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Navigating the Noise: evaluating the occurrence of vessels and cetaceans within Tamatea/Dusky Sound

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Abstract

Vessel use associated with recreation and tourism is currently increasing without limits in Dusky Sound. Passive acoustic monitoring was used to investigate spatiotemporal presence and potential cooccurrence of vessels with the endangered resident subpopulation of Fiordland bottlenose dolphins (*Tursiops truncatus*) and migratory humpback whales (*Megaptera novaeangliae*) within Tamatea/Dusky Sound, Fiordland Marine Area (FMA). Hydrophones were deployed between February 2022 and November 2023 at three recording sites to collect soundscape data within Dusky Sound. The internal coastline of Five Fingers Peninsula, inside Taumoana Marine Reserve, was identified as a previously unrecognised area of significant usage for Fiordland bottlenose dolphins. Detected humpback whale presence coincided with peaks in migration, and though identified by previous visual surveying efforts, the extent of their presence in the area during their northward migration was previously unreported. Humpback whale presence was significantly higher in June compared with other months, which is consistent with their described increased vocalisation behaviour during the northward migration.

Vessel presence detected by passive acoustic monitoring was primarily dictated by usage patterns of tourism and recreational vessels and was greatest in the channel south of Anchor Island, a highly utilised access into Dusky Sound from the outer coast. Monthly equivalent continuous sound levels (LEqs), produced using Automatic Identification System vessel records and sound propagation modelling, illustrated that sound exposure levels regularly reached ~ 150 dB re $1 \mu\text{Pa}^2 \cdot \text{s}$ within the study area. Cruise ship transits were the major contributor to these high levels, with noise levels exceeding the recommended behavioural exposure threshold for continuous sound in much of the area during the late spring and summer months. Proactive management strategies including vessel limits, speed restrictions (slowdowns) and exclusion zones (dolphin protection zones) are likely required in the future to protect these species before the potential impacts from increased tourism is seen in Tamatea/Dusky Sound.

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Chapter 1: Introduction

1.1 Physics of Sound in the Marine Environment

Sound is a waveform with an audible frequency that travels through elastic mediums such as gases, solids and liquids. In water, sound waves travel as longitudinal waves, sometimes known as compressional waves (Rogers & Cox, 1988). Longitudinal sound waves propagate mechanically through water as pressure fluctuations from the equilibrium state and are characterised by particle motion with vibrations back and forth in the same direction as the sound wave is travelling (Rogers & Cox, 1988). As a sound wave travels the particles move from their initial position, collide, rebound and collide again, oscillating with the sound wave as it travels (Bass & Clark, 2003). The characteristics of a sound wave can be described by several units including its frequency, amplitude and wavelength.

The frequency (f) of a soundwave describes the number of oscillations (cycles) occurring per second and is measured in Hertz (Hz). Frequency is useful in characterising the pitch of the sound. The time period (T) of the sound wave describes the amount of time (seconds) that it takes for an oscillation to occur and is the reciprocal of the frequency ($1/f$). The amplitude, measured in decibels (dB), is used to describe how loud a sound is. It represents an averaged measure of the different components of the sound's magnitude (and direction) over time. The wavelength (λ) measures the distance between two peaks (corresponding points) of two consecutive waves. Finally, the velocity at which the sound moves through the medium (c) is described by multiplying the wavelength of the wave by its frequency ($c = \lambda f$) (Nummela & Thewissen, 2008).

Sound pressure is a scalable quantity which refers to fluctuations in the water from the normal hydrostatic pressure due to the sound wave (Hawkins & Popper, 2017). It acts in all directions and is described best by its frequency and temporal quantities as well as its magnitude - it is used by all marine mammals and certain species of fish and is the most commonly measured aspect of sound as it can be sampled with hydrophones. Particle motion refers to the directional oscillations of particles in the water due to the sound wave and is a vector best described by the direction and size of the oscillations as well as their frequency and temporal characteristics. Particle motion is important to many fish species and invertebrates but is less frequently sampled as devices other than hydrophones are required (Hawkins & Popper, 2017).

Sound waves attenuate as they travel through a medium due to sound intensity (energy) being lost, with different mediums having different attenuation rates. Sound propagates very effectively in water, with the speed of sound in water (1500 ms^{-1}) being approximately five times greater than in air (Pine et al., 2014). The rate of attenuation for sound in the ocean varies significantly based on the sound's properties and the geophysical conditions of the

surrounding ocean. The frequency of the sound wave plays a major role in how well it propagates underwater, with lower frequency sounds having a much lower rate of attenuation and traveling much greater distances in the ocean than higher frequency sounds (Pine et al., 2014). High frequency sounds that attenuate quickly usually only travel a few kilometres, whereas low frequency sounds are capable of traveling well over 100 km (Rogers & Cox, 1988).

How audible a sound is at distance in the ocean is dependent on the intensity of the sound and the rate of attenuation, but also on the spreading pattern. The ideal theoretical model is spherical spreading, where sound received from a source decreases uniformly with distance in all directions. In practice, cylindrical type spreading usually occurs due to sound waves interacting with the seabed and surface. Sound propagation is dependent on bathymetry and ocean conditions such as the depth, substrate type, water temperature, and salinity, which in shallow coastal waters creates complex sound fields, impacting propagation due to increased scattering and attenuation (Bailey et al., 2010; Rogers & Cox, 1988). Sound transmission remains one of the least understood aspects of the physics of sound in shallow waters due to the many details regarding the physical attributes of the environment and how much they vary site by site (Radford, 2007).

1.2 The Underwater Soundscape

Sound plays an undeniably important role in life in many ways. Soundscape ecology, or the study of the different sounds present in an ecosystem, is well described in the literature within terrestrial environments. However, the study of marine soundscapes has only emerged over the last 30 years and is still a relatively unexplored area of ecology, especially in New Zealand (Mooney et al., 2020; Pijanowski et al., 2011a; Pijanowski et al., 2011b).

The term soundscape is used to describe the characteristics and sources of the ambient acoustic environment in terms of its temporal, spectral and spatial aspects (Duarte et al., 2021; Erbe et al., 2016a; Pijanowski et al., 2011a). In terrestrial environments, the soundscape is usually defined from the perspective of a (human) listener. Underwater however, soundscapes are considered independently from the perception of the receiver due to uncertainty on how certain marine species perceive sounds (Erbe et al., 2016a; Miksis-Olds et al., 2018). Underwater soundscapes are highly dynamic and vary spatiotemporally due to changing sound contributions and propagation conditions. The effective propagation of sound underwater compared to the rapid attenuation of light has resulted in many species of marine organisms evolving to rely on sound for vital processes and functions (Merchant et al., 2015; Miksis-Olds et al., 2018; Montgomery et al., 2006).

1.2.1 Underwater Sound Sources

The sources of naturally produced sound can generally be broken down into two main groups – biologically produced sounds (biotic) and sounds produced from abiotic sources (abiotic) (Erbe et al., 2016a; Hildebrand, 2009) (Figure 1.1). The third sound source, increasingly contributing to marine soundscapes, is anthropogenically produced sounds (noise) from sources such as vessels, pile driving and sonar systems (anthropogenic) (Duarte et al., 2021). These three sound source categories produce sounds that overlap spatiotemporally to create the overall soundscape at a given site. The unique characteristics such as the composition of its biological community and its geophysical conditions give it a distinct sound signature that varies over time which can be identified and used by various species of marine life for different purposes such as for settlement or other navigational cues (Montgomery et al., 2006; Pijanowski et al., 2011b).

1.2.1.1 Biotic/Biophony

The sounds produced by biological sources including marine mammals, fish, urchins and crustaceans are often known collectively as the biophony (Erbe et al., 2016a; Putland et al., 2017a). The different sounds in a sites biophony depend on the soniferous (sound producing) species present, with sounds usually produced across a wide range of frequencies from 10 Hz to >20 kHz (Putland et al., 2017a). Therefore, the biophony can vary greatly among sites due to different habitat types containing different soniferous species (Radford et al., 2014; Radford et al., 2010; Stanley et al., 2021). Some soniferous species hold their own aural niche within the soundscape (the acoustic niche hypothesis) producing distinct sounds which may change in frequency or timing if overlap occurs (Stanley et al., 2021; Van Opzeeland & Boebel, 2019).

The biophony varies over time and among sites due to differences in the soniferous species present and their basis for producing sound (Radford et al., 2008b; Stanley et al., 2021). Ambient sound pressure levels usually follow predictable diel patterns, typically peaking at dawn and dusk when biological activity and associated sound production is highest. This can be from both intentional signalling and incidental sound production from feeding and biological processes (Radford et al., 2014; Radford et al., 2010; Stanley et al., 2021). When many animals signal continuously for prolonged periods they create a chorus (Cato, 1978). Choruses can be expected to follow seasonal trends in length and intensity as levels of biological activity and contributing species fluctuate. Ambient sound levels at reef sites are typically higher over the new moon and in summer months compared to winter. Migratory soniferous species such as marine mammals can also have a large impact on the soundscape, further contributing to the temporal variability of the biophony (McCordic et al., 2021; Putland et al., 2017a).

1.2.1.2 Abiotic/Geophony

Sound produced from a variety of abiotic sources including wind, waves, earthquakes and rain (geological and climatic) is often known collectively as the geophony (Erbe et al., 2016b;

Putland et al., 2017a). The abiotic sounds that contribute to the overall soundscape are also highly spatiotemporally variable. The relative contribution of the geophony to the soundscape can change over time, for example, sound produced by an earthquake would raise the ambient sound levels, as would a storm with heavy rain and wind driven waves. More exposed areas may have a greater proportion of abiotic sound from wind and waves compared to more sheltered sites. Shallow coastal areas usually have a greater contribution of mid – high frequency sound from wind, waves and rain. Conversely, the deep ocean has a greater contribution of low frequency sounds from tectonic activity such as earthquakes and volcanism (Putland et al., 2017a).

1.2.1.3 Anthropogenic/Anthrophony

Over the last several hundred years industrialisation of human society has rapidly increased, and the world's oceans have become far more accessible and exploitable. Vessels of all sizes are largely powered by engines rather than wind and oars, which has majorly contributed to the growing increase in anthropogenic noise polluting marine soundscapes (Duarte et al., 2021). The invention of sonar to survey the sea floor, commercial seismic exploration for resources, and pile driving in construction of bridges and platforms has further added to the growing contribution of the anthrophony in marine soundscapes (Duarte et al., 2021; Erbe & McPherson, 2017; Merchant et al., 2016).

Vessel noise has increased dramatically in the ocean over the past 100 years as both the number and size of motorised vessels have rapidly increased worldwide (Hildebrand, 2009). From 1945 to 2008 the number of vessels worldwide has been reported to have increased by a factor of 3.5 and the associated gross tonnage by a factor of 10 (Frisk, 2012). The large increase in vessel numbers and size has been the main factor in the increasing levels of low frequency noise in marine soundscapes of up to 3 dB per decade (an effective doubling in sound energy) (Erbe et al., 2019; Frisk, 2012).

1.2.2 Ecological Relevance of Sound Underwater

Sound propagates efficiently over distance in the ocean due to low attenuation and is less limited than sight (loss of light at depth, dark hours and in turbid water), chemical cues (only effective downstream of the olfactory source) or other sensory cues available to marine organisms (Montgomery et al., 2006; Wright et al., 2007b). Therefore, it is unsurprising that hearing and sound production is critical for many marine species during important life functions such as choosing their settlement location, migration and to modify their daily behaviours, e.g., social communication, reproduction, foraging, and navigation (Hawkins & Popper, 2017; Leis & Lockett, 2005; NRC, 2005; Stanley et al., 2012). Due to these reasons, ambient underwater sound is an important feature of marine habitats.

Marine mammals, in particular whales and dolphins, are probably the most well studied group in the ocean producing and using various types of sounds such as 'song', 'clicks' and 'whistles' across a wide range of frequencies in support of crucial life functions (NRC, 2005).

Mysticetes (baleen whales) create signals in the lower to mid-frequencies, largely between 0.01 – 10 kHz, whereas delphinids and other Odontoceti (toothed whales) create higher frequency sounds mainly in the range of 0.1 – 40 kHz (Duarte et al., 2021; Erbe et al., 2019; NRC, 2005). Odontocetes such as sperm whales and various species of delphinids also use bio-sonar systems by creating a series of high frequency clicks and receiving the rebounding sound waves (echolocation) in a similar manner to ships sonar, enabling them to perceive the environment around them for navigation, prey location and capture (Jones, 2005; Roch et al., 2011; Thomas et al., 2004).

Marine mammals also produce a range of mechanical sounds, such as sounds produced by the animals' body hitting the surface of the water. Many whale species breach and slap the surface of the water with either their tail or pectoral fin. Breaching is thought to convey information on size and body mass, and to be a behaviour part of 'play' and socialisation (Dunlop et al., 2008).

1.3 Vessel Sound

Vessels produce sound concentrated largely in the low to mid-frequency range between 0.01 – 30 kHz, with the level and frequency of the sound produced depending on several factors including vessel size, speed and design (Hildebrand, 2009; McKenna et al., 2012; McKenna et al., 2013). Small, motorised boats produce sound peaking in the mid-frequency range with moderate source levels ranging between approximately 130 – 160 dB re 1 μ Pa, and large ships produce sound peaking in the low-frequency range with high sound source levels of up to 200 dB re 1 μ Pa (Erbe, 2002; Erbe et al., 2019; Hildebrand, 2009; McKenna et al., 2012). Although vessels produce substantial mid – high frequency sound, these frequencies propagates less effectively in the water column due to greater rates of attenuation (Hildebrand, 2009). Operational parameters within the same size class of ship such as engine type, ship design, maintenance and speed have a large impact on the sound level produced, with source levels varying up 20 – 40 dB (Hatch et al., 2008; McKenna et al., 2024; McKenna et al., 2013). Vessel sound has been seen to significantly increase ambient sound levels (Stanley et al., 2021; Stanley et al., 2017), for example, different types of vessels in the Hauraki Gulf have been seen to raise ambient sound pressure levels by up to 60 dB in the 50 - 10,000 Hz range (Putland et al., 2017b).

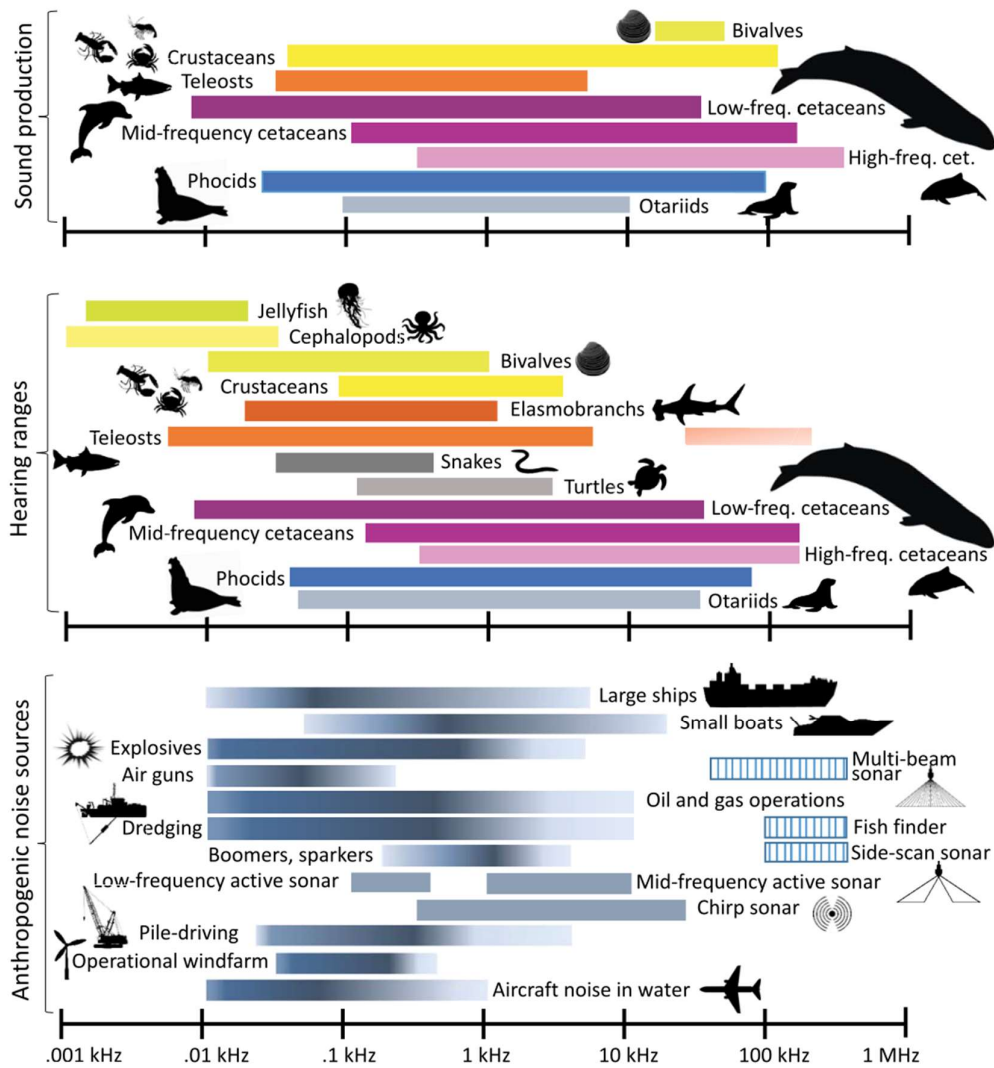


Figure 1.1: Approximate sound production and hearing ranges for marine taxa, and frequency ranges produced by common anthropogenic sound sources shown. Ranges represent the acoustic energy over the sound sources dominant frequency range, and colour shading corresponds roughly with the dominant energy band. Dashed lines have been used to depict the multifrequency nature of sounds produced by sonars. Sourced from Duarte et al. (2021).

The greatest sound source from ships underway is typically from cavitation at the propeller as the created bubble chains enlarge, vibrate and collapse, producing broadband noise and higher frequency harmonics related to blade rate (Gassmann et al., 2017; Ross, 1976). Noise created by the engine and machinery within the ship along with hydrodynamic flow against the ship's hull also propagates into the water as narrow band noise. These combined sound sources create a complex and multidirectional noise field around the ship (Erbe et al., 2019; Hildebrand, 2009). Due to the different sounds sources within ships noise produced is often dynamic and multidirectional creating a complex non-isotropic noise field dependent on depth, bathymetry and angle in relation to the vessel (Erbe et al., 2019). Noise produced by

vessels propagates most effectively downwards in a dipole radiation pattern due to the reflection of sound from the seas surface, in comparison to in the horizontal plane where it is quickly reduced due destructive interference at the surface (Gassmann et al., 2017). Propeller depth (which is increased by vessel size and load) is therefore also an important factor in noise propagation, with shallower depths propagating less noise in the water column (especially in the horizontal plane) than propellers set deeper due to decreasing the effect of the dipole. Noise from the propeller is therefore reduced near the surface (and particularly in front of the vessel due to the hull) which can lead to increased incidents of ship strike (Erbe et al., 2019; McKenna et al., 2012).

The bathymetry, sound speed, seabed characteristics and water properties (temperature and salinity) of the surrounding ocean also effect the propagation of vessel noise (Erbe et al., 2019; MacGillivray et al., 2023; Vagle et al., 2021). Propagation of vessel noise is more localised in shallow coastal waters due to increased reflection of sound from the seafloor and surface causing scattering and partial absorption of the sound waves. Conversely, in deep water the noise field of the vessel is propagated downwards, and without the lost energy from absorption due to the interactions with the seafloor/surface the noise from the ship can propagate great distances. Vessel noise experienced by the receiver is therefore highly variable depending on the position, depth and surrounding environment (MacGillivray et al., 2023; Vagle et al., 2021).

1.3.1 Impacts of Vessel Noise on Marine Life

Given the increasingly pervasive nature of vessel noise in marine soundscapes worldwide, there has been much effort in the past few decades to understand its potential impacts on marine life. Studies have focused largely on marine mammals (particularly cetaceans), but there is a growing number of investigations on potential impacts for fish and invertebrate species (Hawkins & Popper, 2016; Popper et al., 2003). Sublethal impacts from vessel noise include behavioural disturbance, acoustic masking and stress which has the potential to create cumulative long-term impacts at the population scale, especially when combined with other stressors (Cholewiak et al., 2018; Erbe et al., 2019; Putland et al., 2017b; Stanley et al., 2017; Thomsen & Popper, 2024). Behaviour changes in marine mammals in response to vessel noise exposure have been well documented, particularly for cetaceans. Vessel noise has been shown to lead to altered behavioural states at the individual level including changes to metabolic rates, energy budgets, swim speeds, dive frequency, foraging, vocalisation, migration routes, rest, and strandings (Dunlop, 2016; Erbe et al., 2019; Tyack, 2009; Weilgart, 2007b). Impacts can also occur at the population scale, such as through impacted foraging success, increased energy expenditure and heightened metabolic demands for individuals leading to overall reduced reproductive success, slower growth rates and lower survival chances for the population (Tyack, 2009; Weilgart, 2007b). Behavioural responses to vessel noise are highly context and species dependent for cetaceans with influencing factors including species, sex, age, prior experiences with vessel noise, and the individuals behavioural state (Erbe et al., 2019; Weilgart, 2007b). High vessel

noise has been observed to result in displacement and avoidance of habitats particularly in cetaceans which have greater mobility than many fish and invertebrate species (Erbe et al., 2019; Weilgart, 2007b; Wilson et al., 2023a). Though some species may not show observable responses to vessel noise (apparent noise tolerance), they may still experience negative impacts such as increased stress or acoustic masking (Lemos et al., 2022; Weilgart, 2007b). Haematological stress biomarkers and stress responses have been observed in several studies and are thought to lead to further physiological problems such as faster aging and suppression of reproduction, although responses are likely to be highly variable depending on the species and context (Lemos et al., 2022; Wright et al., 2007a).

In addition to these impacts, vessel noise also reduces the communication space available for marine life (the distance at which one member of a species can detect another) through acoustic masking (Cholewiak et al., 2018; Putland et al., 2017b; Stanley et al., 2017). Acoustic masking can occur in the form of energetic masking where the signal produced for communication overlaps with vessel noise produced in a similar frequency at the same time, or informational masking where the information conveyed cannot be discerned by the receiver due to difficulty disentangling the signal from the ambient soundscape (Clark et al., 2009). Soniferous marine species have evolved to adapt to fluctuations in the communication space due to changing contributions from natural sound sources, however, vessel noise has reduced the available communication space beyond the evolutionary context creating negative implications for these species (Cholewiak et al., 2018; Wilson et al., 2023b).

The effects of acoustic masking and reduced communications spaces for marine mammals (particularly cetaceans) has been well described in the literature. A study in the Hauraki Gulf Marine Park in Auckland, New Zealand, observed that the communication space of endangered Brydes whales (*Balaenoptera edeni*) was reduced by up to 87.4 % during routine vessel passages, and by up to 99 % during close passages (> 10km) by large commercial ships (Putland et al., 2017b). In response to vessel noise, cetaceans have been observed to change call frequency, increase source levels and rates of vocalisation (the Lombard effect). However, these responses are variable, energetically costly and context-dependent, with no vocalisations or change seen in some cases (Cholewiak et al., 2018; Clark et al., 2009; Dunlop, 2019; Dunlop et al., 2010; Erbe et al., 2019).

1.3.2 Acoustic Thresholds

Acoustic thresholds are useful in considering the impacts of received noise from anthropogenic activities on marine life. The United States National Marine Fisheries Service (NMFS) (National Marine Fisheries Service, 2018a) published technical guidelines indicating thresholds for different noise sources specific for marine mammals. These guidelines are typically used to assess risk and grant permission for activities such as marine construction or seismic surveys that have a noise associated risk (Daly, 2015; Daly & Harrison, 2012). The different thresholds specified by the NMFS are for different noise sources (intermittent,

continuous, impulsive and non-impulsive) and specify at which received noise level negative impacts are likely to occur. While no specific threshold is available for vessel noise, the continuous noise category is consistent with noise type produced by vessels. The NMFS acoustic threshold states that if received noise from continuous noise sources are above root mean square (RMS) 120 dB re 1 μ Pa, marine mammals are likely to experience negative behavioural disturbance (National Marine Fisheries Service, 2018a). While the NMFS threshold is useful, responses to vessel noise are both context and species dependent. Examples of behavioural disturbance resulting from lower received noise levels have been observed, as well as instances where no response was observed to greater received noise levels (Erbe et al., 2019).

1.4 Passive Acoustic Monitoring

Passive acoustic monitoring (PAM) using hydrophones to record the underwater soundscape has emerged as a powerful way for marine ecologists to investigate and quantify complex marine environments (Mooney et al., 2020). Hydrophone recordings allow for low impact, autonomous monitoring of the biological, abiotic and anthropogenic contributors to a soundscape over large distances and periods of time in a cost-effective manner (McCordic et al., 2021; Mooney et al., 2020). Hydrophones used in PAM record the sound pressure aspect of underwater sound (sound pressure level or SPL) gathering information on the soundscapes spectral and temporal characteristics which are then analysed after the deployments end (Merchant et al., 2015). Long term spectral analysis (LTSA) is used to visualise soundscape data by displaying spectral averages across a defined period. Given that recordings are often over long time periods, manually checking data is highly time consuming and so machine learning technologies have been increasingly utilised to identify signals of interest in an efficient and cost-effective manner (Mooney et al., 2020).

Passive acoustic monitoring offers several advantages over traditional sampling methods in marine environments. Long term soundscape recordings allow for an increased understanding of the spatiotemporal distributions and activity of soniferous species present and the anthropogenic noise contributions occurring across different time scales (McCordic et al., 2021; Mooney et al., 2020; Putland et al., 2017b; Stanley et al., 2021). In contrast, traditional observation-based sampling methods are limited by visibility, cost, sampling area size and weather conditions, and are more invasive for marine life (Mooney et al., 2020). Observation based sampling methods also suffer from inherent bias due to more frequently sampling larger and more visible species during daylight. These studies may also potentially inaccurately assess species due to the behaviour disturbance that may result from human presence (Merchant et al., 2015). Passive acoustic monitoring is also effective at detecting the presence of cryptic soniferous species that may be missed in traditional sampling, and is adept at detecting vessel presence which can be useful for compliance and understanding noise levels (Kline et al., 2020; Mooney et al., 2020). Nonetheless, PAM (like all sampling methods) has its limitations. These include detection of non-soniferous species or those not

vocalising, sound masking, and the identification of sounds to the species level which may be challenging in some cases (Merchant et al., 2015; Mooney et al., 2020). Therefore, combining PAM with other sampling methods such as visual surveying and eDNA technology leads to more comprehensive and complete datasets.

1.5 Automatic Identification System

Automatic Identification System (AIS) utilising very-high frequency (VHF) technology functions as a transmitter of vessel related information and is installed on vessels, geographic marks, search and rescue planes, satellites, and shore facilities (Last et al., 2014; Svanberg et al., 2019). Information transmitted by AIS includes vessel voyage data (vessel load and destination), dynamic data (vessel position and course) and static data (type, name and dimensions), and is used along with radar to provide an overview of vessel traffic and improve maritime safety. The use of AIS was developed in the 1990s and since 2000 has been mandated for many commercial and passenger vessels (over a certain length dependent on the country) by the International Maritime Organisation (IMO) (Robards et al., 2016; Svanberg et al., 2019).

In addition to its original use for vessel collision avoidance, AIS is now also utilised for navigation, search and rescue, fleet monitoring, and in scientific research. Records from AIS utilised in scientific research can increase understanding of vessel presence in an area and its associated overlap with marine life, however sourcing AIS data can be complex (Svanberg et al., 2019). There have been an increasing number of studies in the literature using AIS records to model vessel noise propagation by classifying the noise emitted from different vessel types and combining that with bathymetric and sea conditions (Erbe et al., 2012; MacGillivray et al., 2014; MacGillivray et al., 2023; Pine et al., 2014). However, these models do not account for the smaller recreational vessels absent in AIS records that contribute significant noise to near shore environments, making them most useful when combined with PAM (Hermanssen et al., 2019).

1.6 Marine Reserve Management in New Zealand

Marine reserves, also known as type 1 Marine Protected Areas (MPAs), aim to preserve biodiversity by protecting areas of the ocean from exploitation and anthropogenic threats. When successfully implemented, marine reserves lead to positive conservation outcomes and other cultural and economic benefits for nearby communities (Davies et al., 2018; Kline et al., 2020; McCordic et al., 2021). While impacts of large, global-scale threats to marine life such as climate change, disease and noise pollution are not totally removed by marine reserves, they do increase resilience of communities and provide a degree of local refuge (McCordic et al., 2021). Implementation of marine reserves requires careful ecological study, political support, and extended consultation with the various stakeholders invested in the area, a process that is typically slow and complex (Davies et al., 2018). However, since the

creation of the 1971 Marine Reserves Act and implementation of the first marine reserve in 1977, the total has now grown to 44 completely no-take marine reserves in New Zealand, with more planned (Beentjes, 2023). The Department of Conservation (DOC) also manage Type 2 Marine Protected Areas and utilise other marine protection tools. These include Seamount Area Closures, Marine Mammal Sanctuaries and Benthic Protection Areas, and there are also other areas not managed by DOC like the Motiti Protection Area in the Bay of Plenty (Bay of Plenty Regional Council, 2020; Department of Conservation, 2017).

Most marine reserves in New Zealand are small, encompassing a total of only 0.3 % of New Zealand's Exclusive Economic Zone. Furthermore, New Zealand marine reserves have little to no legislative consideration for anthropogenic noise from vessels, despite the significant evidence of its negative impacts on marine life. This reflects a trend commonly seen in marine reserve design worldwide with existing legislation for noise primarily focusing on marine mammals and seismic exploration, with much less focus on vessel noise (Beentjes, 2023; Daly, 2015; Wright & Moors-Murphy, 2022).

1.7 Study Area: The Fiordland Marine Area

1.7.1 Greater Fiordland Complex

Fiordland lies at the southwestern corner of New Zealand's South Island containing deep lakes and fiords carved by glaciers between 26,000 and 18,000 years ago during the Pleistocene glaciation period (Wing & Jack, 2014a). Some 6,000 - 12,000 years ago after the glaciers retreated the coastal arms flooded with seawater as the sea levels rose, forming the 14 main semi-isolated distinct fiords and their associated arms. These fiords are characterised by their strong physical gradients in depth, salinity, light, and wave exposure (Wing & Jack, 2014a). The fiords are steeply walled, reaching depths > 400 m and are often bound by underwater sills at the entrance from moraine deposits which reduce deep water circulation. Fiordland receives high yearly rainfall of up to 6 – 8 m due to exposure to frequent westerly weather systems, leading to high freshwater and terrestrial inputs (Gibbs, 2001; Stanton & Pickard, 1980). The tannin-stained rainwater forms a low salinity surface layer leading to stratification of the water column and reduced light penetration. A combination of the low surface salinity layer, reduced light penetration, water column stratification, and entrance sills leads to lower productivity within the fiords than outside them, along with circulation patterns closer to that of estuarine systems (Stanton & Pickard, 1980)

The Fiordland (Te Moana o Atawhenua) Marine Area (FMA) was formally created in 2005 to recognise the areas significance and to aid in better conservation and management outcomes. The area totals 9,280 km² from Awarua Point in the north to Sandhill Point in the south, encompassing the fiords and out to 12 nautical miles (22km) offshore from the coast. Within the FMA are 10 marine reserves to aid in protection of the fiords biodiversity and

habitats, as well as to protect several threatened species of marine life impacted by anthropogenic activity (Fiordland Marine Guardians, 2021, 2024).

1.7.2 Cetaceans in Fiordland

The Fiordland Marine area is home to several species of cetaceans of which bottlenose dolphins and migratory humpback whales are the most prevalent, though other species are sometimes present including southern right whales, pilot whales, orca, and dusky dolphins (Corne, 2023; Crowe et al., In Review; Lusseau & Slooten, 2002).

1.7.2.1 Bottlenose dolphins

Bottlenose dolphins (*Tursiops truncatus*) are a well-studied, long-lived and slow-reproducing predatory species of dolphin with a flexible ecology that form dynamic social groups based on habitat type and activity (Currey, 2008; Shane et al., 1986). They are a highly vocal species that can produce and receive sounds over a wide range of frequencies (~2 – 155 kHz) (Jones et al., 2020; Popov et al., 2007). These sounds are often described as mid-frequency ‘whistles’, ‘squeals’ and ‘clicks’ and are thought to be produced for a variety of purposes such as communication, echolocation and foraging (Jones et al., 2020; Luís et al., 2021).

Bottlenose dolphins are found in both hemispheres from tropical to temperate latitudes and in a wide range of habitat types including estuarine, coastal and pelagic habitats, with the extent of their range in high latitudes being limited mainly by temperature (Bennington et al., 2020; Currey, 2008). The two main ecotypes of bottlenose dolphins seen are the pelagic and coastal forms, with the more predominant coastal form of bottlenose dolphins usually inhabiting distinct home ranges (Lusseau & Wing, 2006; Shane et al., 1986). Bottlenose dolphins (particularly near the coast) are exposed to a wide range of anthropogenic activity and related habitat changes which have led to large declines in the numbers of some subpopulations, although the species overall remains common worldwide (Bennington et al., 2020; Currey et al., 2009).

In New Zealand bottlenose dolphins are present in both coastal and pelagic habitats, with coastal bottlenose dolphins being split into three groups inhabiting Northland, Marlborough and Fiordland with very limited exchange among populations (Tezanos-Pinto et al., 2009). Fiordland is home to one of the southernmost populations of bottlenose dolphins in the world (known as Fiordland bottlenose dolphins) that are exposed to challenging environmental conditions near the edge of the species range. This combined with increasing anthropogenic pressures has resulted in small population sizes and low calf survival rates (Currey et al., 2009). Fiordland bottlenose dolphins show several characteristics specific to their cold-water environment, usually being larger with more rotund bodies and smaller flukes, rostrum and fins than other coastal bottlenose dolphins found in warmer waters (Currey, 2008).

Fiordland bottlenose dolphins are designated by the International Union for the Conservation of Nature (IUCN) to be ‘critically endangered’ due to their geographical

isolation, low number of mature individuals and observed rates of decline (Currey et al., 2009; Currey et al., 2011b). There are three bottlenose dolphin subpopulations covered by the IUCN designation which inhabit different areas of the FMA - a northern subpopulation known to roam fiords from Charles Sound through to north of Milford Sound and two well monitored subpopulations within the Doubtful Sound and Dusky Sound complexes respectively (Bennington et al., 2022; Currey et al., 2011b; Lusseau, 2005). These two subpopulations within the Doubtful Sound complex and the Dusky Sound complex are thought to be resident within their discrete fiord systems with little genetic exchange occurring between them, forming closed or semi closed populations (Currey, 2008; Lusseau & Wing, 2006). However, a recent study combining PAM with visual surveying has shown that these subpopulations utilise a larger area than had previously been considered, although there have been no observed interactions between pods (Crowe et al., In Review).

The Fiordland bottlenose dolphin subpopulation in Dusky Sound is thought to be stable and is estimated at 124 individuals, double that of the neighbouring subpopulation in Doubtful Sound which is estimated at 62 individuals (Crowe, 2022). Within Doubtful Sound, the low numbers and observed periods of decline in the subpopulation of Fiordland bottlenose dolphins, have been attributed to low calf and juvenile survival rates from areas of high vessel usage and increased freshwater inputs from the Manapouri hydroelectric power scheme (Bennington et al., 2022; Crowe, 2022; Currey, 2008).

1.7.2.2 Humpback whales

Humpback whales (*Megaptera novaeangliae*) belonging to the parvorder Mysticeti, are found throughout the world's oceans and undertake long seasonal migrations between high-latitude feeding grounds and low-latitude breeding grounds (Clapham, 2018; Corne, 2023; Fleming & Jackson, 2011). Vocalisations by humpback whales are produced in the low to mid-frequency range (0.1 – 4 kHz) and include cyclic, hierarchal vocalisations known as 'song' (produced by males) and signals associated with socialisation and foraging produced by both sexes (Corne, 2023; Warren et al., 2020; Warren et al., 2021). Humpback whales show a large degree of behavioural plasticity and are known to pause in areas to opportunistically forage to supplement energy requirements during migrations (Gales et al., 2009).

There are seven distinct breeding populations or 'breeding stocks' of humpback whales in the southern hemisphere (named A to G) with migratory connections to feeding grounds in the Southern Ocean recognised by the International Whaling Commission (IWC), two of which are in the western and central South Pacific Ocean (Acevedo et al., 2022; International Whaling Commission, 2015). Breeding stock E is located in the southwestern Pacific Ocean and is composed of three sub stocks with breeding areas in northeastern Australia (E1), near New Caledonia (E2) and around the islands of Tonga, American Samoa and Fiji (E3). Breeding stock F located in the central South Pacific Ocean is comprised of two sub stocks with breeding areas around the Cook Islands (F1) and French Polynesia (F2) – stocks E2 - F2

collectively form the Oceania breeding stock (International Whaling Commission, 2016). Humpback whales from the E1 and E2 breeding sub stocks pass through the New Zealand migratory corridor during their northern migration from May to August and during their southern migration from September to December (Constantine et al., 2007; Corne, 2023; Dawbin, 1966; Gales et al., 2009).

Many populations of humpback whales were hunted to near extinction during the mid-20th century, however, populations are recovering due to an international moratorium on whaling in 1986 by the IWC, although rates of recovery differ among breeding populations (Clapham, 2018; Corne, 2023; Fleming & Jackson, 2011). The E1 breeding sub stock has shown rapid rates of recovery with a long-term average abundance increase per annum of 10.9 % and is expected to soon reach peak abundance (Noad et al., 2019). However, the Oceania sub stocks (including E2) remain classified as 'Endangered' by the IUCN and are estimated at below 50 % of pre whaling abundances with low rates of recovery (Childerhouse et al., 2008; Constantine et al., 2012; Corne, 2023).

Within the FMA humpback whales are found in coastal areas near the fjord entrances and the continental shelf with many passing through without stopping. Some individuals have been seen to display short-term residency to forage particularly around the north-western Five Fingers Peninsula and near the entrances of Doubtful and Dusky Sounds (Corne, 2023; Dawbin, 1956). During the northbound migration, humpback whales remain further offshore, whereas on the southbound migration they are more commonly seen close to the coast of Fiordland leading to more frequent visual encounters (Corne, 2023; Dawbin, 1956).

1.7.3 Anthropogenic Activities and Reported Impacts on Cetaceans within the FMA

A variety of commercial and recreational activities associated with vessels occur within the FMA, with the areas of heavy use influenced primarily by accessibility. Road access is limited with just two roads in for a vast area of coastline. The first of these provides access to Milford Sound and the second to Doubtful Sound, although the later also involves crossing Lake Manapouri to reach the access road. Access to other areas within FMA is by vessel or air (Booth, 2022).

Milford Sound is a famous tourist destination due to its scenic values with its relative accessibility from the road and airstrip making it the most utilised area of Fiordland. Approximately 870,000 tourists visited Milford Sound township from the road or air access in 2019, with another approximately 220,000 visiting the fjord on cruise ships (Visitor Solutions Ltd & Fresh Info Ltd, 2021). Popularity of Fiordland as a tourism destination is ever growing, with visitor numbers increasing 69 % between 2006 and 2019, and (with exception to the travel restrictions during the COVID-19 pandemic) is predicted to continue growing at a similar rate with no plans to cap limits (Visitor Solutions Ltd & Fresh Info Ltd, 2021). Historically most vessel-based tourism has been confined within Milford Sound and a lower proportion in Doubtful Sound, however, there is an increasing number of charter vessels and

cruises utilising more remote areas of the FMA, particularly Dusky Sound (Bennington et al., 2022; Booth, 2022; Lusseau et al., 2006a).

Fiordland is popular for recreational activities such as fishing, hunting and hiking, most of which involve vessel use either for transportation or as the primary means around which the activity is based (Booth, 2022). There is extremely limited land based accommodation in Fiordland National Park (FNP), with a backpackers in Deep Cove (Doubtful Sound) and eight DOC huts (Fiordland Marine Guardians, 2021, 2024). Recreational boats have increased in size and power with better navigational and radar equipment than in the past, allowing them to travel more frequently and quickly to remote areas of the FMA such as Dusky Sound and stay longer due to increased fuel capacity. Large yachts and private cruise vessels visiting the FMA have also increased in number (Booth, 2022). Vessel use within the FMA is also increased from activities by the blue cod (*Parapercis colias*) and red rock lobster (*Jasus edwardsii*) commercial fishery which is concentrated mainly near the fjord entrances and outer coast due to restrictions within the internal waters (Fiordland Marine Guardians, 2019, 2021).

Although vessel-based tourism benefits the local economy, concern over long-term unsustainability and environmental impacts has led to increased management efforts and regulation around marine ecosystems in the FMA, such as the creation of marine reserves and increased fishery closures/regulations (Bennington et al., 2022; Lusseau et al., 2006a). Regional policy has aimed to concentrate vessel-based tourism within Milford Sound as a 'sacrificial sound' where its size may act as a natural limitation on usage and associated impacts (Booth, 2022). However, significant impacts within Doubtful Sound from increasing vessel tourism usage prompted commercial use restrictions and Dolphin Protection Zones (Currey et al., 2009; Currey et al., 2011a). Vessel based tourism in the remainder of the FMA is less regulated (similar to Milford Sound) and has been considered to be naturally limited by inaccessibility, however, the significant recent increase in vessel-based tourism in Dusky Sound has prompted concern of potential ecological impacts (Bennington et al., 2022).

Vessel use in the FMA has been seen to negatively impact Fiordland bottlenose dolphins, with a number of studies describing impacts occurring in Milford and Doubtful sounds (Currey et al., 2009; Currey et al., 2011a; Lusseau, 2003a; Lusseau et al., 2006a). Behavioural disturbance such as increased dive intervals, greater time spent travelling, avoidance of areas, and disrupted resting and socialising behaviour have been observed (Currey et al., 2011a; Lusseau, 2003a). Lusseau (2003b) reported vertical avoidance in response to tour boats leading to increased mean diving intervals, with dolphins being observed to react before boats were in visual contact. Males and females were also shown to behave differently, with males actively avoiding boats as soon as they were present, while females switched to a vertical avoidance strategy only when interactions became closer due to higher energetic costs. Vessel strikes have been documented with wounds observed in Fiordland bottlenose dolphins in both these subpopulations as well

as a documented case where a calf was killed in Milford Sound in 2002 (Lusseau, 2005). These combined impacts have been attributed to periods of significant population decline and very low calf survival rates in the resident Doubtful Sound subpopulation (Currey et al., 2009; Currey et al., 2011a).

Potential impacts of vessel use for humpback whales in the FMA are much less understood, although there is likely a significant risk, as has been shown in other regions. Vava'u, Kingdom of Tonga, is a well-known whale-watching destination (Fiori et al., 2019). Humpback whale dive time, number of reorientation events, and respiration rates were observed to be altered in the presence of vessels. Avoidance responses and increased dive times of mothers and calves were seen for one third of tour vessel approaches, with these responses seen to be significantly affected by vessel type (Fiori et al., 2019). Little research has been done for more remote areas of the FMA, with the impacts of increasing vessel use within Dusky Sound for the Fiordland bottlenose dolphin subpopulation and migratory humpback whales still relatively unknown. Not all potential impacts occurring from vessel use within the FMA have been well described for these cetaceans. Studies have focused primarily on observable impacts from vessel interactions, with other potential impacts such as cumulative stress and sublethal physiological impacts, being far less understood.

1.8 Research Aims and Significance of Thesis

The overall aim of this research is to better understand the extent and potential impacts of increased vessel use on Fiordland bottlenose dolphins and humpback whales in Tamatea/Dusky Sound. An underutilised method of remote sensing, passive acoustic monitoring (PAM), will be used to record the underwater soundscape at three sites within the Dusky Sound complex, detailing the spatiotemporal presence of vessels, delphinids and humpback whales. Broadband underwater recordings at these sites will allow for analysis of their relative acoustic presence. Automatic Identification System records, sound propagation models and PAM will also aid in determining the extent of vessel contribution to the environment, and when acoustic behavioural threshold limits are being exceeded within the study area.

The data collected by PAM in the current study will allow for further examination of habitat use by the resident subpopulation of Fiordland bottlenose dolphins and migratory humpback whales. It will also lead to an improved understanding of the contribution vessels have to the soundscape in Dusky Sound and their overlap with these cetaceans. The information gathered will also be used to inform annual visual surveying efforts used for yearly abundance estimates for the Fiordland bottlenose dolphin subpopulation within Tamatea/Dusky Sound. This information is essential for the enhanced management of these at-risk species and potential stressor. While there are management plans in place for some threats to these species within FMA, the noise from vessels and its effects have not been considered, as is the case throughout much of New Zealand. This study is the first of its kind in FMA and will begin the work that will allow for greater and more comprehensive protection and management from vessels and vessel noise. The finding of this study is hoped to aid in positive conservation outcomes for these unique and charismatic species.

Chapter 2: Methods

2.1 Study Location

2.1.1 Tamatea/Dusky Sound:

Tamatea/Dusky Sound is situated in the southern part of Fiordland Marine Area (FMA). It is characterised by strong environmental, physical and inshore/offshore gradients typical of the Fiordland sounds. The maximum depth of Dusky Sound is 319 m, with depths in the entrance between Five Fingers Peninsula and South Point averaging between 150 – 200 m, with an entrance sill of 97 m (Fiordland Marine Guardians, 2021). The entrance to Dusky Sound is wide and reaches 7.9 km across, narrowing around each side of Anchor Island before extending to a maximum of 43.9 km inland through many interconnected inlets, totalling an area of 181 km² (Stanton & Pickard, 1980). Dusky Sound and the adjacent Te Puitaha/Breaksea Sound are interconnected by the Acheron Passage forming the greater Dusky Sound complex (hereby referred to as the Dusky Sound complex). Tourism and consequent vessel presence is currently increasing within Dusky Sound, making it an ideal location to utilise PAM to investigate the contribution of vessel noise and its potential overlap with the resident subpopulation of Fiordland bottlenose dolphins and migratory humpback whales.

2.1.2 Taumoana (Five Fingers) Marine Reserve

Taumoana (Five Fingers Peninsula) marine reserve (hereby referred to as 'Marine Reserve') covers 14.66 km² and is situated alongside Five Fingers Peninsula including Goose Cove to the north, Cormorant Cove to the east and includes Parrot and Pigeon Islands. It was one of eight reserves created by the Fiordland (Te Moana o Atawhenua) Marine Management Act in 2005. The marine reserve encompasses a variety of habitat types such as rocky reef, sand flats, shallows, and estuarine areas and has a high degree of exposure to wind and waves, particularly from the southwest. It contains some of the only protected wave exposed rocky reef habitat in the Fiordland Marine Reserve Network (Fiordland Marine Guardians, 2021, 2024).

2.1.3 Study Sites

There were three recording sites in this study. Five Fingers 02 (FF02) and Five Fingers 03 (FF03) were located within the Taumoana Marine Reserve, and Anchor Island 01 (Anchor01) was located outside the marine reserve on the southern side of Anchor Island (Table 2.1, Figure 2.1). The position of FF02 and FF03 within the marine reserve allowed for underwater recordings to the north of Anchor Island both near the entrance to Dusky Sound (FF03) and further within Goose Cove (FF02). Anchor01 provided soundscape recordings near the entrance to Dusky Sound on the southern side of Anchor Island (Figure 2.1, Table 2.1). The use of unobtrusive yet semi-permanent bottom moorings were permitted within the marine

reserve and FMA by the Department of Conservation and Environment Southland under Resource Consent Application APP-20221881.

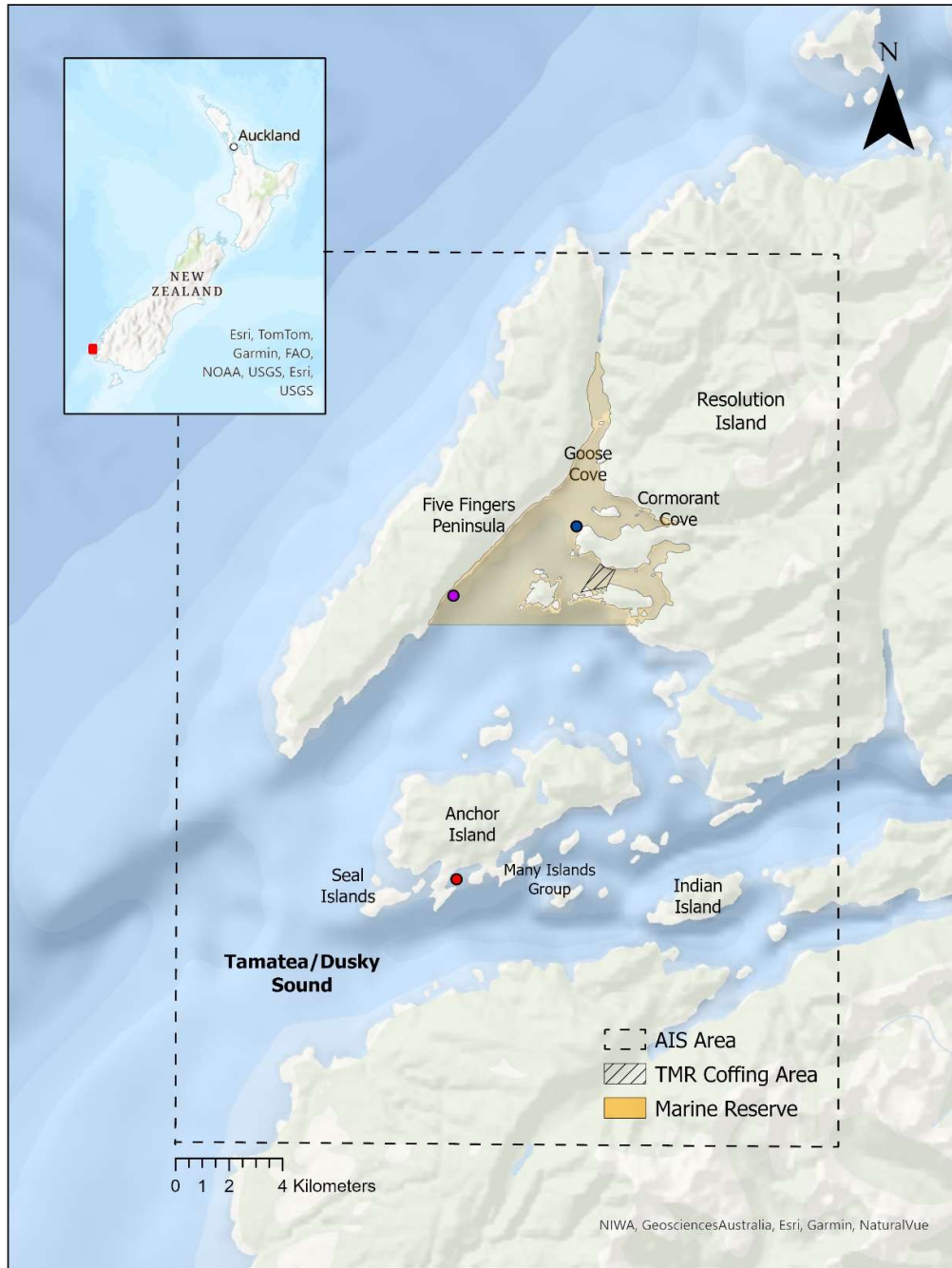


Figure 2.1: Map showing the study area in Tamatea/Dusky Sound (shown relative to New Zealand; inset). Hydrophone recording sites indicated by coloured dots; Red – Anchor Island 01, Magenta – Five Fingers 03, Dark Blue – Five Fingers 02. Dashed border indicates Automatic Identification System record area, orange area indicates boundaries of the Taumoana Marine Reserve, hatched polygon indicates Taumoana Marine Reserve commercial lobster fishery Coffing Area.

Table 2.1: Deployment details for the recording sites including full name, coordinates, number of deployments, protection status, depth of instrument, and habitat characteristics.

Site Identifier	Full Name	Location	Latitude	Longitude	Number of Deployments	Protection Status	Depth of Instrument (m)	Habitat Characteristics
FF02	Five Fingers 02	Cormorant Cove mouth	45.6917 S	166.5453 E	3	Marine Reserve	24	Sand flat adjacent to high relief rocky reef
FF03	Fiver Fingers 03	Five Fingers Peninsula	45.7079 S	166.5040 E	3	Marine Reserve	32	Low relief broken rocky reef and sand
Anchor01	Anchor Island 01	Anchor Island channel	45.7742 S	166.5051 E	4	No protection	35	Low relief broken rocky reef and sand

2.2 Passive Acoustic Data Collection

2.2.1 Deployment Schedule

Underwater acoustic data (soundscape data) was collected using remote hydrophone recorders (SoundTrap 600 STD, Ocean Instruments Ltd, New Zealand) at three sites to encompass all the seasons of the year (where possible) to allow for long-term analysis. New Zealand austral seasons and meteorological dates were used for seasonal timing, with spring defined as 01 September – 30 November, summer as 01 December – 28 February, autumn as 01 March – 31 May and winter as 01 June – 31 August. There were 3 – 4 deployments at each site between 3 – 4 months in duration (Table 2.2). Sampling dates during 2022 and 2023 varied slightly depending on the site and were dependent on battery longevity, servicing schedule and successful retrieval of the instrument. A summary of sampling effort is given in table 2.2 for each site. This equated to a total of 431 days sampled at FF02, 471 days at FF03 and 523 days at Anchor01.

All attempts were made to service the hydrophone at each site four to six months after initial deployment. This was done by triggering the acoustic release to send the mooring to the surface, collecting the mooring from the surface and retrieving the bottom weight (Figure 2.2). The entire system would then be cleaned, and the memory cards and batteries replaced in the hydrophone for redeployment which usually occurred within a day or two of retrieval.

Table 2.2: Gantt chart showing recording effort at each site. Blue shading indicates data present, orange shading indicates no data due to depleted battery, red shading indicates no data present due to loss of acoustic mooring.

Site	2022												
	January	February	March	April	May	June	July	August	September	October	November	December	
FF02			Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
FF03			Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
Anchor01			Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Orange	Orange

Site	2023												
	January	February	March	April	May	June	July	August	September	October	November	December	
FF02	Orange	Orange	Blue	Blue	Blue	Blue	Orange	Red	Red	Red	Red	Red	
FF03	Orange	Orange	Red	Red	Red	Red	Blue	Blue	Blue	Blue	Blue	Blue	
Anchor01	Orange	Orange	Blue	Blue	Blue	Orange	Blue	Blue	Blue	Blue	Blue	Orange	

2.2.2 Instrumentation and Mooring Configuration

SoundTrap ST600 remote underwater hydrophone systems (ST600) were used for all of the underwater recordings in this study. The ST600s have self-noise less than sea state 0 at 100-2000 Hz and < 36 dB re 1 μ Pa above 2000 Hz (Ocean Instruments, Auckland, New Zealand) allowing for high quality soundscape recordings. Sampling rates were set at 48,000 Hz with a flat full-scale frequency response of between 20 – 60,000 Hz (\pm 3dB). The sampling schedule of all the ST600 was set to run continuously at a duty cycle of 60 min/60 min, to restrict each file length to 60 min for ease during processing, and gain was set to 'high'. New Zealand local time was used at the beginning of each deployment and subsequently standardised to New Zealand Standard Time (NZST) for analysis. All ST600s had unique end-to-end response sensitivity and were calibrated by the manufacturer before the beginning of the study and in-house before re-deployment after servicing. Raw data files (.wav files) were downloaded from the two removable MicroSD cards (1 x 512 GB, 1 x 256 GB) and decompressed after retrieval using the SoundTrap host software for further analysis.

Dependent on the sites, deployment occurred in 24 – 35 m of water on primarily sandy substrate interrupted with broken rocky reef, with FF02 adjacent to high relief rocky reef (Table 2.2). The hydrophones were suspended approximately 3 m above the substrate by specifically designed and purpose engineered subsurface moorings to reduce any extraneous noise produced from the mooring itself. The mooring included an acoustic release unit (VR2AR, InnovaSea Systems Inc., Nova Scotia, Canada) and was anchored to the sea floor with a 50 kg rubberised plate weight, above which the mooring was suspended by a buoyant subsurface float. To aid in retrieval of the mooring systems bottom weight and to not leave anything behind in the marine reserve, a weight retrieval system was utilised. (Figure 2.2).

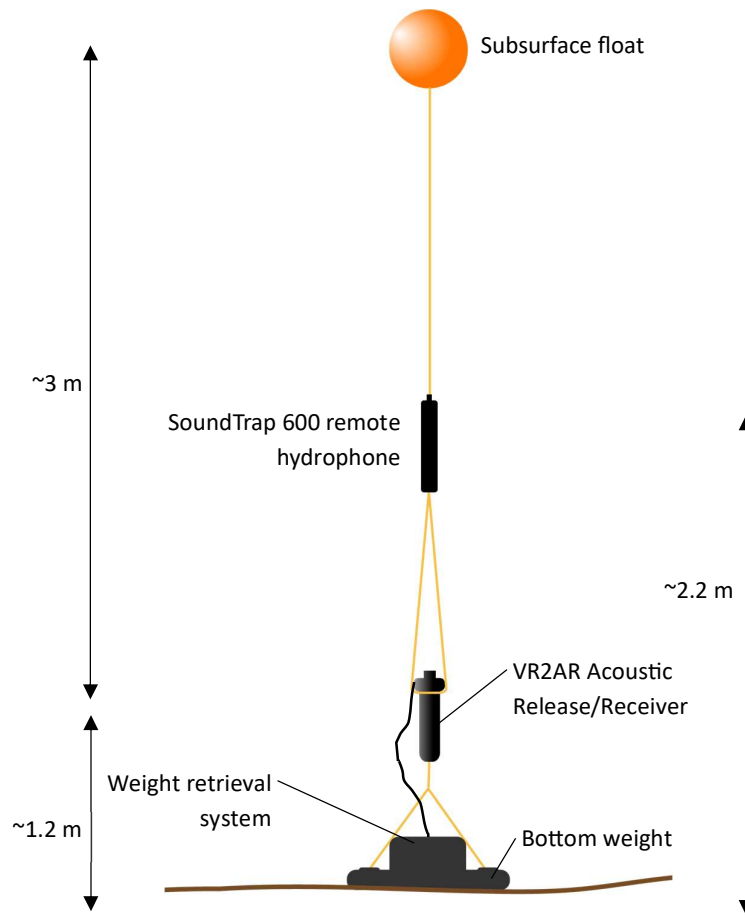


Figure 2.2 Schematic showing configuration of the subsurface mooring system holding the SoundTrap ST600 hydrophone recorder to the substrate.

2.3 Acoustic Data Analysis

All acoustic data (.wav files) were analysed using the MATLAB software (2018a & 2023b) with custom written scripts specifically for each analysis type.

2.3.1 Triton Vessel Detector

Given the large datasets present from the multiple deployments, manual inspection of every minute of the recordings for vessel presence would have been time-prohibitive. Therefore, the Triton Software Package, specifically the Ship Detector remora, (version 1.0 2021 09 21) was utilised (Wiggins et al., 2010) to identify potential vessel passages from Long-Term Spectral Averages (LTSA). These output detections were then manually and aurally inspected to confirm presence or absence of a vessel (Figure 2.3).

Long-term spectral analysis (LTSA), a longer-term average of power spectra (than a typical spectrogram) presented as three-dimensional plots displaying time, frequency and intensity were created from the .wav files data for the deployments. The LTSA plots were presented chronologically, with time averaging (the time over which spectra in an LTSA window are

averaged) set at 5 s, and the frequency bin size set at 12 Hz, with intensity shown by colour to preserve the temporal-spectral resolution of the acoustic data.

Next, the LTSA files for each site were run through the interactive detector to adjust parameters needed at each site to improve the effectiveness of the vessel detector - this step significantly increases the performance of the vessel detector before moving onto batch detections. The LTSA's were analysed in blocks of data (window size), with the power spectral density (PSD) estimates averaged into three bands of frequency which were set depending on the specific sampling parameters of the deployment at that site and the different vessel types present in the data.

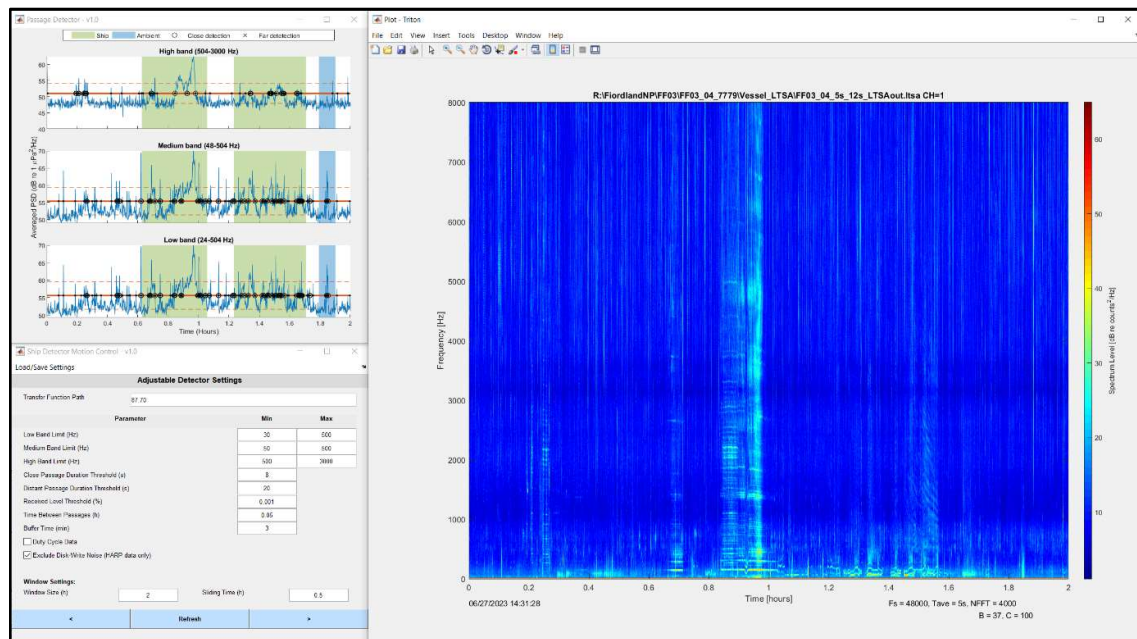


Figure 2.3: Screenshot of Triton Vessel Detector window showing an example of reviewing a vessel detection.

Three main criteria surrounding the averaged PSDs were used by the Triton Vessel Detector to determine if a vessel was present, in which case the start and end times of the event were to be saved (Wiggins et al., 2010).

These criteria were:

1. The signals amplitude was greater than a set time-dependent threshold. This threshold was computed with a histogram of the averaged PSD divided into two equal regions, with the mode of these regions used as the upper and lower levels, the mean of which was used as the time-dependent threshold.
2. The duration of the event above the time-dependent threshold was greater than a specified time – the **close passage duration threshold**. Furthermore, the duration in the higher band needed to be shorter than the medium band to discard signals by delphinids. The event duration also needed to be longer than specified time in the lower and medium bands – the **distant passage duration threshold**. Time in the medium band also had to be shorter than in the lower band to discard the clicks used by delphinids for communication.
3. Events from vessels were distinguished from weather events when a specific percentage of the background noise window was exceeded by averaged received levels in the lower band – **the received level threshold**.

Once these criteria were verified and set, they were kept the same among the different sites to increase consistency and the effectiveness of the Triton Vessel Detector.

In this study the frequency bands were set as follows:

Table 2.3: Triton Vessel Detector frequency band settings.

Parameter	Value
Low band	30 – 500 Hz
Medium band	50 – 500 Hz
High band	500 – 3000 Hz
Close passage duration threshold (s)	8
Distant passage duration threshold (s)	20
Received level threshold (%)	0.001
Time between passages (h)	0.05
Buffer time (m)	3
Window size (h)	2
Overlapping window (h)	0.5

2.3.1.1 Review of the automated vessel detections

The LTSA plots containing potential vessel detections from Triton were presented as 2 – 6 hr binned plots, depending on the length of the detections, with frequency displayed between 0 – 8000 Hz to efficiently display several potential detections of vessels in one window (Figure 2.3). The window used for the LTSA was set to overlap by 0.5 hrs to ensure detections at the beginning or end (1 hr) would not be missed. If a closer view was needed the recording could be shown in more detail by reducing the time of the binned plot window.

The detectors parameters were set conservatively throughout to reduce the possibility of false negatives to near zero, however, this resulted in the need for manual visual inspection of LTSA to find false positive detections. The potential vessel detections were manually verified as either 'Vessel' or 'Ambient', with the false positive rate subsequently reduced to 0 %. After manual inspection to confirm vessel detections was completed for each deployment the results were outputted into .xlsx format for subsequent analysis.

In certain instances, visual inspection of the LTSA of the potential vessel detection was insufficient to accurately identify whether a vessel was present or whether it was a false positive (Figure 2.4). In this case the Raven Pro program (version 1.6) (Cornell School of Ornithology, NY, USA) was used to cross check the recording for accurate identification. The Raven Pro program used a spectrogram view, which could be adjusted on time and sampling resolution for more detailed audible and visual inspection than in the case of the LTSA used by the detector.

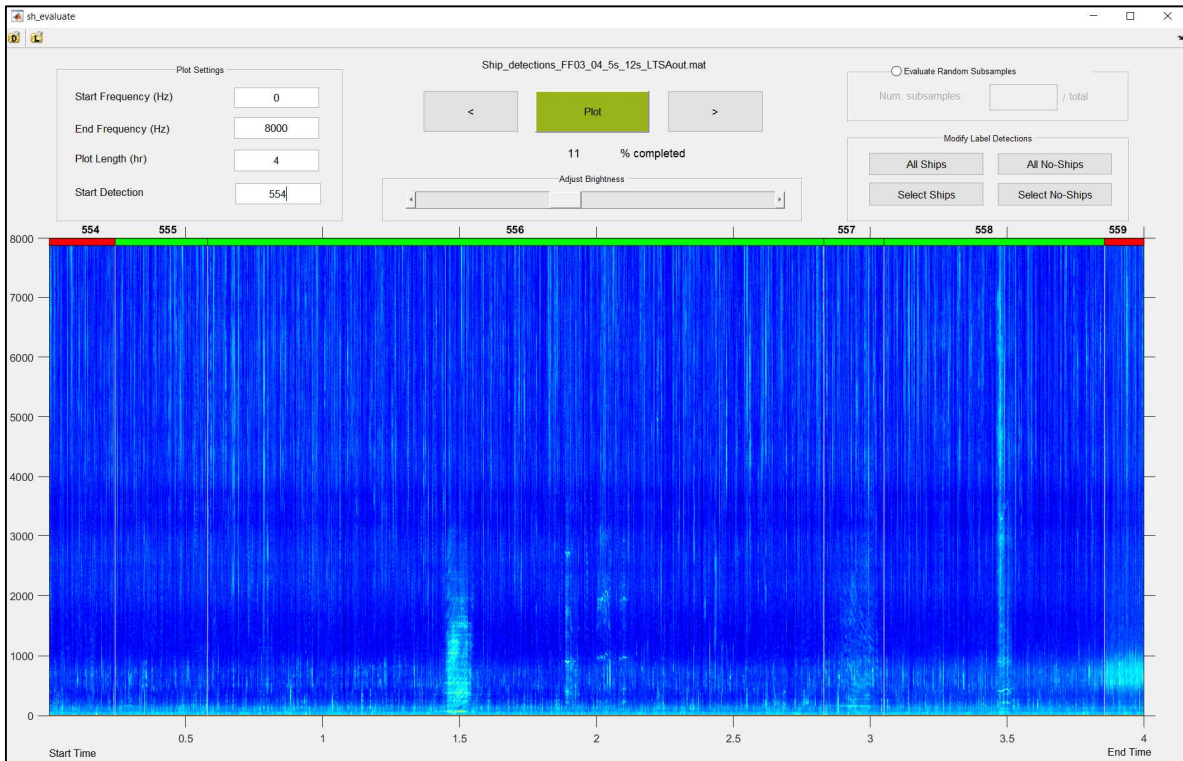


Figure 2.4: Screen shot of Triton Vessel Detector window reviewing potential detections.

2.3.1.2 Validation of vessel detector performance

To understand the accuracy of the Triton Vessel Detector, five days were taken at random for each site across deployment periods and visually and aurally inspected for vessel presence in Raven Pro 1.6 whereby a training selection table file was created. This training file was overlaid on the LTSA along with the detector output from Triton and both sets of results compared. Sensitivity (Equation 1) and False Positive Rates (Equation 2) were then calculated for each of the sites (Yack et al., 2009). When a signal not originating from a vessel was detected and labelled vessel, it was referred to as a false positive and when a signal originating from a vessel was not detected, but was present, it was referred to as a false negative.

$$\text{Sensitivity} = \frac{\text{true positives}}{(\text{true positives} + \text{false negatives})} \quad (\text{Equation 1})$$

$$\text{False Positive Rate} = \frac{\text{false positives}}{(\text{true positives} + \text{false positives})} \quad (\text{Equation 2})$$

2.3.2 FinFinder Acoustic Detectors

The acoustic data collected from the hydrophones at each site was analysed using a machine learning approach to detect sound signals made by humpback whales and delphinids within the recordings. The detectors used for this analysis were within the FinFinder platform, a software platform built within MATLAB (version 2021b) developed by Dr. Matthew Pine and customised by Dr. Jenni Stanley, 2023. FinFinder processes raw audio files for ‘target signals’ of interest (in this case signals that resemble vocalisations from humpback whales and delphinids) which are identified by the software’s detectors containing a series of predictive classification models built using a pretrained version of the ResNet-50 convoluted neural network (from ImageNet (ImageNet. <http://www.image-net.org>)).

The detector used for identifying the presence of humpback whale signal (Table 2.4) was trained using various types of humpback whale signals (such as moans, groans and rasps) from sources in both the Northern and Southern Hemisphere. The delphinid detector used for identifying the presence delphinid signals within the recording was trained using various sources of mid-frequency delphinid whistles, from New Zealand and international animals (Table 2.5).

Each detector within FinFinder consisted of a series of signal processing steps, whereby wavelet denoising were undertaken on the spectrogram. To create a more conservative detector, denoising was used at a low level in the current data set. Both detectors were made to be conservative to reduce the number of false negatives (missed detections), leading to an increased level of false positive detections. To confirm all potential detections

by FinFinder, manual inspection on the detections was carried out so that no false positives were included in results.

Table 2.4: Parameters used in the humpback whale detector (FinFinder) for Fiordland.

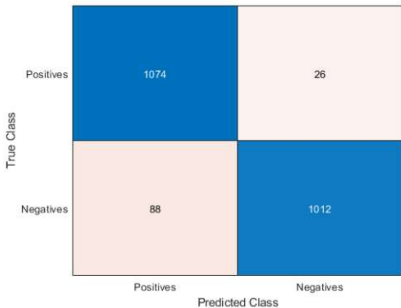
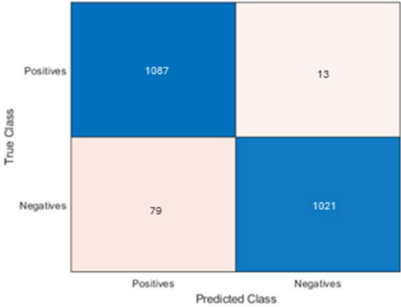
Method	Settings															
Software version	Core v2.1.22															
Computing environment	MATLAB 2023; classification on GPU															
Detection model	HBW_CNN_99_melspec_res50_Sept2022_v4															
Secondary model	HBW_GB_Minke_combined_CNN_97_melspec_res50															
Detector training data set	28,524 spectrogram samples; moans, groans, rasps															
CNN architecture	ResNet-50															
Signal processing	Down sampling to 2 kHz, 5 seconds windows															
Data window for classification	5 seconds															
Spectrogram generation	Mel (512 FFT window, 248 frequency bands)															
Frequency range	0.1 – 1 kHz															
Denoising	Wavelet + transient signal emphasis/normalization															
Initial (trigger detector)	ResNet-50, trained on 28, 524 spectrograms															
Object detector	YOLOv2 Model, trained on 1000 spectrograms															
Output Classes	Positive or Negative If Positives, sorted into low quality (LQ, based on 50-69.9% confidence scores) or moderate/high quality (MHQ, above 70% confidence scores)															
Validation	Manual inspection of spectrogram of every detection, and calculated detection positive hours															
Detector performance (from the confusion matrix)	<p>Validated on 1100 positive and 1100 negative images</p> <p>Precision (true negative rate) = 0.92 or 92 %</p> <p>Recall (true positive rate) = 0.97 or 97 %</p> <p>Overall Accuracy = 0.94 or 94 %</p>  <table border="1" style="margin-left: auto; margin-right: auto;"> <tr> <td rowspan="2">True Class</td> <td>Positives</td> <td>1074</td> <td>26</td> </tr> <tr> <td>Negatives</td> <td>88</td> <td>1012</td> </tr> <tr> <td></td> <td></td> <td>Positives</td> <td>Negatives</td> </tr> <tr> <td></td> <td></td> <td colspan="2">Predicted Class</td> </tr> </table>	True Class	Positives	1074	26	Negatives	88	1012			Positives	Negatives			Predicted Class	
True Class	Positives		1074	26												
	Negatives	88	1012													
		Positives	Negatives													
		Predicted Class														

Table 2.5: Parameters used in the delphinid detector (FinFinder) for Fiordland.

Method	Settings															
Software version	Core v2.1.22															
Computing environment	MATLAB 2023; classification on GPU															
Detection model	Whistles_CNN_97perc_28Feb2023															
Secondary model	N/A															
Detector training data set	33,076 spectrogram samples; 16,538 mid-frequency whistles/burst pulse/buzz samples, 16,538 background sound samples															
CNN architecture	ResNet-50															
Signal processing	Down sampling to 2 kHz, 5 seconds windows															
Data window for classification	2 seconds															
Spectrogram generation	Mel (1024 FFT window, 248 frequency bands)															
Frequency range	1 – 24 kHz															
Denoising	Wavelet + transient signal emphasis/normalization															
Output Classes	Positive or Negative If Positives, sorted into low quality (LQ, based on 50-69.9% confidence scores) or moderate/high quality (MHQ, above 70% confidence scores)															
Validation	Manual inspection of spectrogram of every detection, and calculated detection positive hours															
Detector performance (from the confusion matrix)	<p>Validated on 1100 positive and 1100 negative images</p> <p>Precision (true negative rate) = 0.928 or 92.8 %</p> <p>Recall (true positive rate) = 0.988 or 98.8 %</p> <p>Overall Accuracy = 0.958 or 95.8 %</p>  <table border="1" data-bbox="771 1266 1169 1570"> <tr> <td rowspan="2">True Class</td> <td>Positives</td> <td>1087</td> <td>13</td> </tr> <tr> <td>Negatives</td> <td>79</td> <td>1021</td> </tr> <tr> <td></td> <td></td> <td>Positives</td> <td>Negatives</td> </tr> <tr> <td></td> <td></td> <td colspan="2">Predicted Class</td> </tr> </table>	True Class	Positives	1087	13	Negatives	79	1021			Positives	Negatives			Predicted Class	
True Class	Positives		1087	13												
	Negatives	79	1021													
		Positives	Negatives													
		Predicted Class														

2.3.2.1 Humpback whale detector outputs

Detections labelled as positive by the humpback whale detector within Finfinder were provided in the form of Raven Pro 1.6 (Raven Pro 1.6.4 Interactive Sound Analysis Software, Cornell Lab of Ornithology, NY, USA) sound selection tables and which were linked to the raw .wav files through date and timestamps, with each potential detection being boxed for viewing. Information accompanying each potential detection included the .wav file from which the detection originated, the beginning and end time, the low and high frequency boundaries, the begin date, the trigger probability score (%), end classification (HBW, possible HBW) and classification probability score (%) of the potential detection.

To confirm the potential humpback whale detections by FinFinder were not false positives they were checked visually and/or aurally in Raven Pro to reduce the rate of false positives to zero. Spectrograms were produced with an 8048-point Fast Fourier Transforms (FFTs) and a variable frequency resolution based on the signal of interest. The spectrogram was zoomed in to show a close-up view of the 0 – 1.4 kHz range (to best show the lower frequency signals produced by humpback whales), with the default settings (which could be adjusted as necessary) for viewing set to 75 for contrast and 37 for brightness, with resolution set to 300 pixels. Detection files were 60 seconds in total with a 1 second buffer on each side of the detection boxes in the viewing window. Detections were listened to at a playback rate of 1.0 which could be adjusted to 2.0 to more listen more closely to low frequency sounds (i.e., <0.2kHz). Detections were categorised as positively a humpback whale, not a humpback whale, or marked with a question mark if unsure to recheck. All detections categorised as positive had to: a) sound like a humpback whale, and b) look similar to model spectrograms (Dunlop et al., 2007; Mobley et al., 1988; Payne & McVay, 1971; Winn et al., 1979). Any sounds which did not meet these criteria were marked with a question mark and excluded from further analysis.

All detections were independently processed by a second observer (Dr. Jenni Stanley), and the results were compared. Where the categorizations did not match between observers, the data were investigated more closely (i.e., the full .wav files an hour either side of the detection were reviewed) to check for other humpback whale vocalisations. If other humpback whale vocalisations were present in the raw data, the detection was categorised as positive. When the result of the review was not conclusive, the detection was marked 'unsure' regardless of whether one person had marked it as a humpback whale.

At the end of the 'first pass' through the data, all detections marked as 'positive' were reviewed a second time to confirm humpback whale presence through aural and visual assessment of the full raw .wav file for that hour.

2.3.2.2 Delphinid detector outputs

Detections labelled as positive by the delphinid detector within Finfinder were provided in the form of Raven Pro 1.6 (Raven Pro 1.6.4 Interactive Sound Analysis Software, Cornell Lab of Ornithology, NY, USA) sound selection tables. These sound selection tables were linked to the raw .wav files through date and timestamps, with each potential detection being boxed for viewing (in a similar manner to the output of the humpback whale detector) (Figure 2.5). Information accompanying each potential detection included the .wav file from which the detection originated, the beginning and end time, the low and high frequency boundaries, the begin date, the trigger probability score (%), end classification and classification probability score (%) of the potential detection.

To confirm potential detections of delphinids by FinFinder were not false positives they were checked visually and/or aurally in Raven Pro to reduce the rate of false positives to zero. Spectrograms were produced in the form of 30 boxes displaying the potential delphinid signals arranged in a grid array for confirmation checks.

These spectrograms had a 2048 point Fast Fourier Transforms (FFTs) and a variable frequency resolution based on the signal of interest. The spectrogram was zoomed in to show a close-up view of the 2 – 24 kHz range (to best display the range of delphinid signals), with the default settings (which could be adjusted as necessary) for viewing set to 72 for contrast and 29 for brightness, with resolution set to 300 pixels. Detection files were 60 seconds in total with a 2 second time pad on each side of the detection boxes in the viewing window. Detections were confirmed and categorised as positive or negative, or marked with a question mark if unsure to recheck (Figure 2.5). All detections categorised as a positive had to: a) sounds like a delphinid, and b) look similar to model spectrograms (Díaz López, 2010; Gannon et al., 2005; Nowacek, 2005). Any sounds which did not meet these criteria were marked with a question mark and excluded from further analysis.

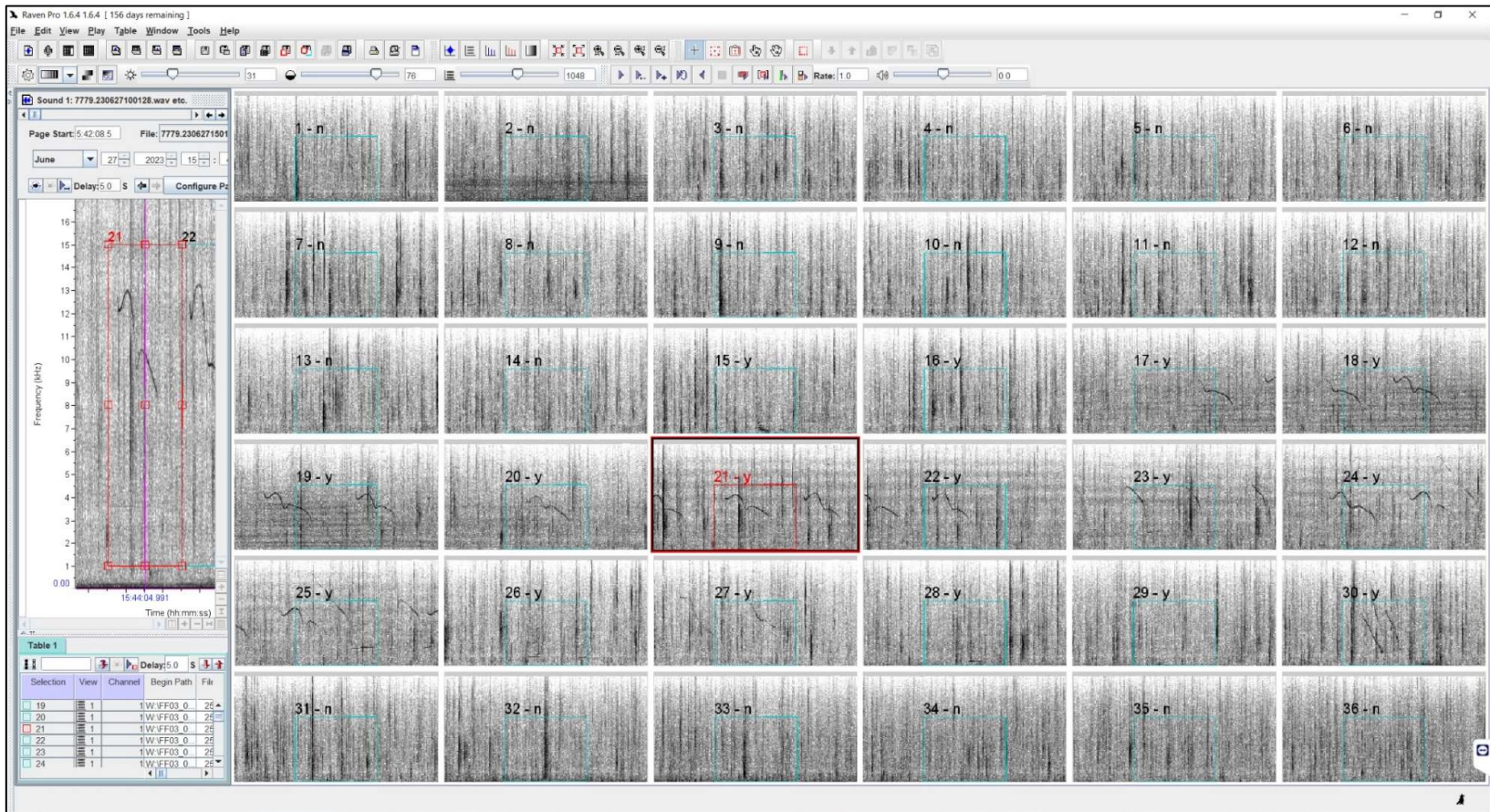


Figure 2.5: Example screenshot of delphinid detector output sound selection table in Raven Pro 1.6., used to verify delphinid signal detections. Blue boxes indicated potential delphinid mid-frequency (1000 – 24,000 Hz), frequency-modulated signal, with the window under current assessment in red.

2.3.2.3 Validation of humpback whale and delphinid detector performance

Aural and visual verification of the potential detections within Raven Pro ensured a missed detections rate (false negatives) of 0 % at the hourly scale. The negative rates of the detectors overall were tested by inspecting random/non-random subsamples of the data which were manually processed for hourly presence of humpback vocalisations and dolphin whistles respectively. Time periods within the deployments used to verify the missed detection rate of the detectors were selected to encompass variability in conditions, including periods from different times of the year and with varying weather conditions, ambient sound levels, vessel presence levels, rainfall, and levels of biological activity.

This validation of the detectors was done by viewing long-term spectral averaging created within the MATLAB (MathWorks Inc., 2018b) based Triton software package (Wiggins et al., 2010), with Raven Pro 1.6 being used for further visual and aural examination to help verify unknown signals. To calculate the precision of the detectors (Table 2.4, 2.5), the number of positive detections observed in the manual screening was compared to those marked positive by the detectors for both species. The rate of true positives (precision), true negatives (recall) and overall accuracy was then calculated for the detectors using a confusion matrix (Baumgartner et al., 2019).

2.3.3 Vessels, Humpback Whale and Delphinid Presence

Verified raw detection data for humpback whales, delphinids and vessels at each site was further analysed so that it could be used to describe trends in spatiotemporal presence at each site. After manual verification of potential recordings from the detectors was complete data was exported in .xlsx format. 'Total Detections' was calculated as the total number of verified detections of a signal of interest across all the deployment periods for each site. Vessel detections were also assigned to the 'hour of day' that they started in to examine the times of the day vessel presence was highest across the seasons and the full sampling effort at each site. All times referred to are New Zealand Standard Time (NZST).

'Positive Presence Hours' were calculated by taking the number of hours in a specified period that had at least one positive acoustic detection within them - i.e. the presence or absence of a detection of a signal of interest within that hour (1 or 0 respectively). In many cases, a positive presence hour may have had multiple detections within it.

After positive presence hours were calculated for humpback whales, delphinids and vessels for each site and deployment period, a dataset for all sampling periods at the sites was created by combining the data. 'Daily Presence' was calculated as the total number of hours during that day containing at least one verified positive detection for the signal of interest (positive presence hours).

As some months had less sampling effort than others, standardised metrics were calculated to ensure accurate comparisons. 'Total Presence' was calculated as the percentage of the

total sampled hours (effort) for the discussed site that contained at least one verified positive detection for the signal of interest (positive presence hours). ‘Monthly Presence’ and ‘Seasonal Presence’ was calculated as the percentage of the total sampled hours (effort) for each month (monthly presence) and season (seasonal presence) that contained at least one verified positive detection for the signal of interest (positive presence hours).

2.4 Statistical Approach

As most months of the year were only monitored once during the study, we could not evaluate monthly inter-annual variability in presence statistically. Instead for the purpose of statistical analysis data were pooled by month within each site, and variation among sites and months were tested.

The effect of Site and Month on positive presence hours of signals of interest were estimated using negative binomial generalised linear models (GLMs) and a log link function (Casção et al., 2020). This model type was chosen due to the data being heavily zero-inflated, which resulted in a lack of fit in other models. Months with incomplete data collection (less than $\frac{3}{4}$ of a month) were excluded from the relevant model. The response (dependent) variable was the number of ‘Positive Presence Hours’ and ‘Site’ and ‘Month’ were factor variables with three (two for humpback whales) and ten levels respectively.

Models were:

$$\begin{aligned} & \textit{Positive Presence Hours} \sim \textit{Month} \\ & \text{and } \textit{Positive Presence Hours} \sim \textit{Season} \end{aligned}$$

Model residuals were checked for model fit and check for meeting the linearity, normality, and homogeneity of variance assumptions of negative binomial regression. As there were no significant deviations away from 0 and greater than 95 % of the residuals were under the absolute value of 2.0, the model is thought to fit the data sufficiently. All analyses were conducted using SPSS Statistics (version 29.0.0.0, IBM Ltd, 2024).

2.5 Vessel Propagation Modelling

Vessel noise maps were used to investigate the noise levels associated with specific vessels visiting the study area between 01 February 2022 – 31 December 2023. These maps were produced for each vessel track, and for each vessel type, registered in the Automatic Identification System (AIS) record for the 23 months. High resolution maps showing the overall noise levels for each month and each year were then produced by combining individual vessel noise maps.

A new program based in MATLAB was developed for this study and concurrent studies that allows the user to produce geo-referenced vessel noise models after uploading the required environmental parameters and AIS data. The code is very efficient at handling very large datasets, via parallel computing and GPU arrays, and produces maps of higher accuracy and resolutions. The novel program allows for flexibility in the propagation loss models used (Ocean Acoustics Ltd, 2023).

2.5.1 Vessel Automatic Identification System and Tracking

Vessel identification and tracking data was gathered using the Automatic Identification System (AIS). Fisheries Science and Information Group, Fisheries New Zealand Maritime New Zealand provided data using the Starboard Maritime Intelligence Platform.

A polygon encompassing all recording sites, with north, south, east and west boundaries, 10 km from the nearest recording site, was set and coordinates for each corner were input into the platform to filter AIS records to within the polygon between 01 February 2022 – 31 December 2023 (Figure 2.1). This polygon was chosen for analysis as it would roughly estimate the area within which a vessel with a source level (SL) of ~180 dB re 1 μ Pa would ensonify the recording sites at levels > 120 dB re 1 μ Pa. The theoretical source level of 180 dB re 1 μ Pa was used as a large proportion of large commercial vessels (carrier and passenger) range from 170 – 190 dB (Chion et al., 2019; Greene & Moore, 1995; Wenz, 1962). For a SL of 180 dB, a coarse estimate of transmission loss (TL) of 60 dB (bringing received levels [RL] to 120 dB), using $TL = 15 \log_{10}(\text{distance})$, would occur approximately 10 km from the source. As discussed further below, this simplified TL equation was chosen to represent the average sound field during our study, while retaining dependence on the principal features of the environment (Hatch et al., 2008).

Vessel positions were taken from the overall AIS records that included a series of time-stamped waypoints and associated data for each vessel category. The vessel categories were:

- Cruise vessels
- Passenger vessels
- Recreational vessels
- Government research vessels

It was also not possible to include AIS information from commercial fishing vessels in this study due to confidentiality.

The AIS records collected during this time were extracted, filtered and reformatted to be used to calculate the number of vessel records on a monthly scale, excluding vessels with a ground speed of zero. Filtering was necessary to extract only the vessel information that was necessary for the study. For each latitude and longitude waypoint, the associated data extracted for the model was, 1) speed over ground (SOG) and the vessel's International Maritime Organisation (IMO) number.

Before being used in the model, the distances between successive waypoints inside individual tracks were calculated (Euclidian distances) and ensured < 20km of each other. This was required as the AIS-provided tracks of each individual vessel were not consistent and therefore large gaps in the vessel's positions existed. Because vessel movements were somewhat erratic between communities, large gaps between waypoints meant that we were unable to accurately model it.

Vessel tracks that were of sufficient resolution were set aside for further processing.

2.5.2 Vessel Noise Modelling: Source Levels

The source spectrum of each vessel class for specific speeds and vessel size was estimated using the reference models by MacGillivray and de Jong (2021). Their reference spectrum model (RSM) is the newest validated model using data from the Vancouver Fraser Port Authority's Enhancing Cetacean Habitat and Observation (ECHO) Program. For specific details on the RSM, please refer to MacGillivray & de Jong (2021).

As the RSM produces spectra that are specific to a vessel's class, size, and speed, those three parameters were required in the vessel noise model. While the speed and vessel type were available from the AIS datasets, the length of each vessel was found through a web search of the IMO/MMSI number.

2.5.3 Vessel Noise Modelling: Propagation Model

A range of propagation models exist that have shown value in predicting range-dependent acoustics. However, as with all models:

- The output accuracy is highly dependent on the input data; and
- Each model can produce different results, despite having the same input data.

As a result, several different propagation model algorithms were considered for this study. They were parabolic equation (PE, RAMGeo), ray tracing (Bellhop), normal modes (Kraken) and energy flux (Weston, 1971).

Tracks were initially run using a combination of normal modes or PE and ray tracing methods, such as that from Pine et al. (2018). The energy flux (EF) model demonstrates a high computational efficiency over range-dependent scenarios, meaning far higher resolutions can be achieved over smaller time periods than for PE/Bellhop. The EF method was also used by (Farcas et al., 2020) to produce validated vessel noise maps of the Northeast Atlantic Ocean.

The EF model incorporates bathymetry, sound speed, seabed reflectivity and frequency. The required environmental parameters were provided by Land Information New Zealand (LINZ). The bathymetry was uploaded to the model program as an ASCII Raster (decimal degrees being the reference coordinates), while the sound speeds were calculated from water temperature and salinity. Seabed reflectivity coefficients were set along 2D transects from the source positions to allow for changing seabed compositions and for this study were set as mixed sand/fine sediment with gravel and rock. Further work should be completed on understanding and mapping the reflectivity when using these models in narrower fiords and sounds due to the great water depth and steep rock walls. Fortunately, the majority of our study area did not have these properties.

Once the water temperature and salinity were set and the seabed-related parameters were defined in the program, the main code was run. The bathymetry transects were extracted as 360 radials from each waypoint (representing 1° bearings) and a bathymetry value was taken for every 100 m along the transect for 100 km. For each of those transects, the propagation loss for each frequency was calculated for every 100 m range point (the sound speed and seabed parameters were also for the same calculation point). The result was a 3D array per frequency, each being a size of 1000 calculation points by 360 radials (totalling 360,000 PL values per waypoint).

The program then calls back the 3D arrays and converts into a 2D map using linear interpolation and nearest neighbour extrapolation. This was completed for each waypoint to produce a single map of the whole track for each frequency. Those maps were then stored in structural arrays and saved in temporary directories for later call back when required. Writing the arrays to data files in temporary directories was necessary as it saved on RAM resources.

2.5.4 Vessel Noise Modelling: Integrating Propagation Model with Source Levels

Each propagation loss map was then called back from their temporary directories and subtracted from the estimated source level, from the RSM, of that frequency.

Monthly equivalent continuous sound pressure levels (LEq) maps were also produced. Unlike the SPL maps, these LEq metrics are not instantaneous layers but include time-integrals in their calculations. Their benefits are that they show average vessel noise over the month (LEq).

The LEq maps for each individual vessel track was produced by taking the logarithmic average (mean) of two successive waypoints, starting from the first waypoint in the AIS record. This provided the LEq layer for a new waypoint between those two, representing the centre of a 'cell'. This mean that the cell sizes were not equal but defined by the distance between waypoints.

This method of analysing per waypoint, instead of using a gridded structure, was to have the model automatically adjust for changing resolution requirements. For example, in narrower waterways, resolutions of 10km x 10km grid cells would be too coarse to capture SOG changes and bathymetries as the vessel moves through and therefore would need to be smaller. However, those smaller cells increase the computational load in areas where higher resolutions are more appropriate, such as offshore when SOG does not change, and the PL coefficients are more stable. Furthermore, by producing the LEq maps via this waypoint analysis, SOG changes in some vessel classes, such as recreational vessels moving slower or changing course a lot, would also be captured.

Chapter 3: Results

3.1 Sound Source Detection

Several presence metrics for signals of interest (vessels, delphinids and humpback whales) were calculated from verified detection data to aid in understanding signal of interest presence over the deployment timeframe at each site. These metrics were also used to create effort corrected metrics to account for the different durations of the deployments seen among sites.

Metrics discussed:

Total Detections – the total number of verified detections of a signal of interest across all deployment periods at the discussed site.

Positive Presence Hours – the number of hours that were positive for at least one verified positive detection of a signal of interest.

Daily Presence – the number of hours during the discussed day that contained at least one verified positive detection of a signal of interest (Positive Presence Hours).

Total Presence - percentage of the total sampled hours (effort) for the discussed site that contained at least one verified positive detection (Positive Presence Hours)

Seasonal Presence – percentage of the total sampled hours (effort) for the discussed season that contained at least one verified positive detection (Positive Presence Hours).

Monthly Presence – percentage of the total sampled hours (effort) for the discussed month that contained at least one verified positive detection (Positive Presence Hours).

3.2 Vessels

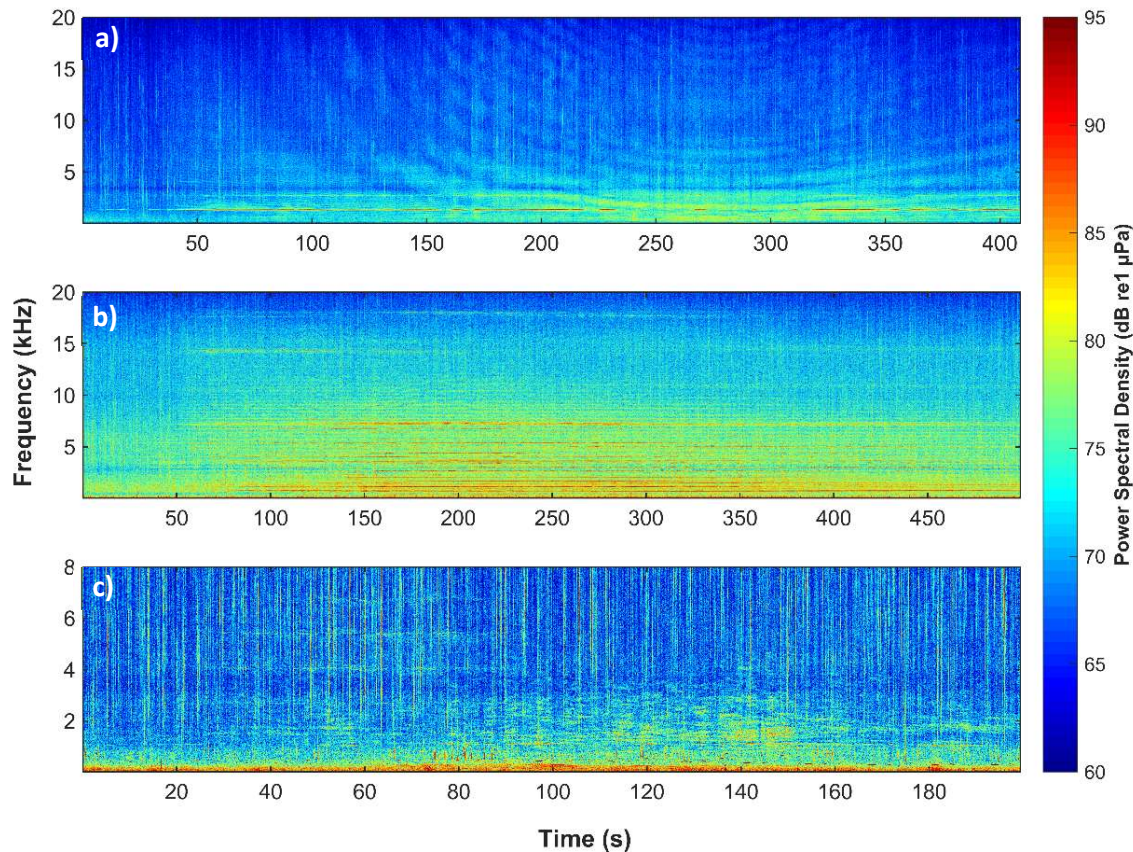


Figure 3.1a – c: Long term spectral averages (LTSA) showing three examples of common vessel signals seen at the recording sites. a) closest point of approach by a large vessel at speed showing the Lloyds mirror effect, b) small vessel transiting at speed close to the hydrophone, c) small vessel transiting past the hydrophone at speed but at a greater distance than the vessel in panel b. All spectrograms produced using: Fast Fourier transformation length = 6048, Hanning window and 80 % overlap.

There were a variety of vessel signatures seen in the recorded data which were dependent on the size of the vessel, speed it was travelling and its behaviour (Figure 3.1a – c). Vessel behaviours such as transition, slow manoeuvring, high speed passing, and anchoring all produce distinct acoustic signatures and were seen in the data. However, categorising vessel behaviour of each vessel detection was outside the scope of the current study. The top panel shows an example signature of large vessel passage towards and then away from the hydrophone, and the distinctive Lloyds Mirror pattern. This can be identified by the increasing and decreasing high intensity noise concentrated in the low frequency range (Figure 3.1a). The middle panel shows an example of a detection of a smaller vessel close to the hydrophone, identifiable by the bands of medium intensity noise in the low to mid frequency ranges (Figure 3.1b). The bottom panel shows an example of a more distant passage of a small vessel which is identifiable by the loss of higher frequency signal and

patchy bands of noise amongst the ambient soundscape, including humpback whale signals (Figure 3.1c).

3.2.1 Vessel Detector Performance

Table 3.1: Triton Vessel Detector performance testing result.

Site	Location	Sensitivity (%)	False positive rate pre-verification (%)	False positive rate post-verification (%)
FF02	Five Fingers 02	96	8	0
FF03	Five Fingers 03	96	7	0
Anchor01	Anchor Island 01	93	21	0

Testing of the Triton Vessel Detector resulted in a sensitivity of 93 % and higher at all sites, a false positive rate of less than 21 % for Anchor01 and less than 8 % for FF02 and FF03. The post-verification rate was 0 % for all recording sites (Table 3.1).

3.2.2 Presence by Site

Five Fingers 02 (FF02)

A total of 9,999 hours were sampled at FF02 from March – December 2022 and again from March – June 2023. Of this, 352 hours were positive for vessels (at least one vessel detection in the hour) which equated to 3.52 % of the total sampling hours (total vessel presence) (Table 3.3).

Seasonal vessel presence (the percentage of hours within the season that were positive for vessel presence) remained relatively stable in 2022 and exhibited no clear trend, ranging from 2.38 – 3.02 %. Seasonal vessel presence appeared to have increased in 2023, with the first two seasons autumn (5.48 %) and winter (5.97 %) being greater than in 2022. Unfortunately, there was no data collected in spring 2023 to observe if this trend continued (Table 3.2).

When examining monthly vessel presence (the percentage of hours within that month that were positive for vessel presence) variation in the data became more apparent, with months ranging from 0.54 – 7.08 % (Table 3.3, Figure 3.5). There was a downward trend from March – May 2022, then a cyclical pattern of alternating monthly fluctuations where presence oscillated between lower and higher levels from June – December 2022. There was no data collected in January and February 2023, but when sampling resumed in March 2023 monthly vessel presence was higher than in any previous month. This continued to increase into April where monthly vessel presence peaked for FF02 over the entire recording period at 7.08 %. Other months of elevated monthly vessel presence were November 2022 (5.14 %), March 2023 (5.65 %) and June 2023 (5.97 %) (Table 3.3, Figure 3.5).

Number of total vessel detections varied by time of day during all seasons (Figure 3.2a-f). When examining total number of vessel detections on a seasonal scale, there were consistently higher numbers of detections during daylight hours compared to dark hours during all seasons. All seasons, except for autumn, had an even spread of detections across daylight hours (07:00 – 18:00), however autumn of both 2022 and 2023 showed peaks in detection numbers between the hours beginning at 12:00 (2022) and 10:00, and again at 15:00 (2023) (Figure 3.2a, 3.2e). The hour with the greatest number of total vessel detections varied among seasons, occurring within hours beginning at 12:00 during autumn 2022, 14:00 during winter 2022, 11:00 and 13:00 during spring 2022, multiple hours beginning at 08:00, 10:00, 14:00 and 18:00 during summer 2022, and 10:00 during autumn 2023 (Figure 3.2a-f).

When combining the data across all recording periods at FF02 there were 424 vessel detections in total. Total numbers of vessel detections were highest during the daylight hours of 08:00 – 18:00 which ranged between 23 – 45 total vessel detections (Figure 3.2f). The hour beginning at 07:00 with 13 total vessel detections (while lower than the daylight hours) was greater than the remaining dark hours which ranged between 0 – 6 detections. The highest total number of vessel detections occurred in the hours beginning at 09:00 and 10:00 with 44 and 45 total vessel detections respectively (Figure 3.2f).

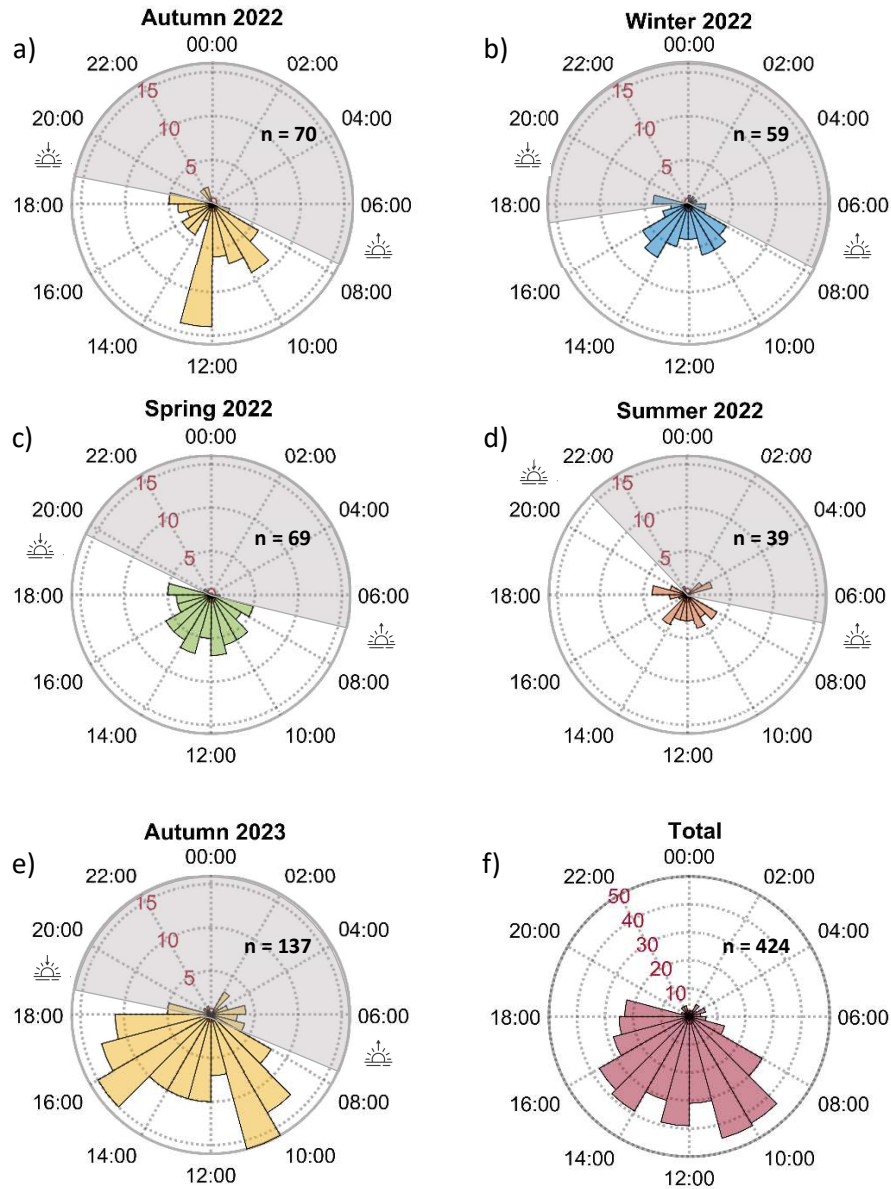


Figure 3.2a – f: Polar plots showing total number of vessel detections per hourly segments for each recording season and overall (total) at Five Fingers O2, with n being total number of hours sampled during that period. Shaded sections indicate dark hours between sunrise and sunset in each season. **Note.** Different scale in plot f, and that these plots illustrate total number of detections which is not an effort corrected metric - care must be taken when considering absolute numbers.

Five Fingers 03 (FF03):

A total of 10,964 hours were sampled at FF03 from March – December 2022 and again from July – November 2023. Of this, 756 hours were positive for vessels (at least one vessel detection in the hour) which equated to 6.90 % of the total sampling hours (total vessel presence) (Table 3.4).

Seasonal vessel presence ranged between 4.76 – 8.92 % at FF03, increasing between autumn (4.76 %) and winter (8.92 %) in 2022 before steadily decreasing through to summer 2022 (6.62 %) (Table 3.2). Unfortunately, no data was collected in autumn 2023, but when sampling resumed, seasonal vessel presence in winter 2023 was 4.77 %, lower than the same period in 2022. Seasonal vessel presence increased in spring 2023 to 8.05 %, with this season being similar between years (Table 3.2).

Monthly vessel presence ranged from 3.61 – 15.18 % at FF03 (Table 3.4, Figure 3.6). There was a decrease from March (5.91 %) to April (3.61 %) before an upward trend until July in 2022 (4.40 – 10.35 %). Monthly vessel presence remained high between July and September ranging from between 9.17 – 10.35 %, before an alternating monthly decrease and increase from October – December 2022. In 2023, no data was collected until July. July – September ranged between 4.70 – 5.83 % and were lower than the same time in 2022. Both years showed an increase from October to November but there was greater increase in 2023 to November (15.18 %) which had the peak monthly vessel presence at FF03 (Table 3.4, Figure 3.6).

When examining the distribution of total number of vessel detections throughout the day, daylight hours (07:00 – 18:00) had the highest number of detections in all seasons, with a relatively even spread (Figure 3.3a-g). The hour with the greatest number of detections varied among seasons, occurring in the hours beginning at 12:00 during autumn 2022 and spring 2023, 14:00 during winter 2022, 15:00 during spring 2022, and 11:00 during summer 2022 and winter 2023 (Figure 3.3a-g).

When combining the data across all recording periods at FF03 there were 910 vessel detections in total. The highest total vessel detections occurred during the daylight hours of 08:00 – 17:00 which ranged between 53 – 95 total vessel detections (Figure 3.3g). The morning and evening hours beginning 07:00 and 18:00 had 38 and 28 total vessel detections respectively, which (while lower than during the daylight hours) were higher than during the dark hours of 19:00 – 06:00 which ranged between 3 – 20 total vessel detections. The greatest number of vessel detections occurred in the hour beginning at 11:00 with 95 total vessel detections (Figure 3.3g).

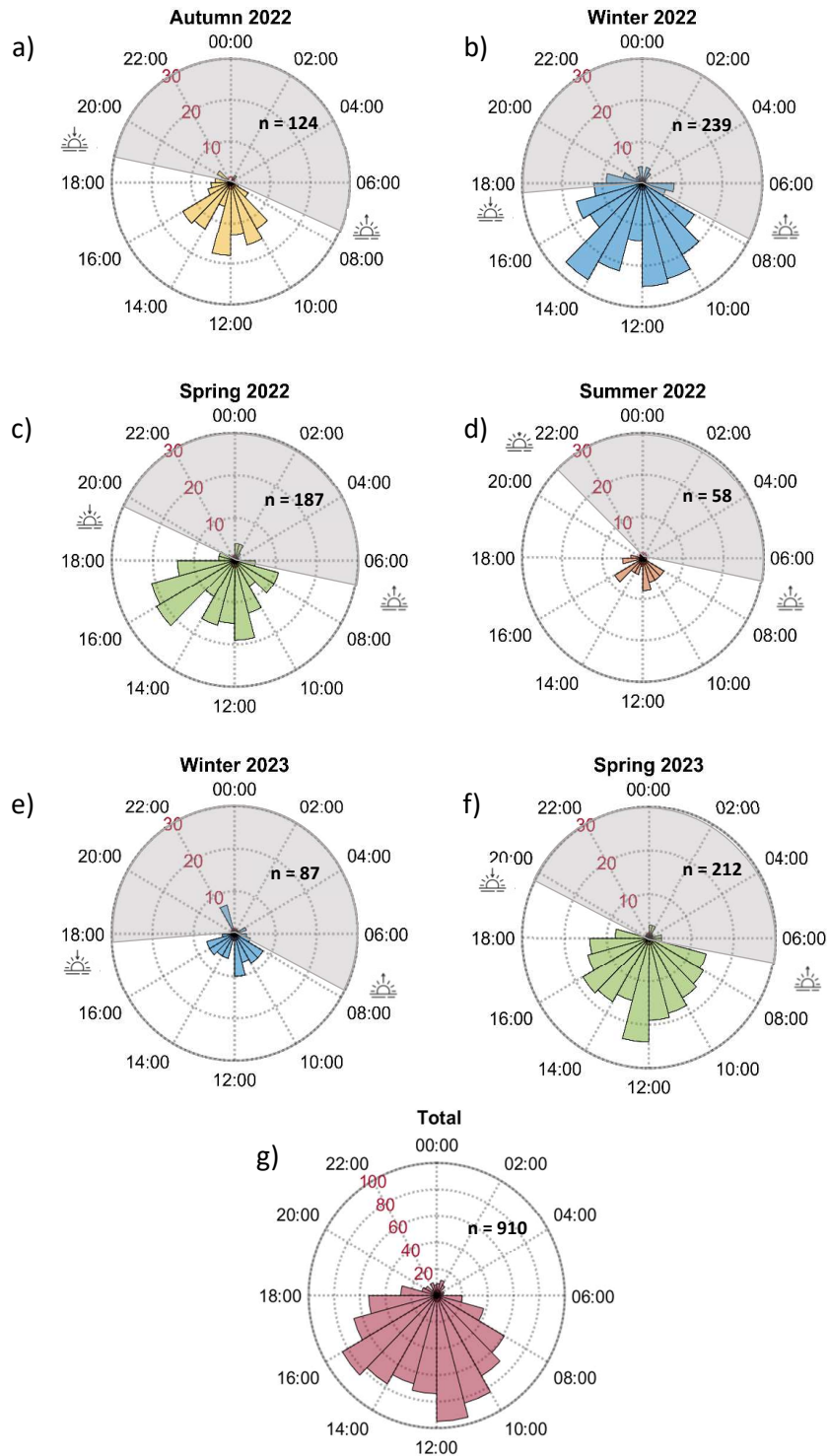


Figure 3.3a – g: Polar plots showing total number of vessel detections per hourly segments for each recording season and overall (total) at Five Fingers 03, with n being total number of hours sampled during that period. Shaded sections indicate dark hours between sunrise and sunset in each season. **Note.** Different scale in plot g, and that these plots illustrate total number of detections which is not an effort corrected metric - care must be taken when considering absolute numbers.

Anchor Island 01 (Anchor01):

A total of 12,144 hours were sampled at Anchor01 from March – December 2022 and again from March – May and July – November 2023. Of this, 1538 hours were positive for vessels (at least one vessel detection in the hour) which equated to 12.66 % of the total sampling hours (total vessel presence) (Table 3.5).

Seasonal vessel presence remained relatively stable in 2022 and exhibited no clear trend, ranging from 12.82 – 13.63 %, whereas in 2023 it decreased from autumn (16.35 %) to winter (6.92 %) before increasing again in spring (11.03 %) (Table 3.2). Unfortunately, there was no data collected in summer 2022. When comparing seasonal vessel presence from 2022 to 2023 there was an increase from 12.82 % to 16.35 % for autumn, a decrease from 13.63 % to 6.92 % for winter and a smaller decrease from 13.30 % to 11.03 % in spring (Table 3.2).

Monthly vessel presence showed variation throughout 2022, with an alternating monthly decrease and increase ranging between 8.06 – 17.08 % from March to November, except for July – September which was consistently greater, ranging between 15.73 – 17.08 % (Table 3.5, Figure 3.7). There was an upward trend between March – May 2023 from 14.78 – 17.61 % with these months being consistently higher than the same period in 2022. There was no data from June 2023, however when sampling resumed monthly vessel presence was similar in July (6.99 %) and August (6.85 %), lower than those months in 2022. Monthly vessel presence decreased from September (9.31 %) to October (5.91 %) before increasing again in November 2023 (19.79 %) which had the peak monthly vessel presence at Anchor01. This was a similar trend to in September – November 2022, but the increase to November was greater in 2023 (Table 3.5, Figure 3.7).

When examining the distribution of the total number of vessel detections throughout the day, daylight hours (05:00 – 19:00) contained the highest number of detections in all seasons, with a relatively even spread (Figure 3.4a-g). The hour with the greatest number of detections varied among seasons, with the greatest occurring in the hours beginning at 16:00 during autumn 2022, 10:00 during winter and spring 2022, 09:00 during autumn 2023, 08:00 during winter 2023 and 17:00 during spring 2023 (Figure 3.4a-g).

When combining the data across all recording periods there were 1951 vessel detections in total. The highest total vessel detections occurred during the daylight hours of 05:00 – 17:00, which ranged between 105 – 161 total vessel detections (Figure 3.4g). The hour beginning at 18:00 had the highest number of detections (68), which while lower than during the daylight hours, was higher than the rest of the dark hours which ranged between 10 – 46 total vessel detections. The greatest number of vessel detections occurred in the hour beginning 10:00 with 161 total vessel detections (Figure 3.4g).

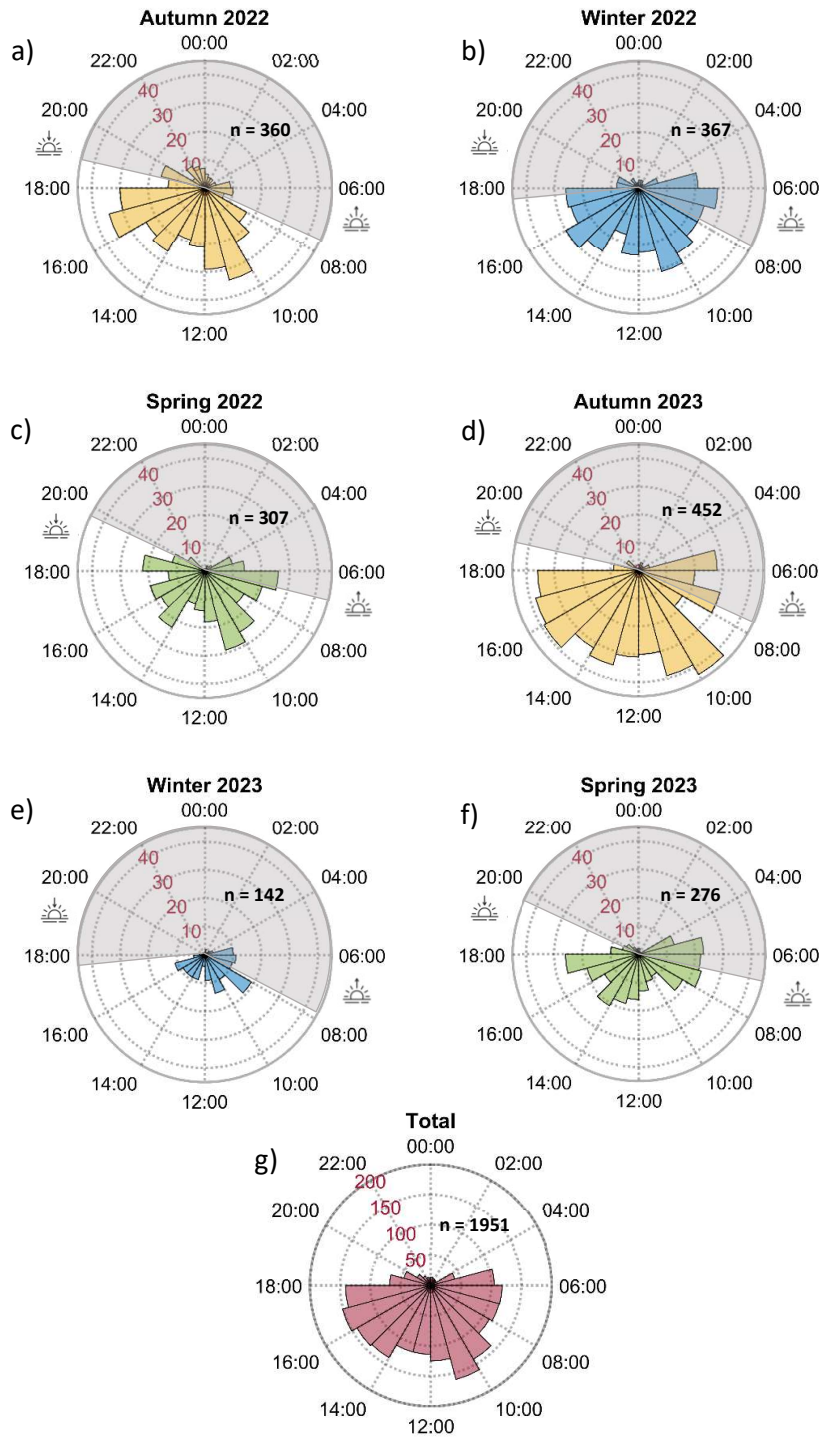


Figure 3.4a – g: Polar plots showing total number of vessel detections per hourly segments for each recording season and overall (total) at Anchor Island 01, with n being total number of hours sampled during that period. Shaded sections indicate dark hours between sunrise and sunset in each season. **Note.** Different scale in plot g, and that these plots illustrate total number of detections which is not an effort corrected metric - care must be taken when considering absolute numbers.

Table 3.2: Table showing number of hours sampled, total number of hours with vessel presence and seasonal vessel presence percentage for all recording sites.

Site	Season	Total Hours Sampled	Vessels	
			Total Presence Hours	Seasonal Presence (% hours)
FF02	Autumn 2022	2208	63	2.85
	Winter 2022	2208	55	2.49
	Spring 2022	2184	66	3.02
	Summer 2022	672	16	2.38
	Autumn 2023	2208	121	5.48
	Winter 2023	519	31	5.97
	Spring 2023	0	-	-
FF03	Autumn 2022	2208	105	4.76
	Winter 2022	2208	197	8.92
	Spring 2022	2184	162	7.42
	Summer 2022	740	49	6.62
	Autumn 2022	0	-	-
	Winter 2023	1488	71	4.77
	Spring 2023	2136	172	8.05
Anchor01	Autumn 2022	2208	283	12.82
	Winter 2022	2208	301	13.63
	Spring 2022	1992	265	13.30
	Summer 2022	0	-	-
	Autumn 2023	2208	361	16.35
	Winter 2023	1488	103	6.92
	Spring 2023	2040	225	11.03

Table 3.3: Table showing total number of hours sampled, total number of hours with vessel presence and monthly vessel presence percentage at Five Fingers 02 (FF02).

FF02		Vessels	
Month	Total Hours Sampled	Total Presence Hours	Monthly Presence (% hours)
February 22	0	-	-
March	744	31	4.17
April	720	21	2.92
May	744	11	1.48
June	720	15	2.08
July	744	33	4.44
August	744	7	0.94
September	720	25	3.47
October	744	4	0.54
November	720	37	5.14
December	672	16	2.38
January 23	0	-	-
February	0	-	-
March	744	42	5.65
April	720	51	7.08
May	744	28	3.76
June	519	31	5.97
July	0	-	-
August	0	-	-
September	0	-	-
October	0	-	-
November	0	-	-
Total	9999	352	3.52

Table 3.4: Table showing total number of hours sampled, total number of hours with vessel presence and monthly vessel presence percentage at Five Fingers 03 (FF03).

FF03		Vessels	
Month	Total Hours Sampled	Total Presence Hours	Monthly Presence (% hours)
February 22	0	-	-
March	744	44	5.91
April	720	26	3.61
May	744	35	4.70
June	720	45	6.25
July	744	77	10.35
August	744	75	10.08
September	720	66	9.17
October	744	27	3.63
November	720	69	9.58
December	740	49	6.62
January 23	0	-	-
February	0	-	-
March	0	-	-
April	0	-	-
May	0	-	-
June	0	-	-
July	744	35	4.70
August	744	36	4.84
September	720	42	5.83
October	744	28	3.76
November	672	102	15.18
Total	10964	756	6.90

Table 3.5: Table showing total number of hours sampled, total number of hours with vessel presence and monthly vessel presence percentage at Anchor Island 01 (Anchor01).

Anchor01		Vessels	
Month	Total Hours Sampled	Total Presence Hours	Monthly Presence (% hours)
February 22	0	-	-
March	744	99	13.31
April	720	78	10.83
May	744	106	14.25
June	720	61	8.47
July	744	123	16.53
August	744	117	15.73
September	720	123	17.08
October	744	60	8.06
November	528	82	15.53
December	0	-	-
January 23	0	-	-
February	0	-	-
March	744	110	14.78
April	720	120	16.67
May	744	131	17.61
June	0	-	-
July	744	52	6.99
August	744	51	6.85
September	720	67	9.31
October	744	44	5.91
November	576	114	19.79
Total	12144	1538	12.66

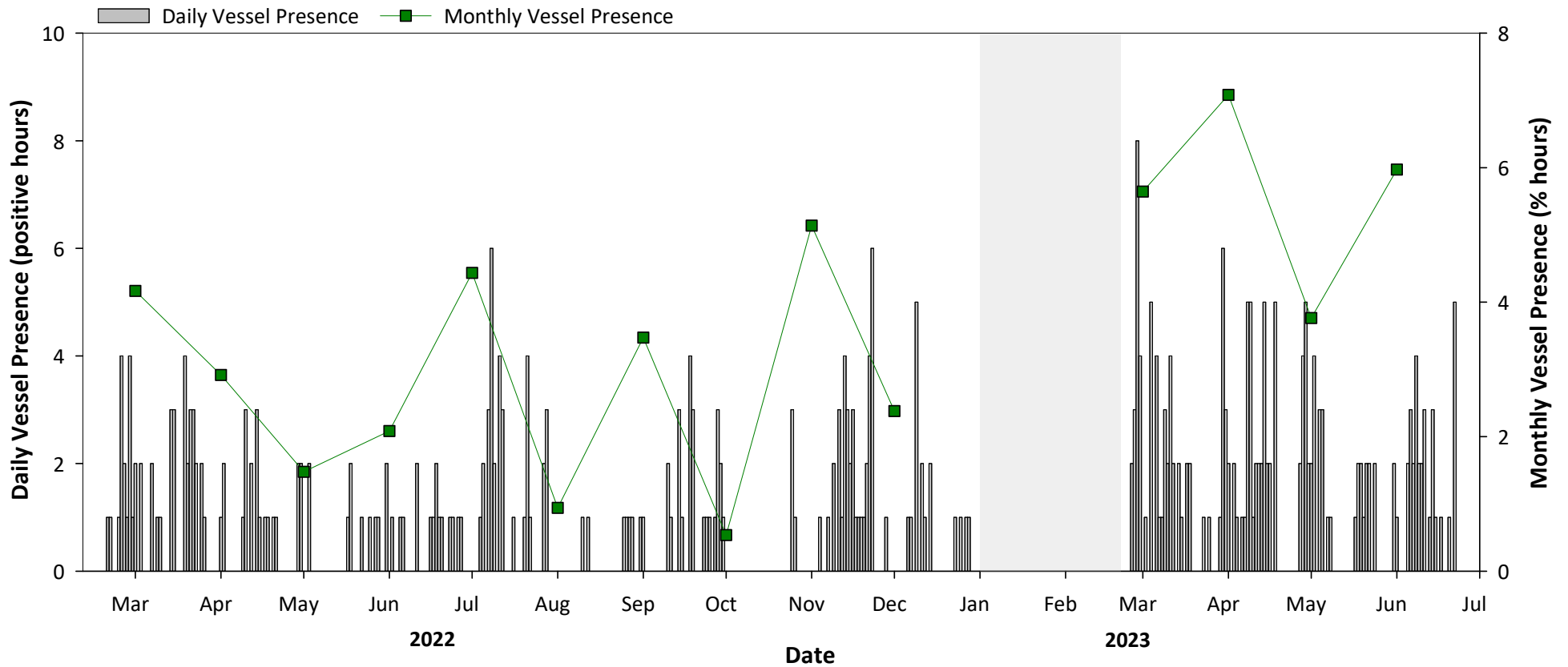


Figure 3.5: Daily vessel presence (the number of hours in that day that contained at least one vessel detection) and monthly vessel presence (the percentage of hours within the month that were positive for vessel presence) at Five Fingers O2 (FFO2) in 2022 and 2023. Grey shaded bars signify no data present.

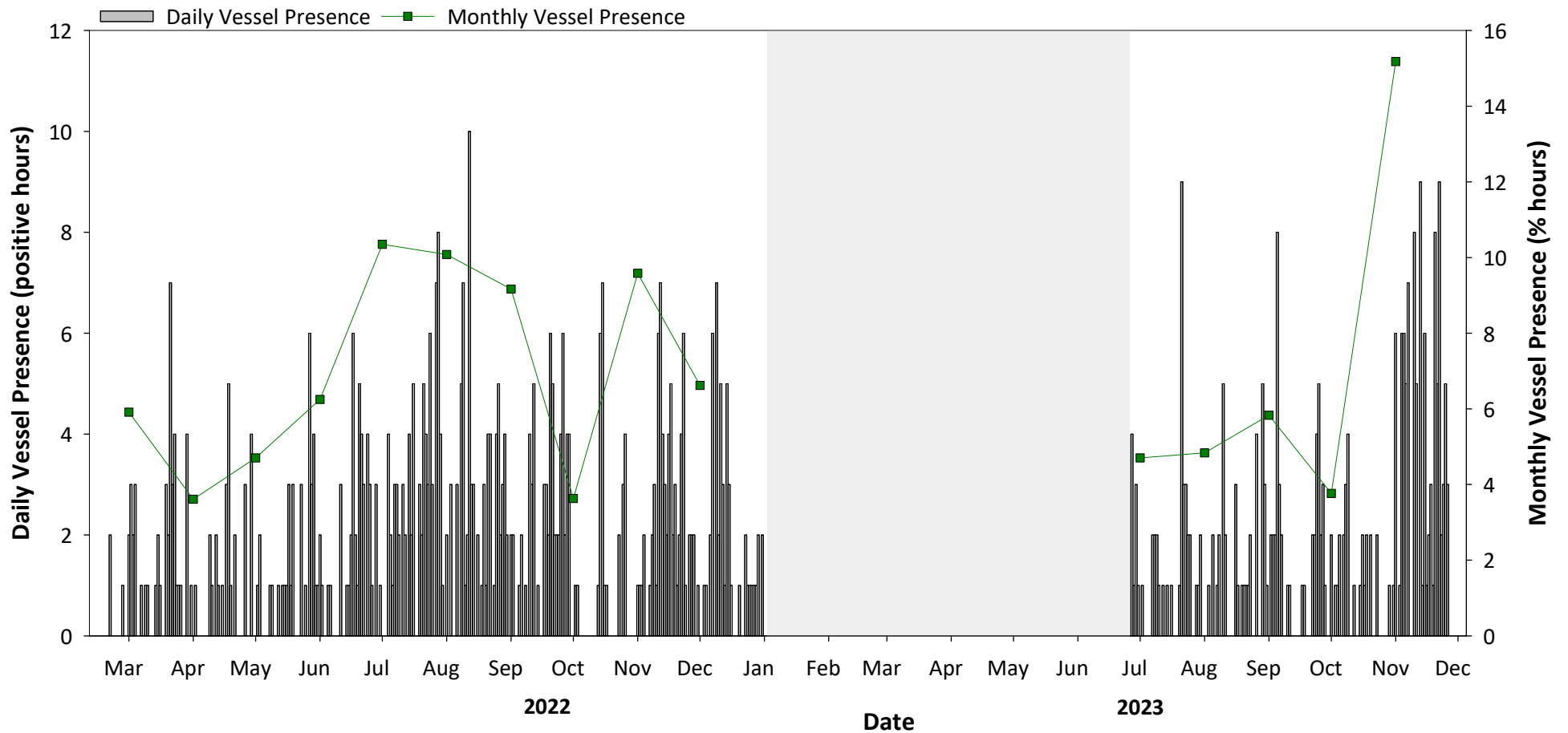


Figure 3.6: Daily vessel presence (the number of hours in that day that contained at least one vessel detection) and monthly vessel presence (the percentage of hours within the month that were positive for vessel presence) at Five Fingers 03 (FF03) in 2022 and 2023. Grey shaded sections signifies no data present.

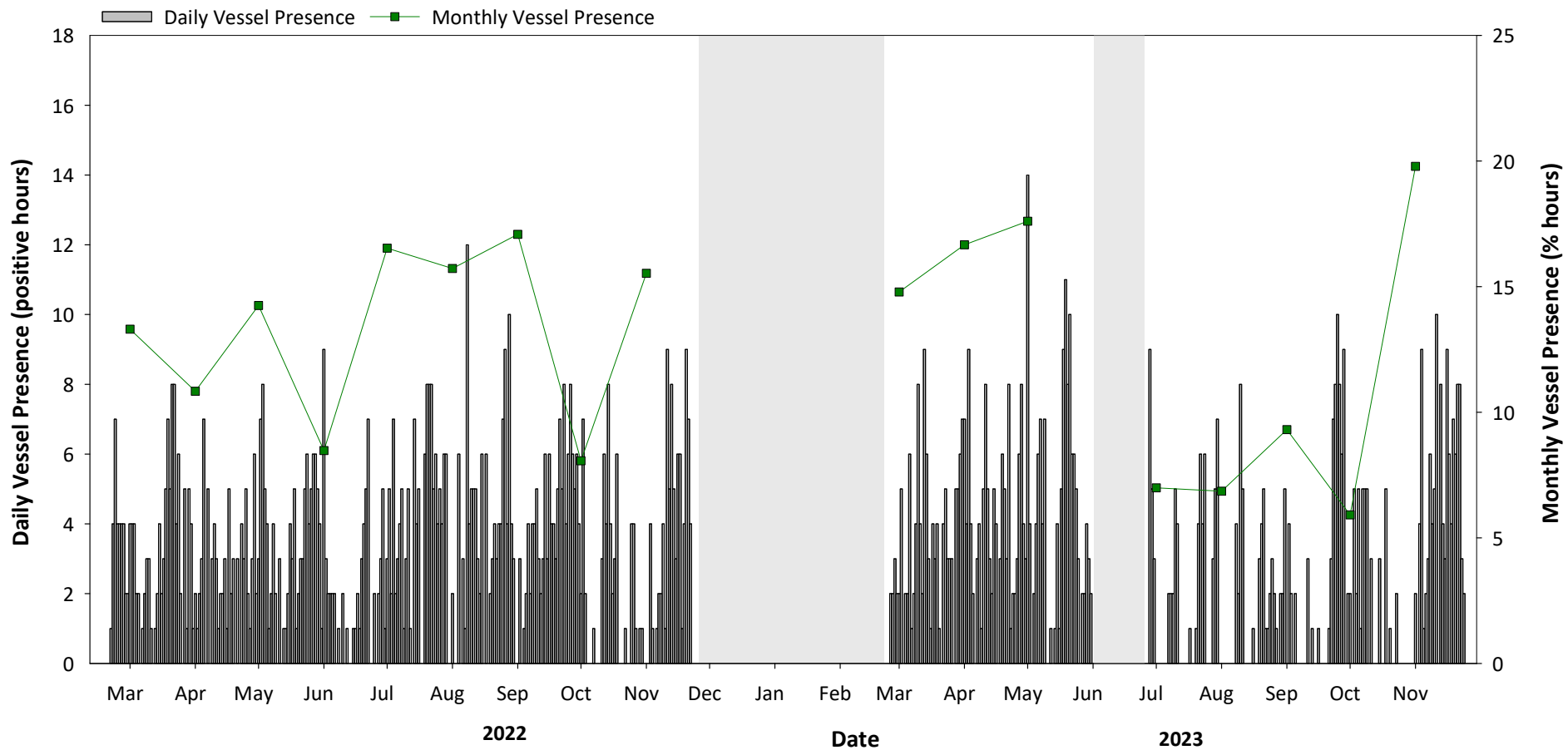


Figure 3.7: Daily vessel presence (the number of hours in that day that contained at least one vessel detection) and monthly vessel presence (the percentage of hours within the month that were positive for vessel presence) at Anchor Island 01 (Anchor01) in 2022 and 2023. Grey shaded bars signify no data present.

3.2.3 Site Comparisons

There was a significant effect of Site ($P < 0.001$) and Month ($p < 0.001$) on Positive Present Hours for vessel acoustic signals (Table S1 & S2). Positive Presence Hours were significantly higher at Anchor01 ($p < 0.001$) compared to both FF03 ($p < 0.001$) and FF02 ($p < 0.001$). Positive Presence Hours were significantly higher in November ($p = 0.04$) when compared to April ($p = 0.864$), March ($p = 0.278$), September (intercept) ($p = 0.01$), July ($p = 0.939$), May ($p = 0.670$), June ($p = 0.278$), August ($p = 0.206$) and December ($p = 0.316$), which were all significantly higher than October ($p < 0.01$) (Table S2).

Direct comparison among all three recording sites was only possible from March - November 2022 and then between two of the sites for December 2022 (FF02 & FF03), March – May 2023 (FF02 & Anchor01), and July – November 2023 (FF03 & Anchor01) as these were the only periods they were sampled simultaneously (Table 2.2). No comparisons among sites were possible for June 2023 which was only sampled at FF02. The same applied for seasonal comparisons, especially when there was no monthly overlap in sampling among sites (Table 3.2).

Total vessel presence was greatest at Anchor01 at 12.66 %, followed by FF03 at 6.90 % and lastly FF02 at 3.52 % (Table 3.3 - 3.5).

Seasonal vessel presence from autumn 2022 to spring 2023 was consistently greatest at Anchor01, followed by FF03, and then FF02. Both FF02 and Anchor01 showed no clear seasonal trend during this period whereas FF03 showed an increase during the winter (Table 3.2). During autumn 2023, again Anchor01 had the higher seasonal vessel presence compared to the only other site sampled, FF02, with both sites showing an increase compared to autumn 2022. During winter and spring 2023 only FF03 and Anchor01 were sampled with Anchor01 having the higher presence of the two in both seasons. When comparing Anchor01 and FF03 to the same seasons in 2022 there was a comparative decrease between years seen at both sites in winter 2023, whereas in spring 2023 there was a comparative increase between years at FF03 and decrease at Anchor01 (Table 3.2).

At a monthly resolution, Anchor01 had the highest monthly vessel presence for every month, followed by FF03 and lastly FF02 (Figure 3.8). All three recording sites showed a decrease in presence from March – April 2022 after which they fluctuated independently with FF02 showing a downward trend until May and then an alternating monthly increase then decrease from June – December 2022 (Figure 3.8). In contrast an upward trend was seen from April - July at FF03, which then remained high until September after which it showed an alternating monthly decrease and increase until December 2022. Anchor01 showed an alternating monthly increase and decrease after April until November 2022, except for July – September which were comparatively higher than other months similarly to during the same period at FF03. All three sites showed a marked decrease in presence from September to October 2022, with most pronounced drops seen at Anchor01 and FF03 (Figure 3.8).

There was no clear similarity between Anchor01 and FF02 (only two sites sampled) for March – May 2023, with Anchor01 showing a steady upward trend whereas FF02 showed an alternating monthly increase and decrease in this period which continued until June 2023 (Figure 3.8).

The fluctuations in monthly vessel presence (when seen) at the three sites during 2022 occurred at the same time and in the same direction, with the difference among sites also appearing to remain similar (Figure 3.8). This was most apparent during September – November where there was a visible decrease and then increase at all sites. Changes were also seen in the same direction during this period for Anchor01 and FF03 between July – November 2023, with both sites having reduced monthly vessel presence in these months compared to the same period in 2022. Both sites then showed a large increase reaching their respective peak monthly vessel presence in November 2023 (Figure 3.8).

When examining total numbers of vessel detections Anchor01 had the highest (1951), followed by FF03 (910) and then FF02 (424) (Figure 3.2f, 3.3g, 3.4g). All three sites had greater total vessel detections during daylight hours compared to dark hours, with detections being evenly spread across similar daylight hours at Anchor01 (05:00 – 17:00), FF03 (08:00 – 17:00) and FF02 (08:00 – 18:00) (Figure 3.2a-f, 3.3a-g, 3.4a-g). All three sites also had early morning and/or evening hours representing a period with intermediate levels of total detections compared to the daylight and dark hours.

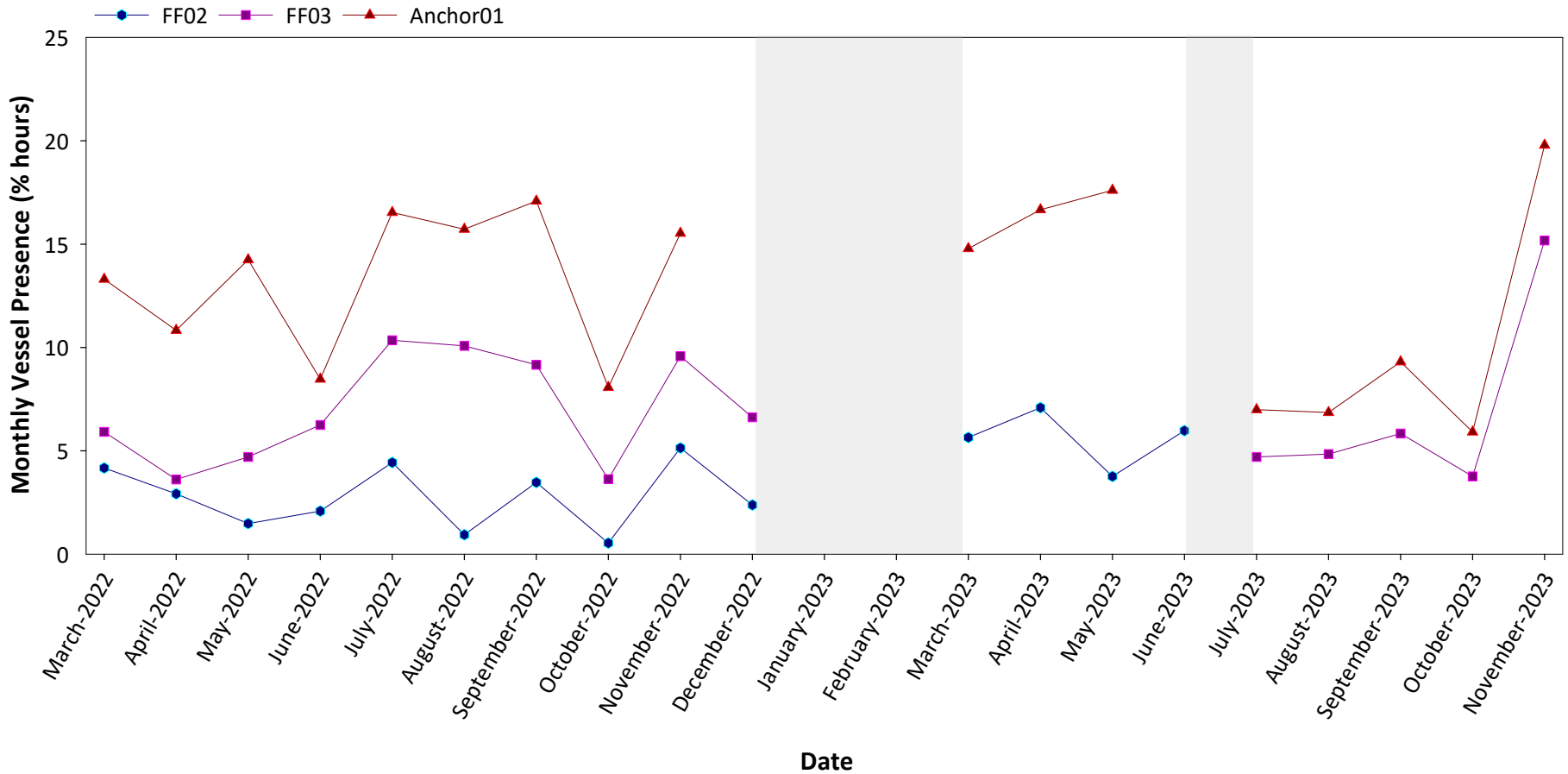


Figure 3.8: Monthly vessel presence (the percentage of hours within that month that were positive for vessel presence) at Five Fingers 02, Five Fingers 03 and Anchor Island 01. Grey shaded bars signify no data present.

3.3 Biologics

3.3.1 Delphinids

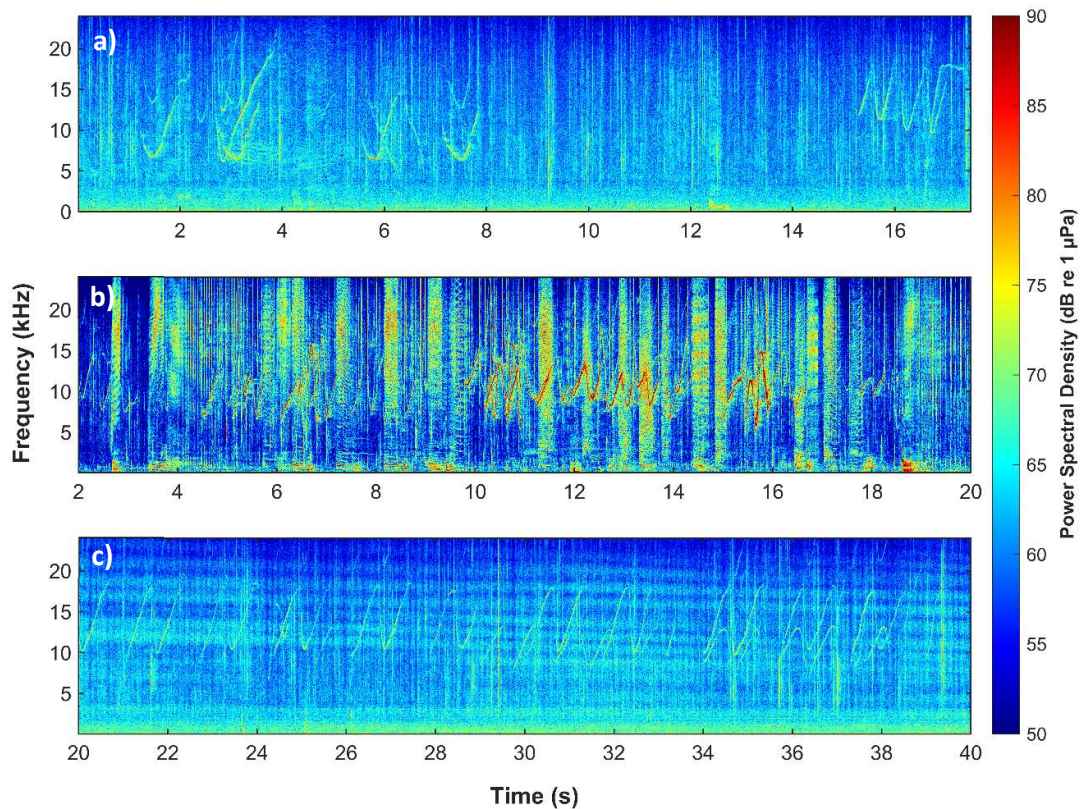


Figure 3.9a – c: Long term spectral averages (LTSA) showing three example signals from Delphinid species (bottlenose dolphin, *Tursiops truncatus*). a) common mid-frequency signature whistles, b) close range foraging signals showing mid-frequency signature whistles, high frequency echolocation clicks and high frequency feeding buzzes, c) common mid-frequency signature whistles coinciding with a vessel signature. All spectrograms produced using Fast Fourier transformation length = 1048, Hanning window and 80 % overlap.

There were variety of delphinid signals seen in the recorded data, including mid-frequency signature whistles, echolocation clicks and feeding buzzes, produced during a number of behaviours. Classifying these were outside the scope of the current study (Figure 3.9a – c).

3.3.1.1 Presence by site

Five Fingers 02 (FF02):

A total of 9,999 hours were sampled at FF02 from March – December 2022 and again from March – June 2023. Of this, 307 hours were positive for delphinid signals (at least one delphinid detection in the hour) which equated to 3.07 % of the total sampling hours (total delphinid presence) (Table 3.7).

Seasonal delphinid presence (the percentage of hours within that season that were positive for delphinid presence) ranged from 1.64 – 4.82 % at FF02 (Table 3.6). In 2022, presence increased from autumn (2.04 %) to winter (3.67 %) before then decreasing in spring (2.24 %) and again in summer (1.64 %). However, it's important to note summer only included one month of data (December), although this metric is effort corrected (Table 2.2, Table 3.6). There was also an increase seen between autumn (4.35 %) and winter (4.82 %) in 2023, however, this increase was not as large as during the same period in 2022. When comparing between years there was an increase seen between autumn 2022 (2.04 %) and 2023 (4.35 %), and between winter 2022 (3.67 %) and 2023 (4.82 %) (Table 3.6). Sampling effort was comparatively lower in winter 2023 than in 2022, although this metric is effort corrected (Table 2.2).

Monthly delphinid presence (the percentage of hours within that month that were positive for delphinid presence) ranged from 0.40 – 6.18 %, peaking in March 2023 (Table 3.7, Figure 3.10). During both 2022 and 2023, presence generally decreased from March to May before then increasing in June at the start of winter, although presence in these months was consistently higher in 2023. From June – December 2022 there was a general decreasing trend in monthly delphinid presence from 4.72 % to 1.64 %, however, no sampling occurred after June 2023 for comparison (Table 3.7, Figure 3.10).

Five Fingers 03 (FF03):

A total of 10,964 hours were sampled at FF03 from March – December 2022 and again from July – November 2023. Of this, 1608 hours were positive for delphinid signals, which equated to 14.67 % of the total sampling hours (total delphinid presence) (Table 3.8).

Seasonal delphinid presence at FF03 ranged from 7.42 – 22.57 %, peaking in spring 2023. In 2022, presence increased from autumn (9.33 %) to winter (16.94 %) before decreasing again in the spring (7.42 %) (Table 3.6). Summer 2022 (8.65 %) showed a slight increase in presence; however, it should be noted the sampling effort was lower in this season with data from December, although this metric is effort corrected. Seasonal delphinid presence was similar during both winter (21.51 %) and spring (22.57 %) in 2023 with both greater when compared to winter (16.94 %) and spring (7.42 %) in 2022 (Table 3.6).

Monthly delphinid presence at FF03 ranged between 6.25 – 27.55 %, peaking during October 2023 (Table 3.8, Figure 3.11). In 2022, presence peaked in June at 23.47 %, with generally increasing monthly presence seen in the months before and generally decreasing seen in the months after June. October had the second lowest monthly presence after which presence appeared to slowly increase until December 2022. Unfortunately, there was no sampling at this site between January – June 2023 due to a lost acoustic mooring. In 2023, presence ranged between 16.94 – 27.55 % from July to November with a cyclical pattern of alternating monthly fluctuations where presence oscillated between lower and higher levels. August – November 2023 had higher monthly presence compared to the same period in

2022, whereas July was similar in both years (17.88 % and 17.74 % in 2022 and 2023 respectively) (Table 3.8, Figure 3.11).

Anchor Island 01 (Anchor01):

A total of 12,144 hours were sampled at Anchor01 from March – November 2022, March – May 2023, and again from July – November 2023. Of this, 309 hours were positive for delphinid signals which equated to 2.54 % of the total sampling hours (total delphinid presence) (Table 3.9).

Seasonal delphinid presence at Anchor01 ranged between 1.96 – 3.17 %, peaking in winter 2022 (Table 3.6). In 2022, presence increased from autumn (2.72 %) to winter (3.17 %) before then decreasing in spring (1.96 %). There was a similar pattern in 2023, with an increase from autumn (2.13 %) to winter (2.96 %) before a decrease in the spring (2.40 %). At Anchor01, seasonal delphinid presence was similar between years and there were only small differences among seasons (Table 3.6).

Monthly delphinid presence at Anchor01 ranged between 0.42 – 5.24 %, peaking in August 2022, however, this peak didn't occur again in 2023 (Table 3.9, Figure 3.12). There was no consistent trend seen in either direction in 2022 or 2023, although 2022 showed greater variation among months (Table 3.9, Figure 3.12).

Table 3.6: Table showing number of hours sampled, total number of hours with delphinid presence and seasonal delphinid presence percentage for all recording sites.

Site	Season	Total Hours Sampled	Delphinids	
			Total Presence Hours	Seasonal Presence (% hours)
FF02	Autumn 2022	2208	45	2.04
	Winter 2022	2208	81	3.67
	Spring 2022	2184	49	2.24
	Summer 2022	672	11	1.64
	Autumn 2023	2208	96	4.35
	Winter 2023	519	25	4.82
	Spring 2023	0	-	-
FF03	Autumn 2022	2208	206	9.33
	Winter 2022	2208	374	16.94
	Spring 2022	2184	162	7.42
	Summer 2022	740	64	8.65
	Autumn 2022	0	-	-
	Winter 2023	1488	320	21.51
	Spring 2023	2136	482	22.57
Anchor01	Autumn 2022	2208	60	2.72
	Winter 2022	2208	70	3.17
	Spring 2022	1992	39	1.96
	Summer 2022	0	-	-
	Autumn 2023	2208	47	2.13
	Winter 2023	1488	44	2.96
	Spring 2023	2040	49	2.40

Table 3.7: Table showing total number of hours sampled total number of hours with delphinid presence and monthly delphinid presence percentage at Five Fingers 02 (FF02).

FF02		Delphinids	
Month	Total Hours Sampled	Total Presence Hours	Monthly Presence (% hours)
February 22	0	-	-
March	744	26	3.49
April	720	16	2.22
May	744	3	0.40
June	720	34	4.72
July	744	22	2.96
August	744	25	3.36
September	720	23	3.19
October	744	16	2.15
November	720	10	1.39
December	672	11	1.64
January 23	0	-	-
February	0	-	-
March	744	46	6.18
April	720	23	3.19
May	744	27	3.63
June	519	25	4.82
July	0	-	-
August	0	-	-
September	0	-	-
October	0	-	-
November	0	-	-
Total	9999	307	3.07

Table 3.8: Table showing total number of hours sampled, total number of hours with delphinid presence and monthly delphinid presence percentage at Five Fingers 03 (FF03).

FF03		Delphinids	
Month	Total Hours Sampled	Total Presence Hours	Monthly Presence (% hours)
February 22	0	-	-
March	744	69	9.27
April	720	45	6.25
May	744	92	12.37
June	720	169	23.47
July	744	133	17.88
August	744	72	9.68
September	720	56	7.78
October	744	47	6.32
November	720	59	8.19
December	740	64	8.65
January 23	0	-	-
February	0	-	-
March	0	-	-
April	0	-	-
May	0	-	-
June	0	-	-
July	744	132	17.74
August	744	188	25.27
September	720	122	16.94
October	744	205	27.55
November	672	155	23.07
Total	10964	1608	14.67

Table 3.9: Table showing total number of hours sampled, total number of hours with delphinid presence and monthly delphinid presence percentage at Anchor Island 01 (Anchor01).

Anchor01		Delphinids	
Month	Total Hours Sampled	Total Presence Hours	Monthly Presence (% hours)
February 22	0	-	-
March	744	24	3.23
April	720	28	3.89
May	744	8	1.08
June	720	3	0.42
July	744	28	3.76
August	744	39	5.24
September	720	11	1.53
October	744	17	2.28
November	528	11	2.08
January 23	0	-	-
February	0	-	-
March	744	21	2.82
April	720	16	2.22
May	744	10	1.34
June	0	-	-
July	744	21	2.82
August	744	23	3.09
September	720	17	2.36
October	744	19	2.55
November	576	13	2.26
Total	12144	309	2.54

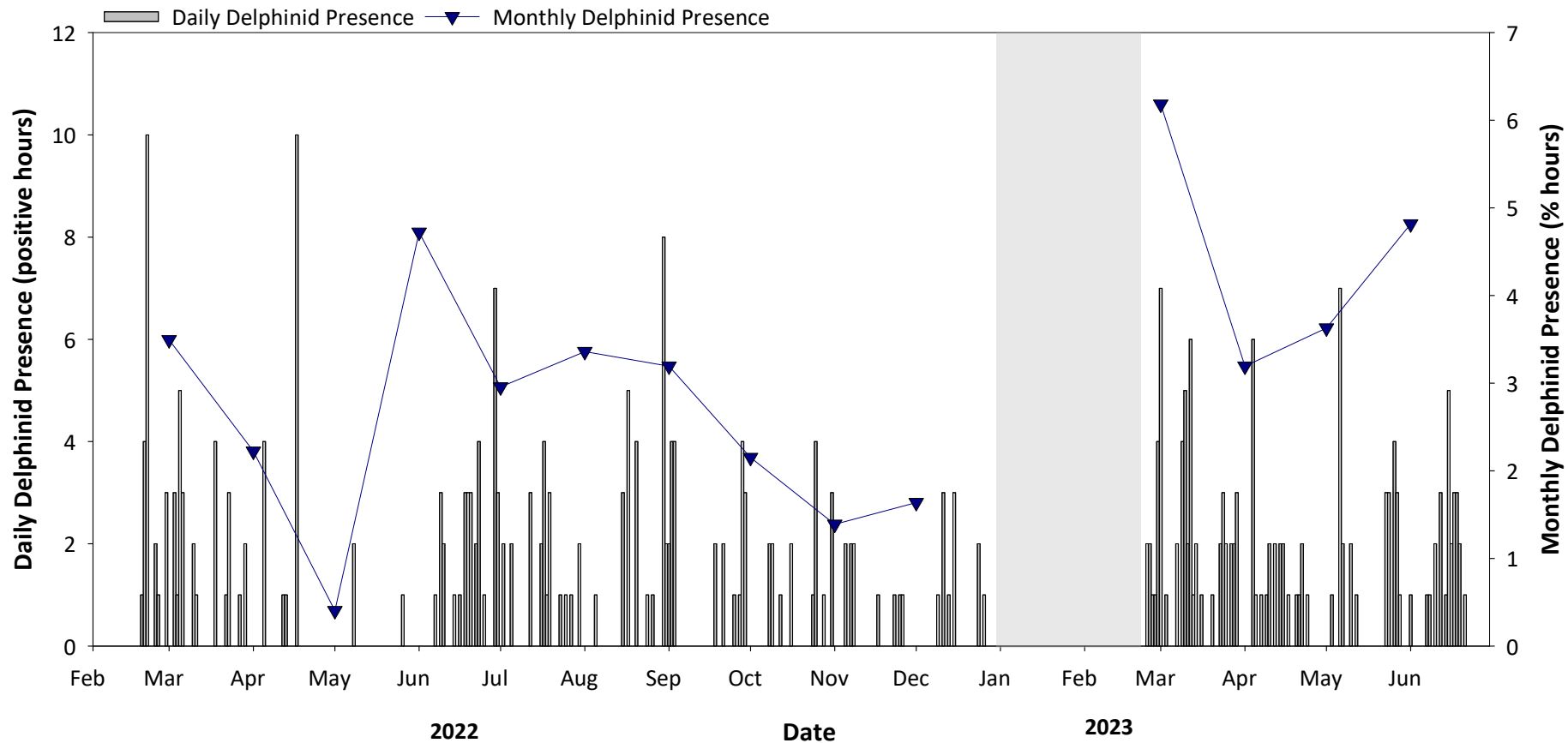


Figure 3.10: Daily delphinid presence (the number of hours in that day that contained at least one delphinid detection) and monthly delphinid presence (the percentage of hours within that month that were positive for delphinid presence) at Five Fingers 02 (FF02) in 2022 and 2023. Grey shaded bars signify no data present.

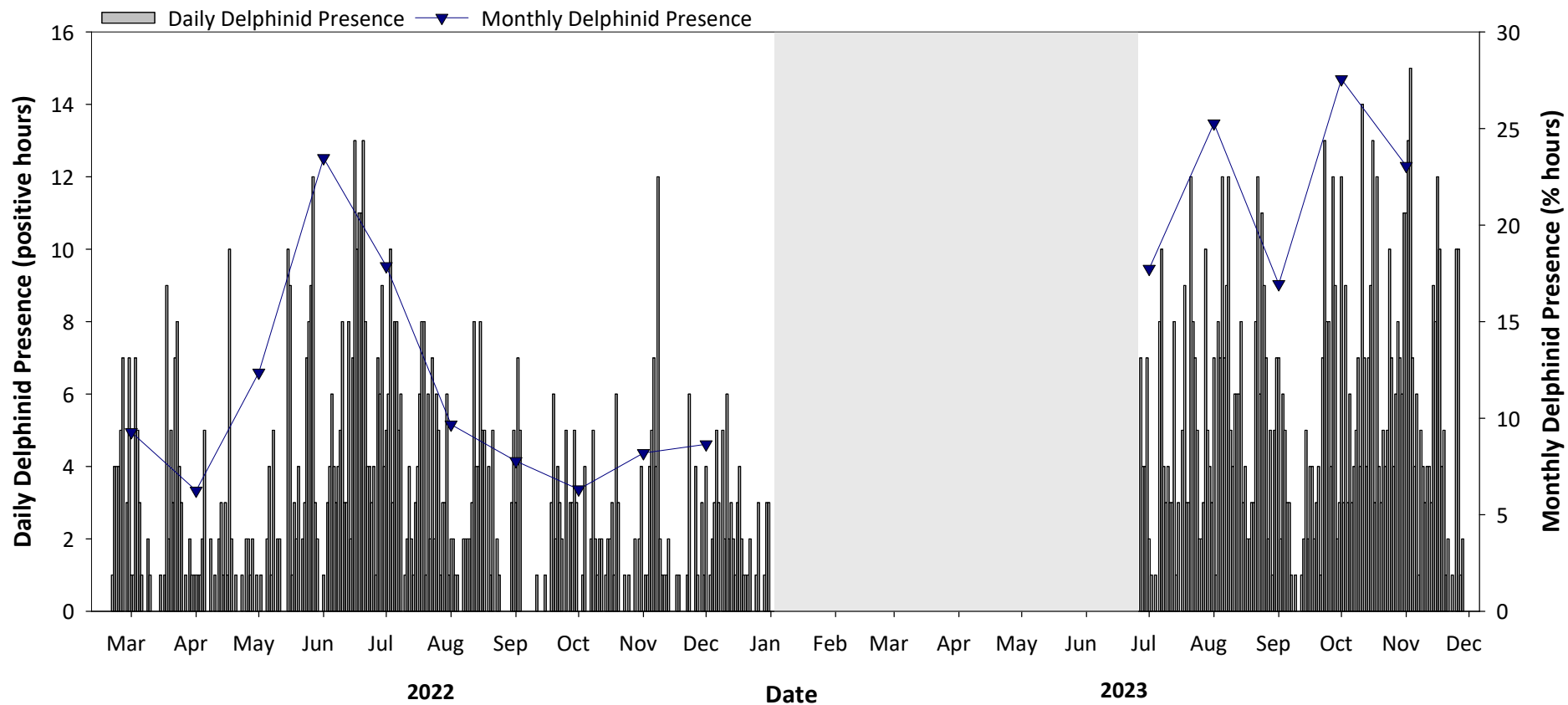


Figure 3.11: Daily delphinid presence (the number of hours in that day that contained at least one delphinid detection) and monthly delphinid presence (the percentage of hours within that month that were positive for delphinid presence) at Five Fingers 03 (FF03) in 2022 and 2023. Grey shaded bars signify no data present.

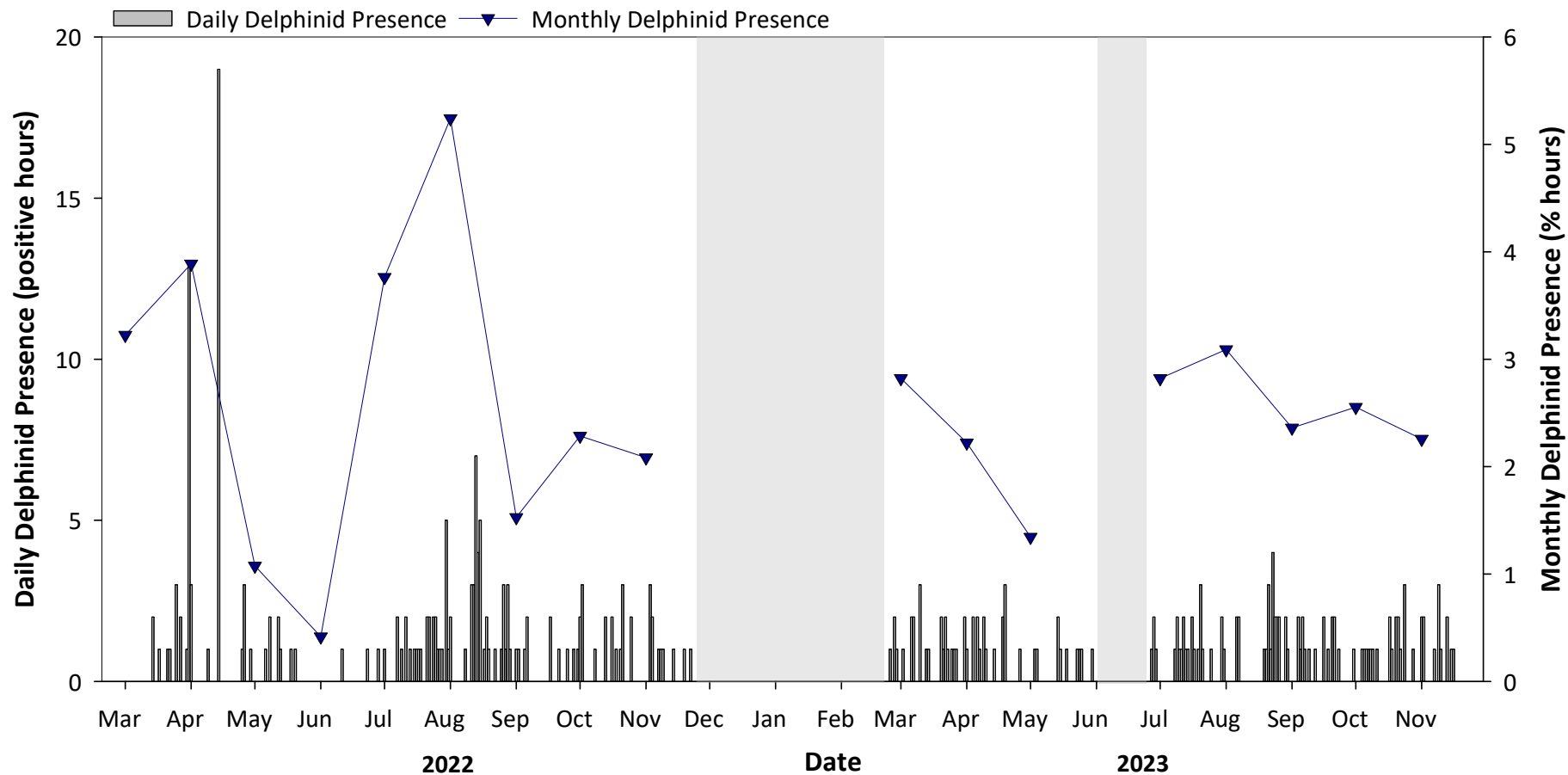


Figure 3.12: Daily delphinid presence (the number of hours in that day that contained at least one delphinid detection) and monthly delphinid presence (the percentage of hours within that month that were positive for delphinid presence) at Anchor Island 01 (Anchor01) in 2022 and 2023. Grey shaded bars signify no data present.

3.3.1.2 Site comparisons

There was a significant effect of Site ($P < 0.001$) and Month ($p < 0.001$) on Positive Present Hours (PPH) for delphinid acoustic signals (Table S3 & S4). Positive Presence Hours were significantly higher at FF03 ($p < 0.001$) when compared to both FF02 ($p < 0.001$) and Anchor01 ($p < 0.001$). Positive Presence Hours were significantly higher in August ($p = 0.06$), July ($p < 0.019$) and June ($p < 0.027$) when compared to October ($p < 0.227$), November ($p < 0.680$), September (intercept) ($p = 0.01$), December ($p = 0.064$), April ($p = 0.832$), March ($p = 0.072$) and May ($p = 0.154$) (Table S3 & S4).

Direct comparison among all three recording sites was only possible from March – November 2022 and then between two of the sites for December 2022 (FF02 & FF03), March – May 2023 (FF02 & Anchor01), and July – November 2023 (FF03 & Anchor01) as this was the only time they were all sampled simultaneously (Table 2.2). No comparisons among sites were possible for June 2023 which was only sampled at FF02. The same applied for seasonal comparisons, especially when there was no monthly overlap in sampling among sites (Table 3.6).

Total delphinid presence (percentage of total hours sampled that were positive for delphinid presence) was greatest at FF03 (14.67 %), followed by FF02 (3.07 %) and then Anchor01 (2.54 %) (Table 3.7 - 3.9).

Seasonal delphinid presence from autumn – spring 2022 was consistently greatest at FF03, peaking in winter, with both FF02 and Anchor01 being similar throughout this period. Throughout winter and spring 2023, FF03 again had higher seasonal dolphin presence compared to Anchor01 (Table 3.6).

FF03 consistently had the highest monthly delphinid presence during March - November 2022 (ranging from 6.25 – 23.47 %), peaking for that year in June (Table 3.7 - 3.9, Figure 3.13). It also had greater variability due to the build-up to its June peak and subsequent drop to August compared to FF02 and Anchor01 which showed fewer clear trends. FF02 and Anchor01 throughout March – November 2022 had similar monthly delphinid presence, with all months below 5 %, except for August at Anchor01 (5.24 %). Between July – November 2023 there was consistently greater monthly delphinid presence at FF03 which ranged between 16.94 – 27.55 % with a fluctuating monthly increase and decrease compared to Anchor01 which remained low and stable between 2.26 – 3.09 % (Table 3.7 – 3.9, Figure 3.13).

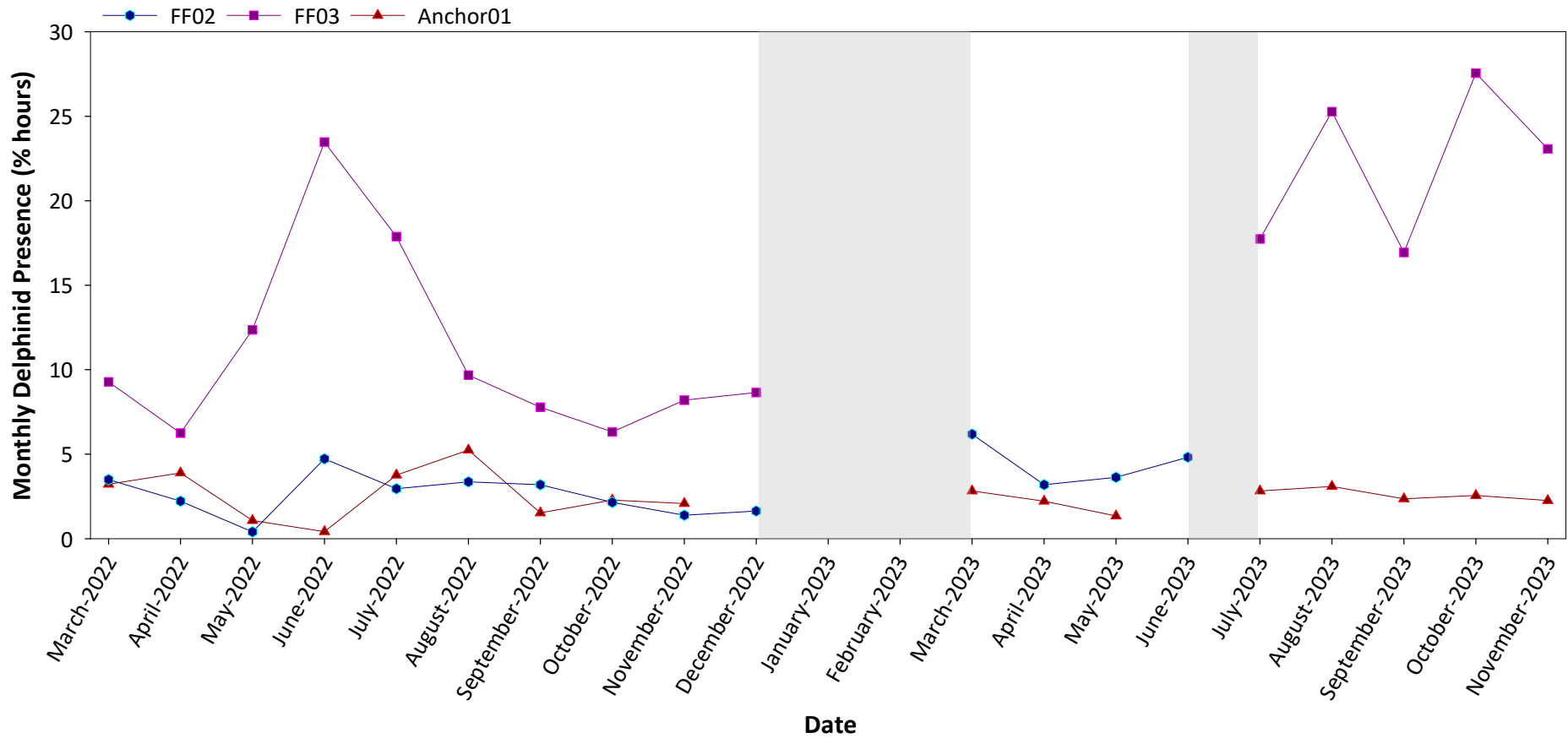


Figure 3.13: Monthly delphinid presence (the percentage of hours within that month that were positive for delphinid presence) at Five Fingers 02, Five Fingers 03 and Anchor Island 01. Grey shaded bars signify no data present.

3.3.2 Humpback Whales

3.3.2.1 Signals of interest

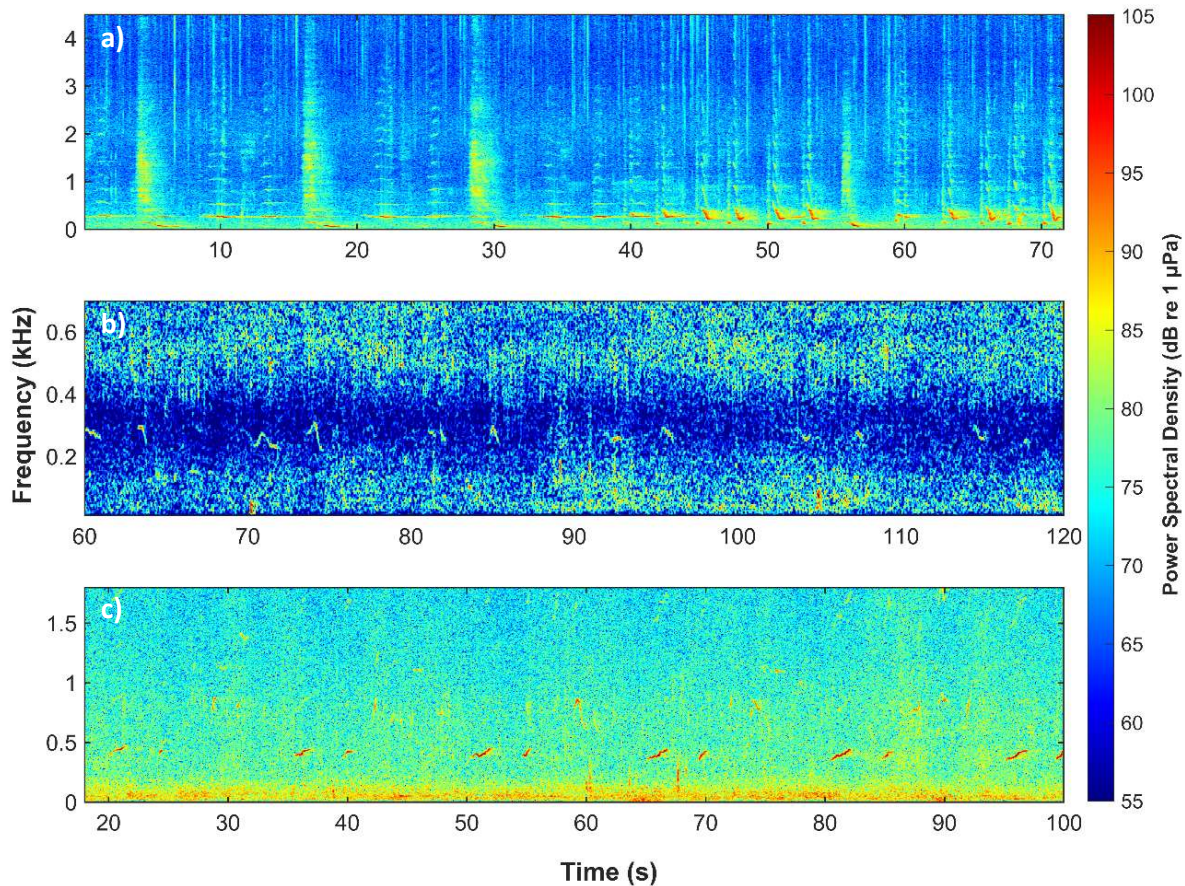


Figure 3.14a – c: Long term spectral averages (LTSA) showing three examples of humpback whale signals. a) complex humpback whale signal including low – mid frequency moans, groans, trumpets, and rasps, b) common low-frequency moans and groans among high ambient sound levels, c) common low-frequency up-calls and moans by two individuals among low – mid ambient sound levels. All spectrograms produced using Fast Fourier transformation length = 10048, Hanning window and 80 % overlap.

There were variety of humpback whale signals from several behaviour types seen in the recorded soundscape data, including low-frequency moans, groans and up-calls, and mid-frequency rasps and trumpets. Classifying these were outside the scope of the current study (Figure 3.14a-c).

3.3.2.2 Presence by site

Five Fingers 02 (FF02):

A total of 9,999 hours were sampled at FF02 from March – December 2022 and again from March – June 2023. Of this, 101 hours were positive for humpback whale vocalisations (at least one humpback whale detection in the hour) which equated to 1.01 % of the total sampling hours (total humpback whale presence) (Table 3.11).

Seasonal humpback whale presence (the percentage of hours during that season that were positive for humpback whale presence) peaked during the winter in both years (Table 3.10). Winter 2023 (9.06 %) had much greater seasonal humpback whale presence than in 2022 (1.59 %). However, it should be noted that only 519 hours of June (the peak month for humpback whale presence in both years) were sampled during winter 2023, possibly increasing the seasonal humpback whale presence compared to if the full season had been sampled. Autumn 2022 and 2023, and spring 2022 had low presence ranging from 0.27 – 0.32 %, and in summer 2022 no humpback whales were detected (although this season only had data from December) (Table 3.10).

Monthly humpback whale presence (the percentage of hours within that month that were positive for humpback whale presence) had two large peaks during June in both 2022 (4.58 %) and 2023 (9.06 %) (Table 3.11, Figure 3.15). April, October and May had smaller peaks between 0.5 – 1 %, with the remaining months having very low or no presence ranging between 0 – 0.28 % (Table 3.11, Figure 3.15).

Five Fingers 03 (FF03):

A total of 10,964 hours were sampled at FF03 from March – December 2022 and again from July – November 2023. Of this, 544 hours were positive for humpback whale signals which equated to 4.96 % of the total sampling hours (total humpback whale presence) (Table 3.12). Unfortunately, there was no sampling at this site between January – June 2023 due to a lost acoustic mooring (Table 2.2).

Seasonal humpback whale presence at FF03 ranged between 0.41 – 8.56%, peaking during winter 2022 (Table 3.10). The lowest seasonal presence in 2022 occurred during autumn (0.91 %) and summer (0.41 %), with the peak seasons being winter at 8.56 % and then spring, which had a smaller secondary peak of 2.47 %. In 2023, presence was highest during winter (7.39 %) and spring (7.87 %). Seasonal humpback whale presence in spring 2023 was over three times higher than spring 2022, whereas winter 2023 was lower than winter 2022 but not by the same magnitude (Table 3.10). It is worth noting that sampling in winter 2023 was incomplete and didn't include data from June which in 2022 had the highest monthly humpback whale presence (Table 2.2, 3.10).

Monthly humpback whale presence ranged between 0.13 – 17.07 %, with peak months occurring in June (14.44 %) and July (8.06 %) in 2022, and during August (10.22 %) and

October (17.07 %) in 2023 (Table 3.12, Figure 3.16). There were smaller peaks in October 2022 (4.44 %) and July 2023 (4.57 %). The remaining months had low humpback whale presence between 0.13 – 3.57 %. July 2023 (4.57 %) was lower than in 2022 (8.06 %), however, the remaining months sampled in 2023 all had greater monthly presence compared to in 2022 (Table 3.12, Figure 3.16).

Anchor Island 01 (Anchor01):

Despite 12,144 hours of sampling across four deployments there were no humpback whale detections at Anchor01 (Table 3.10, 3.13).

Table 3.10: Table showing number of hours sampled, total number of hours with humpback whale presence and seasonal humpback whale presence percentage for all recording sites.

Site	Season	Total Hours Sampled	Humpback Whales	
			Total Presence Hours	Seasonal Presence (% hours)
FF02	Autumn 2022	2208	6	0.27
	Winter 2022	2208	35	1.59
	Spring 2022	2184	6	0.27
	Summer 2022	672	0	0.00
	Autumn 2023	2208	7	0.32
	Winter 2023	519	47	9.06
	Spring 2023	0	-	-
FF03	Autumn 2022	2208	20	0.91
	Winter 2022	2208	189	8.56
	Spring 2022	2184	54	2.47
	Summer 2022	740	3	0.41
	Autumn 2022	0	-	-
	Winter 2023	1488	110	7.39
	Spring 2023	2136	168	7.87
Anchor01	Autumn 2022	2208	0	0
	Winter 2022	2208	0	0
	Spring 2022	1992	0	0
	Summer 2022	0	-	-
	Autumn 2023	2208	0	0
	Winter 2023	1488	0	0
	Spring 2023	2040	0	0

Table 3.11: Table showing total number of hours sampled, total number of hours with humpback whale presence and monthly humpback whale presence percentage at Five Fingers 02 (FF02).

FF02		Humpback Whales	
Month	Total Hours Sampled	Total Presence Hours	Monthly Presence (% hours)
February 22	0	-	-
March	744	0	0
April	720	5	0.69
May	744	1	0.13
June	720	33	4.58
July	744	2	0.27
August	744	0	0
September	720	2	0.28
October	744	4	0.54
November	720	0	0
December	672	0	0
January 23	0	-	-
February	0	-	-
March	744	2	0.27
April	720	0	0
May	744	5	0.67
June	519	47	9.06
July	0	-	-
August	0	-	-
September	0	-	-
October	0	-	-
November	0	-	-
Total	9999	101	1.01

Table 3.12: Table showing total number of hours sampled, total number of hours with humpback whale presence and monthly humpback whale presence percentage at Five Fingers 03 (FF03).

	FF03	Humpback Whales	
Month	Total Hours Sampled	Total Presence Hours	Monthly Presence (% hours)
February 22	0	-	-
March	744	1	0.13
April	720	13	1.81
May	744	6	0.81
June	720	104	14.44
July	744	60	8.06
August	744	25	3.36
September	720	8	1.11
October	744	33	4.44
November	720	13	1.81
December	740	3	0.41
January 23	0	-	-
February	0	-	-
March	0	-	-
April	0	-	-
May	0	-	-
June	0	-	-
July	744	34	4.57
August	744	76	10.22
September	720	17	2.36
October	744	127	17.07
November	672	24	3.57
Total	10964	544	4.96

Table 3.13: Table showing total number of hours sampled, total number of hours with humpback whale presence and monthly humpback whale presence percentage at Anchor Island 01 (Anchor01).

Anchor01		Humpback Whales	
Month	Total Hours Sampled	Total Presence Hours	Monthly Presence (% hours)
February 22	0	-	-
March	744	0	0
April	720	0	0
May	744	0	0
June	720	0	0
July	744	0	0
August	744	0	0
September	720	0	0
October	744	0	0
November	528	0	0
December	0	-	-
January 23	0	-	-
February	0	-	-
March	744	0	0
April	720	0	0
May	744	0	0
June	0	-	-
July	744	0	0
August	744	0	0
September	720	0	0
October	744	0	0
November	576	0	0
Total	12144	0	0

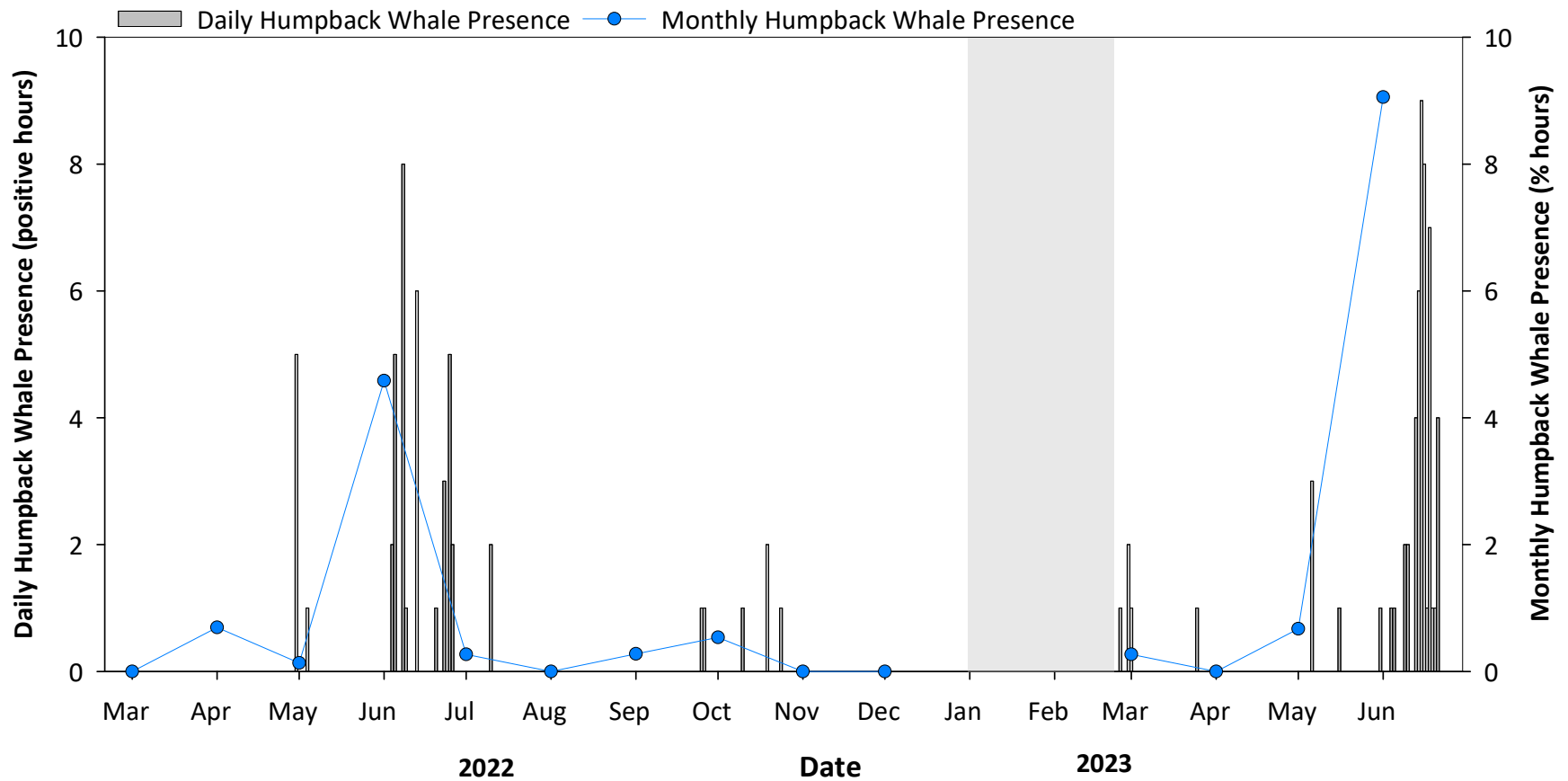


Figure 3.15: Daily humpback whale presence (the number of hours in that day that contained at least one humpback whale detection) and monthly humpback whale presence (the percentage of hours within that month that were positive for humpback whale presence) at Five Fingers 02 (FF02) in 2022 and 2023. Grey shaded bars signify no data present.

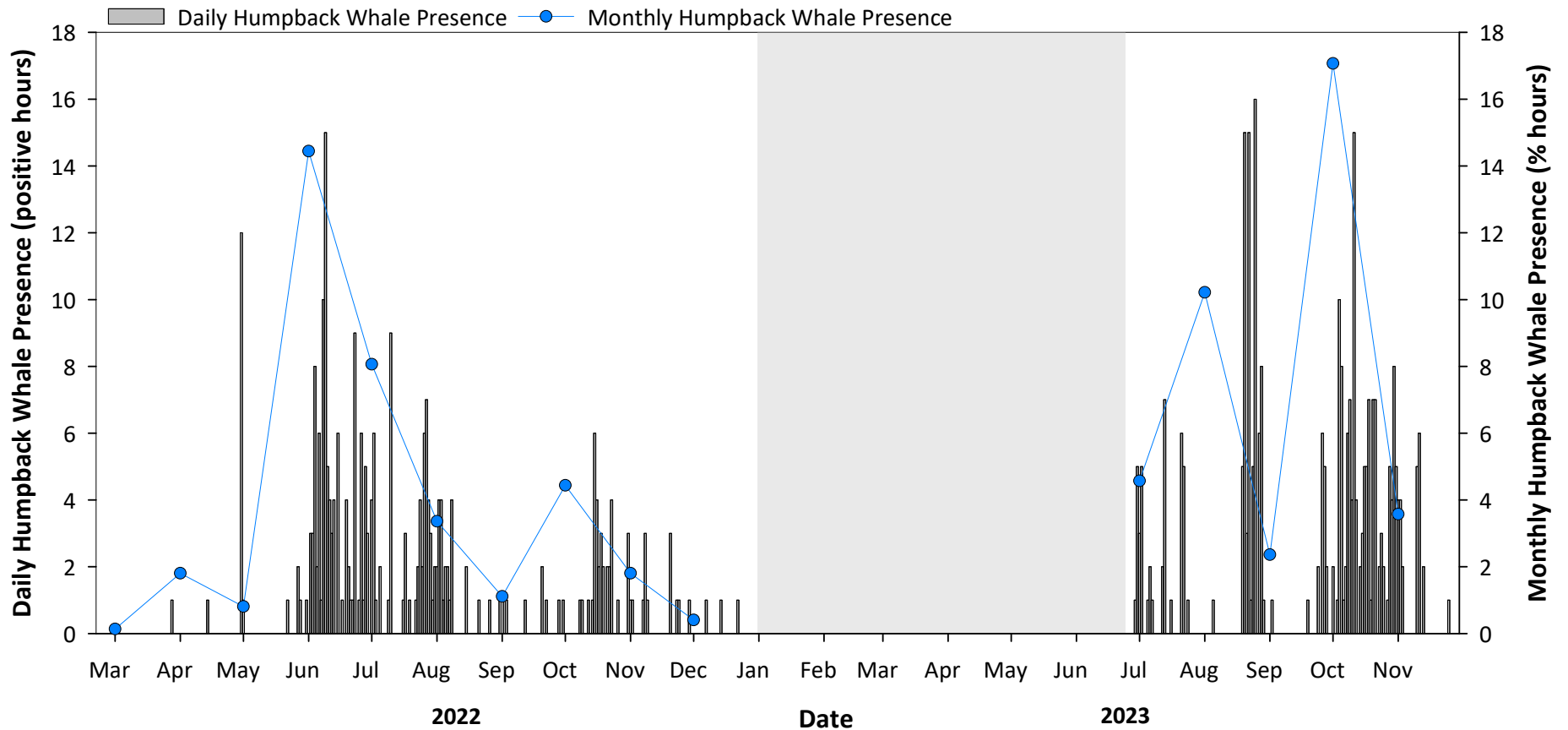


Figure 3.16: Daily humpback whale presence (the number of hours in that day that contained at least one humpback whale detection) and monthly humpback whale presence (the percentage of hours within that month that were positive for humpback whale presence) at Five Fingers 03 (FF03) in 2022 and 2023. Grey shaded bars signify no data present.

3.3.2.3 Site comparisons

There was a significant effect of Site ($P < 0.001$) and Month ($p < 0.001$) on Positive Present Hours (PPH) of humpback whale acoustic signals (Table S5 & S6). Positive Presence Hours were significantly higher at FF03 ($p < 0.001$) compared to at FF02 ($p < 0.001$). Positive Presence Hours were significantly higher in June ($p < 0.001$), October ($p < 0.001$), August ($p < 0.001$) and July ($p < 0.001$) when compared to November ($p < 0.303$), September (intercept) ($p < 0.001$), April ($p = 0.769$) and May ($p = 0.468$), which were all significantly higher than December ($p = 0.012$) and March ($p = 0.007$) (Table S5 & S6).

No humpback whales were detected at Anchor01 and it was therefore excluded from comparisons. Direct comparison between FF02 and FF03 was only possible from March - December 2022. During 2023 sampling did not overlap at FF02 and FF03, and although seasonal humpback whale presence was calculated for winter 2023 at both sites, different months were sampled for this season at each and so any comparison would not be between the same recording periods (Table 2.2). Total humpback whale presence was greater for FF03 (4.96 %) than FF02 (1.01 %) (Table 3.11, 3.12).

Seasonal humpback whale presence in 2022 was consistently higher at FF03 than during the corresponding seasons at FF02 (Table 3.10). Peak seasonal presence occurred during the winter at both FF03 (8.56 %) and FF02 (1.59 %). FF03 had greater seasonal presence during the spring (2.47 %) than it did in autumn (0.91 %), whereas FF02 was similar in autumn and spring (Table 3.10).

Monthly humpback whale presence in 2022 peaked at both sites during June and was greater at FF03 (14.44 %) compared to FF02 (4.58 %) (Table 3.11, 3.12, Figure 3.17). After June 2022, monthly presence decreased rapidly at FF02 compared to at FF03, where it decreased more gradually with higher presence until August. A smaller secondary peak occurred at both sites in October, being greater at FF03 (4.44 %) compared to FF02 (0.54 %), with the remainder of 2022 low at both sites (Table 3.11, 3.12, Figure 3.17).

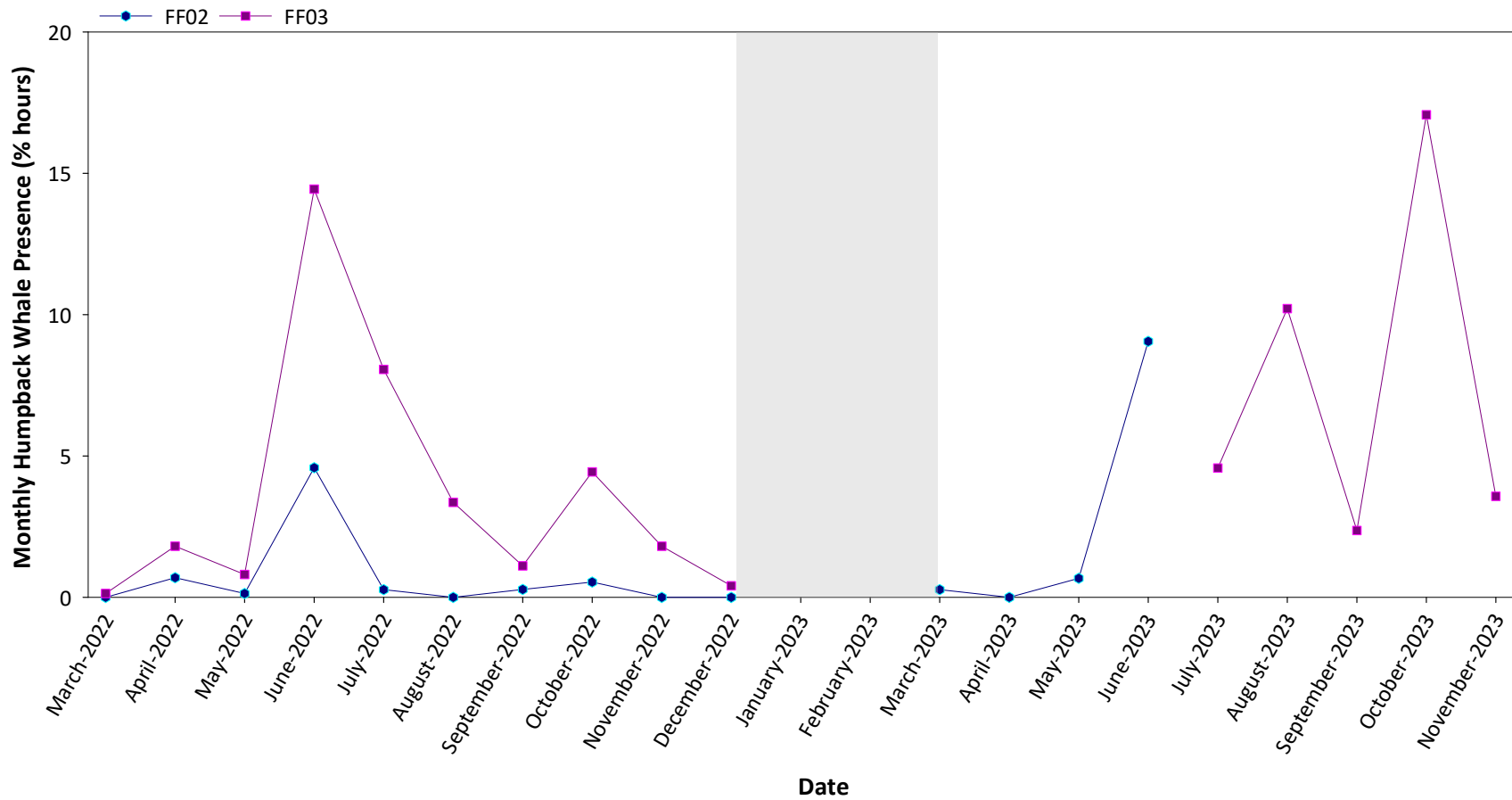


Figure 3.17: Monthly humpback whale presence (the percentage of hours within that month that were positive for humpback whale presence) at Five Fingers 02 and Five Fingers 03. No humpback whales were detected at Anchor Island 01. Grey shaded bars signify no data present.

3.4 Co-occurrence of Vessels and Cetaceans

3.4.1 Five Fingers 02 (FF02)

Of the 9,999 hours sampled at FF02, there were 352 positive presence hours for vessels, 307 positive presence hours for delphinids and 101 positive presence hours for humpback whales. Total presence (the percentage of the overall hours sampled at the site that were positive presence hours) of vessels (3.52 %), delphinids (3.07 %) and humpback whales (1.01 %) was low at FF02 compared to the other sites (Table 3.3, 3.7, 3.11).

Monthly presence (the percentage of hours within that month that were positive presence hours) at FF02 ranged between 0.54 – 7.08 % for vessels, 0.40 – 6.18 % for delphinids and 0 – 9.06 % for humpback whales (Table 3.3, 3.7, 3.11).

Peak months for vessel presence, with the greatest potential for vessel noise exposure, were November 2022 and March, April and June 2023 (Figure 3.18). Monthly delphinid presence also peaked in March 2023 and June 2022 and 2023, making these periods the greatest potential risk for delphinids. However, the other months when vessel presence peaked still had moderate or low delphinid presence and therefore a possibility of overlap. Humpback whales had two large peaks in presence during June in both 2022 and 2023 with the greatest overlap with peak vessel presence and associated risk occurring in June 2023, with other months having a reduced overlap (Figure 3.18). Risk levels were smaller at FF02 compared to other sites due to vessels, delphinids and humpback whales having consistently low presence even in peak months throughout the sampling period (Figure 3.18).

3.4.2 Five Fingers 03 (FF03)

Of the 10,964 hours sampled at FF03, there were 756 positive presence hours for vessels, 1608 positive presence hours for delphinids and 544 hours positive presence hours for humpback whales. Total presence at FF03 was high for delphinids (14.67 %) and humpback whales (4.96 %) and medium for vessels (6.90 %) when compared to the other sites (Table 3.4, 3.8, 3.12).

Monthly presence at FF03 ranged between 3.61 – 15.18 % for vessels, 6.25 – 27.55 % for delphinids and 0.13 – 17.07 % for humpback whales (Table 3.4, 3.8, 3.12).

Monthly vessel presence peaked in November 2023, with other months of elevated presence being July, August, September, and November in 2022 (Figure 3.19). The greatest overlap between peak monthly vessel and delphinid presence therefore occurred in November 2023, with July 2022 also having overlap between the peak monthly vessel presence and moderate levels of delphinid and humpback whale presence. Additional months with peak vessel presence had overlap with either low or moderate levels of delphinid and humpback whale presence. However, the greatest overall impacts from vessel presence likely occurred at FF03 due to levels of delphinid and humpback whale presence in

even the moderate or low presence months being comparatively greater than other sites (Figure 3.19).

3.4.3 Anchor Island 01 (Anchor01)

Of the 12,144 hours sampled at Anchor01 from March – November 2022, March – May 2023 and again from July – November 2023, there were 1538 positive presence hours for vessels, 309 positive presence hours for delphinids and 0 positive presence hours for humpback whales. Total vessel presence was the highest of all the sites at 12.66 %, whereas total delphinid presence was the lowest of the sites at 2.54 % (Table 3.5, 3.9, 3.13).

Monthly presence at Anchor01 ranged between 6.85 – 19.79 % for vessels and 0.42-5.24 % for delphinids (Table 3.5, 3.9, 3.13).

Peak months for vessel presence at Anchor01 were July and September in 2022 and April, May and November in 2023, although remaining months still had high levels of vessel presence compared to other sites. There were no clear months with overlapping peaks in vessel and delphinid presence at Anchor01, rather the site was characterised by low delphinid presence and high levels of vessel presence (and associated risk) throughout the entire sampling period (Figure 3.20).

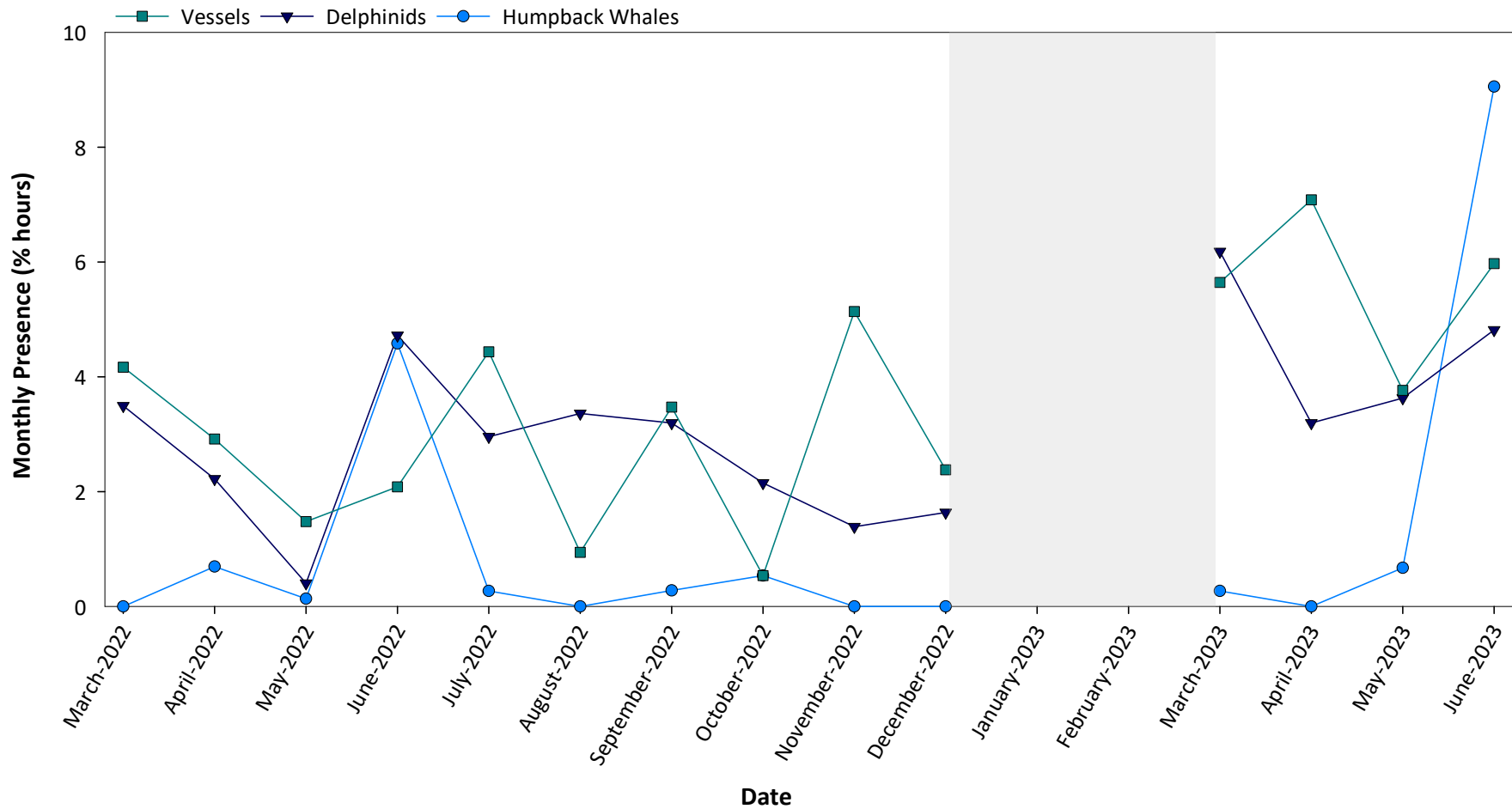


Figure 3.18: Monthly presence (the percentage of hours within that month that were positive for presence of signals of interest) for vessels, delphinids and humpback whales at FF02. Grey shaded bars signify no data present.

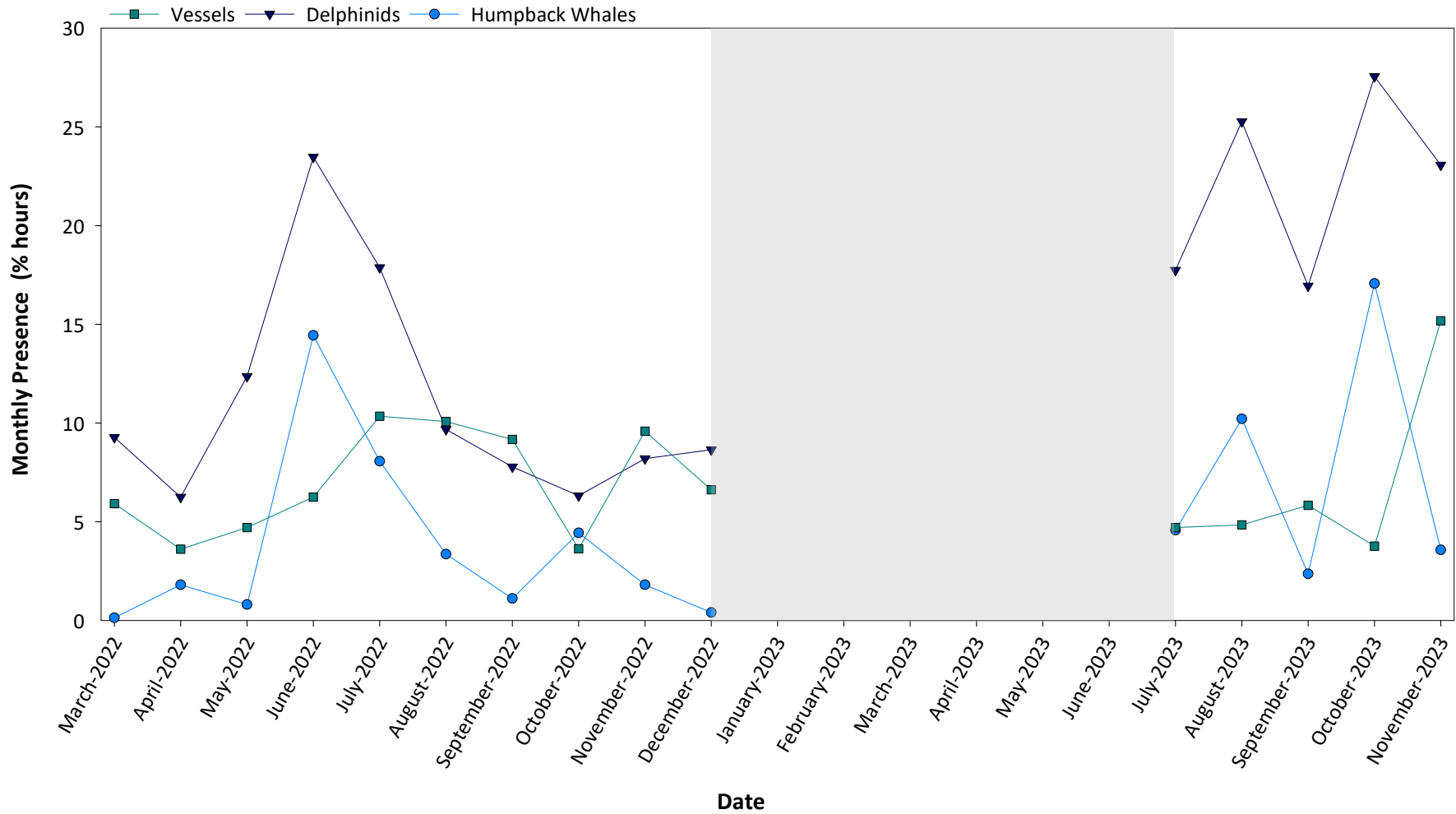


Figure 3.19: Monthly presence (the percentage of hours within that month that were positive for presence of signals of interest) for vessels, delphinids and humpback whales at FF03. Grey shaded bars signify no data present.

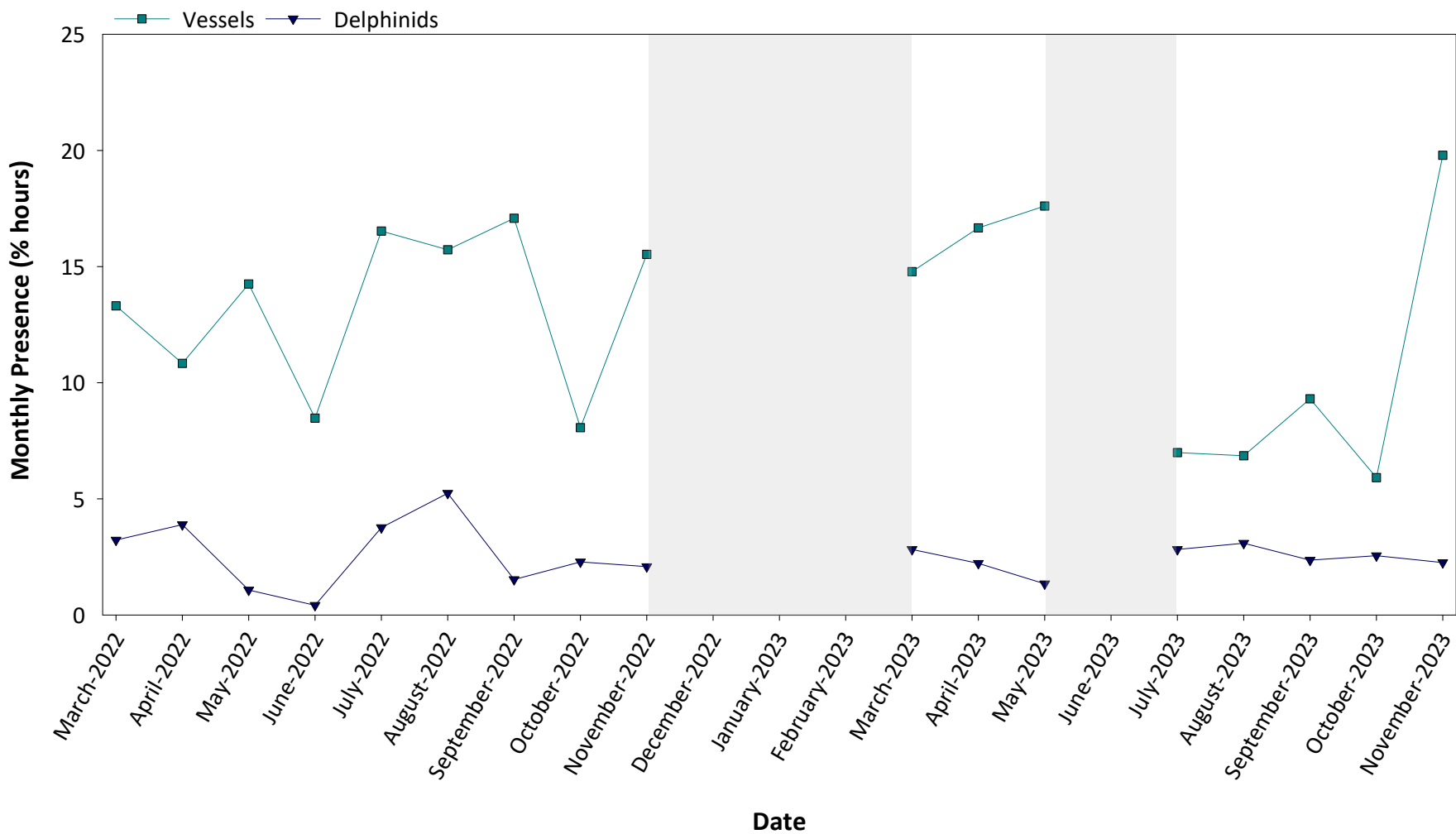


Figure 3.20: Monthly presence (the percentage of hours within that month that were positive for presence of signals of interest) for vessels and delphinids at Anchor Island 01 (Anchor01). No humpback whales were detected at Anchor01. Grey shaded bars signify no data present.

3.1 Vessel Propagation Modelling

3.1.1 Vessel Automatic Identification System and Tracking Records

It should be noted that not all vessels have an Automatic Information System (AIS) installed, with particularly small recreational vessels being underrepresented in the AIS records (Hermanssen et al., 2019). It was also not possible to include AIS information from commercial fishing vessels in this study due to confidentiality.

There were 281 vessel records from four vessel classes - 'Cruise', 'Passenger', 'Government' (Gov), and 'Recreational' - in the AIS records collected between February 2022 – December 2023 within the designated area (Table 3.14, Figure 2.1, S1). Of these records, 71 were from unique vessels.

The most common class of vessel was 'Passenger' vessels, with 167 observed in the AIS records, 16 of which were unique vessels (Table 3.14, Figure 3.21). The 'Passenger' vessel classification included vessels ≤ 100 m (MacGillivray & de Jong, 2021). There were between 3 – 10 records in the 'Passenger' vessel classification during each month with no clear trend over the time.

'Cruise' vessels were the second most common vessel class, with 81 observed in the AIS records, 28 of which were unique vessels (Table 3.14, Figure 3.21). The 'Cruise' vessel class included large passenger vessels > 100 m, with these being predominantly large cruise ships (MacGillivray & de Jong, 2021). 'Cruise' class vessels showed a large peak in number from November 2022 – March 2023 and again in November/December 2023, with these months containing between 8 – 16 'Cruise' class vessels in the AIS records. During the remaining months 'Cruise' vessel records were absent, except for October 2022 (2 records) and April 2023 (1 record).

There was 22 AIS records observed within the 'Recreational' vessel class, 16 of which were unique vessels. There were between 1 - 5 records in the 'Recreational' vessel class in February, March and April in 2022, and in January, February, April and December in 2023, with none in the remaining months (Table 3.14, Figure 3.21).

There were 11 AIS records within the 'Government' vessel class, 3 of which were unique vessels. There were between 1 – 2 records in April, May, October and November in both years and 1 record in June 2022, with none in remaining months (Table 3.14, Figure 3.21).

The trend in the overall number of AIS vessel records in a month from the four vessel classes combined showed an increase during summer months and decrease during winter months. July had the lowest monthly total for overall AIS vessel records in both 2022 (3 records) and 2023 (4 records), with January and February 2023 being peak months at 22 and 23 records respectively (Table 3.14, Figure 3.21).

Table 3.14: Table showing the number of AIS vessel records from each vessel class and combined total records for each month between February 2022 and December 2023 within the designated area.

Month	Cruise	Gov	Passenger	Recreational	Monthly Total
February 22	0	0	10	4	14
March	0	0	8	4	12
April	0	1	7	1	9
May	0	1	10	0	11
June	0	0	6	0	6
July	0	0	3	0	3
August	0	0	9	0	9
September	0	0	7	0	7
October	2	2	7	0	11
November	9	1	6	0	16
December	11	0	6	0	17
January 23	14	0	7	1	22
February	12	0	7	4	23
March	8	0	6	5	19
April	1	2	8	1	12
May	0	1	8	0	9
June	0	1	9	0	10
July	0	0	4	0	4
August	0	0	8	0	8
September	0	0	10	0	10
October	0	1	8	0	9
November	8	1	9	0	18
December	16	0	4	2	22
Total	81	11	167	22	281

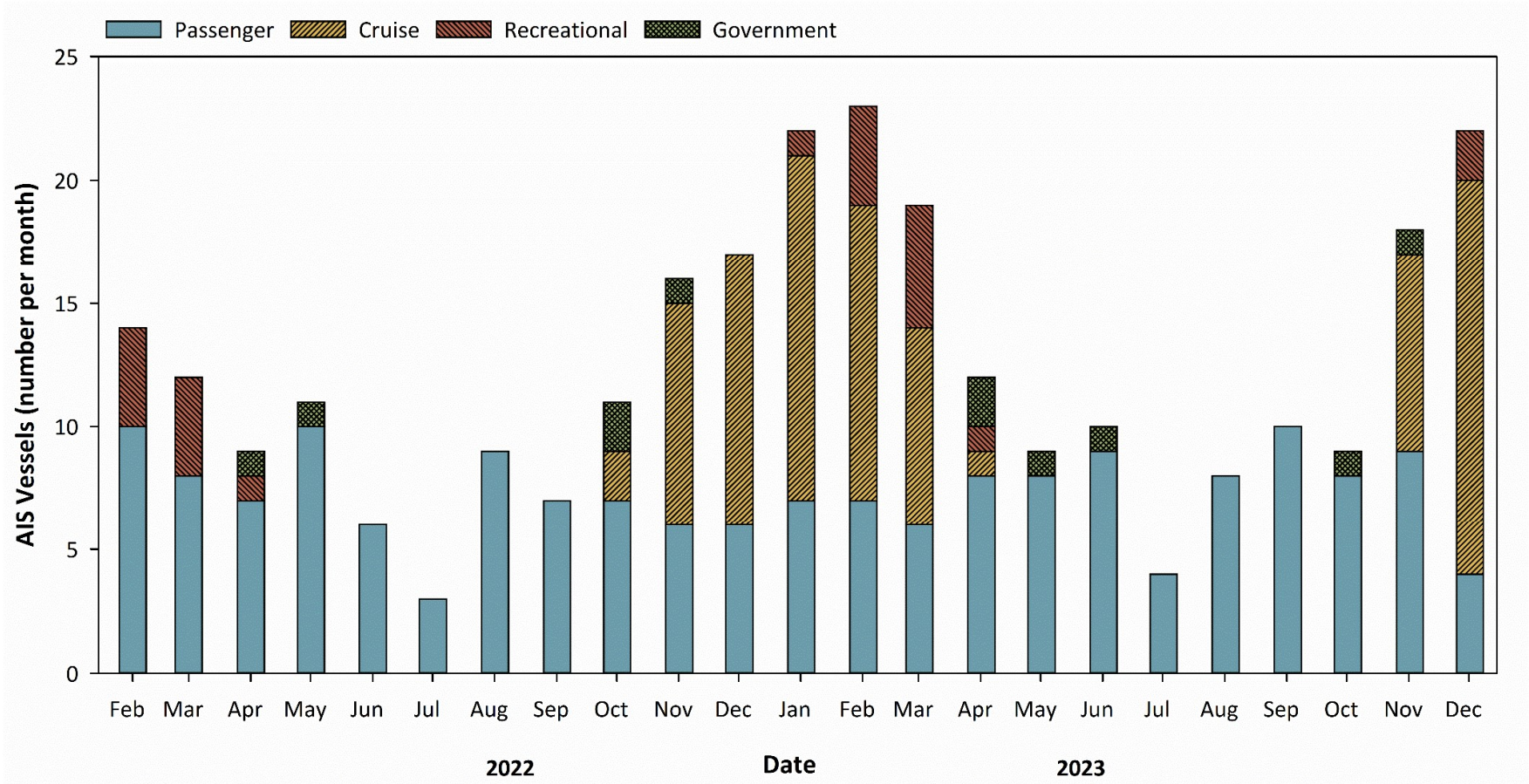


Figure 3.21: Histogram showing the number of unique vessels, and their class observed in AIS records from the designated area during 2022 and 2023.

3.1.2 Vessel Noise Modelling

Monthly equivalent continuous sound levels (LEq) produced by vessels contained within the vessel Automatic Identification System records were seen to vary over time and were generally greater in late spring and summer months, from October to March (with the exception of February and March 2022) (Figure 3.22 – 3.25).

Monthly average vessel noise levels were relatively stable throughout the model area in Dusky Sound from February – September 2022 (Figure 2.1, 3.22, 3.23). Vessel noise levels were consistently greater in the channel to the south of Anchor Island and near Resolution and Parrot Islands with these areas ranging between approximately 80 – 120 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$. The remaining areas of Dusky Sound including the internal coastline of Five Fingers Peninsula, and the outer coast had lower noise levels in this period between approximately 70 – 80 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$.

From October 2022 to March 2023 (late spring and summer) average monthly vessel noise levels increased dramatically, with equivalent continuous sound levels increasing by approximately 15 – 30 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ (90 – 120 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$) in the entire sampling area, including offshore areas outside of Dusky sound (90 – 110 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$). The channel south of Anchor Island had the highest noise levels during this period increasing to approximately 110 – 150 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ with a clear 'route' of noise seen towards the southwest at the entrance and hot spots where vessel paths intersect (Figure 3.23 – 3.25). The area near Parrot and Resolution Islands, further into Taumoana Marine Reserve, showed less of an increase during this period remaining between approximately 90 – 110 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$. There was also a small area on the north side of Anchor Island that appeared to show no change, remaining with low noise levels throughout (Figure 3.23 – 3.25).

Between April and October 2023 noise levels then decreased to similar levels seen in those months in 2022, although with some areas (Anchor Island Channel, lower Bowen Passage and the channel between northeast Anchor Island and southwest Resolution Island) having increased by approximately 5 – 10 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$ (Figure 3.24, 3.25).

Monthly equivalent continuous sound levels increased again in November and December 2023 to levels similar to these months in 2022 (110 – 150 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$), with peak levels occurring at the mouth of Dusky Sound, Anchor Island Channel, lower Bowen Passage and the outer coast (Figure 3.23, 3.25).

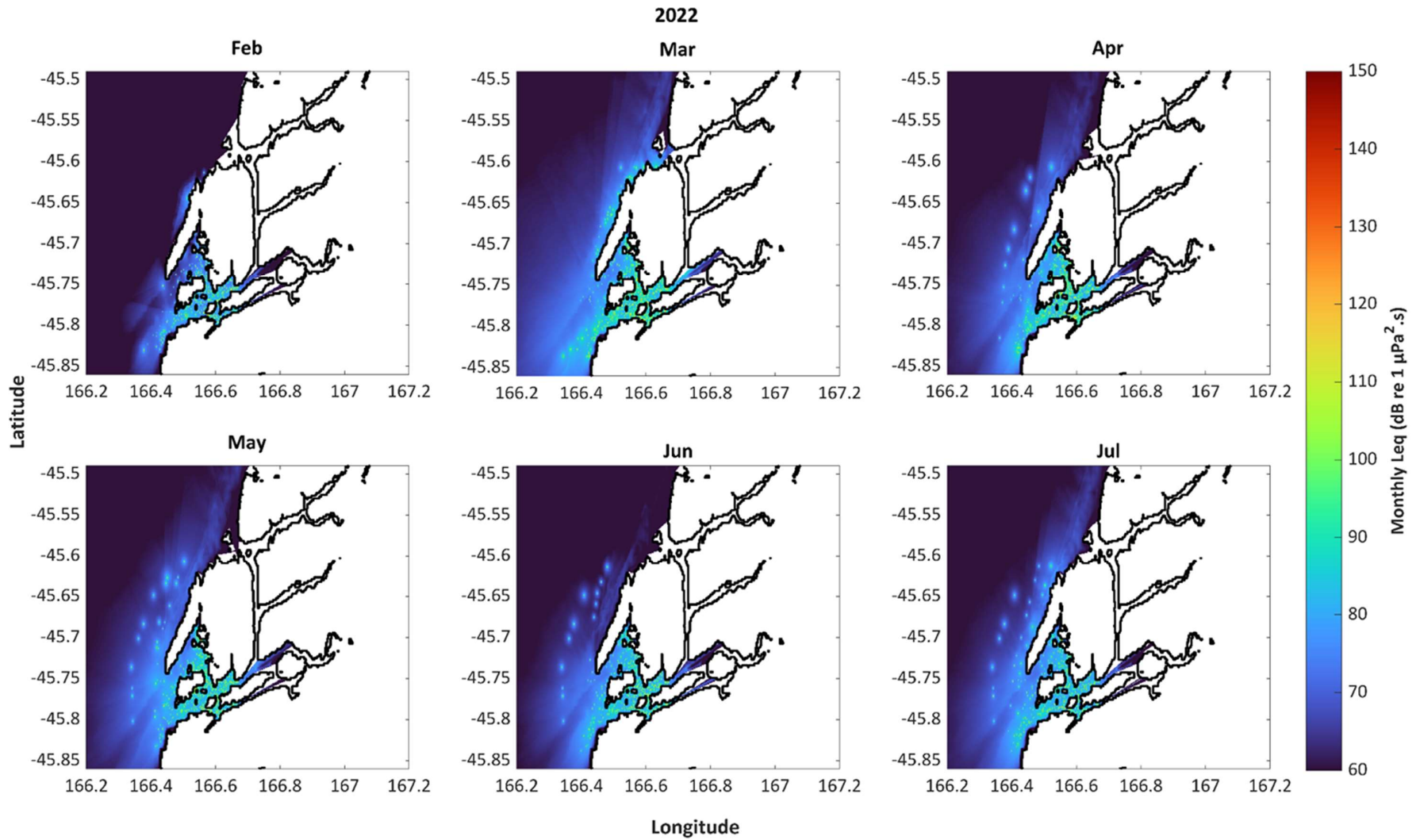


Figure 3.22: Monthly equivalent continuous sound levels (LEq) maps of all vessel types contained within the AIS records from February – July 2022 in the study area.

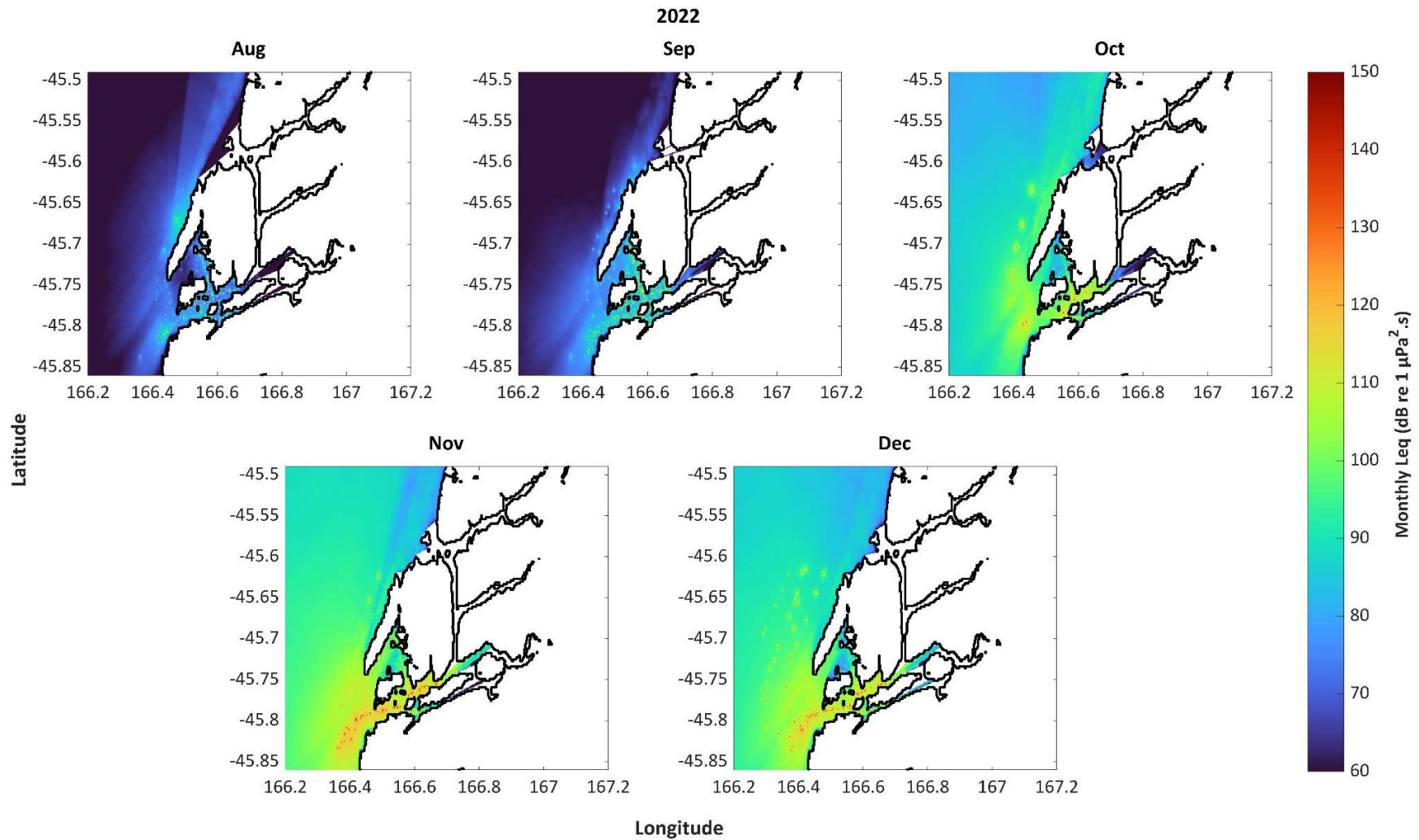


Figure 3.23: Monthly equivalent continuous sound levels (LEq) maps of all vessel types contained within the AIS records from August – December 2022 in the study area.

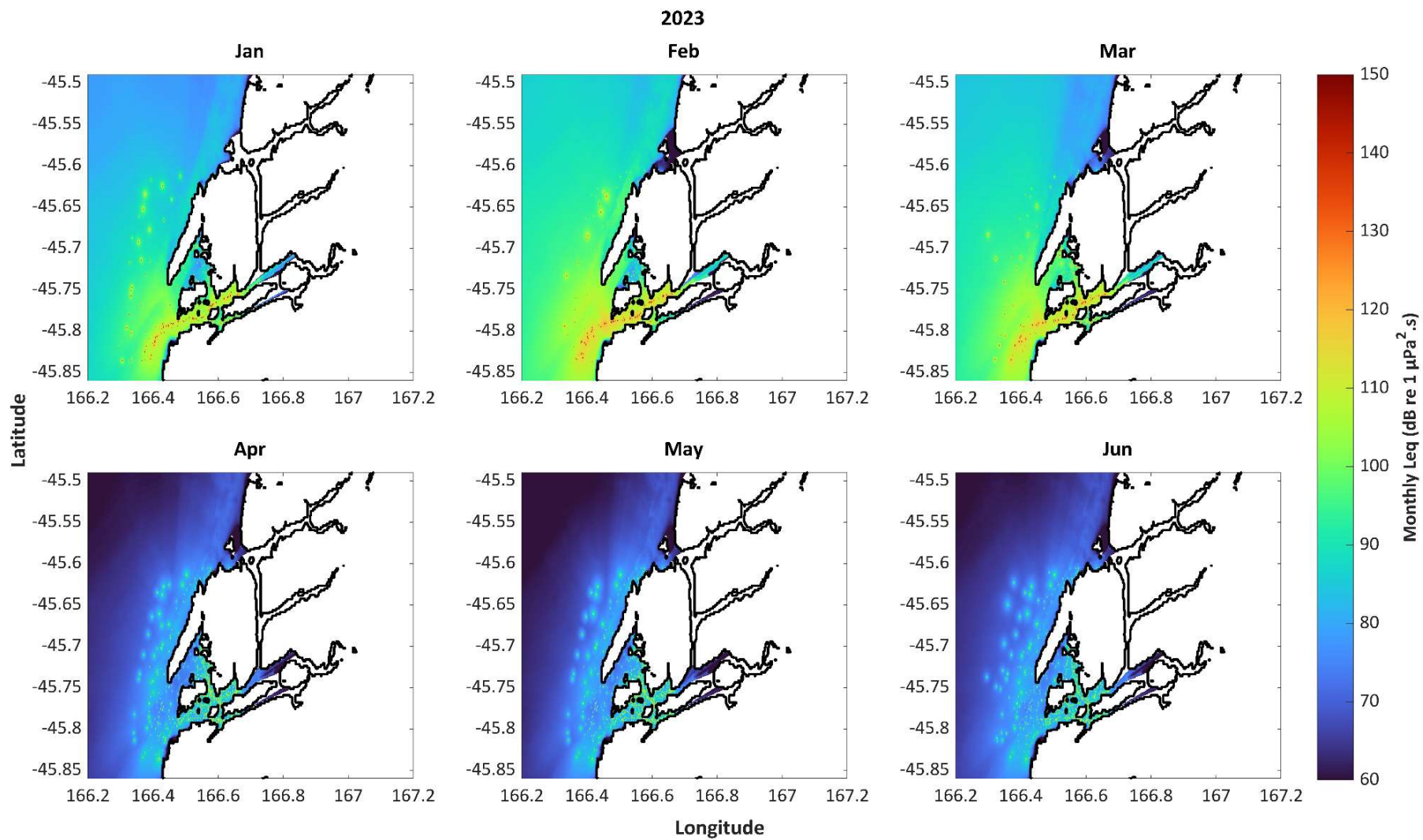


Figure 3.24: Monthly equivalent continuous sound levels (LEq) maps of all vessel types contained within the AIS records from January – June 2023 in the study area.

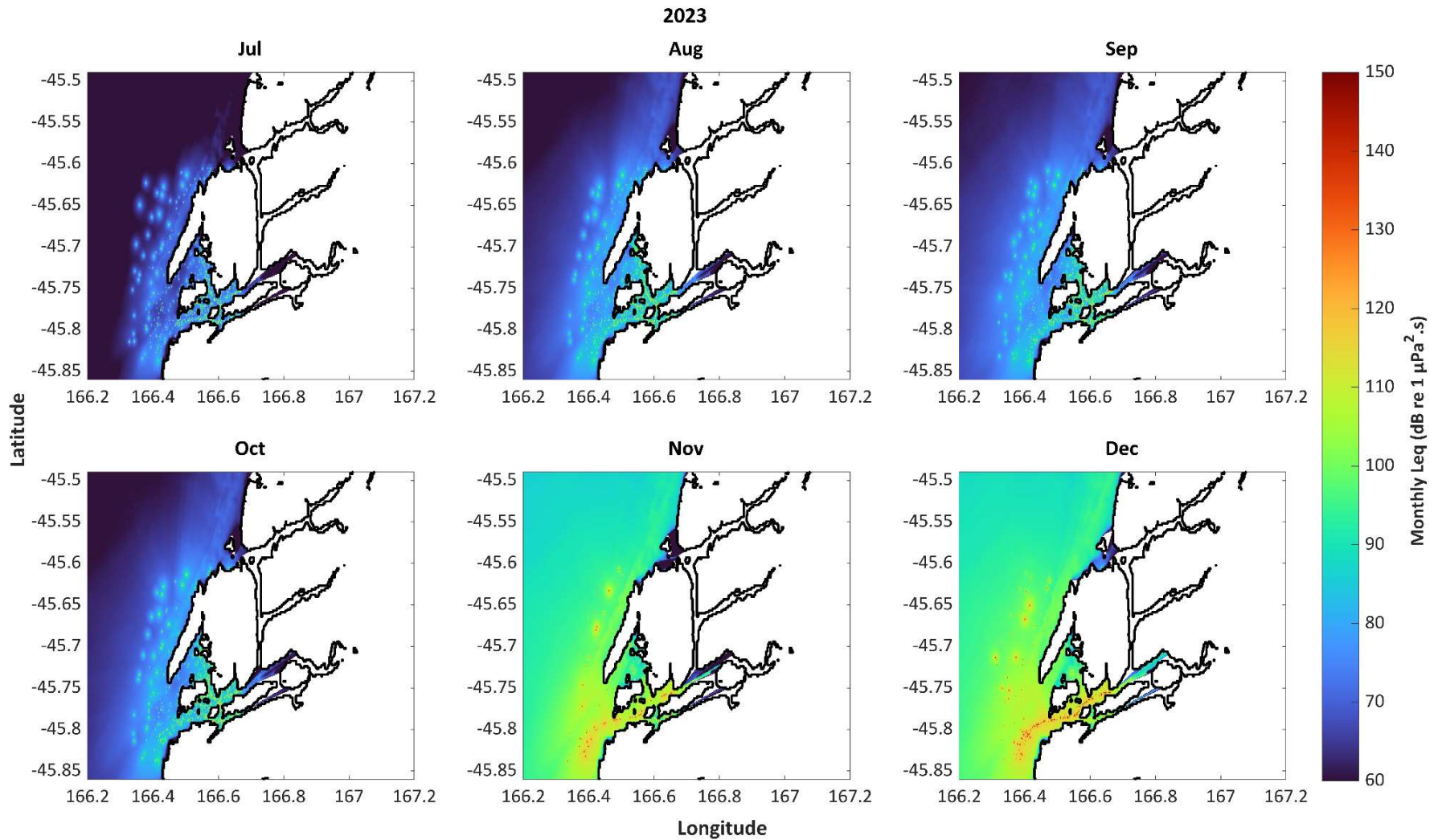


Figure 3.25: Monthly equivalent continuous sound levels (LEq) maps of all vessel types contained within the AIS records from July – December 2023 in the study area.

Chapter 4: Discussion

The number and size of vessels has greatly increased within the world's oceans due to continued industrialisation and economic growth over the past century (Duarte et al., 2021; Erbe et al., 2019; Frisk, 2012). Consequently, vessel noise has also increased, particularly in the low frequency range which has the greatest potential to negatively impact many marine species (Erbe et al., 2019; Putland et al., 2017c; Weilgart, 2007a). Sound is a primary sensory cue for marine mammals and cetacean auditory evolution has taken advantage of the omnipresence of sound cues and the efficiency of communication underwater. Accordingly, it is used in various aspects of their ecology, from feeding to migration, and breeding to socialisation. Furthermore, vessel noise has been observed to negatively impact cetaceans resulting in behavioural disturbance, acoustic masking and stress with potential population level consequences due to cumulative effects (Cholewiak et al., 2018; Erbe et al., 2019; Mooney et al., 2012; Wright et al., 2007a).

The overall aim of this study was to gain a better understanding of the spatiotemporal presence of vessels, delphinids and humpback whales in Tamatea/Dusky Sound, using a combination of passive acoustic monitoring (PAM), vessel Automatic Identification System (AIS) records, and noise propagation modelling. Data collected allowed for the identification of periods when the cooccurrence of high levels of noise and the presence of delphinids and humpback whales increased the risk of negative noise exposures.

The selected positions of the three sites allowed for soundscape recordings from different areas of Tamatea/Dusky Sound, providing an overview of the spatiotemporal trends in presence of vessel, delphinid and humpback whale acoustic signals. Anchor Island 01 was positioned on the southern side of Anchor Island and provided acoustic information for the main channel between the entrance of Dusky Sound and the start of the Bowen and Cook channels (hereby refer to as the 'Anchor Island channel'). Five Fingers 03 was located at an exposed site along Five Fingers Peninsula, providing information on the area north of Anchor Island and was located within the Taumoana Marine Reserve ('Marine Reserve'), halfway between Goose Cove and Five Fingers Point. Five Fingers 02 was also located within the marine reserve, set at the mouth of Cormorant Cove at a less exposed site further north towards Goose Cove and provided information on inner Dusky Sound habitats.

The range of listening space at each site was dynamic and completely dependent on the signals of interest and ambient background sound levels at a specific point in time.

4.1 Vessel Presence

Vessel usage within the Fiordland Marine Area (FMA) is progressively expanding beyond Piopiotahi/Milford Sound and Patea/Doubtful Sound where it has historically been highest

(Bennington et al., 2022; Booth, 2022; Lusseau et al., 2006a). The Regional Coastal Plan for Southland 2013 imposes discretionary activity limits within Doubtful Sound, with limited permits available for vessel tourism operators to preserve remoteness and wilderness values (Booth, 2022; Environment Southland, 2013). No such limits are in place within Milford Sound aiming to concentrate anthropogenic use within this 'sacrificial' fiord to preserve values in others, with its size considered a natural limitation on activities. The more remote fiords within the FMA such as Tamatea/Dusky Sound also have no limits, with use being traditionally restricted by their remote locations (Booth, 2022; Environment Southland, 2013). However, there are now many commercial multiday cruises operating within Dusky Sound, as well as several charter vessels focused on eco-tourism and fishing trips (Booth, 2022). Recreational vessels are also now visiting Dusky Sound in increased numbers, as are large cruise ships in the late spring summer months (October – April) (Environment Southland Regional Council Te Taiāo Tonga, 2021). This has led to greatly increased vessel use within Dusky Sound in recent years with associated impacts for cetaceans also likely increasing (Bennington et al., 2022).

Passive acoustic monitoring at the three sites in this study revealed differences in detected vessel presence. Across the entire recording effort, vessel presence was consistently highest at Anchor Island 01, followed by Five Fingers 03, with the lowest presence being at Five Fingers 02. Variability in monthly vessel presence among the sites remained fairly stable over time, with similarly sized increases and decreases occurring in synchrony in the same direction at all sites during much of the recording period. This suggests that as the overall number of vessels in Dusky Sound changes, the proportion utilising areas near each of the sites remains similar. There is also potential for the same vessel being detected at multiple sites, not necessarily simultaneously but as they transit within the area. Their route may take them past one site and then to another, especially in the case of the sites within the marine reserve (Five Fingers 02 and 03). As for concurrent detections, there are certain circumstances where vessels were detected on more than one of the hydrophones. However, due to the distances among each site (> 5 km line of sight) this was rare. Differences in vessel presence among the three sites showed that vessel use is not uniform within the study area in Dusky Sound.

The unique geography and limited access to Dusky Sound are likely to strongly influence the anthropogenic activities occurring within it (Booth, 2022). There are two ways to access Dusky Sound via vessel; from the outer coast or ocean through the entrance of Dusky Sound or through the Acheron passage from Te Pūaitaha/Breaksea Sound. There is no road access to Dusky Sound, however, helicopter flights from Te Anau to Supper Cove provide an increasingly utilised alternative form of transport for passengers to reach vessels (Booth, 2022).

Differences in vessel detections and associated vessel noise among the sites may be partially explained by their proximity to direct vessel access in and out of the Dusky Sound complex. For example, the Anchor Island channel adjacent to Anchor Island 01 is heavily utilised by

vessels as it provides direct access to and from the coast into Dusky Sound, increasing detected vessel presence. The hydrophone at Five Fingers 02 at the mouth of Cormorant Cove was the furthest site from a direct access point for vessels into the Dusky Sound complex, which may have been a contributing factor to it having consistently the lowest vessel presence of the three sites. Five Fingers 02 was also located in the upper reaches of the marine reserve where there is no access out other than returning from the direction travelled in.

4.1.1 Tourism, Passenger and Recreational Vessels

Tourism is one of New Zealand's fastest growing industries, contributing \$NZ 13.3 billion dollars in gross domestic product (3.7 % of total) in 2023 (Stats NZ, 2024). The interaction between tourism and the environment can place numerous, complex and often conflicting demands on fragile marine ecosystems (Harriott, 2004; Lusseau et al., 2006b). Fiordland is one of the essential destinations for international guests visiting New Zealand, as well as for travelling New Zealanders. Visitors travel to Fiordland to experience "wilderness" and many take scenic cruises in the fiords (Lusseau et al., 2006b). Charter vessels began operating in Fiordland in the mid-1990s with initial focus on fishing and hunting trips, but many charters have now branched into eco or adventure tourism (Booth, 2022). However, long term trends in vessel use within the FMA show that usage is getting more diverse (types of users and vessels), busy periods are extending and vessel size is increasing (Booth, 2022).

Differences in vessel presence among the sites were influenced by the usage patterns of vessels associated with tourism in Tamatea/Dusky Sound including charters, multiday cruises and cruise ships (Bennington et al., 2022; Booth, 2022; Lusseau et al., 2006a). Vessel detections at both Five Fingers 02 and 03 within the marine reserve may have had a higher number of multiday cruises and charters contributing to overall vessel detections and noise due to their focus on eco-tourism. A number of these operations visit the wildlife sanctuary and historic house on Pigeon Island and some may utilise the marine reserve for activities such as diving and wildlife watching (Booth, 2022).

In contrast, the Anchor Island 01 site likely had a greater contribution of detections from vessel traffic accessing the coast to and from Supper Cove where many multiday cruises and charter vessels begin and end trips due to the helicopter access (Booth, 2022). Large international cruise ships accessing the Dusky Sound complex to and from the outer coast must also pass through the Anchor Island channel south of Anchor Island 01 (within 1.5 km and direct 'line of sight') also contributing to vessel detections. These cruise ships enter the Dusky Sound complex from either Te Puaitaha/Breaksea Sound or Dusky Sound depending on the direction of passage, with both routes transiting the Acheron passage and either the Cook or Bowen Channels around Long Island (Environment Southland, 2019). Furthermore, Anchor Island has several walking tracks and is predator free. Consequently, it is visited by both tourists and department of conservation staff due to the high biodiversity and abundance of native bird species present such as the endangered Kākāpō (*Strigops*

habroptilus) (Department of Conservation, 2016; Fiordland Marine Guardians, 2024). Vessel traffic associated with these visits may have also increased vessel detections at the Anchor Island 01 site.

Distance to safe anchorages and moorings may also influence levels of detected vessel presence when comparing among sites (Widmer & Underwood, 2004). Anchorages and moorings within the greater FMA range from small sheltered bays to fully enclosed bays (Fiordland Marine Guardians, 2024). A well-known and very sheltered anchorage is present in Luncheon Cove northeast of the Anchor Island 01 site. This anchorage is heavily used due to the limited number of safe, all-weather overnight anchorages available in the area (Booth, 2022; Fiordland Marine Guardians, 2021) which very likely increased detected vessel presence at Anchor Island 01. Interestingly, during analysis of potential biological signals at the Anchor Island 01 site, a frequent and unusual low frequency noise was detected. When present this signal occurred during the evening hours (usually later than 17:00) and ceased in the morning (prior to 08:00). This signal is likely attributable to an anchored vessel rubbing against its mooring nearby, finishing when the vessel leaves for the day's activities.

The number of vessels associated with tourism and recreation present in Dusky Sound and their usage patterns likely influenced detection levels at the recording sites overtime. Recreational vessels are generally present in greater numbers on weekends and holidays (Kendall et al., 2021; Kline et al., 2020), however, due to their smaller size they are more restricted than larger vessels by rough sea conditions when accessing the area (Booth, 2022). Prior to 2020, a reduced number of multiday cruises operated in Dusky Sound during winter before shifting back to overnight and day cruises in Milford Sound during the summer 'tourist season'. However, international travel restrictions in 2020 – 2021 due to COVID-19 led to year-round trips and a large overall increase in the number of multiday cruises operating in Dusky Sound to cater to the domestic market (Booth, 2022; Lück & Seeler, 2021). Many of these companies have continued to operate year-round trips after travel restrictions were lifted, which was observed in the AIS records with 'Passenger' class vessels remaining consistently high in number in the area during the study period. Consequently, multiday cruises and charter vessels likely contributed a consistent proportion of the overall vessel detections and noise at each site overtime. Conversely, 'Cruise' vessels (cruise ships) were the most observed vessel class in the AIS records during late spring and summer months (November – March) in the study area. During this period they likely represented a considerable addition to the overall number of vessel detections and associated noise at Anchor Island 01 due to their use of the Anchor Island channel (Environment Southland, 2019).

Weather conditions at sea and within the fiord likely influences both the overall number of vessels present within the Dusky Sound complex and the areas they utilise at a given time (Booth, 2022). Accessing Dusky Sound from the north by vessel requires travelling offshore along the coast from Doubtful (or Milford) Sound which limits the number of vessels (particularly smaller recreational vessels) able to reach Dusky Sound during rough sea

conditions. Vessels in Dusky Sound shelter within the inner fiord areas during times of high winds and rough seas (Booth, 2022; Fiordland Marine Guardians, 2024), likely reducing detected vessel presence in the more exposed areas such as this studies sites.

At all sites the total numbers of vessel detections were greater during daylight than dark hours, with peak activity occurring at 10:00 – 12:00 NZST. Unlike container ships and other vessels which travel throughout the night in the open ocean, many of the vessels present within Dusky Sound primarily operate during the day (Booth, 2022). Vessels associated with recreational activities and tourism typically visit Dusky Sound due to its unique wilderness and scenic values, moving around the fiord undertaking activities generally best enjoyed during daylight hours before anchoring at night in sheltered areas. Travel within Dusky Sound is also more complex at night due to the numerous islands and navigational hazards which require quality radar equipment to navigate safely (Booth, 2022; Fiordland Marine Guardians, 2024). Similar diel patterns in vessel activity were observed at Cod Grounds Marine Park in Australia (located approximately 5.5 km off the eastern coast of New South Wales) where a peak in vessel detections occurred in the morning hours (8:00 – 11:00 AEST) (Kline et al., 2020). At both the Cod Ground Marine Park and two of the three sites in the current study (Five Fingers 02 & 03) fishing is prohibited. Consequently, typical patterns indicative of fishing activity including peak vessel presence at dawn and dusk when fishers exploit periods of heightened fish activity to maximise catch were not seen (Rowell et al., 2017).

4.1.2 Commercial and Recreational Fishing

The greater FMA has a variety of regulations in place for commercial and recreational fishing to conserve fish stocks for the future. There are increased regulations on bag limits and methods for commercial and recreational fishing, 10 completely no-take marine reserves (such as Taumoana Marine Reserve) and Internal Waters Management Areas where commercial fishing is prohibited and recreational fishing is further regulated (Fiordland Marine Guardians, 2021, 2024). The Tamatea/Dusky Sound Internal Waters Management Area (hereby referred to as the 'Internal Waters') is from inland of the Passage Islands at the beginning of Bowen Channel, which concentrates fishing pressure in coastal areas. Recreational fishing by recreational boaters and charter vessel passengers occurs in the entrance to Dusky Sound and around Anchor Island and there is also commercial fishing activity, with both primarily targeting red rock lobster and blue cod (Bennington et al., 2022; Corne, 2023; Fiordland Marine Guardians, 2024). Unfortunately, AIS data from commercial fishing vessels in Dusky Sound could not be included in this study due to complications with confidentiality. Thus, the exact areas most utilised by commercial fishing vessels and the numbers present during the study period is currently unknown as detections in the PAM data do not distinguish among vessel types.

Vessel traffic associated with commercial and recreational fishing occurring in Tamatea/Dusky Sound may have also contributed to the differences in detected vessel

presence among sites. Both Five Fingers 02 and 03 were within the marine reserve, whereas Anchor Island 01 had no additional level of protection from either commercial or recreational fishing being outside both the marine reserve and the internal waters (Fiordland Marine Guardians, 2024). Therefore, Anchor Island 01 would have increased detections resulting from vessels associated with fishing. This may have contributed to the comparatively lower detected vessel presence at Five Fingers 02 and 03 which were within the marine reserve where fishing was prohibited. While not as potentially affected by fishing vessel presence as Anchor Island 01, Five Fingers 03 was close (1 km) to the edge of the reserve and some vessels 'fishing the line' would likely be detected by the hydrophone at this site (Kellner et al., 2007). Five Fingers 02 was further inside the marine reserve (> 3 km from the line) and consistently had the lowest numbers of vessels detected, which may be partially attributable to the absence of fishing vessels.

Conversely, inside the Taumoana marine reserve between Pigeon Island and Whidbey Point there is an allocated area for the wet storage of commercial cray pots (coffing area). Because of limited suitable space for storing pots on land in Fiordland, five areas within four marine reserves in the FMA are designated for commercial fishers to keep live red rock lobster (caught outside the reserve) in holding pots and to store inoperable pots (Fiordland Marine Guardians, 2024). However, there is no published knowledge on the frequency in which the site in the marine reserve is used, and visual inspection of satellite imagery for the area throughout 2022/23 illustrated limited use.

4.2 Biologics: Delphinids and Humpback Whales

Delphinid signals were detected at all sites and during every month sampled. While it was not possible to confirm the species for every detection, they can be principally attributed to the resident subpopulation of Fiordland bottlenose dolphins within the Dusky Sound complex (*Tursiops truncatus*), given they are the most prevalent species present (Crowe et al., In Review; Lusseau et al., 2002). Despite this, a small number of detections may have resulted from common dolphins (*Delphinus* sp.) or dusky dolphins (*Lagenorhynchus obscurus*) which are infrequently present in Dusky Sound (Lusseau & Slooten, 2002). Future identification among the delphinid signals to the species level could increase understanding of the spatiotemporal presence of these less prevalent delphinid species within the Dusky Sound complex. This could also help gain further insight into the spatiotemporal dynamics of the Fiordland bottlenose dolphin subpopulation in Tamatea/Dusky Sound at a greater temporal resolution than visual observations can observe. Delphinid presence was consistently greatest at Five Fingers 03 across the full recording effort. There was similar monthly and overall delphinid presence at both Five Fingers 02 and Anchor Island 01, except for during the autumn months of 2023 where detected presence was consistently higher at Five Fingers 02 than Anchor Island 01.

Population dynamics in predators such as the Fiordland bottlenose dolphin are strongly influenced by the availability of prey (Benoit-Bird & Au, 2003; Lusseau & Wing, 2006). Visual

surveying indicates that Fiordland bottlenose dolphins within the Dusky Sound complex consistently use core habitat areas with key prey species and increased prey availability (Bennington et al., 2022). Fiordland bottlenose dolphins feed primarily on fish species associated with rocky reef and demersal habitat and have been observed to individually feed in areas close to the shoreline with rocky reef habitat over 70 % of the time (Lusseau & Wing, 2006; Schneider, 1999). Stable isotope work confirmed that individuals in the Doubtful pod primarily derived their diet from within fiord habitats, although they were also found to forage on several pelagic species (Lusseau & Wing, 2006). Sucker marks have been observed around the mouth of several individuals suggesting squid may also be part of their diet, however, the location where they forage on this prey is currently unknown (Crowe et al., In Review). Modelling within the Doubtful Sound complex showed that the primary driver of habitat use by Fiordland bottlenose dolphins was prey availability, particularly the abundance of the reef fish, girdled wrasse (*Notolabrus cinctus*) (Bennington et al., 2020). Habitat use was also found to be significantly correlated with abiotic variables including sea surface temperature, temperature at depth, water depth, distance to the fiord wall and entrance, seabed aspect, and seabed slope. However, biotic variables doubled the deviance explained by 19.3 % (Bennington et al., 2020).

No-take marine reserves have been seen to significantly increase the abundance and biomass of fish species compared to areas with no protection throughout New Zealand (Costello, 2014; Denny & Babcock, 2004). Within the Taumoana Marine Reserve blue cod (*Parapercis colias*) have been found to be larger and more abundant than outside in areas with no protection, either due to the marine reserve's protection or the existing high quality rocky reef habitat within it (Beentjes, 2023). As well as increased numbers of blue cod, analysis of reef fish communities within the Taumoana Marine Reserve indicate that the area supports an abundance of high trophic level omnivores, leading to stable communities and food webs (Wing & Jack, 2014b). Consequently, it's likely that the marine reserve would have higher overall abundances of prey fish species for Fiordland bottlenose dolphins than many other areas of the Dusky Sound complex open to fishing. Combined with the rocky reef habitat along the internal coastline of the Five Fingers Peninsula the marine reserve likely offers high quality feeding grounds leading to increased usage of the area by Fiordland bottlenose dolphins (Crowe et al., In Review). This may have contributed to the increased detected delphinid presence at Five Fingers 03 given that it was set amongst this coastal rocky reef habitat in the marine reserve. When processing the acoustic detections at this site, it was observed that there was a high number of foraging signals at times of heightened biological chorusing. Starting at sunset and peaking approximately 1 hour following, the ambient soundscape would increase in intensity in the low to mid frequency bands by up to 30 dB re 1 μ Pa. This chorus is due to several species becoming physically and acoustically active during the crepuscular periods (McCordic et al., 2021; Radford et al., 2008a; Radford et al., 2008b; Stanley et al., 2021). During these times there were frequent occurrences of acoustic foraging activity, with a change from predominantly mid-frequency signature whistles to increased echolocation, feeding buzzes and signature whistles. These animals

may be targeting times with increased prey activity to increase their foraging success. How Fiordland bottlenose dolphins recognise periods of increased activity could be an area of future research and could look to determining what cues are being used (e.g., increased sound levels or reduction in light), and their combination.

Conversely, Five Fingers 02 was located further north inside the marine reserve towards Goose Cove at the mouth of Cormorant Cove. This area is composed of high relief rocky shoreline that extends into sandflats, unlike the abundant rocky reef habitats at Five Fingers 03. This may have resulted in reduced prey availability, contributing to the lower detections at Five Fingers 02 (Edgar et al., 2014). Despite Anchor Island 01 being located outside of the marine reserve, and consequently holding no fishing protection, it was set amongst a complex arrangement of islands (the Many Islands group) with an abundance of patch and extensive rocky reef habitats. It is also an area of many submerged rocks and navigational hazards, potentially leading to a decrease in the expected fishing pressure. Due to its protection status, fish abundance and prey availability could be expected to be lower at Anchor Island 01 compared Five Fingers 03, where the high-quality habitat is protected from fishing. However, a combination of factors including habitat quality, topographic complexity discouraging fishing and protection status factors may have led to the comparable detections at both Anchor Island 01 and Five Fingers 02.

Habitat use by Fiordland bottlenose dolphins has been seen to shift seasonally, primarily due to the cold-water temperatures at this southern edge of their range (Bennington et al., 2022; Lusseau & Wing, 2006). During the summer, Fiordland bottlenose dolphins have been observed to shift towards the inner fiords for calving where water temperatures are higher, whereas during winter they shift towards the outer fiords which are influenced by the more stable ocean water temperatures. The drop in temperature in the inner fiords during winter is due to decreasing temperatures in the low salinity surface layer discharging from rivers and catchment areas (Bennington et al., 2022; Schneider, 1999). Expected shifts in Fiordland bottlenose dolphin presence towards outer fiord habitat may have led to the increased detected delphinid presence at Five Fingers 03 during winter in both years, however, it is interesting that delphinid presence remained high during spring in 2023 where it might have been expected to decrease. Unfortunately, there was no data available from January and February in either year at any of the recording sites due to hydrophone maintenance and field work schedules, accordingly comparisons could only be made between autumn, winter and spring. Future investigation utilising PAM at sites within the inner Dusky Sound complex could provide further insights into seasonality in habit use by Fiordland bottlenose dolphins.

Spatiotemporal presence of Fiordland bottlenose dolphins has been well monitored through visual surveying methods, with core areas of habitat usage being identified. Bennington et al. (2022) combined > 40,000km of visual survey effort between 2009 and 2018 in the Dusky Sound complex with kernel density estimation. Dolphin distribution was observed to be fairly consistent during this period, with identified core areas of increased habitat usage within the Dusky Sound complex being the Bowen Channel along Long Island and the

middle/upper reaches of Breaksea Sound. These core usage areas were thought to have increased prey availability and/or to be important for other aspects of Fiordland bottlenose dolphins ecology such as resting or socialising (Bennington et al., 2022). While generally consistent between 2009 and 2018, there were yearly seasonal shifts seen in these core usage areas towards the outer fiords in winter and inner fiords in summer (Bennington et al., 2022).

The area around Anchor Island and the marine reserve was also estimated by Bennington et al. (2022) to have low Fiordland bottlenose dolphin density between 2009 and 2018, particularly during the spring. Detected delphinid presence at Five Fingers 02 and Anchor Island 01 in this study was also reasonably low overall with monthly presence remaining < 6.5 %. Five Fingers 03 had significantly higher detected delphinid presence in this study, with 14.67 % of the total sampled hours containing detections (total presence) and four of the sampled months having > 20 % delphinid presence. This may suggest that the Taumoana Marine Reserve in the vicinity of Five Fingers 03 is an under-estimated habitat area for Fiordland bottlenose dolphins, particularly during winter and possibly spring when delphinid detections by PAM in this study were highest (Crowe et al., In Review).

The apparent differences in results between the visual surveying methods utilised by Bennington et al. (2022) and PAM for the current study was potentially due to the different types of information gathered by these two sampling methods, the degrees of sampling effort applied to areas, and the inherent limitations of both PAM and visual surveying methods in such a large area. Limitations of PAM include species identification (overlap and similarities among signals from different species), sound masking by additional louder sound sources (such as nearby vessels) and behavioural dependent vocalisation (animals may be in an area but exhibiting behaviours that do not include sound production) (Mooney et al., 2020; Stanley et al., 2021). To detect animals visually, surveying effort must coincide with animal presence and/or animal surface availability. Visual surveying effort is often time limited (never continuous for long periods annually like PAM), expensive and generally constrained by weather and daylight (Dalpaz et al., 2021; Smith et al., 2020). Consequently, many studies have concluded that PAM and visual monitoring methods are most effective when used together (Dalpaz et al., 2021; Fleming et al., 2018; Smith et al., 2020).

Visual surveying was also completed approximately four years before the current study. Therefore, it is possible core use areas for Fiordland bottlenose dolphins in the Dusky Sound complex have shifted, although this seems unlikely given they remained fairly consistent between 2009 and 2018 (Bennington et al., 2022). Furthermore, past visual surveying has not focused much effort on the Taumoana Marine Reserve. However, after learning the results of this current study, there are plans to include more effort in the area in the future (Crowe & Corne, Pers. Comm. 2024). Without PAM data from the core use habitat areas identified by Bennington et al. (2022) it is difficult to directly compare delphinid presence, yet, it is interesting that PAM detected such high levels of delphinid presence in an area where visual surveying effort did not. Passive acoustic monitoring at a larger number of sites

throughout different areas of the Dusky Sound complex could accordingly complement future visual surveying efforts (Dalpaz et al., 2021; Fleming et al., 2018; Smith et al., 2020). Gaining a greater understanding of the spatiotemporal distribution and core habitat areas of Fiordland bottlenose dolphins in Dusky Sound may also allow for more robust future visual surveying designs.

There are a very small number of studies that have examined the spatiotemporal distribution of humpback whales in the Fiordland Marine Area (FMA). The two most comprehensive studies found in the literature are a whaling era review of visual surveying results by Dawbin (1956) and a MSc thesis by Corne (2023) which combined visual surveying data with a subsample of the PAM data at Five Fingers 03 in 2022 from the current study (Corne, 2023; Dawbin, 1956). It should be noted that initial site selection in this study was not intended to comprehensively capture presence of humpback whales, however, upon initial analysis of vessel and delphinid presence it was observed that there was also a substantial presence of humpback whale signals. Due to the relatively little information available on the use of Fiordland as a potential intermediate stop-over for migratory humpback whales, it was decided that these would be included in the current study.

Humpback whale presence was seen to be consistently highest at Five Fingers 03 followed by Five Fingers 02 during the recording effort in terms of overall, seasonal and monthly detected presence. Despite having the longest recording effort of the sites, there were no confirmed detections observed at Anchor Island 01. There were 23 detections classed as questionable, however, there was not enough evidence to conclude they were positive humpback whale signals.

Humpback whales undertake long annual migrations between high-latitude feeding grounds and low-latitude breeding grounds. They are observed near New Zealand and the coastline of Fiordland biannually while migrating between northeastern Australia/New Caledonia (winter breeding grounds) and the Southern Ocean (summer feeding grounds) (Corne, 2023; Dawbin, 1956; Warren et al., 2020). It has been reported that the majority of humpback whales migrating past Fiordland remain offshore some distance from the outer coast, with a smaller number displaying short-term residency, primarily within the entrances of Doubtful and Dusky Sound (Corne, 2023; Dawbin, 1956).

The relative geographic position of each site within the Dusky Sound complex was a contributing factor to the differences in detected humpback whale presence. Five Fingers 03 was located halfway along the internal coastline of the Five Fingers Peninsula closer to the entrance of Dusky Sound than Five Fingers 02 which was located further north into Taumoana Marine Reserve. Five Fingers 03 also had a direct 'line of site' to the entrance of Dusky Sound and would be capable of detecting vocalising whales from a considerable distance offshore in favourable conditions (Frazer & Mercado, 2000). This site was also not obscured by islands or complex bathymetry as was the case at Anchor Island 01 and to a lesser extent Five Fingers 02. Estimating this distance for a single point in time, without

accounting for the acoustic propagation properties of the environment would be misleading and it's likely the detection distance could vary by a factor of ten or more over the recording period (Helble et al., 2013). The distance a certain signal can be detected by PAM is influenced by many factors including (but not limited to) the hydrophone type, depth and placement, varying ambient noise levels, source levels of the signal of interest, and competing signals. Factors dictating transmission loss (the rate at which received sound levels will decrease with distance) including sound speed, sound intensity, local bathymetry, and bottom type also influence distance at which a signal can be detected by PAM (Helble et al., 2013).

A study by Cholewiak et al. (2018) detected humpback whales from 5 – 30 km away using a hydrophone set at a similar depth to that in the current study. While there are many parameters influencing sound propagation among sites, both sites within the marine reserve would be capable of detecting humpback whales migrating offshore past the entrance of Dusky Sound, with several detections at Five Fingers 03 during 2022 being linked to humpback whales observed offshore (Corne, 2023). However, given that received sound levels decrease with distance, the proportion of the vocalisations from migrating humpback whales detected within Dusky Sound would be expected to decrease away from the sounds entrance. The hydrophone being positioned further away from the sounds entrance and in shallower waters likely contributed to Five Fingers 02 having very similar monthly trends but a reduced number of signal detections in each month compared to Five Fingers 03.

As mentioned above, regardless of the length of recording effort, Anchor Island 01 contained no confirmed humpback whale detections over the length of the study. This site was the closest to the entrance of Dusky Sound and was set in a relatively open area amongst several small islands on the southern side of Anchor Island. One potential explanation for the lack of confirmed detections was the interference of several small islands surrounding the hydrophone which may have led to humpback whale signals failing to propagate into the area. The complex nature of sound propagation makes this difficult to evaluate without having further information on the submarine topography and applying listening space models. However, the lack of received signals in times where there was confirmed presence supports this hypothesis. Future studies utilising PAM in Dusky Sound aiming to detect humpback whale signals may benefit from repositioning this hydrophone to the offshore side of these small islands. However, this may prove difficult given that the area is very exposed to prevailing weather, swell and wind from the southwest, which was a fundamental factor in the initial site selection decision. This site was also originally located to target cruise ship signals transiting in and out of Dusky Sound via their nominated route rather than humpback whales (Environment Southland, 2019).

Kernal density estimates and the actual encounters from visual surveying effort between 2008 to 2022 also predicted the southern side of Anchor Island 01 to be a low probability area for humpback whale encounters (Corne, 2023). In contrast, the area of Dusky Sound north of Anchor Island including Taumoana Marine Reserve near Five Fingers 03 was a high

probability area. This was reportedly due to the areas physical characteristics being suited to short-term residency by migrating humpback whales for supplementary foraging and/or resting. The area around Five Fingers 03, which had the highest predicted density of humpback whales by Corne (2023) also had the greatest number of positive acoustic detections in the current study. The lack of any detections at Anchor Island 01 in this study also supports the low density estimates for that area (Corne, 2023). Finally, Anchor Island 01 consistently contained the highest detected vessel presence and associated LEqs (vessel noise) of all sites. This may have resulted in a reduced listening space and consequently reduced detected signals due to acoustic masking of vocalisations, reduced vocalisation activity or avoidance of the area by humpback whales (Dunlop, 2016, 2019).

Humpback whale presence collected in the current study also exhibited temporal variation. Detected monthly humpback whale presence was greatest during June in both years at Five Fingers 02 (which had no recording in spring 2023), whereas bimodal peaks were seen in Five Fingers 03 which had the greatest presence in June and a smaller peak in October 2022. Recording only occurred from July to November at Five Fingers 03 in 2023, but both August and October showed large increases in humpback whale presence compared to 2022 and all other sampled months in 2023. These findings were generally consistent with previous reports on the migration timings for humpback whale in Fiordland. Dawbin (1956) reported that humpback whales were present during their northbound migration from May to August and during their southbound migration from September to December, with peak sightings occurring in the middle of these periods (from late June to mid-July and from late October to late November respectively). Recent research by Corne (2023) reported similar findings.

The direction of migration has been observed to influence habitat preference and vocalisation behaviour in humpback whales. During the northern migration past Fiordland, humpback whales are known to migrate further offshore at a more constant rate and have comparatively higher vocalisation activity (singing) (Corne, 2023; Dawbin, 1956; Warren et al., 2020). In the FMA, increased visual detections have been reported during the southern migration, with whales passing nearer to the coast and some individuals displaying short-term residency to forage and rest, particularly near the entrances to the Doubtful and Dusky Sound complexes (Corne, 2023; Dawbin, 1956).

June had the highest humpback whale detection presence at both sites in 2022 (March – December sampled). Dawbin (1956) recounted the lack of visual sightings of humpback whales within the sounds during the northern winter migration in the pre-whaling era, while Corne (2023) reported low numbers of visual sightings during winter from 1992 – 2022. The findings of the current study further suggest that the current placement of hydrophones within Dusky Sound could detect vocalising whales migrating northward offshore beyond the usual range of visual surveys. Alternatively, the relatively low number of days spent per season on visual survey may have missed the peak of presence, unlike PAM which occurs continuously. There was a smaller secondary peak in detections during October 2022 which coincides with the southern migration in the spring. Corne (2023) also stated that 95 % of

visual encounters from 2008 to 2022 were during the southern spring migration. These acoustic and visual findings together support a comparative reduction in vocalisation activity during the southern migration, consistent with behavioural patterns described for humpback whales (Warren et al., 2020). Accordingly, it seems unlikely that the number of humpback whales in detectability range was lower during this period, but rather they were less vocal resulting in fewer detections.

In contrast, peak humpback whale presence in 2023 occurred during October at Five Finger 03 and June at Five Fingers 02. October is reported to be during a period of reduced vocalisation activity on their southern migration, and therefore, fewer acoustic detections may have been expected in that month in the current study (Corne, 2023; Warren et al., 2020). However, the high detections could either suggest more humpback whales were present in 2023 than in previous years and/or that the humpback whales present were more vocal. Unfortunately, no recording occurred at Five Fingers 03 from January to June 2023 so presence during the winter could not be compared with spring. However, when examining the trends in both sites during 2022, Five Fingers 02 mirrored the general patterns seen at Five Fingers 03 yet was proportionately lower. This is likely due to the distance of the hydrophone at Five Fingers 02 from the outer coast and entrance of Dusky Sound, consequently detecting a smaller proportion of vocalisations to that of Five Fingers 03. This considered, Five Fingers 02 had greatly increased detected presence during June 2022 compared to June 2023, possibly suggesting that detected presence would have been much higher during June 2023 at Five Fingers 03 as well. This may suggest that the number of humpback whales migrating past Dusky Sound was much greater in 2023 which could have led to the high detected presence in October at Five Fingers 03. Another possible explanation is that an individual or a small number of humpback whales were short-term residents within the entrance of Dusky Sound in October 2023, which has been previously reported to occur in spring months (Corne, 2023). If this was the case, they would have likely increased detections during that month due to increased vocalisations associated with feeding or socialising (Corne, 2023; D'Vincent et al., 1985; Schall et al., 2021; Stimpert et al., 2007).

4.2.1 Co-occurrence of Vessels and Cetaceans

Vessel usage through recreation, tourism and commercial fishing is increasing in the Dusky Sound complex (Bennington et al., 2022), which will lead to associated increases in vessel noise and impacts to the soundscape. Interactions with and noise from vessels have been seen to negatively impact cetaceans through disturbance and acoustic masking, causing changes to their behaviour, foraging activity, vocalisations, energy budgets, habitat use, and increased physiological stress (Bauer & Herman, 1985; Marley et al., 2017; Pirotta et al., 2015; Rey-Baquero et al., 2021; Weilgart, 2007b). These effects can negatively impact the fitness of individuals, but also have wider cumulative impacts for populations impacting their long-term viability, particularly when combined with other stressors (Erbe et al., 2019; Heenehan et al., 2017b; Thomsen & Popper, 2024; Tyack, 2009; Wright et al., 2007a).

The periods with the greatest overlap between peak presence for vessels, delphinids and humpback whales, and associated levels of potential acoustic exposure risk varied among the sites. The greatest overlap for delphinids occurred during March and July 2022 and in March 2023 at Five Fingers 02, and July - September 2022 and November 2023 at FF03. Anchor Island 01 was characterised by consistently high vessel presence and consistently low delphinid presence throughout.

Despite the current medium levels of vessel usage at Five Fingers 03, it is likely to have the greatest impacts due to the high detected presence of Fiordland bottlenose dolphins. Similarly, while Anchor Island 01 has the lowest detected delphinid presence it represents an area of significant risk due to the high vessel presence (up to 14 positive presence hours per day) (Heenehan et al., 2017a). Vessel usage within FMA is currently highest in the more easily accessible Milford and Doubtful Sounds (Bennington et al., 2022). Nevertheless, vessel presence is currently increasing in the more remote areas which historically have had lower vessel usage and were potentially used as refuge or resting areas for these animals (Cárdenas Hinojosa et al., 2020; Heenehan et al., 2017b; Southall et al., 2009) The Doubtful Sound complex contains a resident subpopulation of Fiordland bottlenose dolphins and Milford Sound is one of seven fiords used by the northern subpopulation, with increasing vessel use and interactions in the early 2000s prompting researchers to investigate potential impacts (Currey et al., 2011a; Lusseau, 2003a, 2004; Lusseau & Higham, 2004).

Fiordland bottlenose dolphins in both the Doubtful Sound complex and Milford Sound bore scars from collisions with vessels, and in 2002 a calf was killed in Milford Sound after being struck by a tour boat, reducing that years reproductive success for the northern subpopulation by 50 % (Currey et al., 2011a; Currey et al., 2011b; Lusseau, 2004; Lusseau et al., 2006a). Significant behavioural disturbance has regularly been observed in response to vessels by many dolphin species (Mills et al., 2023; New et al., 2020; Ng & Leung, 2003). Disrupted resting and socialising behaviours and increases in dive intervals and time spent travelling to avoid tour boats has been observed in Fiordland bottlenose dolphin populations (Currey et al., 2009; Lusseau, 2003b, 2005). Avoidance of Milford Sound was seen during periods of high vessel traffic (reducing the northern subpopulations range by 1/7th) indicating the biologically significant impact of vessel-based tourism (Lusseau, 2005). Very low calf survival rates due to the cumulative effects of vessel interactions and increased freshwater inputs from the Manapouri power scheme were attributed to a 34 % decrease in the Doubtful Sound subpopulation over 12 years (Currey et al., 2007). Furthermore, modelling by Lusseau et al. (2006a) and Currey et al. (2009) showed unsustainable rates of population decline and a high risk of extinction for Fiordland bottlenose dolphins due to the cumulative effects of these increasing vessel interactions. This work successfully led to the 'critically endangered' designation for Fiordland bottlenose dolphins by the International Union for Conservation of Nature (IUCN) (Currey et al., 2011b).

For humpback whales, the months with the greatest potential for negative impacts in relation to vessel exposure relate heavily to their migration behaviour. October was seen to

be the peak month for the spring migration when humpback whales are reported to be closest to the coast and the sound entrance in high numbers (Corne, 2023). Risks are likely greatest for individuals displaying short-term residency at the entrance and inside of the Doubtful and Dusky Sound complexes due to the high vessel use in those areas (Corne, 2023). During the winter northward migration peak overlap occurred during June and July 2022 and June 2023, however, there may be a somewhat lower risk during this period due to whales reportedly passing offshore, further away from coastal areas which are highly utilised by vessels (Constantine et al., 2007; Warren et al., 2020). The number of humpback whales migrating through the FMA is expected to keep increasing as the population continues to recover from whaling (Corne, 2023). Given this, it would be beneficial to implement regulations to protect them. Lowering vessel speed limits near the entrances of Doubtful and Dusky Sounds during October could likely benefit migrating humpback whales by reducing vessel noise levels and the potential for ship strikes. Of particular concern are cruise ships due to their size, speed, lack of manoeuvrability, and their line of travel at times and through areas that may also be utilised by humpback whales (Ritter & Panigada, 2019; Webb & Gende, 2015). Although Environment Southland restricts the number of cruise ships that can be present in a fiord in a day, numbers of cruise ships in the FMA are increasing (Environment Southland Regional Council Te Taiao Tonga, 2021; Fiordland Marine Guardians, 2019). Smaller tourism vessels also present a risk to these animals. Whilst commercial tour operators are subject to strict time limits and viewing area restrictions for large whales (Kinsey, Pers. Comm. 2023), charter vessels and recreational users are under no such restrictions, creating the possibility for individual whales to be subjected to repeat vessel encounters. This is especially true for short-term resident whales within the FMA.

In addition to the effects discussed above, vessel exposure can lead to changes in the acoustic behaviour of both delphinids and humpback whales and to the soundscape leading to short-term acoustic masking of biologically and ecologically important sounds (Buckstaff, 2004; Cholewiak et al., 2018; Dunlop et al., 2010; Erbe et al., 2016c; Luís et al., 2014; Rey-Baquero et al., 2021). Bottlenose dolphins exhibited increased whistle rate at onset of vessel approach compared to during and after approaches in Sarasota Bay, Florida (Buckstaff, 2004). It was hypothesised that this may reflect heightened arousal through increased motivation for animals to move close together, or a way to compensate for acoustic masking, similar to repeating oneself. Conversely, two studies in the Sado Estuary, Portugal, reported a decrease in mean overall call rates in the presence of operating vessels, as well as changes in the frequency and duration of whistles and pulsed sounds (grunt, squeak, creak) (Luís et al., 2014; Sobreira et al., 2024). In a study on humpback whales by Fournet et al. (2018), increased ambient sound levels from cruise ships and tour boats led to an increase in the source levels of their calls (non-song vocalisations), which continued to increase incrementally with increasing ambient sound levels. The probability of vocalising whales in that studies survey area was also 31 – 45 % lower when vessel noise contributed to the soundscape compared to when only natural sounds were present (Fournet et al., 2018). Other observed behavioural changes in humpback whales resulting from vessel noise

exposure include reductions in foraging activity (Blair et al., 2016), increased metabolic rates and swim speeds (Sprogis et al., 2020), and displacement behaviour (Scheidat et al., 2004; Schuler et al., 2019), with the degree of these responses driven by the magnitude of the vessel noise (Sprogis et al., 2020).

These short-term changes to movement patterns and behavioural states in individuals may lead to increase levels of physiological stress and long-term population level impacts through cumulative effects (Blair et al., 2016; Dunlop, 2016; Schuler et al., 2019). High levels of vessel use also increases the risk of ship strike for humpback whales which can result in injury or death, with the risk particularly high when large and fast-moving vessels such as cruise ships are present (Fleming & Jackson, 2011).

4.3 Vessel Noise Modelling

Sound propagates far more effectively in the ocean than in air, however, vessel noise and its impacts on marine life is not currently considered in management plans within the FMA or throughout New Zealand (Daly, 2015; Environment Southland, 2013). Low frequency noise produced by vessels propagates great distances and has been correlated with ship speed and size (Findlay et al., 2023; McKenna et al., 2012; McKenna et al., 2016; McKenna et al., 2013).

Noise propagation models were run for all vessels contained in the AIS records between February 2022 and December 2023 within the designated study area in Tamatea/Dusky Sound. From the results noise maps were created illustrating monthly average equivalent continuous sound levels (LEq) which indicated the levels of sound occurring in the area for each month. It should be noted that commercial fishing vessels in the AIS records could not be included in the study due to issues with confidentiality, furthermore, small recreational vessels were significantly underrepresented as most do not use the system (Hermannsen et al., 2019). Monthly average LEqs were seen to be comparatively low throughout the study area during April – September in both 2022 and 2023, with the highest levels occurring in the Anchor Island channel and near Resolution and Parrot Islands (~80 – 120 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$). Monthly average LEqs during this period were determined largely by usage patterns of ‘Passenger’ vessels including multiday cruises and charters which were the most prevalent class in the AIS records in this period. For clarity, ‘Passenger’ vessels ≤ 100 m, ‘Cruise’ vessels > 100 m (MacGillivray et al., 2014).

The months of October – March had greatly increased monthly average LEqs, with noise levels highest in the Anchor Island channel (~110 – 150 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$), with a notable ‘route’ of increased noise to the southwest at the entrance of the sound. The large increase in monthly average LEqs during this period in much of the study area can be attributed to ‘Cruise’ vessels (large cruise ships) which greatly increased in number within the areas AIS records in this period compared to other vessel classes which remained similar to previous months. Cruise ships transit through the Anchor Island channel while accessing

Tamatea/Dusky Sound to and from the outer coast, towards or from the south (and to a lesser extent from the north), although some may transit along the coast further offshore (Environment Southland, 2019; Environment Southland Regional Council Te Taiao Tonga, 2021). Noise levels were highest in these known cruise ship routes; however, there was also a comparative increase offshore and throughout much of Dusky Sound in these summer months likely due to the effective propagation of noise from these large vessels (MacGillivray et al., 2014; MacGillivray et al., 2023; Putland et al., 2017c; Stanley et al., 2017). Conversely, LEqs showed little increase in areas frequented by multiday cruises and charters around Parrot and Resolution Islands compared to the winter. This was to be expected given they remained in similar numbers in the AIS records and the area is less exposed to noise from cruise ships due to islands (Booth, 2022; Environment Southland, 2019).

Cruise ships visiting Dusky Sound are large (mainly between 200 – 300 m long) and travel at a speed of approximately 16 knots leading to the high noise levels in late spring and summer (Environment Southland, 2019 & AIS Records). However, during February and March 2022 noise levels were comparable to the quieter winter months. This was likely due to restrictions on international cruise ships operating within New Zealand and their absence from the FMA due to the COVID-19 pandemic (Booth, 2022). A reduction in ambient sound levels was also seen similarly in the New Zealand's busiest waterway, the Hauraki Gulf Marine Park. The strict lockdown during the COVID-19 pandemic in March and April 2020 banned all non-essential services and travel on land and sea, leading to ambient sound levels dropped nearly threefold in the first 12 hours (Pine et al., 2021). The number of vessel detections using PAM and the number of 'Passenger' and 'Recreational' class vessels in the AIS records were relatively comparable in February and March 2022 to during the same period in 2023 when monthly average LEq were much higher (increase of ~ 30 dB re 1 $\mu\text{Pa}^2\cdot\text{s}$). This provides insight into how large cruise ships contribute heavily to monthly LEq levels in Dusky Sound. Cruise ships were not present in Dusky Sound in late spring and summer months in as high numbers as smaller vessels and did not appear to impact the monthly vessel presence metric detected using PAM. However, due to their large size and speed they were seen to have a large and disproportionate effect on monthly cumulative noise levels (LEq) within the soundscape (Frankel & Gabriele, 2017; Hatch et al., 2008).

The United States National Marine Fisheries Service (NMFS) published a set of technical guidelines on acoustic thresholds for continuous sound sources, with metrics developed to inform impact assessments within the United States legal system. However, these guidelines and associated levels are used as a standard in many countries due to a low number of available thresholds (Wright et al., 2023). The onset of behavioural disturbance in marine mammals is stated to occur above a received root-mean-square (RMS) received level of 120 dB re 1 μPa (National Marine Fisheries Service, 2018b). In the current study, localised areas such as the Anchor Island channel and the channel between Anchor and Resolution Islands approached this level when no cruise ships were present, due to noise from vessels of other types. However, when cruise ships were present (during late spring and summer months)

the monthly average LEqs rose notably above this threshold in many parts of Dusky Sound and the outer coast on either side of the entrance.

Consequently, the Anchor Island channel area had the greatest associated exposure risks for cetaceans from high vessel noise (also reflecting the findings from PAM), particularly during late spring and summer, and to a lesser extent during the remainder of the year. Vessel noise levels were consistently greater than the 120 dB re 1 μ Pa threshold in the lower Bowen Channel included in the study area, which is also a core habitat usage area of Fiordland bottlenose dolphins (Bennington et al., 2022). High noise exposure risk in the summer cruise season was not only limited to this cruise ship route. Due to effective propagation conditions, monthly average LEqs throughout much of Dusky Sound and offshore were close to or greater than the 120 dB re 1 μ Pa threshold. It is important to remember the current model is conservative as it did not account for noise from recreational and commercial fishing vessels as well as other commercial ships such as tankers, military and cargo vessel (which were excluded from the AIS records). Accordingly, noise levels (and associated impacts) were likely greater than modelled (Hermanssen et al., 2019).

These points considered, responses of and long-term impacts for cetaceans from vessel interactions and noise are highly context-dependent (Erbe et al., 2019). While many studies have detailed the significant negative impacts that may occur (Bauer & Herman, 1985; Marley et al., 2017; Pirotta et al., 2015; Rey-Baquero et al., 2021; Weilgart, 2007b), without ground truthing it is difficult to predict potential responses and describe cumulative effects (Erbe et al., 2019). Given that vessel use is currently increasing in Tamatea/Dusky Sound (Booth, 2022), long-term studies of cetaceans (particularly the resident subpopulation of Fiordland bottlenose dolphins) is necessary to establish the scale of population consequences that may be occurring (Erbe et al., 2019).

4.4 Management implications for Tamatea/Dusky Sounds

The Department of Conservation (DOC) recognise the numerous studies on the effects of vessel noise on the well-being of marine mammals (Department of Conservation, 2016). Nonetheless, a coordinated and legislated action to manage cumulative anthropogenic noise is lacking throughout New Zealand, despite the broad recognition of the risks to specific species and wider ecosystem functioning (Daly, 2015). That being said, by supporting research like this, DOC is making the first steps towards better understanding the extent of this anthropogenic stressor and building advanced ways to manage it.

In addition to the existing protections detailed in the Marine Mammals Protection Act (1978) and the Marine Mammals Protection Regulations (1992), a voluntary code of management was put in place for the Patea/Doubtful Sound complex in 2008 to reduce impacts of vessel/dolphin interactions (Department of Conservation, 2008; Guerra & Dawson, 2016). This code of management created dolphin protection zones with restrictions for vessel traffic in areas known to be most utilised by Fiordland bottlenose dolphins (totalling 10.6 % of the

fiords area) along with guidelines to ensure encounters with dolphins were left to chance (Department of Conservation, 2008). By 2012 this code of management successfully reduced the observed proportion of time dolphins were exposed to vessels from 11 % to 2 %, with encounters between dolphins and vessels seen to be significantly lower and for reduced time periods (Guerra & Dawson, 2016). Furthermore, Fiordland bottlenose dolphins were seen to use dolphin protection zones at significantly higher rates than other areas of the Doubtful Sound complex. The success of this voluntary code of management for the Doubtful Sound complex has been attributed to the ongoing cooperation of vessel tourism operators (who were involved in its development), and the optimal positioning of the dolphin protection zones (Bennington et al., 2022; Guerra & Dawson, 2016). Given the increasing vessel usage within the Dusky Sound complex (Booth, 2022), proactive management is needed to protect its resident Fiordland bottlenose dolphins and their habitat. The success of the Code of Management in the Doubtful Sound complex suggests a similar approach could likely be successfully implemented within the Dusky Sound complex. Focus should go to protecting important habitats and highly utilised areas such as those newly identified by PAM in this study and by Bennington et al. (2022) through visual surveying.

The risks to cetaceans associated with vessel noise were identified in this study to be greatest in the Anchor Island channel due to it being a highly utilised access route for vessels into the Dusky Sound complex (Environment Southland, 2019). Although the study area for the noise model did not include the entire Bowen Channel it is likely that it and other areas of concentrated vessel use (such as the Acheron Passage) in the Dusky Sound complex would have similar high noise levels. Noise increases with vessel speed and size (McKenna et al., 2016; McKenna et al., 2013), which was seen in the study area by the disproportionate increase in monthly LEqs when cruise ships were present. The size of impacts for cetaceans is also related to the level of vessel noise experienced (Sprogis et al., 2020). Therefore, vessel slow down measures are a frequently utilised management strategy to effectively reduce the impacts of vessel noise for marine life (Findlay et al., 2023; Pine et al., 2018). Findlay et al. (2023) modelled how various mitigation methods (technological modifications and slowdowns) can limit impacts on marine mammals. The area exposed to ship noise was reduced markedly with moderate source-levels reductions (6 dB) which can be achieved by small reductions in speed (20 %) and concluded that cumulative noise impacts can be reduced immediately with slowdowns, needing no modification to ships. Under ideal conditions, lowering ship source level by 6 dB reduces its acoustic footprint by as much as 75 %, thereby greatly reducing the number of animals impacted (Zinke, 2023).

Slowdowns could likely be effectively utilised in high usage areas of the Dusky Sound complex (such as the Anchor Island channel) for all commercial vessels. However, more general speed reductions for cruise ships in the FMA will likely lead to the greatest reductions in noise and associated impacts during summer months (Frankel & Gabriele, 2017; Hatch et al., 2008).

4.5 Limitations and Future Research Directions

The limitations of this study have been largely described throughout the results and discussion sections. There are several aspects of the study that could be improved through future research.

Passive Acoustic Monitoring:

- Adding additional recording sites. Anchor Island 01 was sufficient at detecting vessels transiting around the north of the Island, as well as up and down the Anchor Island Channel. However, due to various islands blocking the propagation of sound from the mouth of Dusky Sound and the outer coast, the hydrophone was unable to detect humpback whale signals at that site.
- Identification of signals to the species level in delphinids. Although contributions from other species would have been low due to natural habitat preference and distribution of other delphinid species, it would be beneficial to separate these species for advancing knowledge. Very little is known about the behaviour and distribution of other species in FMA.
- The loss of acoustic moorings, equipment maintenance schedules and lower than expected battery life prevented comparison among sites in some periods during this study. As it is an isolated area of New Zealand, further field work comes at a high cost. However, adding extra hydrophones on the acoustic moorings to overlap deployment periods could reduce periods of time with no data.
- The acoustic recordings gathered during this study contain an enormous amount of information. Further investigation into the received effects of vessel noise on the natural soundscape, potential effects on the timing of biological signals and on acoustic behaviours of the animals (not exclusively cetaceans) would be beneficial to the overall understanding of anthropogenic pressures in FMA.

AIS records and the consequent propagation modelling: The exclusion of many commercial vessels from the AIS records and the underrepresentation of recreational vessels in the AIS records in general, reduced the modelled monthly equivalent continuous sound pressure levels. For future studies, improved access to AIS records is needed to gain a more comprehensive view of the noise levels (Hermannsen et al., 2019).

Finally, the response of cetaceans to vessel noise and disturbance are variable and context-dependent, requiring long-term study to correctly characterise (Erbe et al., 2019). There could be more research into understanding the effects seen in these populations, in addition to what is currently known on avoidance behaviour.

4.6 Conclusions

Passive acoustic monitoring was used in this study to describe spatiotemporal presence of Fiordland bottlenose dolphins and migratory humpback whales, and their overlap with vessels in Tamatea/Dusky Sound. Taumoana Marine Reserve along the internal coast of Five Fingers Peninsula was found to be an area of increased usage by Fiordland bottlenose dolphins, previously underestimated by visual surveying efforts (Bennington et al., 2022; Crowe et al., In Review).

Humpback whale presence was highest during migration periods also observed by visual surveying efforts (Corne, 2023; Dawbin, 1956), with the greatest detections occurring in the northern migration, consistent with known vocalisation behaviours (Warren et al., 2020). Vessel presence was seen to differ among sites and was dependent on access routes and usage patterns of vessels associated with tourism and recreation in Dusky Sound.

Noise propagation modelling from AIS records in Dusky Sound showed noise levels were greatly increased in late spring and summer when cruise ships were present, with monthly cumulative LEqs consistently reaching ~ 150 dB re $1 \mu\text{Pa}^2 \cdot \text{s}$ in cruise ship transit routes (Environment Southland, 2019). Given vessel use is currently increasing without limits in Dusky Sound (Booth, 2022), increased management of vessels through speed reductions and the creation of management plans for this subpopulation of Fiordland bottlenose dolphins is recommended before wide scale impacts are felt in these populations of cetaceans.

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Supplementary Materials

Table S1. Summary table of the model effects showing the effect of Site and Month on Positive Presence hours of vessel signals.

Source	Type III		
	Wald Chi-Square	df	Sig.
(Intercept)	136.238	1	<.001
Site	209.326	2	<.001
Month	64.071	9	<.001

Dependent Variable: PPH_vessel
Model: (Intercept), Site, Month

Table S2. Summary table of the model parameter estimates showing the effect of Site and Month on Positive Presence hours of vessel signals.

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test			Exp(B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	Sig.		Lower	Upper
(Intercept)	.557	.1112	.339	.775	25.080	1	<.001	1.745	1.404	2.171
[Site=Anchor]	.610	.0821	.449	.770	55.165	1	<.001	1.840	1.566	2.161
[Site=FF02]	-.698	.0986	-.892	-.505	50.173	1	<.001	.497	.410	.603
[Site=FF03]	0 ^a	.	.	.	.	.	.	1	.	.
[Month=April]	.025	.1471	-.263	.314	.029	1	.864	1.026	.769	1.368
[Month=August]	-.181	.1435	-.463	.100	1.596	1	.206	.834	.630	1.105
[Month=December]	-.212	.2111	-.625	.202	1.004	1	.316	.809	.535	1.224
[Month=July]	-.011	.1424	-.290	.268	.006	1	.939	.989	.748	1.308
[Month=June]	-.179	.1655	-.504	.145	1.176	1	.278	.836	.604	1.156
[Month=March]	.091	.1447	-.193	.374	.391	1	.532	1.095	.824	1.454
[Month=May]	-.062	.1447	-.345	.222	.182	1	.670	.940	.708	1.248
[Month=November]	.414	.1438	.132	.696	8.291	1	.004	1.513	1.141	2.005
[Month=October]	-.751	.1530	-1.051	-.451	24.110	1	<.001	.472	.350	.637
[Month=Sept]	0 ^a	.	.	.	.	.	.	1	.	.
(Scale)	1 ^b									
(Negative binomial)	1 ^b									

Dependent Variable: PPH_vessel
Model: (Intercept), Site, Month

- a. Set to zero because this parameter is redundant.
b. Fixed at the displayed value.

Table S3. Summary table of the model effects showing the effect of Site and Month on Positive Presence hours of delphinid signals.

Tests of Model Effects

Source	Wald Chi-Square	Type III	
		df	Sig.
(Intercept)	5.809	1	.016
Site	452.165	2	<.001
Month	39.176	9	<.001

Dependent Variable: PPH_delphinids
Model: (Intercept), Site, Month

Table S4. Summary table of the model parameter estimates showing the effect of Site and Month on Positive Presence hours of delphinid signals.

Parameter Estimates

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test			Exp(B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	Sig.		Lower	Upper
(Intercept)	1.096	.1186	.863	1.328	85.338	1	<.001	2.992	2.371	3.775
[Site=Anchor]	-1.759	.0926	-1.941	-1.578	360.846	1	<.001	.172	.144	.206
[Site=FF02]	-1.540	.0976	-1.731	-1.349	248.976	1	<.001	.214	.177	.260
[Site=FF03]	0 ^a	.	.	.	.	.	.	1	.	.
[Month=April]	-.037	.1738	-.378	.304	.045	1	.832	.964	.686	1.355
[Month=August]	.429	.1546	.126	.732	7.700	1	.006	1.536	1.134	2.080
[Month=December]	-.404	.2182	-.832	.024	3.429	1	.064	.668	.435	1.024
[Month=July]	.341	.1549	.038	.645	4.860	1	.027	1.407	1.039	1.906
[Month=June]	.397	.1696	.065	.730	5.481	1	.019	1.488	1.067	2.074
[Month=March]	.297	.1651	-.026	.621	3.239	1	.072	1.346	.974	1.860
[Month=May]	-.244	.1709	-.579	.091	2.035	1	.154	.784	.561	1.095
[Month=November]	.067	.1624	-.251	.385	.170	1	.680	1.069	.778	1.470
[Month=October]	.188	.1560	-.117	.494	1.458	1	.227	1.207	.889	1.639
[Month=Sept]	0 ^a	.	.	.	.	.	.	1	.	.
(Scale)	1 ^b	.	.	.	.	.	.	.	.	.
(Negative binomial)	1 ^b	.	.	.	.	.	.	.	.	.

Dependent Variable: PPH_delphinids

Model: (Intercept), Site, Month

a. Set to zero because this parameter is redundant.

b. Fixed at the displayed value.

Table S5. Summary table of the model effects showing the effect of Site and Month on Positive Presence hours of humpback whale signals.

Source	Wald Chi-Square	Type III	
		df	Sig.
(Intercept)	158.597	1	<.001
Site	118.303	1	<.001
Month	235.514	9	<.001

Dependent Variable: PPH_HB
Model: (Intercept), Site, Month

Table S6. Summary table of the model parameter estimates showing the effect of Site and Month on Positive Presence hours of humpback whale signals.

Parameter	B	Std. Error	95% Wald Confidence Interval		Hypothesis Test			Exp(B)	95% Wald Confidence Interval for Exp(B)	
			Lower	Upper	Wald Chi-Square	df	Sig.		Lower	Upper
			(Intercept)	-.873	.2270	-1.318	-.428		14.774	1	<.001	.418	.268	.652
[Site=FF02]	-1.862	.1712	-2.198	-1.527	118.303	1	<.001	.155	.111	.217
[Site=FF03]	0 ^a	.	.	.	.	.	.	1	.	.
[Month=April]	.105	.3568	-.594	.804	.086	1	.769	1.111	.552	2.235
[Month=August]	1.218	.2719	.685	1.751	20.053	1	<.001	3.379	1.983	5.759
[Month=December]	-1.603	.6401	-2.857	-.348	6.269	1	.012	.201	.057	.706
[Month=July]	1.188	.2732	.653	1.724	18.914	1	<.001	3.281	1.921	5.605
[Month=June]	2.777	.2869	2.214	3.339	93.633	1	<.001	16.064	9.154	28.190
[Month=March]	-1.707	.6365	-2.954	-.459	7.190	1	.007	.181	.052	.632
[Month=May]	-.286	.3941	-1.059	.486	.527	1	.468	.751	.347	1.626
[Month=November]	.313	.3042	-.283	.910	1.061	1	.303	1.368	.754	2.484
[Month=October]	1.707	.2645	1.188	2.225	41.639	1	<.001	5.511	3.281	9.254
[Month=Sept]	0 ^a	.	.	.	.	.	.	1	.	.
(Scale)	1 ^b									
(Negative binomial)	1 ^b									

Dependent Variable: PPH_HB

Model: (Intercept), Site, Month

a. Set to zero because this parameter is redundant.

b. Fixed at the displayed value.

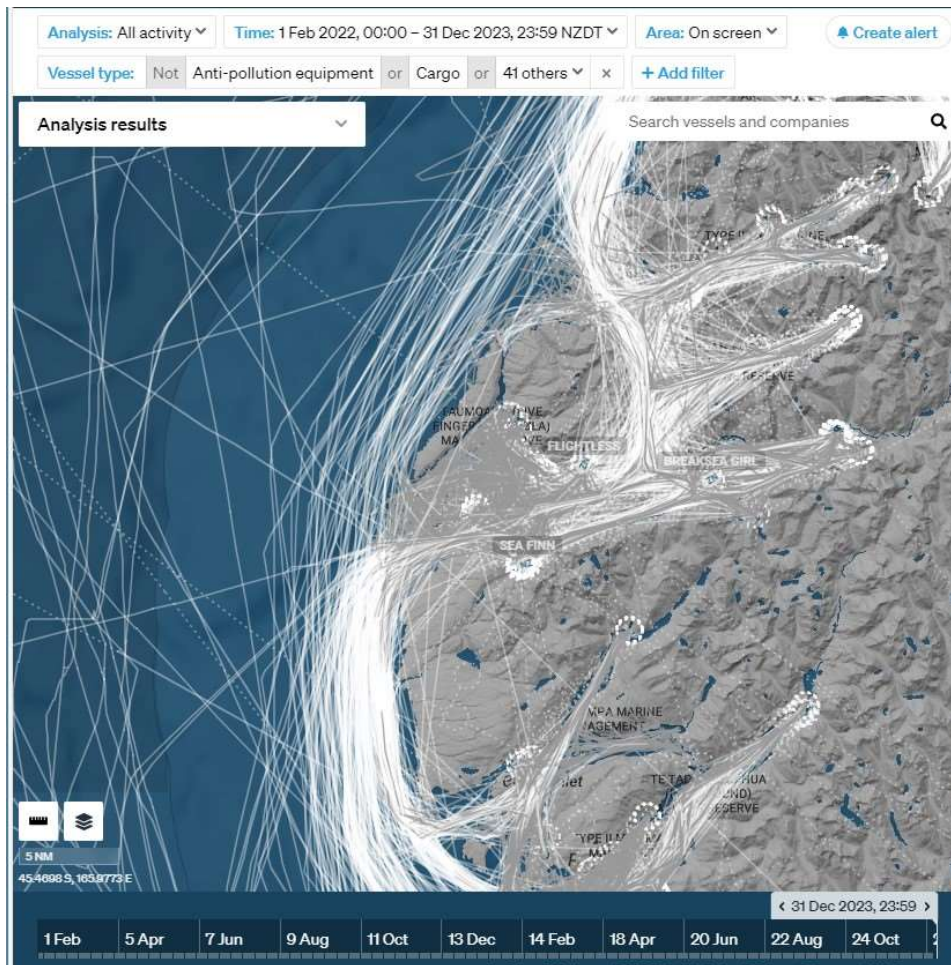


Figure S1. Screenshot of StarBoard AIS Platform illustrating vessel tracks included in the study area from February 2022 – December 2023.