all the biological sound sources contributing to the marine soundscape. Marine fauna is acoustically active in bandwidths between 10Hz (low-frequency range of some baleen whales) up to 170kHz (high-frequency range for porpoises). The different frequencies at which sounds are produced correlate to the spatial scale at which the sound will travel (Au & Hastings, 2008). Geophony consists of all geological and physical processes contributing to the underwater acoustic environment. This includes all weather- and seasonality-induced activity, such as rain, storms, wind, hurricanes, and ice formation and melting. Next, it also includes all subsea seismic activity, such as earthquakes and volcanic activity, as well as sounds produced by active hydrothermal vents. Most geophonic sounds, with sound sources spread across different spatial scales, can be detected over a relatively large spatial scale (up to 10.000km) and a varying temporal scale from a couple of hours (earthquakes and volcanoes) up to years (cracking ice) (Duarte et al., 2021; Hildebrand, 2009; Wenz, 1962).

1.1.1.1 Blue whale acoustics

One of the most powerful sounds biologically produced are calls of blue whales (*Balaenoptera musculus*), which are characterized by a high intensity (maximum recorded at 188 dB re 1 μPa) and low-frequency (16-100 Hz) (McDonald et al., 2001; Rivers, 1997; Cummings & Thompson, 1971). The Northeast Pacific blue whale song is known to be one of their twelve distinct songs, solely produced by males and consisting of two parts: the pulsed unit with multiple overtones (A-call), and the harmonic tonal unit (B-call) (Širović & Oleson 2022; McDonald et al., 2006). Each of these components has a duration of approximately 12-20 seconds, but the combination of A-B-calls as a song can last for hours (up to several days in some cases). Songs are hypothesized to be associated with female attraction (McDonald et al., 2001; Thompson et al., 1996). Both female and male individuals have been recorded producing foraging-related D-calls: a downsweep from 90-25Hz lasting between 1-4 seconds (Oleson et al., 2007a).

1.1.1.2 Fin whale acoustics

Fin whales (*B. physalus*) generally produce two high-intensity (up to 189 dB re 1 μPa) frequency-modulated call types across the eastern North Pacific, named the 20 Hz and the 40 Hz call (Watkins, 1981, Širović et al., 2013). Both calls are mainly produced by animals in groups (Watkins, 1981), and have a yearly high presence in the Northeast Pacific, specifically off Southern California (Širović et al., 2013). The 20 Hz call is a short-frequency downswept pulse with its center frequency around 20 Hz, generally produced in a stable sequence creating a song (e.g. Watkins, 1981; Watkins et al., 1987; Edds, 1988; Širović et al., 2004; Širović et al., 2013). These songs are likely linked to mating behavior or mate attraction (e.g. Croll et al., 2002). However, the 20 Hz calls or pulses can also be produced in irregular sequences or counter-calls, which are hypothesized to be social calls (e.g. McDonald et al., 1995). The slightly higher-frequency, short-duration (< 1 second) call with its energy most-often centered between 75-40 Hz is called the 40 Hz call (Watkins, 1981; Širović et al., 2013). This call has been recorded as a singular call or as a combination of multiple calls, overall without sequencing (Watkins, 1981). Investigation on seasonal occurrence of 40 Hz calls revealed that these calls can be associated with foraging fin whales (Širović et al., 2013; Croll et al., 2001a; Watkins, 1981).

1.1.2 Anthropogenic sound field

In contrast to natural sound sources, the anthropogenic sound field is created by human activities that are affecting the natural marine soundscape. Shifts in the biophony and geophony are impacted by climate change and decreasing biodiversity, as well as the contribution of human sound sources, i.e. anthrophony (Duarte et al. 2021). Typical sources of anthropogenic noise include explosives, seismic exploration, low-frequency active sonars, acoustic deterrent devices (ADD), shipping traffic, and industrial activities (Duarte et al., 2021; Hildebrand, 2009). Noise from (mostly commercial) shipping vessels is known to considerably overlap with the hearing ranges of marine fauna, especially in the lower frequency bands. 'Masking' of communication space in the low-frequency bands highly influences the ability of baleen whales to use their acoustic environment, both actively (producing sound) and passively (hearing) (e.g. Cholewiak et al., 2018).

1.1.2.1 Shipping traffic

Noise pollution from shipping traffic is currently the biggest contributor to anthropogenic noise in the ocean within the lower frequencies (below 400 Hz) with an increase in acoustic intensity of approximately 3 dB per decade through the early 2000s (McDonald et al., 2006; Erbe et al., 2019; Miksis-Olds & Nichols, 2016; Miksis-Olds et al., 2013; Andrew et al. 2002, 2011). As the intensity of marine traffic is increasing, so is its contribution to underwater noise. A global increase of at least 20 dB of low-frequency noise in the ocean compared to pre-industrial times is estimated (Hildebrand, 2009). In recent decades, smaller boats and recreational watercrafts are also becoming more abundant worldwide, with an increase of 1% per year in the United States (between 1980-2017) and 3% in Australia (between 1999-2009) (U.S. Department of Homeland Security, 2018; Nsw Government Maritime, 2010). These boats generally produce noise with peaks at higher frequencies (broadband up to 48 kHz) and are mainly contributing to noise pollution in coastal acoustic environments (Erbe et al., 2016; Erbe, 2013).

The sound levels of big ships (including container ships, ferries, and such) can vary depending on the size and speed of the vessel, with a peak source level at frequencies 10-50 Hz up to 200 dB (Hildebrand, 2009). However, small reductions in cargo vessel speed can substantially reduce the impact of their noise on marine mammals (Findlay et al., 2023). The perception of noise highly depends on the hearing range of the affected organism; low-frequency cetaceans such as baleen whales perceive ship noise louder at lower frequencies (<1kHz), but high-frequency marine mammal groups will perceive the higher frequency noise more prominently (Duarte et al., 2021; Findlay et al., 2023).

As commercial shipping is the biggest marine noise pollutant both temporally and spatially (Duarte et al., 2021), and the main contributor to the global increase in low-frequency noise (Redfern et al., 2017), it is important to investigate its impact on the ambient soundscape. Low-frequency noise from large vessels is known to travel basin-wide, however, the impact on the ambient sound levels is highest near big ports and main shipping lanes (Hildebrand, 2009). Especially the northern hemisphere is exposed to a higher shipping density, with some locations differing up to 20 dB from the southern hemisphere (Hildebrand, 2009; Cato, 1976). It is of utmost importance to investigate the impact of noise pollution in areas where high-intensity shipping overlaps with important habitats for marine fauna dependent on their acoustic environment. Large whales are particularly vulnerable to noise pollution, as well as potential ship collisions, in areas with high densities of shipping traffic (Rockwood et al., 2017; McKenna et al., 2015; Jensen et al., 2003; Laist et al., 2001).

1.1.2.2 Overlap between shipping noise and whale calls

Natural and anthropogenic sounds occur at similar frequencies. For example, blue and fin whales producing low-frequency calls can have their calls interact with other low-frequency geophysical and anthropogenic sound sources occurring at same frequencies (Figure 1, Figure 2, Figure 3). As a result, low-frequency noise pollution from shipping traffic appears to influence both acoustic activity and behavioral changes of blue and fin whales (Castellote et al., 2012; Melcon et al., 2012; Clark et al., 2009; Croll et al., 2001a; Bradbury & Vehrencamp, 1998).

Melcon et al. (2012) found a significant behavioral response in the acoustic activity of blue whales exposed to shipping noise in the mid-frequency range (1-8 kHz), with an increase in D-calls during higher ship noise intensity. This contrasted with less calling activity in the presence of high intensity mid-frequency sonar and explosion noises. Somewhat in contract to that finding, foraging behavior of blue whales was not affected by low-frequency noise in another study, while their distribution and vocal activity were related to prey abundance (Croll et al., 2001a). Furthermore, McKenna et al. (2009) showed that shipping activity within 4 km of a hydrophone negatively affected the detectability of blue whale B-calls, making their fundamental frequency not detectable above ambient noise levels. Higher harmonic levels suggested, however, that blue whales were acoustically active during shipping passages, but their calls were masked by the ship noise, with the possibility of impacting their communication range.

The effect of shipping activity on fin whales was revealed by recordings from the Mediterranean, where there was less fin whale acoustic activity during periods with higher levels of shipping noise, which suggests that singers might move away from areas with high noise exposure (Castellote et al., 2012). Fin whales also shift the frequency of their 20 Hz calls to a lower center frequency, potentially allowing them to communicate amidst the noise (Clark et al., 2009; Bradbury & Vehrencamp, 1998). However, frequency shifts are known to require extra energy, thereby affecting the life functions regarding vocal behavior (Bradbury & Vehrencamp, 1998). Furthermore, communication masking in the lower frequency bands, as well as decreasing communication space as a result of shipping noise, significantly impacts the acoustic environment in which fin whales are vocally active (Clark et al., 2009).

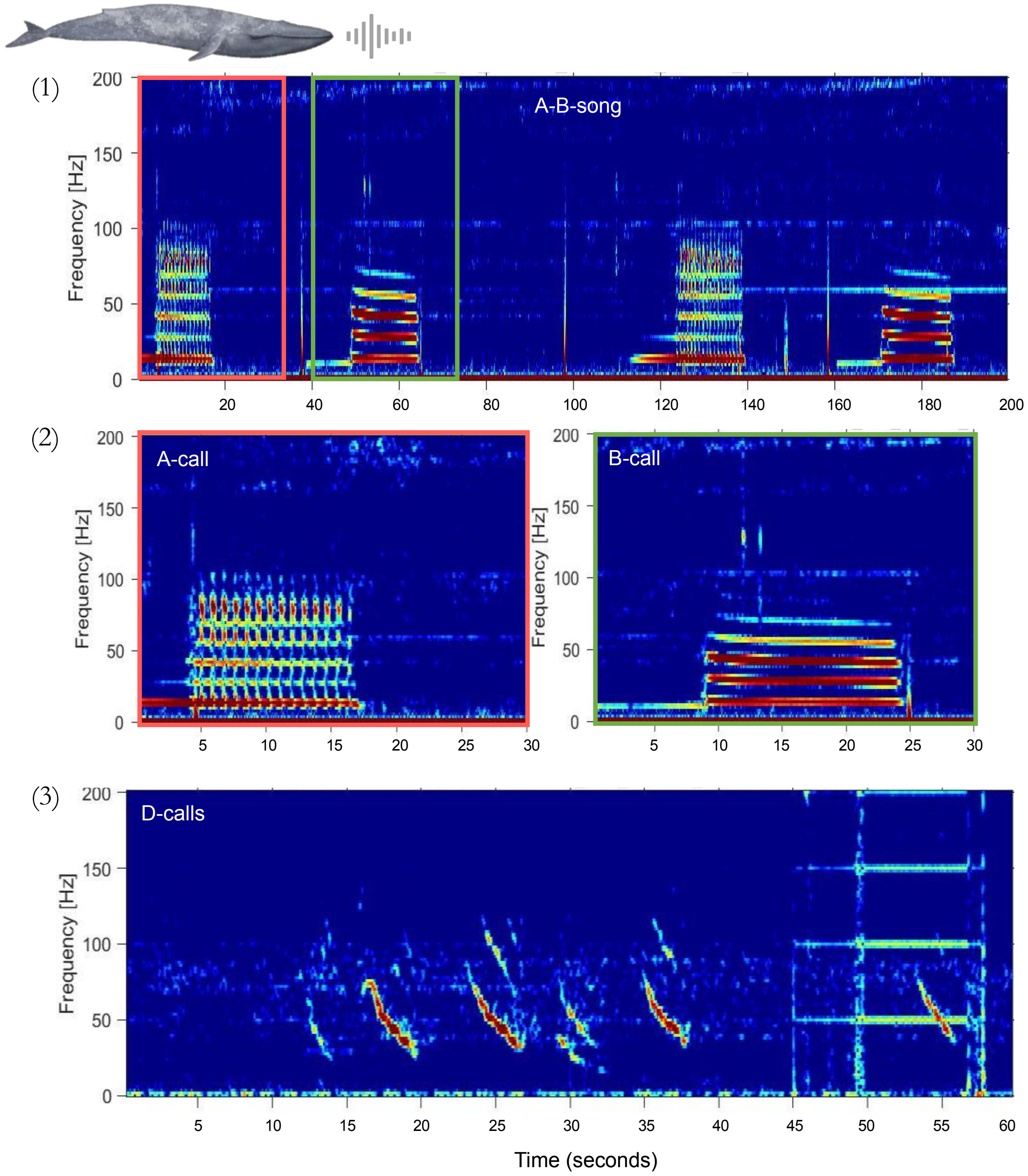

Figure 1. Spectrogram examples of blue whale (*B. musculus)* (1) A-B-song, with an A-call framed in red and a B-call framed in green, (2) singular A- (framed in red) and B-calls (framed in green), and (3) D-calls from southern California. Spectrograms created with 1000-point Fast Fourier Transform and 90% overlap. Note different time scales across spectrograms.

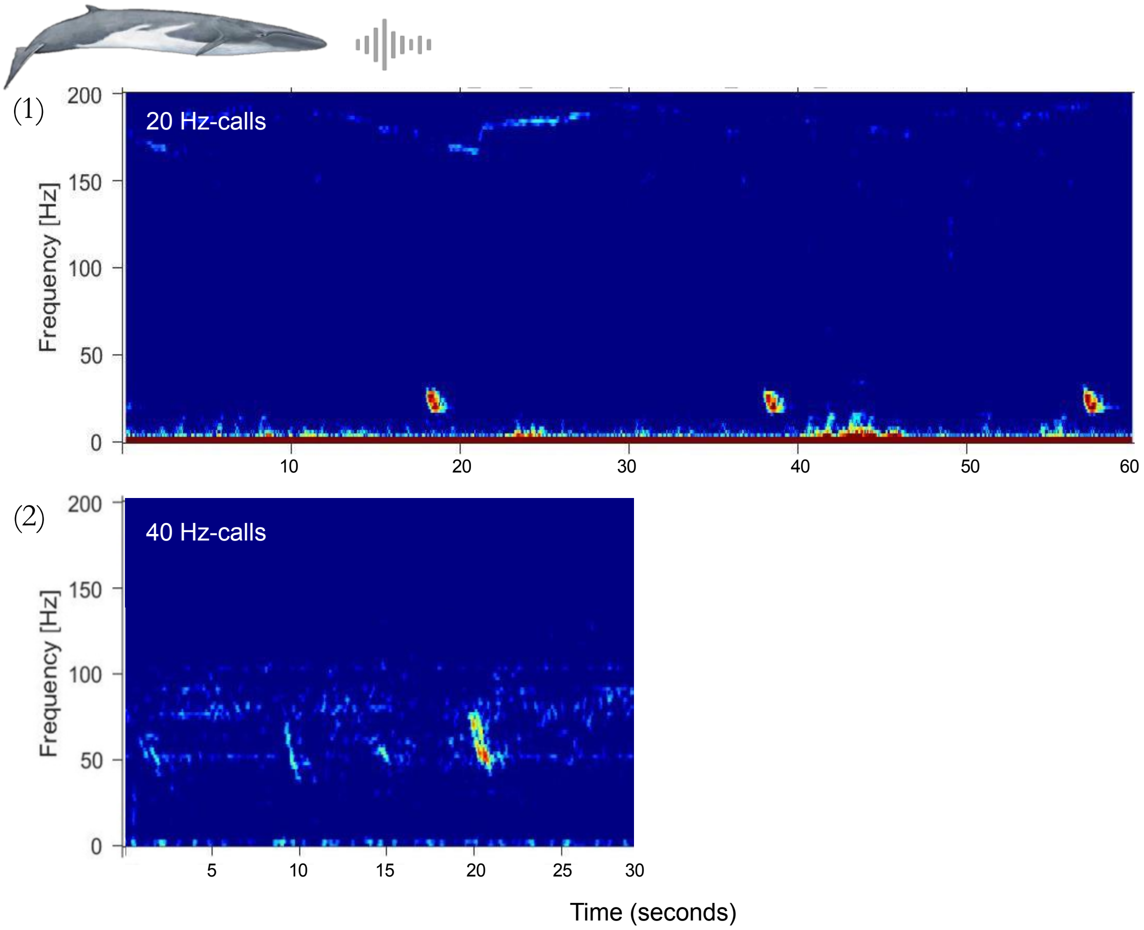

Figure 2. Spectrogram examples of fin whale (*B. physalus)* (1) 20 Hz-calls and (2) 40 Hz-calls from southern California. Spectrograms created with 1000-point Fast Fourier Transform and 90% overlap. Note different time and frequency scales across spectrograms.

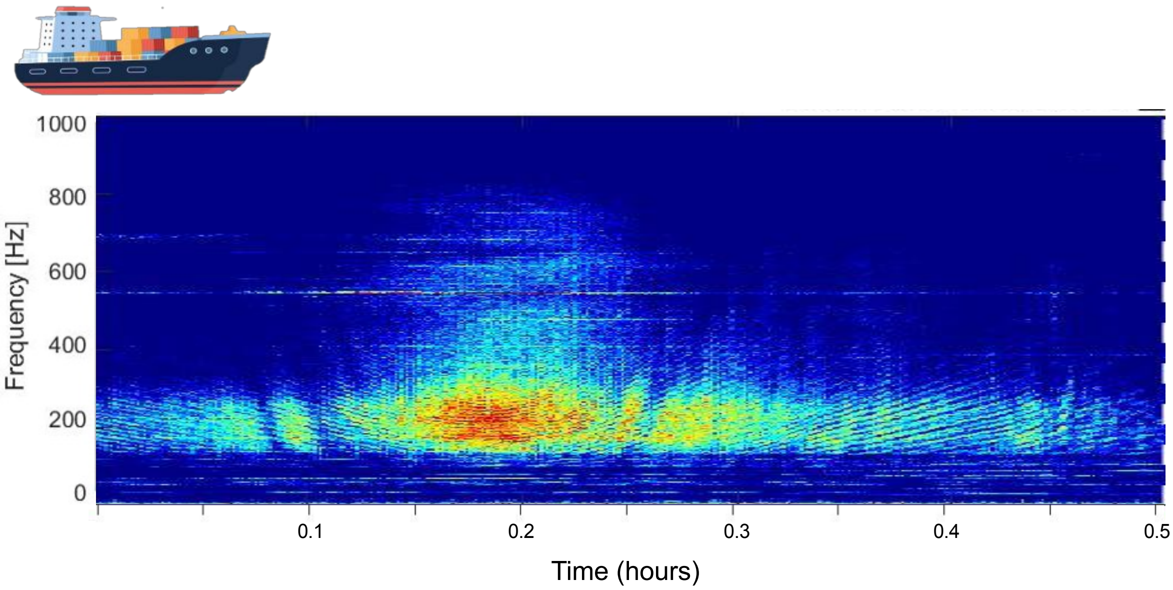

Figure 3. Spectrogram example of a ship passage. Spectrogram created with 1000-point Fast Fourier Transform.

1.2 Blue and fin whale ecology

Blue whales are currently listed as 'endangered' on the International Union for the Conservation of Nature (IUCN) Red List, but their population trend is increasing with approximately 5,000-15,000 mature individuals worldwide (Cooke, 2018a). The blue whale population known as the Northeast Pacific stock was assumed to be the largest population in the world with approximately 2,000 individuals (Calambodikis & Barlow, 2004; Barlow, 1995), but the increasing population of Antarctic blue whales (+ 7-8% per year) might mean this Southern Ocean population has now surpassed it (Olson et al., 2021). Groups of Northeast Pacific blue whales migrate between summer-time foraging grounds at mid and higher latitudes off the west coast of North America, to breeding grounds at lower latitudes off Central America in the winter, as confirmed by acoustic recordings (Rice et al., 2021a; Rice et al., 2021b; Širović et al., 2015; Stafford et al., 2001). They primarily feed on subsurface concentrations of euphausiids (krill), that are plentiful in the colder waters in upwelling regions (Croll et al., 2001b; Fiedler et al., 1998). During the foraging season in the summer and fall, they can be found foraging in Southern Californa, as well as in further north to areas including waters off British Columbia and Alaska (Calambokidis et al., 2009; Koot, 2015; Rice et al., 2021b). During the breeding, winter season, Northeast Pacific blue whales migrate to the Eastern Tropical Pacific, including the Costa Rica Dome and off Baja California, Mexico (Paniagua-Mendoza et al., 2017; Sears et al., 2013; Calambokidis et al., 2009).

Fin whales are the second largest animals on earth, after blue whales, and are listed as 'vulnerable' on the IUCN Red List. They, however, show an increasing population trend with approximately 100,000 individuals worldwide (Cooke, 2018b). Fin whale migration patterns vary amongst groups within the Northeast Pacific population, including movements between higher latitudes feeding areas around the Gulf of Alaska and the western coast of the United States in the summer (to feed on krill and fish), to lower latitude overwintering off Baja California (Mizroch et al., 2009). As revealed by acoustic recordings and visual sightings of fin whales, some groups are year-round inhabitants of particular areas in the Northeast Pacific, such as the Southern California Bight region (Širović et al., 2017; Forney & Barlow, 1998), as well as in the productive higher latitudes including the Gulf of Alaska (Mizroch et al., 2009). The distribution of Northeast Pacific fin whale populations therefore appears to not be fully understood.

1.3 Santa Barbara Channel as trophic hotspot

1.3.1 Local upwelling

The bathymetry and climate conditions of Southern California allow for coastal upwelling of cold and nutrient-rich deep water. The Santa Barbara Channel is a particularly well-studied transition zone, because of its local upwelling (Santora et al., 2017). This Channel is a region in the northern part of the Southern Californian Bight, extending from Baja California in Mexico to Point Conception off the Californian coast. The Channel Islands with rocky reefs and kelp forests provide a habitat for a great diversity of marine fauna. Upwelling in the Santa Barbara Channel is usually initiated as local equatorward winds pick up towards the end of winter (late February), followed by a strong increase in primary production, after which zooplankton grow, succeeded by the arrival of large whales (Croll et al., 2005). This local upwelling process is curl-driven, thereby mixing nutrients in the water column, making this an extremely productive area, or a so-called 'trophic hotspot' (Santora et al., 2017; Croll et al., 2005).

1.3.2 Habitat for blue and fin whales

Southern California is a highly important habitat for blue and fin whales, especially because of its function as main feeding ground (Redfern et al., 2017; Calambokidis et al., 2015; Forney et al., 1995). Blue whale population in the Californian waters generally reaches its peak acoustic activity during the fall and early winter (Širović et al., 2015; Oleson et al., 2007a). The year-round presence of fin whales has been observed (Širović et al., 2013, 2015; Forney et al. 1995), whereas the area functions as a seasonal foraging habitat for blue whales from (at least) June to October (Fiedler et al., 1998). However, the detection of acoustic activity of both species reveals that some of their populations remain in the area longer, varying in time periods over the years (Širović et al., 2015; Širović et al., 2013; Oleson et al., 2007a).

1.4 Santa Barbara Channel as main shipping lane

The Santa Barbara Channel is not only a trophic hotspot, but also a main shipping route between the United States and Asian markets (Smith et al., 2022). Increased ambient noise levels in the Channel Islands Marine Sanctuary (CINMS) have been measured, mostly attributed to an increase in commercial shipping traffic (Redfern et al., 2017; McKenna et al., 2009). Thirteen Marine Protected Areas (MPAs) have been established in the area, covering 21% of the sanctuary waters, however shipping traffic arriving at and departing from the Ports of Los Angeles (LA) and Long Beach (LB) is not hampered by the MPAs, resulting in the pollution of the acoustic environment (NOAA, 2023). The Santa Barbara Channel is particularly sensitive to this high intensity of local shipping traffic because of its bathymetry, trapping noise (McDonald et al., 2008). As reported by Redfern et al. (2017), protected areas in the Santa Barbara Channel overlap with the main shipping routes, particularly contributing to the noise pollution, especially within the communication range of blue and fin whales. It is therefore important to investigate the impact of low-frequency noise on the acoustic behavior of these whales in this area. Additionally, the Channel allows for an excellent area to study the impact of noise resulting from the local traffic to the two main nearby ports (LA and LB), because sounds from the deep-sound channel do not propagate into this basin (McDonald et al., 2008).

1.5 The impact of Covid-19 on the marine soundscape

During the Covid-19 pandemic, global economic activity changed drastically, decreasing shipping traffic substantially between March and June 2020 compared to previous years (March et al., 2021). A number of studies found that the first effect of the Covid-19 pandemic on the marine soundscape was a quieter ocean during the peak of the travel restrictions due to the pandemic (Jalkanen et al., 2022; Longden et al., 2022; Smith et al., 2022; Dahl et al., 2021; Ryan et al., 2021; Thomson & Barclay, 2020). However, the reduction of noise in the marine soundscape as a result of Covid-19 already commenced in November 2019 (Jalkanen et al., 2022). A globally reduced activity for container ships between 5.62 and 13.77% and between 19.57 and 42.77% for passenger traffic was measured (Millefiori et al., 2021). Off the Oregon coast, container shipping activity showed a substantial reduction, with a decline between 17-19% and a 1.6 dB reduction (in the 63 Hz-octave band representative of underwater shipping noise) in the second quarter of 2020 compared to the previous 5 years (Dahl et al., 2021). A similar trend in shipping noise was found off Monterey Bay, with a 1-1.5 dB decrease measured during February 2020, with the strongest decrease of 2-2.5 dB in June 2020, after which noise levels started increasing again (Smith et al., 2022; Ryan et al., 2021). The total global decrease of underwater noise as a result of Covid-19 reached similar noise levels as measured in 2017 (Jalkanen et al., 2022). Interestingly, an increase in vessel activity during the pandemic restrictions was measured in Sarasota Bay, Florida (Longden et al., 2022), with varying effects on dolphin whistle activity in the area. This result, combined with knowledge from previous studies investigating the effects of low-frequency vessel noise on whale vocalizations (e.g. Redfern et al., 2017; Castellote et al., 2012; Melcon et al., 2012; McKenna et al., 2009), suggests that the impact of the pandemic on the marine soundscape, including marine fauna, might differ extensively across the globe. The effect on blue and fin whale acoustic behavior from presumed reduced noise levels from shipping activity during and the pandemic has not been previously investigated.

2. RESEARCH AIM AND HYPOTHESES

2.1 Research questions

The assumed decrease in shipping activity at the start of the pandemic, and parallel decrease in ambient noise in the marine soundscape, provides for a natural experiment to compare patterns of whale calling from periods prior to and during the pandemic, to when shipping traffic was restored back to 'normal'. Most previous research has focused on comparing underwater noise levels during the pandemic to previous years, with research efforts lasting until the summer of 2020 when the noise levels appeared to be restored to those before the Covid-19 outbreak (e.g. Longden et al., 2022; Smith et al., 2022; Dahl et al., 2021; Ryan et al., 2021; Thomson & Barclay, 2020). In this study, I investigated the impact of shipping levels on the calling activity of blue and fin whales in the Santa Barbara Channel. To do so, I considered number of shipping passages and several environmental variables (including sea surface height, sea surface temperature, and chlorophyll a concentration) as predictor variables, and the calling abundance per call type of blue and fin whales as response variable.

To investigate this overarching research question, I divided it into three testable sub-questions:

I. Did the levels of calling activity per call type and shipping traffic activity differ between 2019/20 and 2020/21?

II. Was there a lagging correlation between either of the environmental variables and blue and fin whale calling activity?

III. Was there a relationship between either of the predictor variables (shipping traffic activity and the environmental factors) and calling activity of each call type over time?

2.2 Hypotheses

For the main research question, the null hypothesis for this study is that shipping activity will have no effect on the calling abundance of blue and fin whales. The alternative hypothesis considers shipping activity to affect blue and fin whale calling activity. The null- and alternative hypotheses (respectively H0 and H1) of the sub-questions are listed below:

I. Difference in calling activity and shipping traffic between two years.
   H0: There is no significant difference in calling activity of blue and fin whales and shipping traffic activity between 2019/20 and 2020/21.
   H1: There is a significant difference in calling activity of blue and fin whales and shipping traffic activity between 2019/20 and 2020/21.

II. Lagged correlation between either of the environmental variables and blue and fin whale calling activity.
   H0: There is no significant lag in correlation between either of the environmental variables and blue and fin whale calling activity.
   H1: There is a significant lag in correlation between some of the environmental variables and blue and fin whale calling activity.

III. Relationships between predictor variables (including shipping traffic activity and the environmental factors) and calling activity of blue and fin whales.
    H0: There is no significant relationship between the predictor variables and the calling activity of blue and fin whales.
    H1: There is a significant relationship between the predictor variables and the calling activity of blue and fin whales.

3. MATERIALS AND METHODS

3.1 Study site

In this study, I used acoustic data that were recorded in the Santa Barbara Channel (SBC). The acoustic buoy was deployed at 34.1124° N, 119.7744° W at a depth of 180 m (Figure 4). This location was chosen because it is on the northern slope of the Channel Islands, in the vicinity of the prevailing shipping lanes to and from the ports of Los Angeles (LA) and Long Beach (LB), but due to the sound propagation characteristics of the area sounds received at this location are coming exclusively from the basin north of the Channel Islands (Širović, 2018). I, therefore, assumed that the hydrophone collected data mostly from this area in which blue and fin whales are known to actively feed.

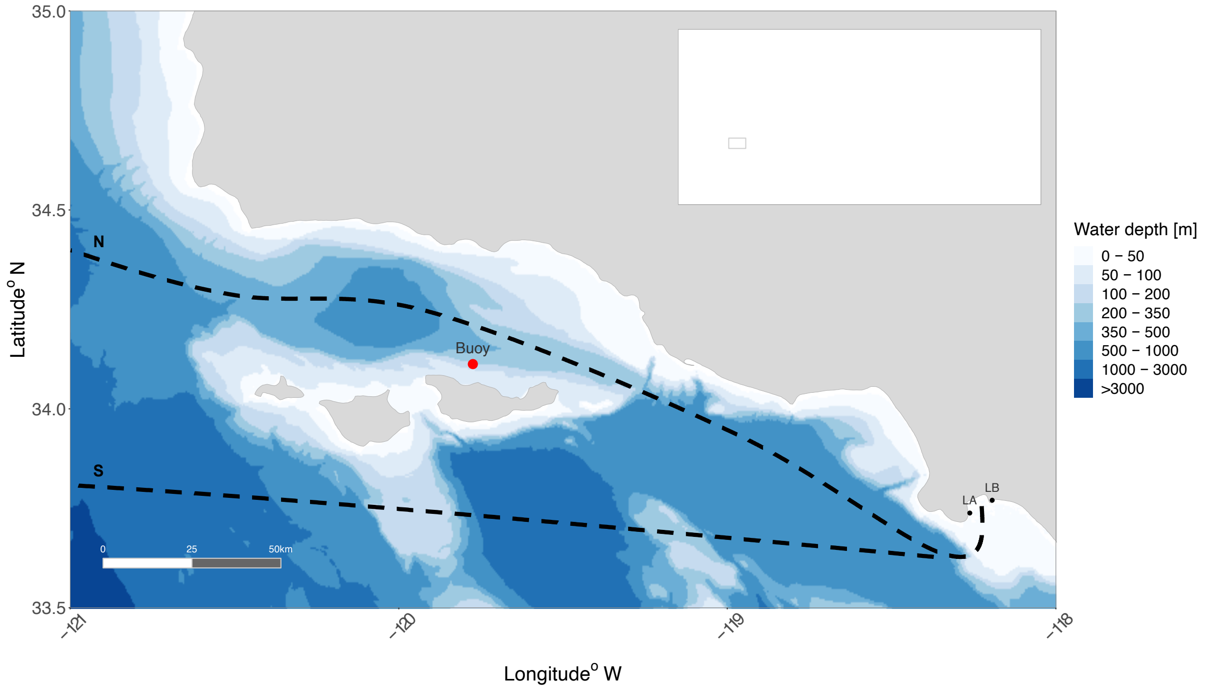

Figure 4. Map of the study site. Buoy with hydrophone marked as red dot. Dashed lines represent main northern (N) and southern (S) shipping lanes to and from Ports of Los Angeles (LA) and Long Beach (LB). Map created using software program R.

3.2 Data collection

3.2.1 Acoustic data

To investigate the potential effects of shipping traffic on the calling occurrence of blue and fin whales, I analyzed four months (November 25th – March 25th) of passive acoustic data from two consecutive years (2019/20-2020/21). The first year represents the period immediately before the onset of the pandemic and its start, and the second year represents the return to pre-pandemic shipping conditions. I used the same time periods of each year to remove the need to account for the seasonal variation in baleen whale acoustic behavior. Acoustic data were recorded using the passive acoustic monitoring system DMON (digital acoustic monitoring instrument) (Baumgartner et al., 2019). The DMON hydrophone and recording system had a sensitivity of -203.0 dB re V/µPa rms with a total gain of 33.2 dB, zero-to-peak voltage of 1.5 V, and 16-bits A/D converter. The buoy was deployed and started recording immediately on November 23rd 2019 and it was retrieved on March 30th 2021. Data were recorded at a sampling rate of 2 kHz, on a duty cycle that recorded for 30 minutes of every hour, recording from hh:40:00 – hh:10:00, to optimize data storage.

To allow for efficient analysis, I created long-term spectral averages (LTSAs) with 5 second temporal and 1 Hz frequency resolution. Fast Fourier Transforms (FFT) were used to create spectrograms from the timeseries of data, visualizing the distribution of acoustic energy at different frequencies over time (Au & Hastings, 2008). I executed this by accessing the software program Triton via MATLAB (Version 2019b). I used Triton to visualize the LTSAs and spectrograms and manually log the occurrence of blue and fin whale calls, as well as log ship passages. Because of the different frequency and temporal scale at which blue and fin whale calls versus ship passages occur, I divided the detection and logging into two rounds: I first logged the blue and fin whale calls, and second I logged each visible ship passage.

3.2.1.1 Blue and fin whale call detection

To detect blue (Northeast Pacific A, B, and D) and fin (20 and 40 Hz) whale calls, I set the spectrogram variables to display 60-second plots within a 0-200 Hz frequency band. The FFT size was set to 1000-points with a 90% overlap and Hanning window, to optimize time and frequency resolution. Brightness and contrast were respectively set to 50 and 1000, with occasional adjustments to get a positive identification of potential calls, after which returning them to the original settings of 50/1000. Presence of each distinct call type was logged within every 15 minute bin of data and calls presence is reported as number of 15 min bins per day with a call.

3.2.1.2 Ship passage detection

I logged each individual ship passage within every 30 minutes of data. I did so by analyzing the LTSAs with brightness and contrast respectively set to 50 and 1000 within a 0-1000 Hz frequency band. The FFT size was set to 1000-points. Obvious presence of ship noise at a frequency of 200 Hz was used to log the start and end of a ship passage in case this was not cut off by the 30-minute ON/OFF sampling. If only part of the passage was visible, the start or end was marked at the start or end of duty cycle, respectively. Since I was interested in the number of passages by day, and that a passage generally occurred in less than 30 minutes, this method was sufficient to account for all passages within the recorded period. The ship passage data is represented as the number of passages per day.

3.2.2 Environmental data

I accessed environmental satellite data using the European Union Copernicus Marine Service Information (CMEMS; managed by the Copernicus Programme of the European Union, from https://www.data.marine.copernicus.eu/en). I extracted data for sea surface height (SSH), sea surface temperature (SST), and chlorophyll a (Chl a) (Table 1). Acoustic propagation models developed for the SBC (Širović 2018) were used to estimate the area over which environmental data was gathered and averaged (Figure A1). I chose to focus on the area with relatively low transmission loss, so that the acoustic and environmental data would most likely be from the same area. This led me to extract data from an area of 34.0° by 34.5° N and 119.25° by 120.25° W from 25 October 2019 until 26 March 2021 to cover the entire research period. Environmental data was extracted and analyzed one month prior to the whale calling and shipping data, to enable the time lag analysis. I assumed that a possible delay between upwelling events and response of the system in the form of increase in prey and whale abundance could be up to two weeks (Croll et al., 2005; Service et al., 1998; Dugdale & Wilderson, 1989). SSH, SST and Chl a had a daily temporal resolution, and a varying spatial resolution which are summarized in Table 1. The data from CMEMS were available for the entire duration of interest for all variables.

Table 1. Overview of environmental variables used in modeling, along with their appropraite units and spatial scales, and data sources for each variable.

Variable	**Unit**	**Spatial scale (° meridian)**	**Dataset ID**	**Source**
Sea Surface Height (SSH)	m (above sealevel)	0.25 * 0.25	SEALEVEL_GLO_PHY_L4_MY_008_047	https://doi.org/10.48670/moi-00148
Sea Surface Temperature (SST)	°C	0.05 * 0.05	SST_GLO_SST_L4_REP_OBSERVATIONS_010_024	https://doi.org/10.48670/moi-00169; Good et al., 2020; Lavergne et al., 2019; Merchant et al., 2019
Chlorophyll a (Chl a)	mg/m^3	0.036 * 0.036 (original 4km)	OCEANCOLOUR_GLO_BGC_L4_MY_009_104	https://doi.org/10.48670/moi-00281

3.3 Statistical analysis

3.3.1 Temporal scale assessment

To ensure sample independence of the response variables, I calculated the integral timescales (ITS) for each call type to assess over which time period (in days) the call counts should be averaged (Table 2). The ITS (T*) calculations were done using a custom code in MATLAB based on the following formula (1) in which $\Delta\tau$ is the time series for the number of lag steps (N'), and $\rho(\tau_i)$ is the autocorrelation for the lag (τ_i) with respect to time (Emery & Thomson, 2001).

$$T^* = \frac{\Delta\tau}{2}\sum_{i=0}^{N'}[\rho(\tau_i) + \rho(\tau_{i+1})] \tag{1}$$

I calculated the ITS using the entire sampling period for fin whales, but due to blue whale migration southward in early winter, the ITS was calculated only over the time period of their calling presence. Next, I only used the second study period (2020/21) to calculate the ITS for blue whale A-, B-, and D-calls and fin whale 20 Hz-calls, because of low counts in the first year (2019/20). However, I used both study periods to calculate the ITS for fin whale 40 Hz-calls, because of their consistent presence in the data. The ship passage counts and environmental variables were then also averaged over the same ITS per call-type for subsequent analyses.

Table 2. Overview of call types and study periods for which the corresponding ITS values (in days) were calculated. Note that the 'ITS (used)' column represents a rounded T*-value which I used for further calculations.

Call type	Study period	ITS (T*)	ITS (used)
Blue whale A-call	2020/21	4.98	5
Blue whale B-call	2020/21	5.1441	5
Blue whale D-call	2020/21	3.5851	5
Fin whale 20 Hz-call	2020/21	7.1461	7
Fin whale 40 Hz-call	2019/20	1.5825	2
	2020/21	1.8166	

3.3.2 Difference in calling activity, shipping traffic, and environmental variables between two years

Before statistically investigating the difference in the call counts per call type (averaged according to ITS-values), counts of shipping passages, and environmental variables, I tested each variable for normal distribution using the Shapiro-Wilk normality test (Royston, 1982). Since the data were not normally distributed, I used non-parametric approaches. To visualize the data, I used boxplots for all call types and shipping. I then used the non-parametric and non-paired Mann-Whitney U-test to test if the calling and shipping activity, and SSH, SST, and Chl a differed significantly between the two years (Hollander et al., 2013; Bauer, 1972). For each statistical test, I assumed strong significance when $p < 0.05$, weak significance when $p < 0.1$, and no significance if $p > 0.1$. I performed all visualizations and analyses of the data using software program R (Version 2022.12.0+353).

3.3.3 Lag in correlation between the environmental variables and blue and fin whale calling activity

I used cross-correlation lag analysis to investigate whether there was a lag in time between either of the environmental variables (SST and Chl a) and calling activity of the different call types (Emery & Thomson, 2001). To do so, I separated the data for the two years and used the ccf() function in R creating Lag-ACF (i.e. 'Auto-Correlation Function') plots for each study period and each call type with corresponding SST and Chl a values. Note that SSH was not used for this analysis because of high concurvity with SST (see section 3.3.4.1 below). Consequently, I extracted the peak ACF-value and the related lag at this peak when this relation was significant, significant, i.e. when the peak crossed the 95% confidence interval in the plot. The lag on the x-axis was given in time units, which corresponded to the used ITS-values per call type. Thus, in order to interpret the lag of the cross-correlation, I multiplied the lag with the ITS-value per call type to identify the lag in days. A positive ACF-value can be interpreted as the predictor occurring before the calling activity. Inversely, a negative ACF-value can be interpreted as calling activity occurring before the predictor variable. I assumed that the lag-coefficient was only biologically relevant when positive, as that is when it could suggest the potential lagged response of calling activity as a function of changing SST or Chl a. Environmental variables that showed a significant lagged effect on calling activity were used in subsequent models with their lag fitting the corresponding calling activity. The variables that did not show a significant lagged effect on calling activity were used in the models with the original environmental data.

3.3.4 Relationships between shipping activity, environmental factors, and blue and fin whale calling activity

To statistically analyze the potential relationships between the four predictor variables (shipping, SSH, SST, and Chl a) and the response variable (call counts per call type) over time, I created Generalized Additive Models (GAMs) using the 'mgcv' package in software program R (Wood, 2017). GAMs were used in order to include multiple independent predictor variables, described by smoothed spline functions (Hastie & Tibshirani, 1987). I created a dataframe for each call type and shipping, SST and Chl a over the entire study period (i.e. both years combined) averaged over their corresponding ITS-values (Table 2).

3.3.4.1 Model determination and assessment

I tested each call type for zero-inflation and overdispersion to determine which distribution to use for GAM fitting. None of the call types showed zero-inflation, but only fin whale 40 Hz-calls showed equidispersion. Therefore, the GAM for fin whale 40 Hz-calls was fitted to a Poisson distribution and the GAMs for blue whale A- B-, and D-calls and fin whale 20 Hz-calls were fitted to a Tweedie distribution (Wood, 2017). The call counts were rounded to integers to fit the distributions.

To determine which of the candidate predictor variables to use in the models, I tested for concurvity (i.e. dependence) of the environmental predictor variables. I found high concurvity between SSH and SST in all cases (concurvity > 0.8), hence I decided to exclude SSH from the models. The remaining predictor variables were allowed to be smoothed using the $s(x_i)$ function, allowing for non-parametric smoothing, and exploring potential non-linear relationships between the predictors and response variable. All models were fitted using 'Restricted Maximum Likelihood' (REML) to determine the smoothing parameters of each predictor variable. I set the knots (k) for each predictor variable to a value for which the model was not showing underfitting nor overfitting, leading to a k = 3 for blue whale A- and D-calls, and fin whale 20 Hz-calls, and k = 5 for blue whale B-calls and fin whale 40 Hz-calls.

I tested different models for each call type, with each singular and all possible permutations of predictor variables (Formulas 2-8). I examined the fitness of all models by inspecting the output of the diagnostic plots and their corresponding values. Subsequently, I tested different models and determined best-fitted model using the Akaike Information Criterion (AIC) (Sakamoto et al., 1986). In case the lowest AIC-values of models were <1 different, and results of the models were similar (i.e. including significant predictors, similar % Deviance explained), I chose the model simplest model (i.e. fewest predictor variables).

$$g(E(Y_i)) = \; call\ type_i \sim s(shipping_i) + \; \varepsilon \tag{2}$$

$$g(E(Y_i)) = \; call\ type_i \sim s(shipping_i) + s(SST_i) + \; \varepsilon \tag{3}$$

$$g(E(Y_i)) = \; call\ type_i \sim s(shipping_i) + s(SST_i) + s(Chla_i) + \; \varepsilon \tag{4}$$

$$g(E(Y_i)) = \; call\ type_i \sim s(SST_i) \; + \; \varepsilon \tag{5}$$

$$g(E(Y_i)) = \; call\ type_i \sim s(SST_i) + s(Chla_i) + \; \varepsilon \tag{6}$$

$$g(E(Y_i)) = \; call\ type_i \sim s(Chla_i) + \; \varepsilon \tag{7}$$

$$g(E(Y_i)) = \; call\ type_i \sim s(shipping_i) + s(Chla_i) + \; \varepsilon \tag{8}$$

As a result of this process (Table A1:Table A5), the final chosen model for blue whale A- and B-calls included all predictor variables (shipping, SST, and Chl a; Formula 4). For blue whale D-calls and fin whale 20 Hz-calls I selected the model the included shipping and Chl a as predictors (Formula 8). Finally, for fin whale 40 Hz-calls I selected the model that included SST and Chl a as predictors (Formula 6). From the model summary of chosen models, I report the following values: p-values for each predictor~response relationship, Reference degrees of freedom (Ref. df), either F-value (for blue whale A-, B-, D-calls, and fin whale 20 Hz-calls) or Chi-squared (X^2) (for fin whale 40 Hz-calls), test-statistic (R^2), and the deviance explained (%).

4. RESULTS

In total, I analyzed 241 days (over the total two time periods), including 2892 hours of data for blue whale Northeast Pacific A-, B-, and D-calls, fin whale 20 Hz- and 40 Hz-calls, and ship passages. While there were more periods with detected blue whale calls, fin whale 40 Hz calls were the most consistently present across the two years (Table 3).

There was generally higher calling activity during 2020/21 for all blue whale call-types and fin whale 20 Hz-calls, with extremely low presence during 2019/20 (Figure 5). Blue whale A- and B-calls were only detected during four days in the 2019/20, with their last detection on December 21st 2019. Blue whale D-calls were detected on a total of 7 days in the same period, with its last detection on December 31st 2019. Fin whale 20 Hz-calls were present during 12 days in 2019/20. Fin whale 40 Hz-calls were continuously present throughout both years, with some fluctuations in daily averages. There were clear peaks in their presence during both periods; in 2019/20 there was a peak around the first week of December and later that same month, while there was a peak in the middle of January 2021 during the second period. In 2020/21, two clear detection peaks can be observed in blue- and fin whale 20 Hz-calling activity. The first peak for blue whales is at the end of November / beginning of December 2020, and the second peak is later that month around December 24th. The second peak is concurrent with the first clear peak for fin whale 20 Hz-calls, with a second peak around January 8th 2021. This second peak of fin whale 20 Hz-calls is also observed for blue whale D-calls, and weakly for A- and B-calls. Generally higher daily calling activity was observed in 2020/21 for all blue whale call types and fin whale 20 Hz-calls (Figure 5).

Shipping passages were present throughout the entire sampled time, with some daily fluctuations, but no clear difference between the two years (Figure 5). The environmental conditions, as described by SST, SHH and Chla variables, were substantially different for both years. SSH and SST appear to follow a similar trend, with overall lower values in 2020/21 than 2019/20 and a decrease in values over time, indicative of lower temperatures and lower SSH, later in the study period. Both SSH and SST show an evident and more pronounced drop at the end of 2020/21 compared to the previous year. Overall, Chla concentration was generally lower in 2019/20 than 2020/21. Some peaks of Chl a are observed in late October, mid-December, and early-January during 2019/20, however, the peaks in Chl a concentration are approximately twice as high in 2020/21 study period compared to the previous year, with a clear longer-lasting peak from late February into March 2021 (Figure 5).

Table 3. Summary of number of counts of 15 min bins with each call/sound type during each study period, as well as total over the total duration of the study. Number of samples left after averaging data across appropriate ITS to create independent samples is also presented.

Call/sound type	2019/20 (count)	2020/21 (count)	Total (count)	Sample size (n) after averaging into independent samples
Blue whale A-call	29	1131	1160	26
Blue whale B-call	22	1270	1292	26
Blue whale D-call	22	316	338	26
Fin whale 20 Hz-call	91	767	858	36
Fin whale 40 Hz-call	545	296	841	122
Ship passages	1294	1225	2519	[redacted]

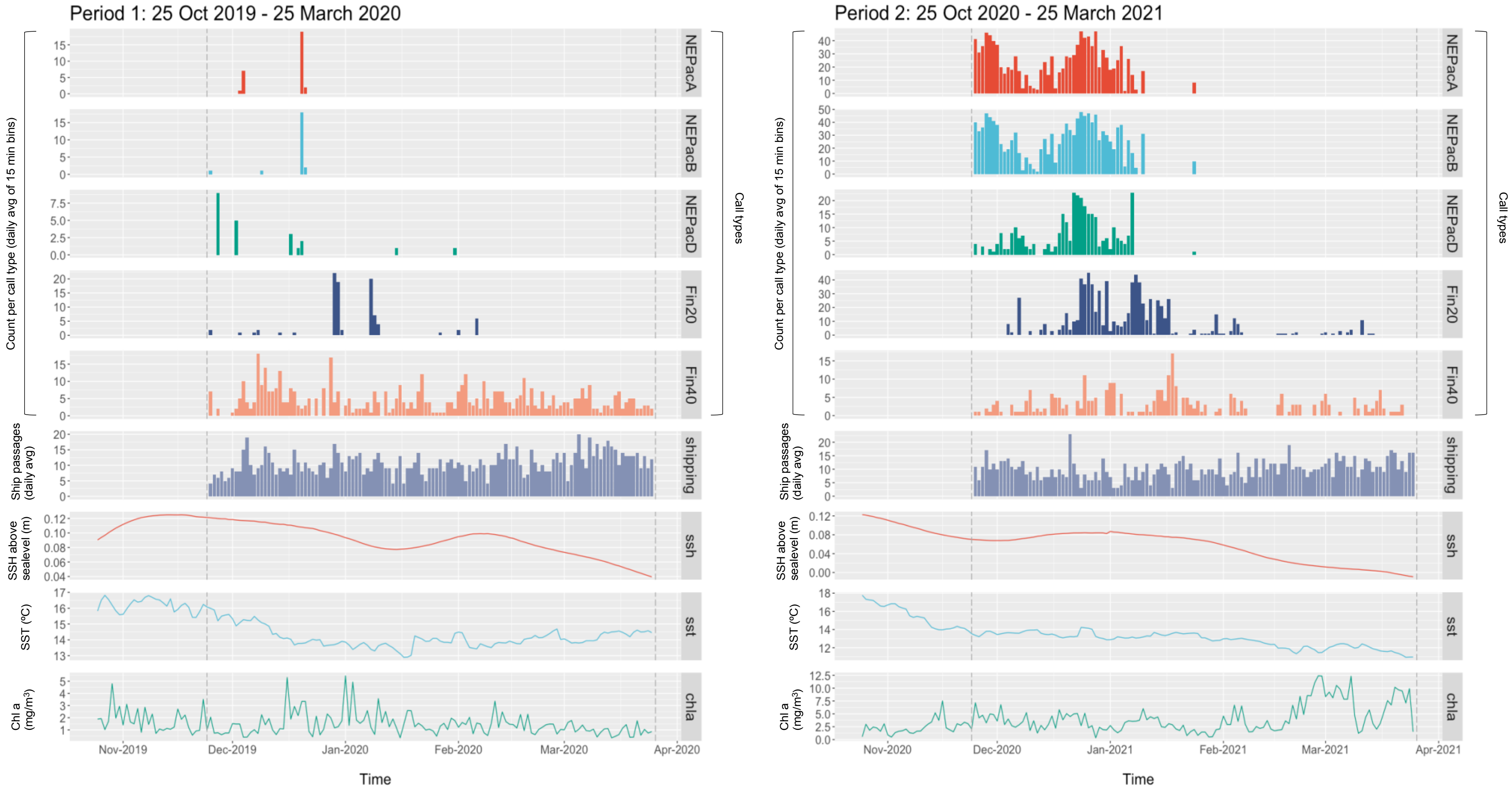

Figure 5. Count of (top to bottom) Northeast Pacific (NEPac) blue whale A-, B-, and D-calls, and fin whale 20 Hz- and 40 Hz-calls over 15 min bins and counts of ship passages with first year from November 25, 2019 – March 25, 2020 on the left and second year from November 25, 2020 – March 25, 2021 on the right. Remotely sensed environmental data for Sea Surface Heigth (SSH in m above sealevel), Sea Surface Temperature (SST in °C) and chlorophyll a (chla in mg/m^3) is shown in three bottom panels, with first year from October 25th 2019 – March 25th 2020 on the left and second year from October 25th 2020 – March 25th 2021 on the right. Dotted line represents start and end of sampling effort. For all variables, presented data are daily averaged counts or values. Note that y-axis scales differ for different variables between years.

4.1 Calls, ship passages, and environmental variables per period

There was a significant difference between the two years in the occurrence of blue whale A-calls (Mann-Whitney U-test, $W = 17.5$, $p = 3.00 * 10^{-3}$), blue whale B-calls (Mann-Whitney U-test, $W = 17$, $p = 2.97 * 10^{-4}$), blue whale D-calls (Mann-Whitney U-test, $W = 33$, $p = 6.50 * 10^{-3}$), and fin whale 20 Hz-calls (Mann-Whitney U-test, $W = 73.5$, $p = 4.50 * 10^{-3}$), with higher call rates in 2020/21 occurring for all those call types (Figure 6). Fin whale 40 Hz-call rates also had a significant difference between the years (Mann-Whitney U-test, $W = 2831$, $p = 6.27 * 10^{-7}$), with higher calling activity in 2019/20 (Figure 6). No significant difference was found for counts of shipping passages between the two years (Mann-Whitney U-test, $W = 7915$, $p = 0.328$). Furthermore, all environmental variables (SSH, SST, and Chl a) differed significantly between the two years. Overall lower values were observed in 2020/21 for SSH (Mann-Whitney U-test, $W = 18784$, $p < 2.2 * 10^{-16}$), as well as for SST (Mann-Whitney U-test, $W = 18888$, $p < 2.2 * 10^{-16}$). This was opposite for Chl a, which generally had higher values 2020/21 (Mann-Whitney U-test, $W = 3626$, $p < 2.2 * 10^{-16}$).

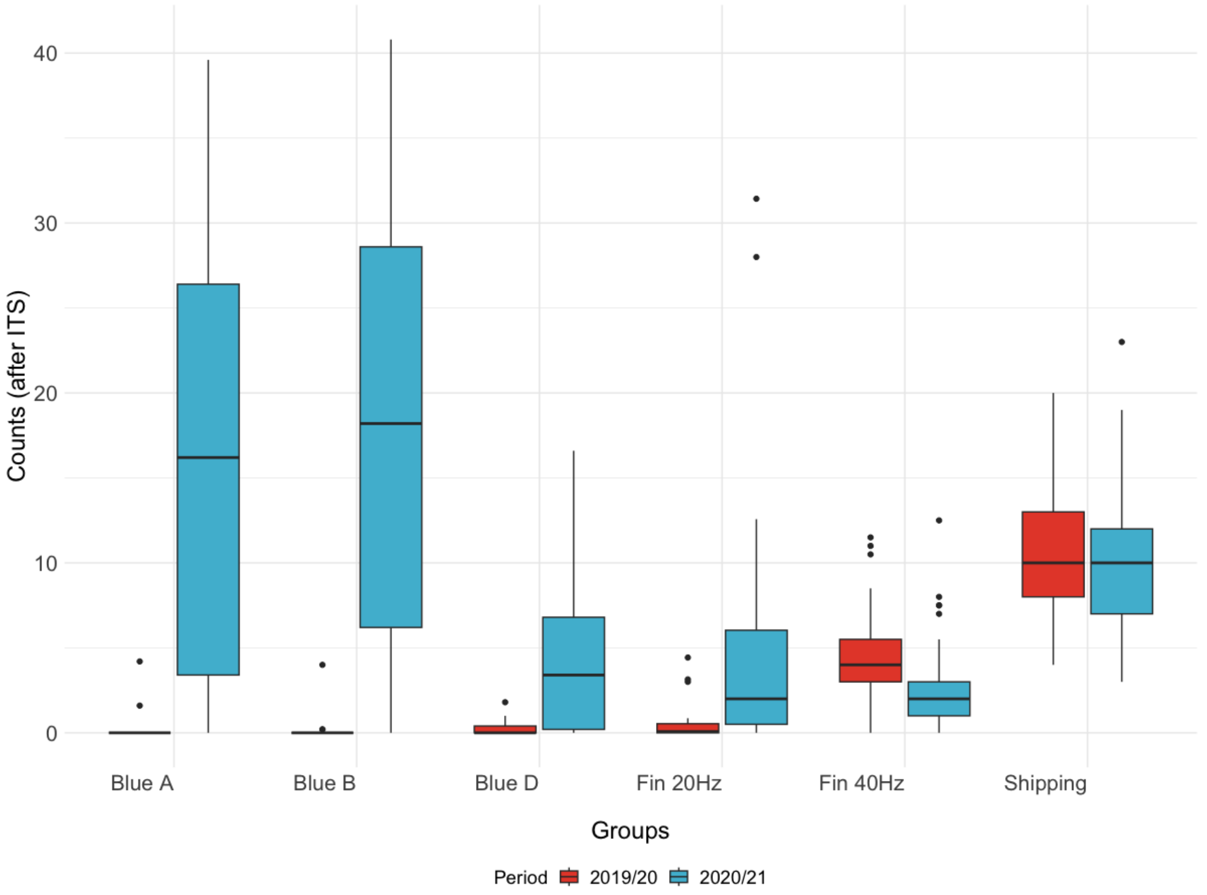

Figure 6. Boxplot representing the difference in total counts (after ITS-calculations) between two sampled time periods (i.e. 2019/20 and 2020/21) for all call types (blue whale A-, B-, and D-calls, and fin whale 20 Hz- and 40 Hz-calls) and shipping passages.

4.2 Time-delay between calling activity and environmental variables

There was a significant time delay between SST and blue whale B-calls during 2020/21, and for fin whale 20- and 40 Hz-calls in 2019/20 (Figure 7). Blue whale B-calls showed a lag of three ITS-units, i.e. 15 days. The lag for fin whale 20 Hz-calls was four, hence 28 days, and for fin whale 40 Hz-calls it was six, i.e. 12 days. Subsequently, only fin whale 20 Hz-calls showed a significant lagged effect, of one time-unit i.e. 7 days, on Chl a concentrations during 2019/20 (Figure 8). These results are included in the subsequent models of blue whale B-calls, and fin whale 20- and 40 Hz-calls, in the case of which variables used for fitting were lagged by the appropriate number of days.

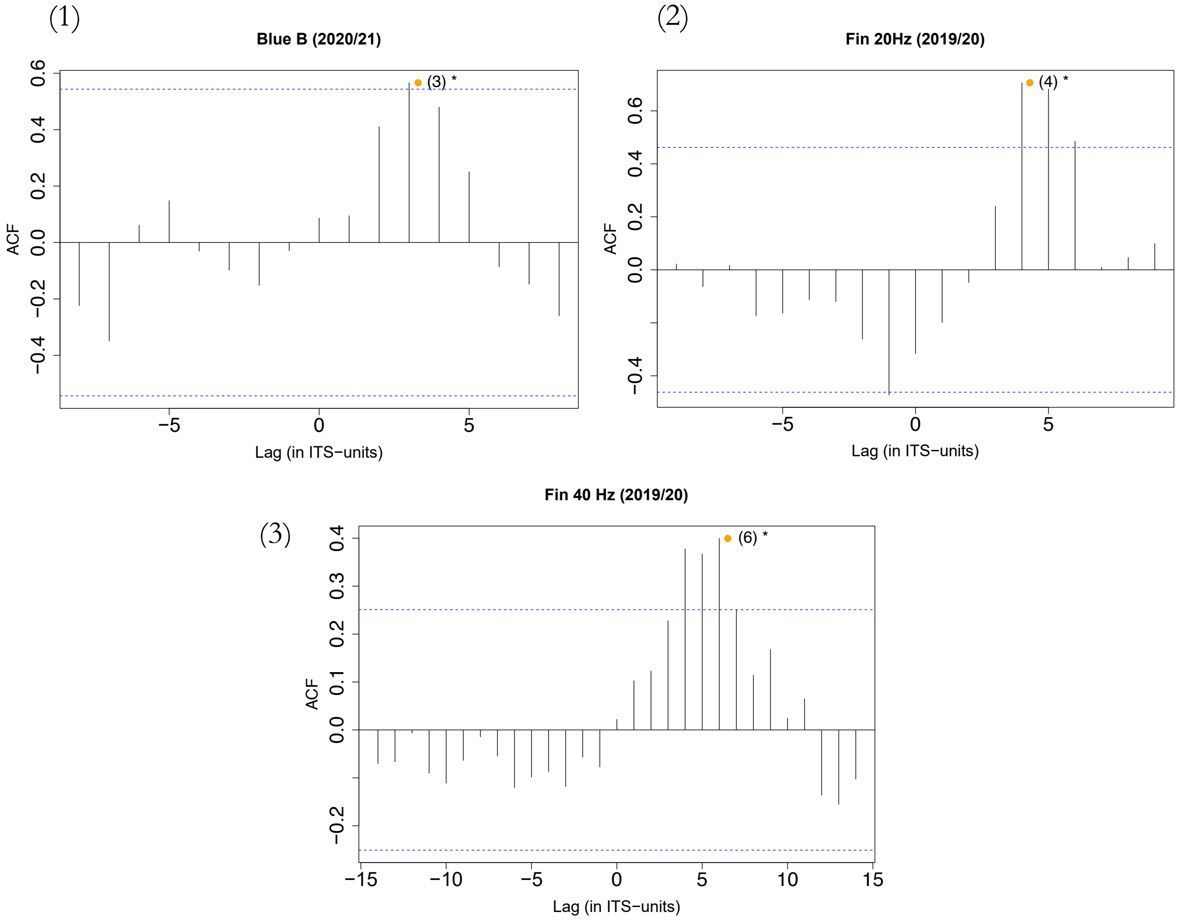

Figure 7. Significant lag (*) in cross-correlations of SST and (1) blue whale B-calls in 2020/21, (2) fin whale 20 Hz-calls in 2019/20, and (3) fin whale 40 Hz-calls in 2019/20. (Value) in plots represents lag in ITS-units.

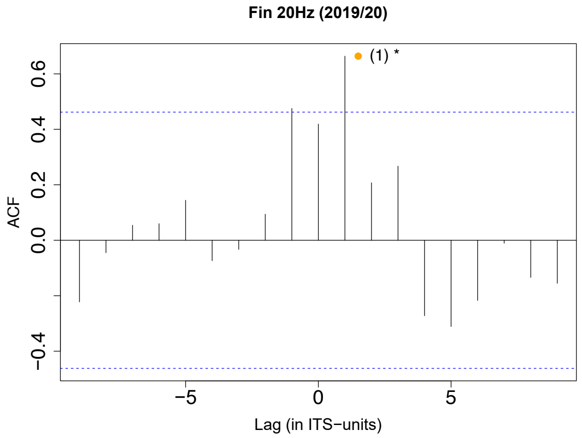

Figure 8. Significant lag (*) in cross-correlation of Chl a and fin whale 20 Hz-calls in 2019/20. (Value)* in plot represents lag in ITS-units.

4.3 Relationship between calling activity, shipping, and environmental variables

The best-fitted models investigating the relationship between calling activity and shipping and the environment all included shipping and Chl a, with additional inclusion of SST for blue whale A-calls and fin whale 40 Hz-calls (Table 4). There was a strong significant effect of Chl a on calling activity of all call-types. Shipping was found to strongly affect blue whale D-calls and fin whale 20 Hz-calls, as well as weakly affecting blue whale B-calls. SST (lagged) only showed a significant effect on fin whale 40 Hz-calling activity.

4.3.1 Effect of shipping and environmental variables on blue whale calls

Even though the best-fitted model for blue whale A-calls included all three predictor variables (shipping, SST, and Chl a), with a deviance explained of 51% (Table 4), there was only a significant relationship between blue whale A-calls and Chl a, with a general positive relationship between the two (Figure 9). The best-fitted model for blue whale B-calls included shipping and Chl a as predictor variables, which had an explained deviance of 55.9% (Table 4). There was a strong significant relationship between Chl a and blue whale B-calling activity with an overall positive trend. A weakly significant, negative relationship was found between shipping and blue whale B-calls (Figure 9). For blue whale D-calls, the best-fitted model also included shipping and Chl a as predictors. This model had an explained deviance of 40.3% with a strong significant effect from both predictors (Table 4). Shipping and D-calling activity had a negative linear relationship while the relationship between D-calling and Chl a was positive and nearly linear (Figure 9).

4.3.2 Effect of shipping and environmental variables on fin whale calls

For fin whale 20 Hz-calls, the best-fitted model included shipping and lagged Chl a, which explained 66.7% of the deviance (Table 4). Both predictors showed a strong significant effect on the calling activity; the effect of shipping on 20 Hz-calling activity was negatively linear, and the effect of Chl a was positive for smaller values but was poorly defined at higher values due to the small number of samples (Figure 10). The best-fitted model for fin whale 40 Hz-calls included all predictor variables (shipping, lagged SST, and lagged Chl a) with an explained deviance of 24.4% (Table 4). There was a strong significant effect of lagged SST and lagged Chl a on the calling activity of fin whale 40 Hz-calls. The relationship between SST and calling activity showed a positive relationship for the middle values of SST and was flat on the extremes, whereas the trend of Chl a showed a weak negative linear relationship with calling activity of 40 Hz-calls (Figure 10).

Table 4. Results of all Generalized Additive Models (GAMs) per call type. Test-statistics of each model was in accordance with distribution that model was fitted to (F-value for blue A-, B-, D-calls, and fin whale 20 Hz-calls, and X^2-value for fin whale 40 Hz-calls). Significant values are displayed in bold (* for strong significance, and . for weak significance).

Response variable	Predictor variables	Model results			Model assessment		
Call type	**Predictor**	**Ref. df**	**Test-statistic (F / X^2)**	**p-value**	**R^2**	**Deviance explained**	**AIC**
Blue A	Shipping	1.73	1.69	0.136	-0.247	51%	132.6
	SST	1.00	0.432	0.518			
	Chl a	**1.00**	**13.2**	**$1.47 * 10^{-3}$ ***			
Blue B	**Shipping**	**2.13**	**2.48**	**0.0989 .**	-0.11	55.9%	127.9
	Chl a	**1.88**	**10.2**	**$9.47 * 10^{-4}$ ***			
Blue D	**Shipping**	**1.00**	**5.18**	**0.0324 ***	-0.339	40.3%	98.8
	Chl a	**1.45**	**8.80**	**$2.87 * 10^{-3}$ ***			
Fin 20 Hz	**Shipping**	**1.00**	**24.3**	**$2.41 * 10^{-5}$ ***	0.764	66.7%	131.0
	Chl a (lag)	**2.00**	**12.4**	**$1.44 * 10^{-4}$ ***			
Fin 40 Hz	Shipping	1.00	2.51	0.113	0.205	24.4%	545.3
	SST (lag)	**3.74**	**25.2**	**$3.25 * 10^{-5}$ ***			
	Chl a	**1.00**	**3.88**	**0.0488 ***			

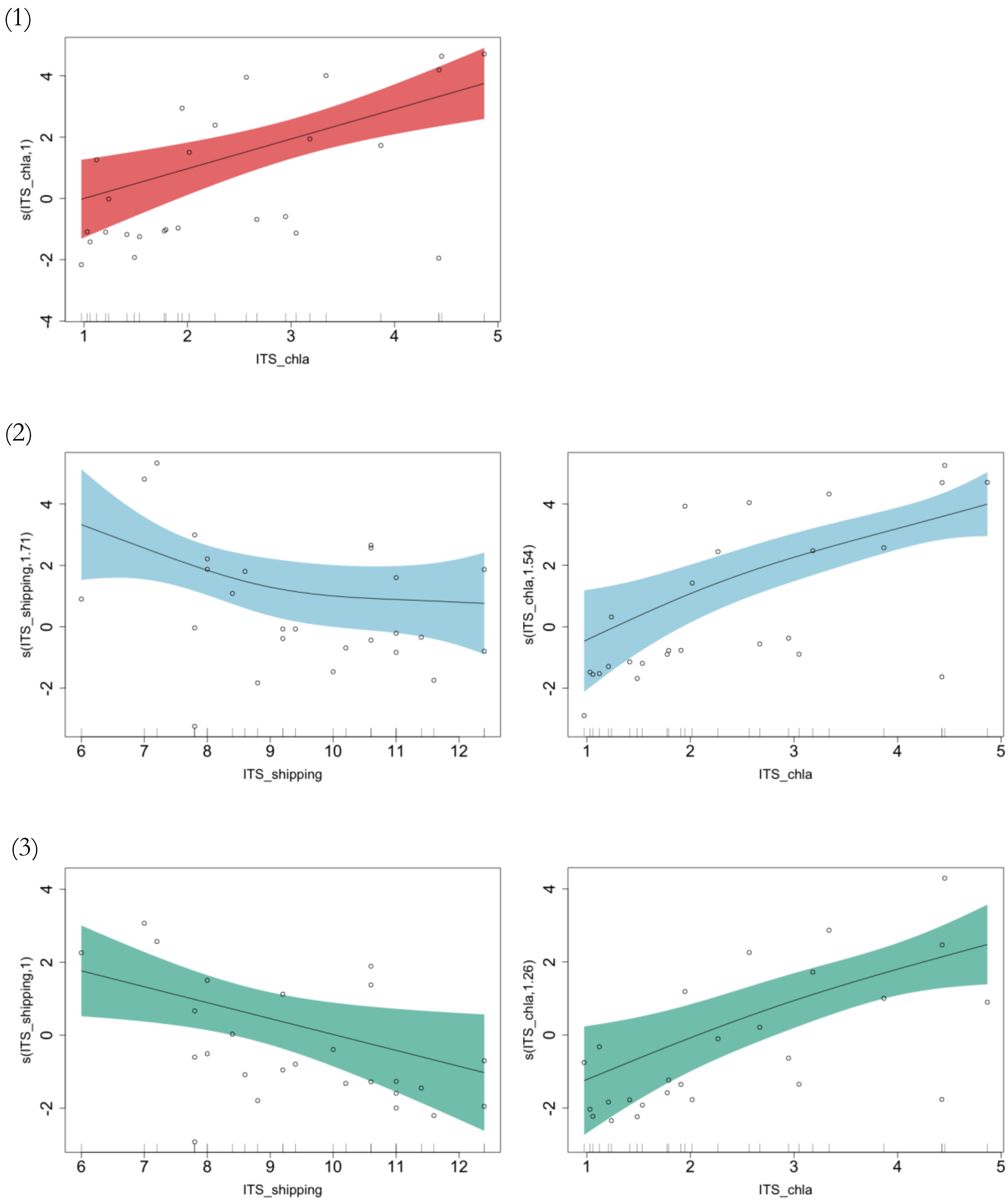

Figure 9. The mean-adjusted partial fit of predictor variables for best blue whale call-type Generalized Additive Models: (1) A-call, (2) B-call, and (3) D-call model. Higher values on the y-axis indicate more call-detections. The plots show the average of the partial fit (solid line), the standard error of this fit (color shading), and the partial residuals (o). The vertical lines along the x-axis indicate the number of observations at each value of the predictor variable.

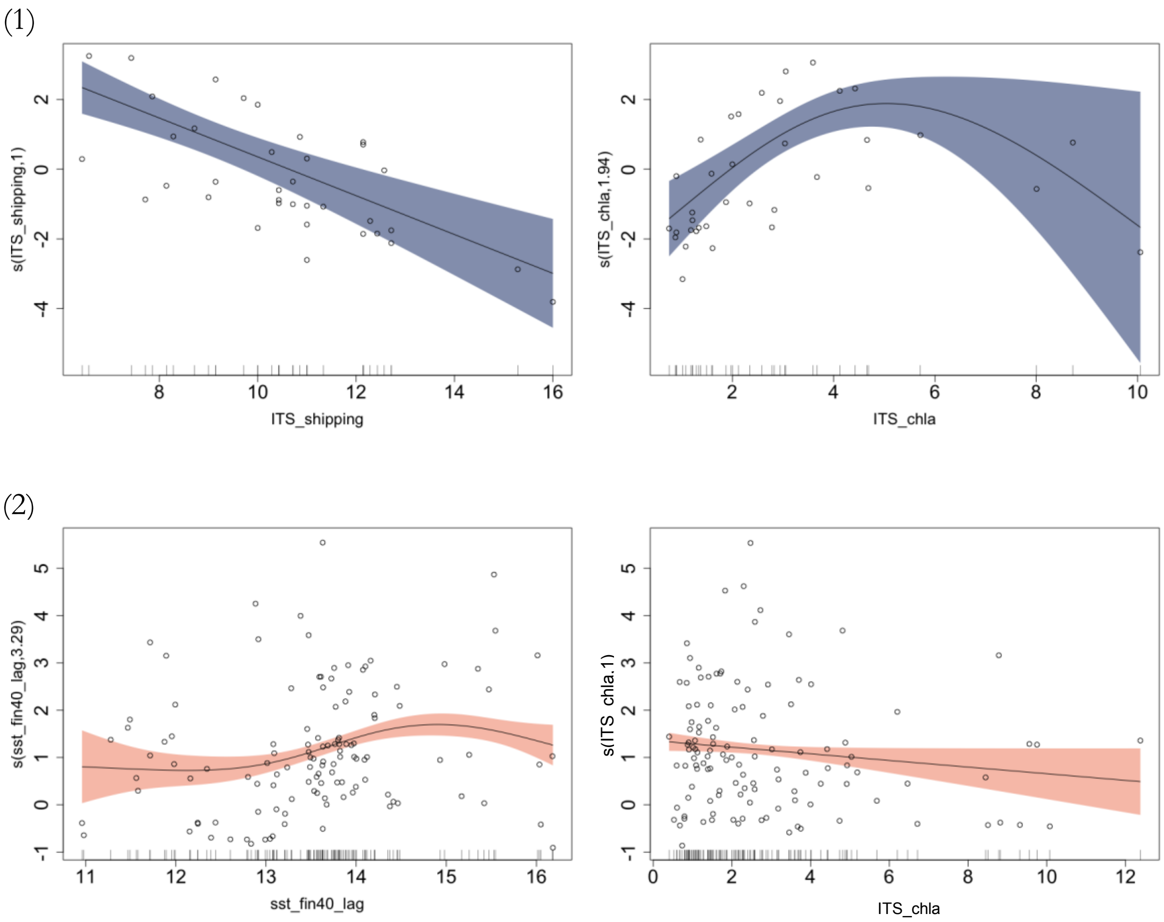

Figure 10. The mean-adjusted partial fit of predictor variables for best fin whale call-type Generalized Additive Models: (1) 20 Hz-call, and (2) 40 Hz-call model. Higher values on the y-axis indicate more call-detections. The plots show the average of the partial fit (solid line), the standard error of this fit (color shading), and the partial residuals (o). The vertical lines along the x-axis indicate the number of observations at each value of the predictor variable.

5. DISCUSSION

This study was the first to investigate the effect of shipping on blue and fin whale calling abundance in the Santa Barbara Channel before, during, and after the Covid-19 pandemic. Interestingly, the abundance of shipping passages did not differ between or across the sampled time periods, hence no clear effect of the Covid-19 pandemic on shipping traffic was observed from these acoustic data. However, there was a clear difference in whale calling activity between the two years. Blue whale calls were fairly absent during 2019/20, and present with significantly higher activity of all call-types in 2020/20. This same pattern was observed for fin whale 20 Hz-calls. Only fin whale 40 Hz-calls were persistent throughout both years, even with higher activity in 2019/20. Although the shipping intensity did not significantly differ between 2019/20 and 2020/21, an overall negative impact of shipping on calling activity was still observed for blue whale B- and D-calls, as well as for fin whale 20 Hz-calls.

Occurrence of whales is also affected by environmental conditions. Initial upwelling can be measured by SSH and SST, and I used those variables as a proxy. High rates of primary productivity are measured by chlorophyll a concentration, but this biological response is known to have a delay between 6 to 10 days from initial changes in the physical environment (Dugdale & Wilderson, 1989; Service et al., 1998). I found a significant lagged relationship between SST and blue whale B-calls (in 2020/21), and fin whale 20 Hz- and 40 Hz-calls (both in 2020/21) of respectively 15, 28, and 14 days. However, when adjusting for these lagged values in the models, no significant effect of SST on blue whale B-calls and fin whale 20 Hz-calls was found. Thus, only the activity of fin whale 40 Hz-calls was significantly affected by SST when adjusted for the delayed effect. No relationship between blue whale A- and D-calls and SST was found.

The environmental variables related to upwelling and primary production can be considered as a proxy for prey abundance. The high energy demand of blue and fin whales encourages them to seek areas of high primary and secondary productivity in search for extremely dense patches of prey (Savoca et al., 2021; Goldbogen et al., 2006; Croll et al., 2005). In this study, I found a general positive effect of Chl a on all call-types except fin whale 40 Hz-calls, which showed a slight negative relationship. Remarkably, Chl a was only significantly affecting fin whale 20 Hz-calls when tested for a delayed effect (7 days), whereas all other call-types did not show a significant relationship when testing for a lagged effect of Chl a. Peaks in primary productivity (Chl a) will only lead to peaks in krill abundance after some more time (up to 4 months) (Croll et al., 2005). However, the results of this study show an effect of chlorophyll a on fin whale 20 Hz-calls with already a 7-day delay. It is important to note that the temporal scale of this study was 4 months of 2 consecutive years, hence potentially not long enough to observe the full impact of changes in chlorophyll a concentration on blue and fin whale calling activity.

5.1 Shipping before, during, and after the pandemic

5.1.1 Delayed temporal trend of shipping decrease during Covid-19

The first goal of this research was to investigate the difference between shipping and calling activity between the winters of 2019/2020 and 2020/2021. Although there was a clear difference between calling activity for each call type between the years, shipping traffic was present throughout the entire timeseries. The null hypothesis that there was no clear difference between the years can thus be rejected for the calls, but not for shipping. This finding is in contrast to the significant decrease of shipping noise and overall shipping traffic that other studies found during the Covid-19 pandemic (March et al., 2021; Ryan et al., 2021, Thomson & Barclay, 2020).

For example, the study by Ryan et al. (2021) found a persistent decrease of low-frequency vessel noise in the Monterey Bay region starting in February 2020 until July 2020. Globally, the Covid-19 pandemic caused a decrease of 24% in shipping noise (at 63 Hz 1/3 octave band) between 2019 and 2020, mostly affecting the Arctic, Greenland Sea, and the Gulf of California (Jalkanen et al., 2022). The research performed by Jalkanen et al. (2022) stated that the global decrease of noise levels was measured from October/November 2019 onwards. Another study with a global spatial scale investigating the effect of Covid-19 on marine traffic was performed by March et al. (2021), who found that the change in marine traffic density in the U.S. only decreased in late February / early March, similar to findings of Ryan et al. (2021). Acoustic data off Canada's Pacific coast revealed contrasting results, where one site showed a significant decrease in low-frequency noise from the first quarter of 2020, but another location did not show the same trend (Thomson & Barclay, 2020). Moreover, several studies found different temporal changes of the effect of Covid-19 on low-frequency noise levels caused by a reduction in shipping (Jalkanen et al., 2022; March et al., 2021; Ryan et al., 2021; Thomson & Barclay, 2020) .

Since the first year of data from this study only covered the beginning of the Covid-19 pandemic, until late March 2020, it appears that the shipping traffic in the Santa Barbara Channel was not yet affected by the global pandemic by that point. Investigating acoustic data from March 2020 onwards could reveal the later effects of the pandemic on shipping activity in this area. A relatively quick recovery of shipping traffic was found to commence in July 2020 (Ryan et al., 2021), which could suggest that even if such a decrease occurred during the time between the two periods analyzed in this study, there could easily have been a restoration of pre-pandemic shipping activity in this region by the second study period (November 2020 – March 2021). Contrastingly, Jalkanen et al. (2022) found another decreasing trend in global underwater noise-levels at the end of 2020, potentially related to the second wave of lockdowns in that period. This coincides with the second study period of this study (November 2020 – March 2021), which could indicate there were indeed lower noise levels in 2019/20 as a result of Covid-19, yet the same decrease was found during 2020/21 as a result of the second wave of lockdowns. This could explain the similar activity of shipping traffic in 2019/20 and 2020/21 observed in this study. Comparing the number of shipping passages or the source levels (in dB) of noise produced by the shipping traffic in both periods of this study to values of pre-pandemic conditions would be essential to confirm this hypothesis.

5.1.2 Policy-based shipping lanes from and to Ports of LA and LB

Another possible explanation for the continuous presence of shipping traffic could be related to the implementation of the 'Ocean-Going Vessel Fuel Rule' that was implemented for the Santa Barbara Shipping lane in 2009, and further updated in 2011 (Klotz & Berazneva, 2022; CARB, 2008). The main incentive of this rule was to reduce health impacts on humans from fine particulate matter (PM) resulting from the high shipping intensity by reducing vessel speed and require use of fuel with lower sulfur content. Two other incentives of this rule included reducing the risk of whale collisions and decreasing noise pollution by shipping traffic. Before this rule, approximately 95% of all voyages to and from the Ports of LA and LB traveled through the SBC, but after the rule was implemented, this percentage was reduced to 15% after six months. The policy was modified in 2011, increasing the region of the emission control area (ECA) up to 24nm from the shoreline of the Channel Islands. This modification appeared to reduce avoidance of the

Channel, leading to 60% usage of the SBC after six months of implementation (Klotz & Berazneva, 2022), with an overall decreasing trend of noise produced by shipping (ZoBell et al., 2021).

This policy was still in place during the time period in which this study was conducted. As shipping activity related to transits from and to Asian ports decreased earlier than other shipping traffic during the Covid-19 pandemic (e.g. Dirzka & Acciaro, 2022), it would be interesting to investigate if vessels transiting between Asian ports and LA and LB were mostly using the shipping lanes north or south of the Islands. As I found no change in shipping activity between 2019/20 and 2020/21, this could suggest that shipping traffic north of the islands was less connected to international transport (which by this point was the part mostly affected by Covid-19) (Jalkanen et al., 2022), but instead was driven by traffic going along the coast of North America. I did not have access to data with which I could determine this, therefore investigating the details of transiting vessels south of the Channel Islands during this time period would be an interesting follow-up to evaluate the potential impact of Covid-19 on the marine soundscape across the broader area.

5.2 Noise-driven distribution of blue and fin whales: behavioral change or masking?

Before digging into the effects of the environmental variables (in subquestion II and III), I first investigated the impact of shipping on the calling activity of blue and fin whales as part of the third subquestion. For blue whale B-, and D-calls, and for fin whale 20 Hz-calls I found a clear negative relationship between the intensity of shipping traffic and calling activity. The null hypothesis that shipping does not have an effect on these call types can therefore be rejected. There are generally three possible explanations for the observed trend: (1) whales responded to shipping traffic and either moved away from the source or did not call in the presence of shipping, (2) the shipping noise masked potential calls, or (3) there were generally fewer whales in the study area during periods of higher shipping, but this difference could have been driven by other factors.

5.2.1 Blue whales and ship noise

A study performed by McKenna et al. (2009) in the Santa Barbara Channel found that the distance between the hydrophone and a transiting vessel severely impacted the ability to detect blue whale B-calls at distances below 4 km. Whereas A- and B-calls of blue whales often occur as a song, B-calls can also be observed repeatedly without prior A-calls (Oleson et al., 2007b; Thompson, 1996). The weak negative effect of shipping on blue whale B-calls could therefore be due to the limited detectability of these calls during periods when shipping passages were < 4km from the hydrophone, hence masking the B-calls. McDonald et al. (2009) observed a frequency shift with a declining trend for blue whale B-calls. One of their hypotheses describes the shift as a potential adaptation to increasing low-frequency noise levels in the ocean. However, this lower frequency of B-calls would result in lower source levels of the call, and therefore likely not outweigh increased noise (McDonald et al., 2009). The persistence in the declining frequency of blue whale B-calls thus remains uncertain. In this study, I did not investigate the potential frequency-shift in blue whale B-calls as a result of shipping noise, however results from this study indicate, and thereby aligning with results from McKenna et al. (2009), that blue whale B-calls were likely masked by shipping noise.

The findings in this study show a negative relationship between shipping activity and blue whale D-calls, which is in contrast to the findings of Melcon et al. (2012). Their study found an increased abundance of D-calls during periods with higher shipping noise at mid-frequencies (1-8 kHz). On the other hand, they found lower rates of D-calls during exposure to MFA sonars with similar frequencies. In this study, I used noise from ship passages located at 200 Hz to determine shipping activity, hence the different measures used to measure shipping activity between this study and Melcon et al. (2012) (shipping noise measured at respectively 200 Hz and 1-8 kHz) could suggest that the different results are incompatible. Again, the negative relation between shipping activity and D-calls in this study could be related to masking of calls due to low-frequency ship noise. However, if shipping activity actually decreases or masks blue whale D-calling activity, this could potentially interfere with their feeding behavior, as this call-type is associated with foraging (Oleson et al., 2007a). It is important to note that in this study, I detected fewer blue whale calls throughout 2019/20 compared to 2020/21, which could also indicate the absence of blue whales at this time, unrelated to shipping. This would be in accordance with findings from Croll et al. (2001a), who found that their distribution pattern was rather linked to oceanographic parameters associated with upwelling and prey than driven by noise. But late December, they can be expected to have departed this region and started their migration south (Szesciorka et al., 2020; Širović, 2015)

5.2.2 Fin whales and ship noise

Fin whale calls were present throughout the entire sampling period, dominated by 40 Hz-calls. Interestingly, only 20 Hz-calls were negatively affected by ship noise. As predicted by a model created by Cholewiak et al. (2018) fin whale song (regular sequence of 20 Hz-calls; Watkins et al., 1987) is highly impacted by masking, decreasing up to 90% of their total communication space. Shipping activity was present at a constant rate throughout the entire study, whereas fin whale 20 Hz-calling activity was higher in 2020/21, and 40 Hz-calls were present throughout both years with slightly higher activity during the first year. If 20 Hz-calls were indeed masked by ship noise, this would be in contrast to findings in the 2020/21 study period, when shipping intensity was similar to the first, yet higher activity of 20 Hz-calls was found. This could suggest that other (non-exclusive) factors, such as environmental and behavioral variability, are able to further explain the difference in calling activity between the years. Another study found that fin whales were generally less acoustically active when exposed to more shipping noise (Castellote et al., 2012), but this does not seem in line with the persistent presence of 40 Hz-calls.

In a behavioral context, when using different call types as proxies for distinctive whale behavior, fin whale 20 Hz-song is most likely related to a reproductive function, since it is exclusively produced by male individuals (Croll et al., 2002). Irregular 20 Hz-pulses are hypothesized to be related to social behavior, in the form of contact maintenance (McDonald et al., 1995). In this study, I did not differentiate between the two types of 20 Hz-calls, limiting the ability to relate the effect of shipping activity on specific fin whale behavior. However, the model results could suggest that ship noise negatively impacts social behavior of fin whales, as well as the ability of male singers to attract females. On the other hand, fin whale 40 Hz-calls are hypothesized to be related to foraging behavior (similar to blue whale D-calls) (Širović et al., 2013; Watkins et al., 1981). Their persistent presence, seemingly unaffected by shipping noise, could suggest that calling behavior of fin whales is less bothered by ship noise in feeding contexts. This would be in line with the predictions of Redfern et al. (2017), who found that fin whale habitats overlap with noisier waters, compared to the main habitats of blue and humpback whales.

In this study, I did not explore the potential frequency-shift of fin whale 20 Hz-calls as a response to shipping noise (Bradbury & Vehrencamp, 1998). However, in this important year-round fin whale habitat (Širović et al., 2015; Širović et al., 2013), where they co-occur with high densities of shipping traffic (Smith et al., 2022; Redfern et al., 2017; McKenna et al., 2009), it would be interesting to investigate if fin whales adjust their frequency to increase their communication space amidst the noise (Clark et al., 2009). It is essential to understand the changes in acoustic behavior regarding frequency shifts, as producing calls at suboptimal frequencies requires more energy for the whales to produce sounds (Castellote et al., 2012; Bradbury & Vehrencamp, 1998).

5.3 Productivity-driven distribution of blue and fin whales

The second subquestion of this study was to explore the effect(s) of potential time-delayed correlations between the environmental variables SST and Chl a and calling activity. I found significant results for blue whale B-calls (15 day-delay in 2020/21), and fin whale 20 Hz- and 40 Hz-calls (respectively 28- and 14 day-delay both in 2019/20) responding to SST, as well as a significant lagged relationship between chlorophyll a and fin whale 20 Hz-calls (7 day-delay in 2019/20). The null hypothesis of the second subquestion stating that SST does not have a delayed effect on calling activity of blue whale B-calls (2020/21), fin whale 20 Hz- and 40 Hz-calls (2019/20) can therefore be rejected. As for chlorophyll a, the null hypothesis that chlorophyll a does not have a lagged impact on calling activity can only be rejected for fin whale 20 Hz-calls.

As part of the third subquestion, I tested for potential relationships between environmental factors and calling activity. Chlorophyll a, as an indicator of primary productivity, showed a clear positive effect on all call types of blue whales and a lagged positive effect on fin whale 20 Hz-calls, but not for fin whale 40 Hz-calls. Contrastingly, fin whale 40 Hz-calls appeared to be significantly affected by chlorophyll a in a negative linear relationship. Consequently, the null hypothesis that chlorophyll a does not impact the calling activity per call type can be rejected for all call types. Furthermore, SST only directly affected fin whale 40 Hz-calling activity, hence the null hypothesis that SST does not impact the calling activity can only be rejected for this call type.

5.3.1 Blue whales annual calling variability in SBC

Blue whale calls were almost exclusively detected in 2020/21. The best-fitted model to predict their calling activity included a significant effect of chlorophyll a for all call types (both years), as well as a lagged effect of SST on blue whale B-calls of 15 days (only 2020/21). Stafford et al. (2009) described a model in which blue whale calling was mostly related to SST with a 2 month-delay. In general, there is a persistent presence of blue whale calls from August to December in this part of the Northeast Pacific (Širović et al., 2015; Stafford et al., 2009; Oleson et al., 2007a; Stafford et al., 2001). The sampled time of this study reaches from late November to late March, thereby not covering the time at which blue whales are presumably most present in the area. This could indicate that the potential 2-month lag of SST as measured by Stafford et al. (2009) cannot be observed in this dataset because of the limited temporal scale.

The clear correlation between Chl a and all blue whale call types is in line with findings from previous studies (e.g. Burtenshaw et al., 2004; Smith et al., 1986). The diet of blue whales is relatively simple, as it consists almost exclusively of euphausiids (e.g. Fiedler et al., 1998), and therefore persists low in the foodweb. It is thus not surprising that the early signs of primary productivity, as indicated by chlorophyll a concentration, are closely related to blue whale calling activity. On the other hand, Stafford et al. (2009) found that blue whale calls were more closely related to SST than Chl a, which was not observed in this study.

The extent of calling activity of blue whales is quite variable over the years (e.g. Szesciorka et al., 2020; Širović et al., 2015; Stafford et al., 2009), also varying amongst areas within the Southern California Bight (Lewis & Širović, 2018; Širović et al., 2015). During the feeding season of blue whales from the summer through early winter, their distribution is mostly driven by the distribution of their prey (Szesciorka et al., 2020; Croll et al., 2001a). Blue whales seek areas of extremely high densities of krill, which are very local (Savoca et al., 2021; Goldbogen et al., 2006; Croll et al., 2005). And since blue whales are not year-round habitants of the Santa Barbara Channel (as opposed to some fin whale populations) (e.g. Širović et al., 2015), their (calling) presence or absence in the SBC is most likely affected by the prey-availability (Croll et al., 2001a). When comparing the two years of this study, the second year shows evidence of higher productivity, most likely caused by the strong La Niña event that occurred in that winter of 2020/21, which was the sixth strongest since 1982 (Hasan et al., 2022; Li et al., 2022). The higher productivity in the second year could explain the higher calling activity and longer persistence of blue whales in this area compared to the relatively less productive 2019/20 winter season. This would be in line with findings from Truong & Rogers (2023) who detected higher calling activity of pygmy blue whales (*Balaenoptera musculus brevicauda*) in the eastern Indian Ocean during La Niña conditions.

The lower calling activity during 2019/20 could be explained by the lower productivity, potentially leading the whales to migrate to southern breeding grounds relatively early, or seek foraging grounds elsewhere. During warmer years, with lower prey abundance in the Southern California region, blue whales are also found feeding opportunistically along their migration route, instead of going to particular well-known foraging grounds such as the SBC (Irvine et al., 2014; Calambokidis et al., 2009; Mate et al., 1999). Given the seemingly lower productivity, indicating lower prey abundance, during the first year of this study, it is possible that blue whales sought foraging grounds elsewhere. Generally, the movement range of Northeast Pacific blue whales is large during the foraging season, and the timing at which blue whales arrive and depart their well-known foraging habitats in the Southern California region, including the SBC, shows annual variability (Szesciorka et al., 2020; Širović et al., 2015; Irvine et al., 2014). The annual calling variability between 2019/20 and 2020/21 observed in this study is therefore in line with previous findings.

An additional explanation for the annual variability in calling activity of blue whales is enlightened by Szesciorka et al. (2020). They found a relationship between higher calling activity in the Southern California region when SST was relatively low in the previous year, as lower SST indicates higher and lipid-richer euphasiids abundance. The arrival of blue whales in this region, indicated by D-calling activity, was hypothesized to be linked to memory of environmental variables from previous years as cues for migrating from and to productive foraging grounds. During the study-period of 10 years, Szesciorka et al. (2020) found that whales arrived earlier every spring season, up to 1 month in the final year (2017). Even though the whales arrived at the foraging ground earlier, they did not leave the site sooner, hence prolonging their entire stay in the area. Investigating the environmental circumstances of 2018/19 might provide us with more understanding of the low calling activity of blue whales in 2019/20, potentially resulting from memory from the previous year (Szesciorka et al., 2020). Contrastingly, the findings of this study showing higher calling activity in 2020/21 is not in line with findings of Szesciorka et al. (2020), as their study's outcome would predict lower SST in 2019/20 should have occurred to be followed by higher calling activity in 2020/21. This was not the case in this study, as I observed relatively higher SST-values in 2019/20. The high productivity during 2020/21, as a result of a La Niña event, could have led to an even high calling activity of blue whales in 2021/22 as a result of this memory, but this has to be further explored. The role and timing of La Niña and El Niño events and its potential impact on timing of migrating from and to foraging grounds was not taken into account by Szesciorka et al. (2020), so it is not clear how these periods fit within the proposed hypothesis.

La Niña is generally characterized by lower SST and higher chlorophyll production and zooplankton biomass (Bograd & Lynn, 2001; Philander, 1985), and the phenomenon is usually found as a follow-up to an El-Niño event (Lynn & Bograd, 2002; Philander, 1985). However, the 2020/21 La Niña event was observed without any El Niño beforehand, which is in contrast to the general pattern (Li et al., 2022; Hasan et al., 2022). When observing data from this study, I found a gradual increase in blue whale D-calls in 2020/21. Blue whale D-calls are often related to foraging behavior, as described by e.g. Oleson et al. (2007b) and McDonald et al. (2001), explaining their positive linear relationship with Chl a, likely indicating higher prey abundance. The finding from my study that blue whale D-calls are highly present during late fall and early winter (last detection on January 24th 2021) is slightly in contrast to the findings of Szesciorka et al. (2020) and Oleson et al. (2007a) who found typical high occurrence from April through November. Since the dataset of this study only covers late November through late March, we can only interpret the observed trends in this period, however the high blue whale D-calling activity in these data could be explained by the relatively higher productivity during this time, and therefore potentially related to prolonged foraging during this La Niña-year.

Oleson et al. (2007a) found that blue whale A-B song and B-singular calls were typically recorded from June to January in Southern California. In this study, both A- and B-calls were recorded until mid-January 2021, thereby supporting findings from previous studies in the Southern California region (e.g. Lewis & Širović, 2018; Oleson et al., 2007a; Oleson et al., 2007b). Although I did not distinguish between A-B-song and repeated or singular B-calls, I found that A-calls were only observed in combination with a following B-call, but not vice versa. This explains the overall higher activity of B-calls in the 2020/21 data (1270 total counts in 15min bins) compared to A-calls (1131 total counts in 15min bins), supporting findings by Oleson et al. (2007a). Contrary to songs, Lewis & Širović (2018) found that singular A- and B-calls can be used by males as social bonding calls during feeding. The co-presence of the foraging-related D-calls and (potentially singular) A- and B-calls in this study could imply that these A-B-calls were actually social bonding calls during foraging. Consequently, these findings could suggest blue whale behavior related to both (social) foraging and reproductive behaviors, as I did not investigate the different sequences in which the calls occur.

5.3.2 Fin whales appear as true SBC inhabitants

Fin whale calls were detected during both consecutive years of this study, with higher activity of 40 Hz-calls in 2019/20 and higher 20 Hz-calling during 2020/21. Their persistent presence is in accordance with findings from other studies, where fin whale calls were detected year-round in Southern California (Redfern et al., 2017; Širović et al., 2017; Širović et al., 2015; Stafford et al., 2009; Forney & Barlow, 1998). As they appear to be true inhabitants of SBC, with migration patterns that are not yet fully understood, it is not surprising that their calls, dominated by 40 Hz-calls, were found throughout the entire study.

The environmental variable related to the prevalence of fin whale calls are found to mostly be SST, with a time-delay up to 3 months in the Northeast Pacific (Stafford et al., 2009). This is in contrast to blue whales, which were found more closely related to Chl a concentration. The pattern as described for fin whales by Stafford et al. (2009) was also found in this study, with a lagged effect of SST on both 20 Hz- and 40 Hz-calls (28 and 12 days in 2019/20, respectively). Chl a was also found to have a lagged effect on fin whale 20 Hz-calls, with a delay of seven days. The longer delayed effect of SST on fin whale calling occurrence found in Stafford et al. (2009) is hypothesized to be due to the more complex foodweb of fin whales compared to that of blue whales. They are considered generalists (Kawamura, 1980; Nemoto, 1970), and therefore have a longer delay in responding to changes in primary productivity (Stafford et al., 2009).

Interestingly, fin whale 40 Hz-calls were found to be less common in 2020/21 during La Niña, compared to the less-productive previous year. If these calls are related to foraging behavior (Širović et al., 2013; Croll et al., 2001a; Watkins, 1981), it would be expected that the calling abundance would be higher during 2020/21. Since some populations of fin whales are found to be year-round inhabitants of the SBC it could be that their calling activity is not as closely related to environmental variability as is the case for blue whales. Furthermore, the potential response of fin whale calling activity to environmental factors may not be fully observable due to the limited timescale of this study, which would have been too short to detect their response to changes in oceanographic features and prey availability (Stafford et al., 2009).

The behavioral context of fin whale 20 Hz-calls is assumed to be different when produced in a song or as singular pulses (Croll et al., 2002; Watkins, 1981). However, since I combined all variants into one call-type for this study, it is complicated to distinguish the type of behavior related to the calling activity of 20 Hz-calls. The significant difference in 20 Hz-calling abundance between the two years as observed in this study can be due to various non-exclusive reasons. For example, different environmental circumstances can be causing the difference. Generally, 20 Hz-song is abundant in the late fall and winter (Širović et al., 2013; Stafford et al., 2007; Nieukerk et al., 2004; Watkins et al., 2000), which was the case in 2020/21. However, since the sampling period of this study does not cover the complete feeding season, it is not possible to determine the temporal separation of the fin whale calls, as described by Širović et al. (2013). Širović et al. (2015) found overall variability in fin whale 20 Hz-calling activity depends on location in the Southern California Bight region. The relatively lower presence of 20 Hz-calls during the first year of this study is somewhat in line with findings from Širović et al. (2015), who found that the SBC might not be the preferred area of fin whales (at least as suggested by 20 Hz-call detections). The higher calling activity during 2020/21 could therefore potentially be a behavioral response to different environmental conditions driven by the La Niña event.

5.4 The role of blue and fin whales in a bigger context

Blue and fin whales are extremely important ecosystem engineers (Roman et al., 2014). The understanding of the functional roles of great whales increased after commercial whaling drastically decreased their abundance (Christensen, 2006). These functional roles are generally described by the whale carbon and oxygen flux, creating the so-called 'Whale Pump' (Roman & McCarthy, 2010), in which whales: (1) contribute to horizontal and vertical nutrient transfer, (2) higher productivity rates, and (3) act as a source of food and habitat possibilities (Roman et al., 2014). Horizontal nutrient transfer describes the process of nutrient transfer from foraging grounds at higher latitudes to breeding areas at lower latitudes. Transporting nutrients within the water column by feeding in the deeper waters and releasing feces in the surface column is known as vertical nutrient transfer (Lavery et al., 2010; Roman & McCarthy, 2010). Subsequently, the recovery of large whale species after whaling has increased global productivity rates, especially in the regions where the whales forage and breed. Lastly, whales are an important food source for other marine fauna, as well as acting as a habitat when their carcasses sink to the ocean floor. In this way, they also transport fixed carbon from the surface to the deep-sea (Smith et al., 2015; Roman et al., 2014).

Investigating the acoustic behavior of blue and fin whales has the potential to explain the distribution of these great whales on large spatial and temporal scales. Understanding their distribution could help us discover the recovery pattern after commercial whaling, as well as assessing their main feeding and breeding grounds. Gathering more knowledge about important habitats for blue and fin whales, including their migratory routes, can allow us to establish areas where human-environment interactions should be reduced in order to conserve essential marine space for these baleen whales. This is of particular importance in areas where anthropogenic activities exert high pressure on the marine environment (Duarte et al., 2021; Redfern et al., 2017; Clark et al., 2009; McKenna et al., 2009; McDonald et al., 2008), as is the case in the SBC.

5.5 Conservation of the marine soundscape

With shipping as the current main contributor to low-frequency noise in the marine soundscape, it is essential to continue research efforts on its impact on the acoustic environment of marine flora and fauna (Erbe et al., 2019; Redfern et al., 2017; Melcón et al., 2012; Croll et al., 2001a). This study has shown the negative effect of shipping noise on blue and fin whale calling detections, due to masking or behavioral changes, or both. Shipping is the biggest contributor to noise across wide temporal and spatial scales and overlaps severely with frequency bands of marine fauna hearing ranges and sound productions (Duarte et al., 2021). The occurrence of high noise levels derived from intense shipping activity in whale habitats is concerning, because of their dependence on acoustic communication for maintaining population dynamics, mother-calf interactions, and mate attraction (Au & Hastings, 2008; Oleson et al., 2007b; Croll et al., 2002; Bradbury & Vehrencamp, 1998; Edds-Walton, 1997). Moreover, regions experiencing extensive noise levels can indicate degraded acoustic environments (Redfern et al., 2017), leading to ecological and conservational concerns on large scales.

Several science-based policies have been established in Southern California to monitor and reduce the impact of shipping traffic on the marine soundscape, especially regarding great whales. Reducing vessel speed has been found to be an effective measurement to reduce noise (ZoBell et al., 2021), thereby reducing the impacts on marine mammals (Findlay et al., 2023), as well as reducing the risk of ship strikes with whales (Freedman et al., 2017). Other regulations such as the 'Green-Fuel Rule' in California indirectly benefit the marine soundscape by reducing vessel speed in important marine habitats. Vulnerable marine environments have benefitted from the establishment of the CINMS, as measured by reduced noise levels in this area compared to the general noise levels of the Santa Barbara Channel (Redfern et al., 2017). As well-described by Duarte et al. (2021), human anthropogenic activities have already managed to alter the marine soundscape severely from local to global scales. Continuing efforts to conserve the underwater acoustic environment is essential to conserve a healthy marine ecosystem, as the marine flora and fauna are dependent on acoustic properties of the ocean.

5.6 Limitations and future research

There are some limitations and difficulties when using and interpreting acoustic data. First of all, using acoustic data to investigate the impact of shipping noise on calling behavior is limited by the fact that acoustics can provide us with knowledge about the presence of whales, yet the absence of calls does not necessarily imply the absence of whales. Comparing these data to estimates provided by visual survey of blue and fin whales could be helpful to provide evidence for the actual (near) absence of blue whales in the SBC 2019/20, hence providing potential information about the acoustic behavioral response to shipping activity. Secondly, acoustic monitoring does not provide us with knowledge of abundance estimates of blue and fin whales. This knowledge is essential for conservation efforts, especially with regard to exploring the recovery of these whales after intensive whaling. Third, using calling activity as a proxy for more or less whale presence is conflicted by context-dependence. This means that certain behavioral contexts, for example, enhanced B-calling activity because of long-duration repetitive sequences or songs during the start of the breeding season (Oleson et al., 2007a, 2007b), might accelerate calling activity, not necessarily implying greater whale presence. At last, masking of low-frequency blue and fin whale calls by low-frequency (shipping) noise limits our ability to detect calls during times of overlapping occurrence (Erbe et al., 2019; Cholewiak et al., 2018; Clark et al., 2009; McKenna et al., 2009). Investigating the impact of shipping levels on calling activity is therefore limited by timings at which the two do not overlap to such an extent that the whale calls are completely masked. This could potentially be prevented to a certain extent by monitoring the calls with a hydrophone that is further away from the main shipping lane (i.e. > 4 km) (McKenna et al., 2009).

Further, I did not differentiate between different call-types in the form of song or irregular calls, thereby complicating our ability to interpret the behavioral context related to active calling periods of both blue and fin whales. Fully understanding the behavioral context during calling activity of blue and fin whales could provide us with insights on potential behavioral responses to shipping activity, especially during periods of enhanced or reduced shipping. For future research, it would be interesting to study the behavior related to different call-types, which would require a more fine-scale analysis including the separation of calls produced as irregular sequences or songs (especially true for blue whale A- and B-calls and fin whale 20 Hz-calls) (e.g. Širović & Oleson, 2022; Širović et al., 2015; Širović et al., 2013; Oleson et al., 2007b). In this way, we could further examine the potential effect of shipping noise and environmental factors on different behavioral activity in the Santa Barbara Channel. Examples of studies further investigating the impact of shipping activity on specific calling behavior could include studying the yearly increase of blue whale B-calls, as found by Lewis & Širović (2018), and explore whether the increase in production of this call-type could be related to an increase in shipping noise. As blue whale B-calls have high source levels and travel over extremely long distances, their yearly increase could be a compensation for increasing noise levels. Another example could be to study the potential effect of increased low-frequency noise, such as that from shipping traffic, on frequency shifts of call-types as found for fin whale 20 Hz-calls (Castellote et al., 2012; Bradbury & Vehrencamp, 1998).

Subsequently, this study is limited by a relatively small spatial and temporal scale. As for implications regarding the temporal scale, the main feeding season for blue whales during the late summer / fall in the SBC was not covered. Especially during 2019/20, this could have had a big impact on the findings of this study, as low productivity in the area could have driven blue whales to migrate southward earlier. The spatial distribution of blue whales within the Southern California Bight region has appeared to vary over the years (Širović et al., 2015). The relatively small spatial scale of this study does not include other important blue whale foraging habitats in this region, limiting the potential to study the broader foraging grounds of blue whales. Increasing the spatial and temporal scale of this study could improve our understanding of the calling variability of fin whale 20 Hz-calls during the two years, which could be explained by habitat preference, interannual calling variability, external forces, or a non-exclusive combination (e.g. Širović et al., 2015; Širović et al., 2013). Additionally, the limited spatial and temporal scale of this study also reduces our ability to investigate the potentially-delayed impact, or the effect of the second wave of the Covid-19 pandemic on shipping activity to a fuller extent.

The SBC is a region in which intensive human activities and vulnerable marine ecosystems interact (Smith et al., 2022; Redfern et al., 2017; Santora et al., 2017; Calambokidis et al., 2015; McDonald et al., 2008; Croll et al., 2005; Forney et al., 1995). The impact of noise is not only of great concern for baleen whales, but also for other species that depend on a healthy acoustic environment. If this is not studied thoroughly, conservation efforts might be too late, which could result in a degrading natural soundscape and decreasing biodiversity (e.g. Duarte et al., 2021). This trend, caused by a decline in vocalizing species, has already been observed in other marine habitats such as coral reefs and kelp forests, endangering biodiversity (Gordon et al., 2018; Gottesman et al., 2020).

Findings from this study indicate that blue and fin whales seek areas of high productivity indicating dense patches of prey, even amidst persisting shipping noise in the SBC. Noise from shipping activity overlaps with frequencies of blue and fin whale calls, thereby affecting their ability to use their acoustic environment. Investigating the timing of blue whale arrival, potentially driven by memory (Szesciorka et al., 2020), and daily variations in calling and foraging activities (Calambokidis et al., 2019; Oleson et al., 2007b), could help us to establish a policy in which shipping activity overlaps less with blue whale calling and foraging activity, thereby also reducing the risk of ship strikes (Calambokidis et al., 2019). The year-round presence of some fin whale populations in this area is also of concern in light of conservation efforts, because of the overlap with high intensities of shipping traffic and noise-levels. Studying their year-round movement and calling activity in the entire Southern California region could help us gain more knowledge regarding their preferred habitats in order to conserve these and potentially limit the whales' interaction with shipping traffic and enhanced noise levels.

Since this is the first study to investigate the potential effect of the Covid-19 pandemic on the shipping activity in the Santa Barbara Channel, but I did not find any clear difference in shipping activity, it would be interesting to compare this data to other sites covering the same time periods which showed a marked decrease in shipping activity, to study the effects of the decrease in shipping activity on whale acoustic behavior. A potential delayed effect of Covid-19 on the marine soundscape of the Santa Barbara Channel could be revealed when including data from a longer timescale. Comparing acoustic data from La Niña to other sites in the Northeast Pacific could provide us with a broader scope in understanding of the behavioral response in calling activity to enhanced productivity as an effect of La Niña. Moreover, combining environmental data with prey abundance estimates, as well as shipping noise, over a bigger spatial and temporal scale would allow us to gain knowledge about the potential trade-off between prey- or noise- driven distribution of blue and fin whales.

6. CONCLUSION

The main objective of this study was to investigate the impact of shipping traffic on calling activity of blue and fin whales in the Santa Barbara Channel. No difference in shipping activity as a result of Covid-19 was found, yet an overall high intensity of shipping traffic maintained throughout the entire period. Fin whale whales were continuously acoustically active, whereas blue whale calls were almost exclusively detected during periods of enhanced productivity as a result of La Niña. These findings contribute to existing research by providing additional proof of continuous presence of fin whales in the Santa Barbara Channel, seemingly unaffected by the persistent shipping traffic. On the other hand, blue whales mainly inhabit their foraging ground north of the Channel Islands in favorable environmental circumstances. Understanding the effect of anthropogenic noise on whale acoustic behavior is important to sustain a healthy underwater soundscape, contributing to a healthy marine ecosystem. The Santa Barbara Channel's unique bathymetry, combined with its role as a major shipping route and baleen whale foraging area, makes it exceptionally susceptible to variations in the marine acoustic environment. Including a thorough investigation of call-types in relation to behavior, as well as including data from visual surveys and prey distribution over a bigger temporal and spatial scale would enlarge our understanding of the effect or potential trade-off of shipping traffic and environmental factors on blue and fin whale ecology. Continuing interdisciplinary research including marine biology, acoustics, and environmental policy will be essential in developing sustainable solutions to mitigate the impact of anthropogenic noise on marine life.

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8. APPENDIX

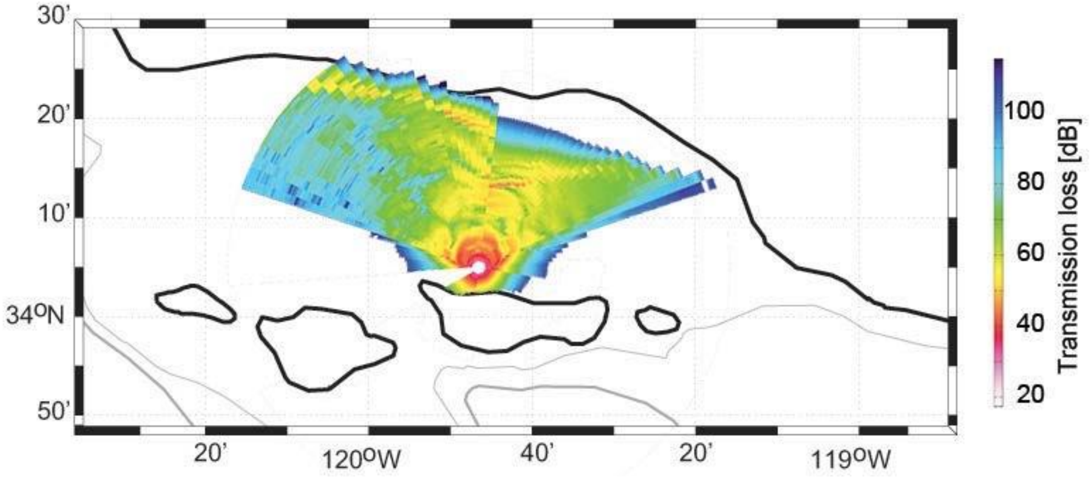

Figure A1. Propagation model for north slope of Santa Cruz Island (Santa Barbara Channel). Total transmission loss from buoy deployed at 34°6'0" N and 119°45'51" W at 167m depth. To the west, the area limit was dependent on radial length used in model, not necessarily the maximum detection range. Figure from Širović (2018).

Table A1. Results of seven Generalized Additive Models for blue whale A-calls. The test statistics for each model variable (Ref. df, test-statistic F, and p-value) are presented. The R^2-value and the deviance explained (%) by the model are represented in the model assessment. AIC-values were calculated for all models, resulting in model 3 (rastered) as the best-fitted model for blue whale A-calls.

Model	**Predictor(s)**	Model results			Model assessment		
		Ref. df	**F**	**p-value**	**R^2**	**Deviance explained**	**AIC**
1	Shipping	1	0.027	0.87	-0.040	0.12%	144.4
2	Shipping	1.31	0.099	0.912	-0.081	1.35%	142.1
	SST	**1.00**	**3.95**	**0.0589**			
3	Shipping	1.73	1.69	0.136	-0.247	51%	132.6
	SST	1.00	0.432	0.518			
	Chl a	**1.00**	**13.2**	**$1.47 * 10^{-3}$ ***			
4	SST	1	4.44	**0.0458 ***	0.0557	16.1%	139.8
5	SST	1.00	1.19	0.287	0.356	40.6%	134.0
	Chl a	**1.29**	**6.51**	**0.0123 ***			
6	**Chl a**	**1.77**	**7.29**	**$4.04 * 10^{-3}$ ***	0.402	39.2%	133.4
7	Shipping	1.31	0.099	0.912	0.0362	17.6%	142.1
	Chl a	**1.00**	**3.95**	**0.0589**			

Table A2. Results of seven Generalized Additive Models for blue whale B-calls. The test statistics for each model variable (Ref. df, test-statistic F, and p-value) are presented. The R^2-value and the deviance explained (%) by the model are represented in the model assessment. AIC-values were calculated for all models, resulting in model 7 (rastered) as the best-fitted model for blue whale B-calls.

Model	**Predictor(s)**	Model results			Model assessment		
		Ref. df	**F**	**p-value**	**R^2**	**Deviance explained**	**AIC**
1	Shipping	1	0.079	0.782	-0.0357	0.355%	140.0
2	Shipping	2.19	1.12	0.331	0.185	31%	140.2
	SST	3.15	1.171	0.193			
3	**Shipping**	**2.52**	**2.53**	**0.0697**	0.0206	64.1%	128.8
	SST (lag)	2.75	0.947	0.426			
	Chl a	**1.00**	**15.04**	**$9.36 * 10^{-4}$ ***			
4	SST (lag)	2.70	1.62	0.363	$-7.23 * 10^{-4}$	14.8%	139.6
5	SST (lag)	1.00	0.290	0.596	0.319	44.3%	131.0
	Chl a	**2.23**	**5.73**	**$8.47 * 10^{-3}$ ***			
6	**Chl a**	**2.47**	**5.42**	**$8.45 * 10^{-3}$ ***	0.42	45.1%	129.1
7	**Shipping**	**2.13**	**2.48**	**0.0989**	-0.11	55.9%	127.9
	Chl a	**1.88**	**10.2**	**$9.47 * 10^{-4}$ ***			

Table A3. Results of seven Generalized Additive Models for blue whale D-calls. The test statistics for each model variable (Ref. df, test-statistic F, and p-value) are presented. The R^2-value and the deviance explained (%) by the model are represented in the model assessment. AIC-values were calculated for all models, resulting in model 7 (rastered) as the best-fitted model for blue whale D-calls.

Model	**Predictor(s)**	Model results			Model assessment		
		Ref. df	**F**	**p-value**	**R^2**	**Deviance explained**	**AIC**
1	Shipping	1	0.782	0.385	$-4.83 * 10^{-3}$	3.15%	107.7
2	Shipping	1	0.763	0.391	$-4.85 * 10^{-3}$	11%	107.6
	SST	1	1.76	0.197			
3	**Shipping**	**1.00**	**5.15**	**0.0346 ***	-0.305	42.9%	100.6
	SST	1.00	0.237	0.6311			
	Chl a	**1.79**	**5.98**	**0.0132 ***			
4	SST	1	1.71	0.203	0.0392	7.81%	106.4
5	SST	1.91	1.41	0.327	0.142	40.6%	101.5
	Chl a	**1.96**	**4.20**	**0.0296 ***			
6	**Chl a**	**1.86**	**4.02**	**0.0262 ***	0.179	29.5%	101.4
7	**Shipping**	**1.00**	**5.18**	**0.0324 ***	-0.339	40.3%	98.8
	Chl a	**1.45**	**8.80**	**$2.87 * 10^{-3}$ ***			

Table A4. Results of seven Generalized Additive Models for fin whale 20 Hz-calls. The test statistics for each model variable (Ref. df, test-statistic F, and p-value) are presented. The R²-value and the deviance explained (%) by the model are represented in the model assessment. AIC-values were calculated for all models, resulting in model 7 (rastered) as the best-fitted model for fin whale 20 Hz-calls.

Model	**Predictor(s)**	Model results			Model assessment		
		Ref. df	**F**	**p-value**	**R²**	**Deviance explained**	**AIC**
1	**Shipping**	**1**	**18.1**	**$1.56 * 10^{-4}$ ***	0.292	36.2%	146.8
2	**Shipping**	**1.00**	**16.5**	**$2.92 * 10^{-4}$ ***	0.466	42.5%	147.2
	SST (lag)	1.83	1.71	0.293			
3	**Shipping**	**1.00**	**22.1**	**$5.07 * 10^{-5}$ ***	0.75	66.6%	132.9
	SST (lag)	1.00	0.212	0.649			
	Chl a (lag)	**2.00**	**9.33**	**$6.5 * 10^{-4}$ ***			
4	SST (lag)	3.05	2.22	0.106	0.0344	19.2%	159.2
5	SST (lag)	1.95	2.12	0.178	0.122	43.9%	148.3
	Chl a (lag)	**1.99**	**8.45**	**$1.3 * 10^{-2}$ ***			
6	**Chl a (lag)**	**1.99**	**9.07**	**$9.13 * 10^{-4}$ ***	0.126	36.7%	148.4
7	**Shipping**	**1.00**	**24.3**	**$2.41 * 10^{-5}$ ***	0.764	66.7%	131.0
	Chl a (lag)	**2.00**	**12.4**	**$1.44 * 10^{-4}$ ***			

Table A5. Results of seven Generalized Additive Models for fin whale 40 Hz-calls. The test statistics for each model variable (Ref. df, test-statistic F, and p-value) are presented. The R²-value and the deviance explained (%) by the model are represented in the model assessment. AIC-values were calculated for all models, resulting in model 3 (rastered) as the best-fitted model for fin whale 40 Hz-calls.

Model	Predictor(s)	Model results			Model assessment		
		Ref. df	**X^2**	**p-value**	**R^2**	**Deviance explained**	**AIC**
1	Shipping	1.00	2.48	0.115	$1.38 * 10^{-2}$	0.925%	599.2
2	Shipping	1.00	2.03	0.154	0.202	22.9%	547.3
	SST (lag)	**3.72**	**52.6**	**$< 2 * 10^{-16}$**			
3	Shipping	1.00	2.51	0.113	0.205	24.4%	545.3
	SST (lag)	**3.74**	**25.2**	**$3.25 * 10^{-5}$ ***			
	Chl a	**1.00**	**3.88**	**0.0488 ***			
4	**SST (lag)**	**3.63**	**51.7**	**$< 2 * 10^{-16}$**	0.204	21.9%	547.9
5	**SST (lag)**	**3.61**	**23.9**	**$5.59 * 10^{-5}$ ***	0.209	24.2%	546.7
	Chl a	2.56	4.69	0.159			
6	**Chl a**	**1.00**	**28.1**	**$< 2 * 10^{-16}$**	0.107	12.9%	566.9
7	Shipping	5.50	6.48	0.32	0.125	17.2%	566.8
	Chl a	**1.00**	**27.3**	**$7.64 * 10^{-8}$ ***			

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