Comparing Polar Ocean Soundscapes

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OCEAN OZA ACOUSTICS

For my family

For Oma Maja – whom I miss dearly

Content

Summary

Soundscapes integrate ecological processes and dynamics, and intact acoustic environments are vital for a myriad of marine species. Anthropogenic (man-made) climate change, biodiversity loss, and pollution cause global ecosystem alterations, including the acoustic environment, which manifests in changing soundscape patterns and dynamics. In contrast to the rest of the globe, sea ice-covered areas of polar oceans are considered to harbour some of the last pristine soundscapes. Nevertheless, climate change, sea ice loss, and shifting species distributions pose a significant threat to the integrity of polar acoustic environments. Additionally, anthropogenic impacts such as fisheries, oil and gas exploration, and noise pollution are expected to increase as these areas become increasingly accessible for human activities due to declining sea ice cover. However, the Arctic and the Southern Ocean are affected differently by climate change and noise pollution. The Arctic is warming three to four times faster than the global average and experiencing unprecedented sea ice loss, leading to a poleward shift in the spatiotemporal distribution of marine mammals. At the same time, anthropogenic activities increase. By contrast, the Southern Ocean soundscape is considered relatively pristine due to its remoteness and still extensive sea ice cover, which limits human accessibility at least seasonally and regionally. Nonetheless, sea ice has been declining regionally in the Southern Ocean over the past decade. Despite these threats to polar ecosystems, baseline information on the contemporary state of polar ocean acoustic environments is largely lacking, or at best, patchy in nature. Therefore, the broader objective of my dissertation is to assess baselines on polar ocean soundscape characteristics and patterns across different spatiotemporal scales to shed light on the contemporary status of the acoustic ecology of both anthropogenically impacted and 'pristine' polar ecosystems.

The technological advances in passive acoustic monitoring over the last two decades have provided researchers with the opportunity to observe and study marine ecosystems across large temporal and geographical scales. It is now possible to analyse soundscape data over years to decades and spanning across ocean basins. The large-scale availability of soundscape data now enables researchers to address questions about the distribution of soniferous species, noise pollution, and the dynamics of the acoustic environment. For example, in the context of large-scale spatiotemporal environmental gradients, climate oscillations, and global ecosystem alterations. However, assessing and comparing soundscape patterns and dynamics more holistically across different spatial and temporal scales to facilitate an understanding of natural variability and to monitor ecological shifts is still a developing field. In my dissertation, I therefore aim to (i) explore acoustic marine mammal community dynamics and (ii) test the suitability of multiple ecoacoustic metrics along with clustering to characterise polar ocean soundscape patterns and their spatiotemporal variability. Thereby, I aim to enable large-scale explorations of cumulative ecological responses to climate change through changes in soundscape patterns.

The background to my dissertation is set out in Chapter 1, along with the specific aims of the dissertation. I introduce the concept of acoustic environments and soundscapes, outline polar ocean soundscapes, briefly summarise the effect of climate change, changes in species

distribution, and noise pollution on the acoustic environment. I then emphasise the importance of large-scale passive acoustic monitoring, and introduce ecoacoustic metrics in this context.

I present the first insights into the year-round acoustic community composition of marine mammals in a lower-latitude Arctic region off Southeast Greenland (Tasiilaq), in conjunction with regional sea-ice conditions, in Chapter 2. I show that the dynamic of the acoustic marine mammal community composition shifts with the seasonal sea ice conditions. The findings of Chapter 2 support the assumption that in polar oceans, acoustic marine mammal turnover dynamics are subject to change due to alterations of sea ice conditions.

Chapter 3 explores the suitability of a set of ecoacoustic metrics to compare and infer cumulative acoustic similarity or dissimilarity within and between two polar ocean soundscapes, which are affected differently by anthropogenic actions. I found that the anthropogenically impacted and year-round sea ice-free eastern Fram Strait lacks a pronounced seasonal pattern due to year-round anthropogenic noise and wind-mediated sounds. By contrast, the seasonal sea ice conditions and the acoustically dominant marine mammals governed the seasonal soundscape patterns of the ‘pristine’ Weddell Sea. The results show that applying multiple ecoacoustic metrics along with clustering can reflect the acoustic state and reveal spatiotemporal variability and similarity within and between different polar ocean soundscapes. Chapter 3 lays the foundation to evaluate polar ocean soundscapes over large spatiotemporal scales, which I present in Chapter 4. Moreover, Chapter 3 presents, to my knowledge, the first ambient sound levels for standardised and recommended frequency bands for the Southern Ocean.

I then investigate a basin-wide soundscape dataset, spanning multiple locations and timeframes across multiple years in Chapter 4. I present an approach to compare multiple soundscapes over large temporal and spatial scales to infer spatiotemporal variability in soundscape patterns. I infer diversity in soundscape patterns and regimes by applying clustering and statistical community composition analysis. The results reveal that spatiotemporal soundscape diversity and regimes in the Weddell Sea are governed by the recording depth, overall water depths, the seasonal sea ice conditions as well as the acoustic ecology of marine mammals. In Chapter 3 and Chapter 4, I suggest that intact polar ocean soundscapes are characterised by pronounced seasonal soundscape dynamics with high complexity and diversity in soundscape patterns. I hypothesise that sea ice loss and the prolongation of the open-water period, along with changes in species spatiotemporal distribution, and increasing anthropogenic activities, might lead to a weakening of the seasonal patterns and increasing homogenisation of Southern Ocean soundscapes.

In Chapter 5, I summarise the main findings of my dissertation by placing them into a broader ecological context. I also discuss the limitations of the study with respect to the ecoacoustic diversity metrics and suggest ways in which the study design could be improved. Finally, I explore potential avenues for future research. This includes the extension of my work on datasets from across the Arctic, increasing monitoring efforts in the Southern Ocean, extending studies by environmental correlates, and applying the established approach to ecosystem management and conservation, and assessing the rate of soundscape change.

1

INTRODUCTION

This chapter first provides a brief introduction to marine acoustic environments and explains the concept of soundscapes and why they are complex. Second, I introduce the soundscapes of the polar oceans and emphasis the most significant biological, abiotic and anthropogenic (man-made) sound sources that contribute to the acoustic environments of the polar oceans. I do this to illustrate the variability and complexity in sound sources and their compositions, which shape soundscape dynamics and the diversity in soundscape patterns of polar oceans. Third, I outline the environmental changes on both polar ecosystems in the context of climate change, biodiversity loss, and pollution – the triple planetary crisis (UNFCCC, 2022) – and how the manifoldness of this crisis affects the acoustic environment. Fourth, I outline ecoacoustic metrics as a methodological approach to study soundscape complexity and spatiotemporal variability in soundscape patterns. Lastly, this chapter concludes with an overview of the aims and structure of the conducted studies within my dissertation.

The acoustic environment in marine systems

In the ocean, sound travels faster (1500 m/s) than in air (343 m/s) and can propagate over large spatial scales. Low-frequency sounds (<100 Hz) can propagate over 1000 km (Jensen *et al.*, 2011), whereas high-frequency sounds are attenuated quickly (Jensen *et al.*, 2011). As visibility is greatly restricted in marine environments, marine species are highly adapted to the acoustic conditions and many of them utilise sound for communication, mating, orientation, and foraging. Thus, in many cases, they are strongly susceptible to anthropogenic noise and changing acoustic environments (Gordon *et al.*, 2018; Duarte *et al.*, 2021). Accordingly, the acoustic environment is considered a fundamental part of marine ecology and the awareness of preserving the integrity of marine acoustic environments has increased in recent years. Studies have demonstrated that marine species heavily rely on intact soundscapes (for an explanation see next section) as a critical information medium for decision making (Gordon *et al.*, 2018; Lillis and Mooney, 2018; Pysanczyn *et al.*, 2023). For example, fish and invertebrate larvae orient towards complex soundscapes of healthy reefs and increase their settlement rate (e.g., Gordon *et al.*, 2018; Lillis and Mooney, 2018; Pysanczyn *et al.*, 2023).

What are soundscapes?

The 'soundscape' is part of the acoustic environment and describes the assemblage of sounds received at a particular time in space and integrates essential ecosystem processes. The soundscape is created by biological and geophysical sounds, as well as anthropogenic noise emitted from organisms (marine mammals, fish, and invertebrates), the abiotic environment (wind-wave interaction, earthquakes, ice), and human activities (ships as well as resource exploration and extraction), respectively (Pijanowski *et al.*, 2011a; Duarte *et al.*, 2021; Erbe *et al.*, 2025a). A general concept is presented in Fig. 1. Sound sources produce different signal types with different sound source levels, peak frequencies, frequency modulation, and duration. This high variability in signal types causes soundscapes to differ in the overall sound intensity (amplitude) and the distribution of the intensity over frequency and time (spectro-temporal complexity; Pijanowski *et al.*, 2011a; Sueur and Farina, 2015; Erbe *et al.*, 2025a). As the various sound sources appear and move along environmental gradients, they create a complex acoustic assembly with high variability across small to large temporal and geographical scales (Pijanowski *et al.*, 2011a). Additionally, dispersion, reverberation, and absorption of the sound as it propagates through the environment, for example, bouncing between the sea surface, sea ice, and the ocean bottom, adds to the spatiotemporal variability of soundscape patterns (Bradfer-Lawrence *et al.*, 2025; Erbe *et al.*, 2025a). Given that the factors that create and influence soundscapes are interconnected, changes in one condition can trigger multiple alterations across various levels, causing changes in soundscape patterns (Fig. 1, arrows; Pijanowski *et al.*, 2011a; Bradfer-Lawrence *et al.*, 2025).

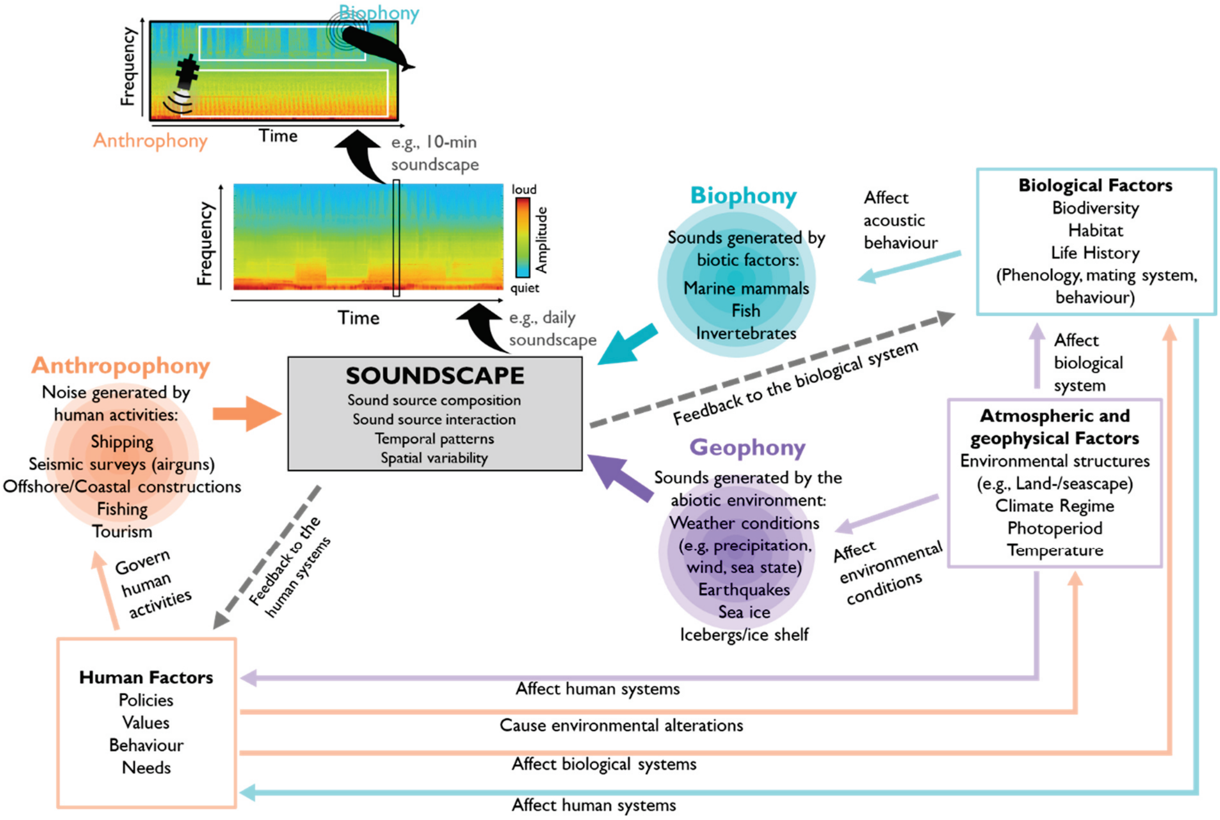

Fig. 1. General concept on the formation of marine soundscapes and the interactions and effects of the underlying factors. The biophony is created by the actively and passively produced sounds from marine species. The geophony summarises all geophonic sounds that are created by the abiotic environment, such as weather patterns, sea state, earthquakes, or ice. The anthropophony summarises man-made noise, noise generated actively or passively by human activities. The biophony and the geophony, in the absence of the anthropophony, form a natural soundscape. The framework is adapted from Pijanowski et al. (2011a). The spectrograms are taken from OPUS (Open Portal to Underwater Soundscapes), Creative Commons CC-BY 4.0 Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research 2025, www.opus.aq, last accessed July 2025.

Polar ocean soundscapes

The polar oceans are of special interest as they are considered to be least affected by anthropogenic noise pollution on a global scale (Fig. 1.2; Halpern *et al.*, 2008; Haver *et al.*, 2017; Duarte *et al.*, 2021; Jalkanen *et al.*, 2022) and the sea ice covered areas are assumed to comprise the last 'pristine' acoustic environments (PAME, 2019; Halliday, 2021). However, both polar oceans are experiencing highly different levels of climate change (Arias *et al.*, 2023) and noise pollution (Haver *et al.*, 2017; Jalkanen *et al.*, 2022). Several sea ice-free Arctic Ocean areas, such as most of the Nordic Seas and around the Svalbard Archipelago, are already strongly affected by year-round anthropogenic noise as sea ice declines (Stocker *et al.*, 2020; Jalkanen *et al.*, 2022; Heaney *et al.*, 2024). In contrast, in the Southern Ocean the anthropogenic activities are restricted to certain areas and times (Haver *et al.*, 2017; Erbe *et al.*, 2019; Jalkanen *et al.*, 2022). Therefore, in this dissertation, the soundscapes of the Southern Ocean are considered as a reference for a relatively ‘pristine’ acoustic environment. In contrast, the soundscape of the Arctic Ocean serves as a reference for an acoustic environment that is already strongly impacted by anthropogenic activities. Studying soundscapes using a bi-polar approach provides the opportunity to better understand natural and disturbed polar ocean soundscape patterns and dynamics. Moreover, it provides insights into possible future changes which the Southern Ocean acoustic environment might experience in the light of the triple planetary crisis. In my dissertation, I am focusing on polar ocean areas of the Atlantic sector (Fig. 1., black boxes).

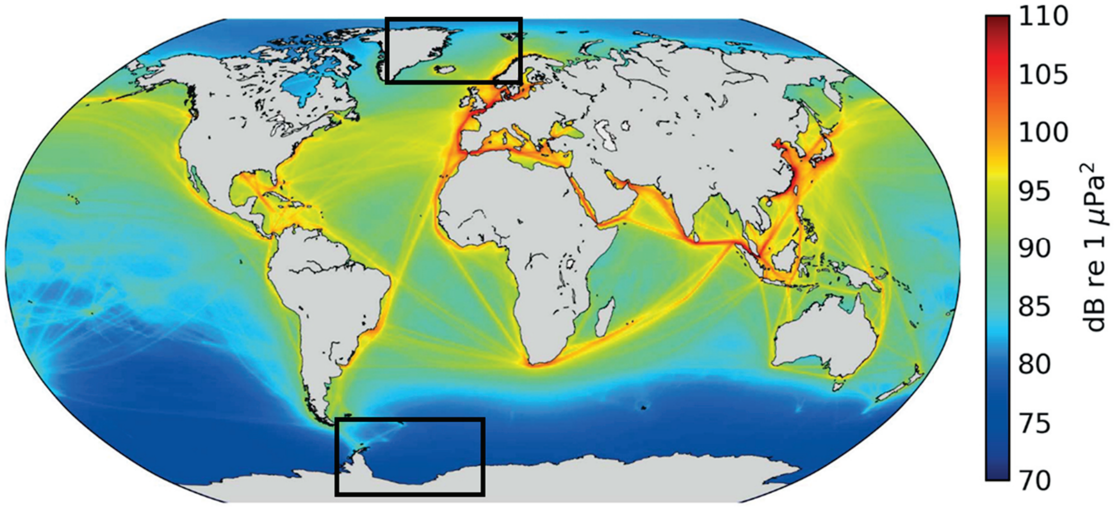

Fig. 2. “Average sound level estimated globally from marine traffic (at 100 Hz), based on average shipping activity measured from automatic identification system (AIS) data for 2014.” Figure taken from Duarte *et al.* (2021). Reprinted with permission from AAAS”. Modified by the black boxes that indicate the areas of interest in my dissertation.

Polar ocean soundscape characteristics and components

One characteristic of polar ocean soundscapes is the seasonal variability in soundscape characteristics driven by the annual cycle of sea ice cover, wind-mediated sounds, the acoustic behaviour of marine mammals but also due to seasonal fluctuation in anthropogenic activity (e.g., Haver *et al.*, 2017; Menze *et al.*, 2017; Ladegaard *et al.*, 2021; Yun *et al.*, 2021Ahonen, 2017 #1396). Nevertheless, in the absence of anthropogenic noise, natural polar ocean soundscapes, of the Arctic and Southern Ocean, are characterised predominantly by marine mammal vocalisations, ice, and wind-mediated sounds (e.g., Dziak *et al.*, 2015; Menze *et al.*, 2017; Halliday *et al.*, 2020; Mo *et al.*, 2023). Fig. 3 and Fig. 4 provide an example of polar ocean soundscapes. The following sub-sections outline the dominant sound sources of the bio-, geo-, and anthropophony of both polar oceans in more in detail.

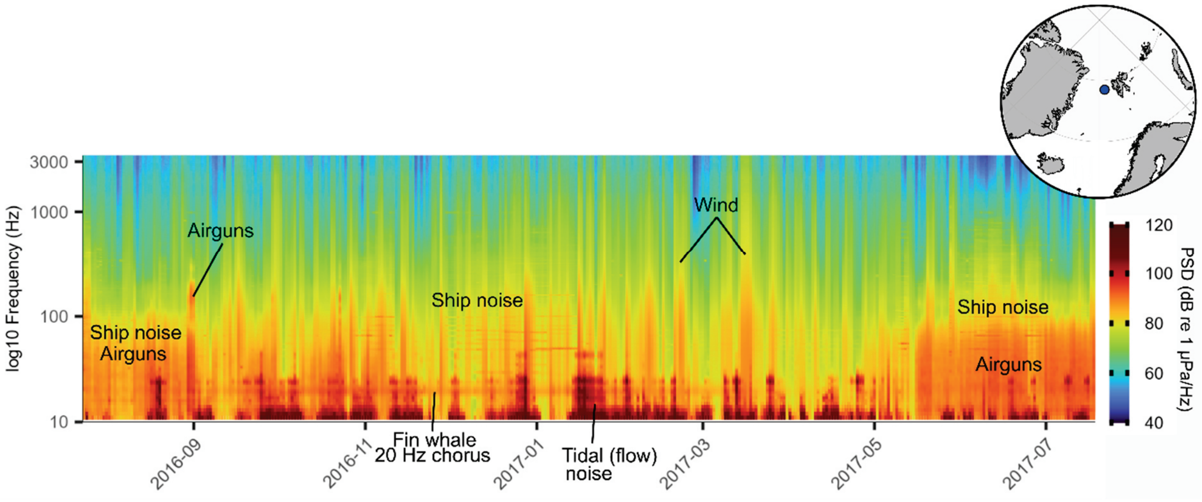

Fig. 3. Long-term spectral average (daily mean) of an example of a soundscape of the eastern Fram Strait (data available from Thomisch et al. (2023a) which is sea ice-free year-round. Due to the absence of seasonal sea ice cover the seasonal variability is less pronounced and mainly governed by the seasonal increase of anthropogenic activity. Parts of the soundscape shown here are utilised in Chapter 3.

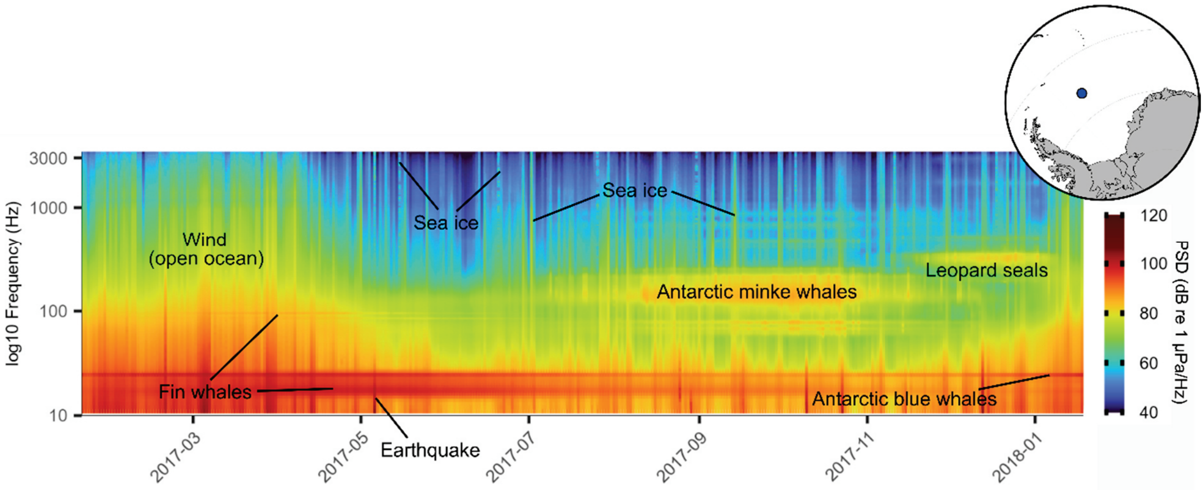

Fig. 4. Long-term spectral average (daily mean) of an example of a soundscape of the Weddell Sea (data available from Thomisch et al. (2023b) with seasonal sea ice cover governing the seasonality in ambient sound levels. Additionally, visible are the species-specific soundscape patterns of the acoustically dominant (chorus forming) marine mammal species. Parts of the soundscape shown here are utilised in Chapter 3.

Polar ocean biophony:

While information on acoustic signatures of fish and invertebrates in polar oceans is sparsely known, vocalisations of cetaceans and phocids are the best studied and most dominant biophonic component of polar ocean soundscapes (Van Opzeeland and Hillebrand, 2020). In terms of overall marine mammal biodiversity, the waters around Greenland provide habitats for 22 species of pinnipeds and cetaceans, including eight endemic and pagophilic (ice-associated) species (Ugarte et al., 2020). Around the Svalbard Archipelago and in the Greenland Sea, ten cetacean species, four phocids, and walruses are visually observed (Vacquié-Garcia *et al.*, 2017; Storrie *et al.*, 2018; Hamilton *et al.*, 2021; Bengtsson *et al.*, 2022). The overall marine mammal biodiversity around Antarctica spans 21 species: six pinnipeds and 15 cetaceans (Lowther, 2018). Of these, four phocids and one baleen whale species are endemic to the Antarctic pack ice and marginal sea ice zone, respectively (Lowther, 2018).

Not all of these species contribute equally to the soundscape. Some marine mammal species extensively vocalise throughout the breeding season to attract mates or defend underwater territories, or both (e.g, Croll *et al.*, 2002; Van Parijs and Clark, 2006; Van Opzeeland *et al.*, 2010; Stafford *et al.*, 2012), whereas other species exhibit a more cryptic, lower, or clustered vocal behaviour (e.g, Madsen *et al.*, 2002; Moors and Terhune, 2004; Deecke *et al.*, 2005; Ahonen *et al.*, 2019). The extensive vocalising of many individuals of the same species at the same time, for example during the mating season, causes a phenomenon called chorusing. Chorusing can locally and seasonally increase sound levels in species-specific frequency bands, contributing to seasonal soundscape patterns in the Arctic Ocean (Fig. 3; e.g., Ahonen *et al.*, 2017; Llobet *et al.*, 2023) and in the Southern Ocean (Fig. 4; e.g., Menze *et al.*, 2017; Yun *et al.*, 2021).

In the sea-ice free areas and periods in the Fram Strait and Greenland Sea, fin whales (Table 1) are known to produce such chorusing bands from late summer to spring (Fig. 3; e.g., Klinck *et al.*, 2012; Ahonen *et al.*, 2017; Haver *et al.*, 2017). Other species that contribute to biophonic patterns in the sea ice-free areas and periods are blue, sperm, and sei whales (e.g., Klinck *et al.*, 2012; Nieukirk *et al.*, 2020; Ahonen *et al.*, 2021; Meister *et al.*, 2024; Pöyhönen *et al.*, 2024) as well as humpback whales and delphinids (e.g., De Vreese *et al.*, 2018; Ladegaard *et al.*, 2021; Llobet *et al.*, 2023). In sea ice-covered areas and during winter and spring, bowhead whale songs can regionally increase ambient sound levels* (Ahonen *et al.*, 2017). Moreover, bearded seals, narwals, belugas and walruses can regionally contribute to the sea ice covered biophony (e.g., Llobet *et al.*, 2023).

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* In my dissertation, instead of 'ambient noise' I am using the term 'ambient sound' which I define as all sounds except for acoustic self-noise to refer to broadband sound pressure levels because there is no specified signal of interest in this dissertation. I am using the term 'noise' specifically when referring to (identified) non-natural sounds, such as from anthropogenic activities. With this, I would like to stress the negative connotation associated with the word 'noise' and its classification as environmental pollution. However, this distinction was not applied in chapter 2 – there I use 'ambient noise' to refer to broadband sound pressure levels.

Table 1.1. Marine mammal species mentioned in the introduction and corresponding Latin names

Systematic	**Common name**	**Latin name**
Cetaceans		
Mysticetes		
Balaena	Bowhead whale	*Balaena mysticetus*
Rorquals	Antarctic blue whale	*Balaenoptera musculus intermedia*
	Antarctic minke whale	*Balaenoptera bonaerensis*
	Blue whale	*Balaenoptera musculus*
	Fin whale	*Balaenoptera physalus*
	Humpback whale	*Megaptera novaeangliae*
	Minke whale	*Balaenoptera acutorostrata*
	Sei whale	*Balaenoptera borealis*
	Southern Right whale	*Eubalaena australis*
Odontocetes	Sperm whale	*Physeter macrocephalus*
Monodontidae	Beluga	*Delphinapterus leucas*
	Narwhal	*Monodon monoceros*
Delphinidae	Killer whale	*Orcinus orca*
Pinnipedia		
Phocids	Bearded seal	*Erignathus barbatus*
	Crabeater seal	*Ommatophoca rossii*
	Leopard seal	*Hydrurga leptonyx*
	Ross seal	*Lobodon carcinophaga*
	Weddell seal	*Leptonychotes weddellii*

In the Southern Ocean, the austral summer biophony is acoustically dominated by fin whales and Antarctic blue whale choruses (Fig. 4; Menze *et al.*, 2017; Burkhardt *et al.*, 2021; Yun *et al.*, 2021). Moreover, in the sea-ice covered months, pagophilic phocids, such as leopard and crabeater seals, and the Antarctic minke whale are known to produce intense choruses (Fig. 4; Menze *et al.*, 2017; Yun *et al.*, 2021). Additionally, to the acoustically dominant marine mammals, there are vocalisations of Weddell and Ross seals as well as humpback, sperm, right, and killer whales, which can regionally and seasonally contribute to the biophony and ambient sound levels of the Southern Ocean (e.g., Boebel, 2017; Van Opzeeland and Hillebrand, 2020; Giorli and Pinkerton, 2023; Wöhle *et al.*, 2023). Moreover, the acoustic marine mammal diversity is highest before sea ice breakup (Van Opzeeland and Hillebrand, 2020).

The low-frequency (<100 Hz) and very loud (~189 dB re 1 µPa) vocalisations of fin and (Antarctic) blue whales are estimated to be able to propagate over large distances (from approximately 55 to over 200 km, depending on the bathymetry; Širović *et al.*, 2007; Ahonen *et al.*, 2021). Thus, low frequency vocalisations can acoustically connect environments across large spatial scales. By contrast, the vocalisations of phocids, sperm, bowhead, and Antarctic minke whales are estimated to transmit over much shorter ranges (from 6 to 40 km;Terhune and Ronald, 1986; Cleator and Stirling, 1990; Madsen *et al.*, 2002; Bonnel *et al.*, 2014; Filun *et al.*, 2020), characterising soundscapes on a more local scale.

Polar ocean geophony:

Wind-mediated and ice-generated sounds are the main geophonic components of polar soundscapes (Fig. 3 and Fig. 4). Wind-mediated sound includes sounds generated from breaking waves and shear on the water surface, is broadband and increases sound levels particularly between 300-500 Hz, depending on the sea state (Fig. 5; Erbe *et al.*, 2025a). The sea ice cover fundamentally shapes the seasonality of polar ocean soundscapes, with high ambient sound levels in summer and low ambient sound levels in winter (Fig. 4). Sea ice cover can uncouple the effect of wind-mediated sounds on the soundscape, as it blocks the wind from the sea surface (e.g., Menze *et al.*, 2017; Mo *et al.*, 2023). Open water sound levels have been reported to be on average up to 20 dB re 1 µPa louder than during sea ice-covered conditions (Ahonen *et al.*, 2017; Menze *et al.*, 2017; Ladegaard *et al.*, 2021). Ice (sea ice, icebergs, ice shelfs, and tidewater glaciers) produces a great variety of loud sounds when it is under thermal stress, disintegrating and unstable, moving and drifting, and colliding, calving, or grounding (e.g., Boebel *et al.*, 2008; Matsumoto *et al.*, 2014; Wilcock *et al.*, 2014; Dziak *et al.*, 2015; Mo *et al.*, 2023). These ice-generated sounds can increase ambient sound levels during sea ice-covered conditions and cause ambient sound levels which can be 20 dB louder than average quiet open water ambient sound levels (Urick, 1984; Wilcock *et al.*, 2014; Dziak *et al.*, 2015; Ladegaard *et al.*, 2021; Mo *et al.*, 2023). In the Southern Ocean, sounds generated from icebergs and ice shelfs are prominent characteristics of the austral summer soundscape (Boebel *et al.*, 2008; Matsumoto *et al.*, 2014; Dziak *et al.*, 2015). In contrast, in the Arctic Ocean, the sounds of icebergs are concentrated in fjords and along coasts, where tidewater glaciers terminate and icebergs calve and drift along (e.g., Podolskiy and Sugiyama, 2020). Lastly, natural seismic activities, such as earthquakes, contribute mainly to the lower frequencies (Fig. 4 and Fig. 5; Erbe *et al.*, 2025a).

Polar ocean anthropophony:

Even though the polar oceans are considered to have low anthropogenic activity in contrast to the global average, this does not mean they are entirely free from anthropogenic noise (Duarte *et al.*, 2021; Jalkanen *et al.*, 2022). Commercial fishery and shipping, tourism, and seismic explorations for oil and gas form the main anthropogenic activities in the sea ice-free polar oceans. The Arctic Ocean soundscape, and particularly the Nordic Seas, are experiencing higher anthropogenic activity than the Southern Ocean (Lancaster *et al.*, 2021; Jalkanen *et al.*, 2022; Heaney *et al.*, 2024). Besides ship noise, low-frequency impulsive noise from towed seismic airgun surveys is a prominent contribution to the summer soundscape of the Arctic Ocean (Fig. 3; Klinck *et al.*, 2012; Ahonen *et al.*, 2017; Haver *et al.*, 2017).

In contrast, the Southern Ocean experiences the least number of anthropogenic activities on a global scale and is considered one of the last relatively pristine areas due to its remoteness and extensive seasonal sea ice cover (Halpern *et al.*, 2008; Jalkanen *et al.*, 2022). These anthropogenic activities in the Southern Ocean include krill fishery (Savoca *et al.*, 2024) and tourism (Senigaglia *et al.*, 2025), but also research (Breitzke, 2014; Erbe *et al.*, 2019). However, these activities are concentrated towards the sea ice-free summer months and the Antarctic Peninsula. This temporal and spatial concentration can cause regionalised high-impact pressure on local Antarctic ecosystems.

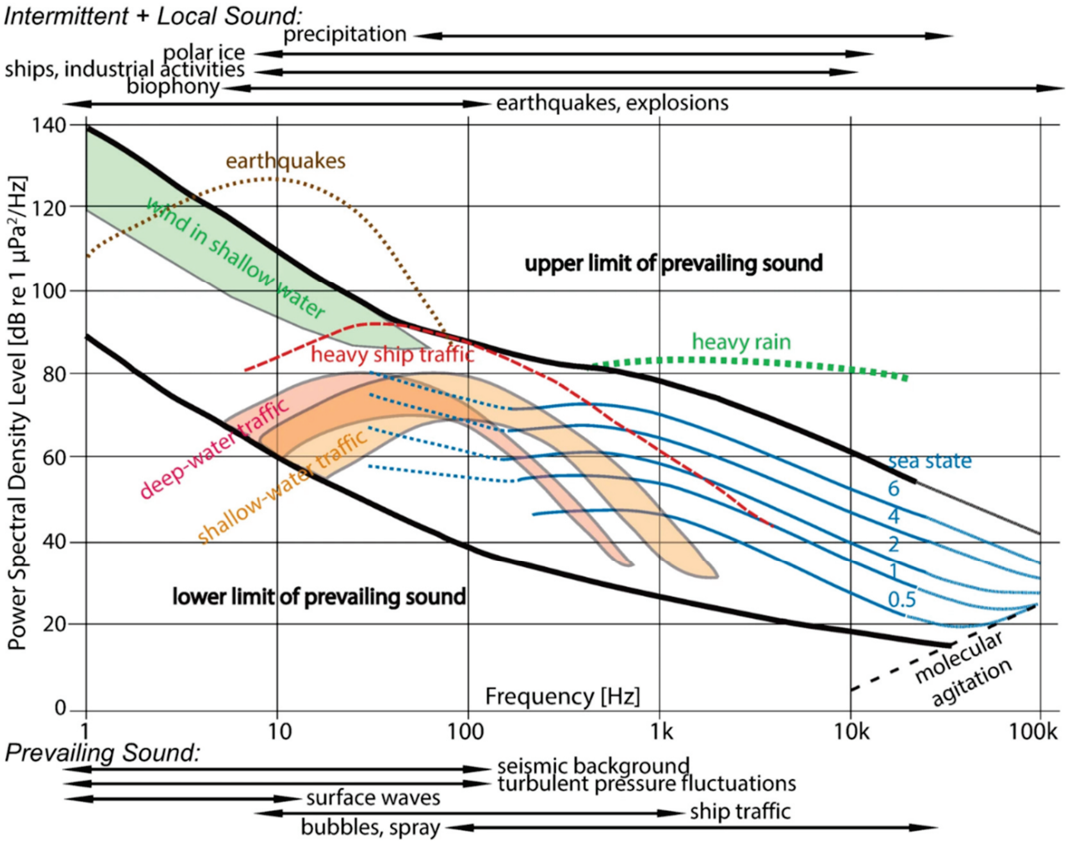

Fig. 5. "Generalised ocean ambient sound spectrum. Spectra of prevailing and local underwater sound sources between 1 Hz and 100 kHz, drawn after Wenz (1962) and Cato (2008)". Figure taken from Erbe et al. (2025a), Creative Commons CC BY 4.0.

The following figures (Fig. 6 to Fig. 9) provide a summary and overview of the dominant sound sources characterising the soundscapes and display a glimpse into the soundscape variability created by the interplay of multiple sound sources in the Arctic Ocean (Fig. 6 and Fig. 7) and in the Southern Ocean (Fig. 8 and Fig. 9).

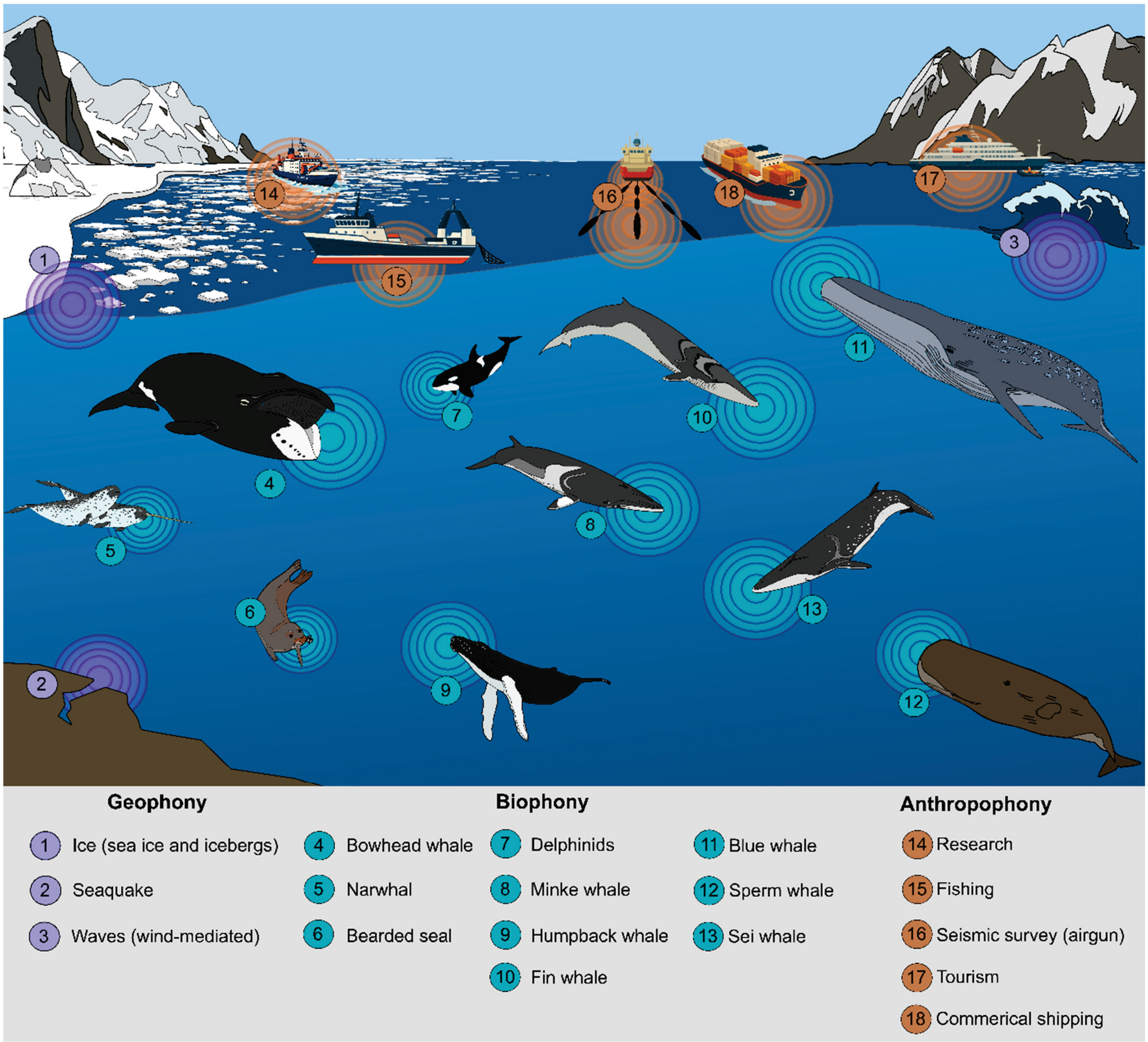

Fig. 6. Common sound sources of the soundscape of the Greenland Sea and Fram Strait, Arctic Ocean. This schematic shows some of the cetacean and one phocid species which are regularly acoustically detected in the Atlantic Sector of the Arctic (e.g., Klinck et al., 2012; Ahonen et al., 2021; Ladegaard et al., 2021; Llobet et al., 2021; Llobet et al., 2023; Meister et al., 2024; Pöyhönen et al., 2024). Moreover, the Greenland Sea and Fram Strait already experiences increased anthropogenic presence, particularly in the sea ice free areas. See Tab. 1 for scientific Latin names. The author of this dissertation designed the graphic. The ship icons were generated with OpenAI's ChatGPT-4o (version July 2025).

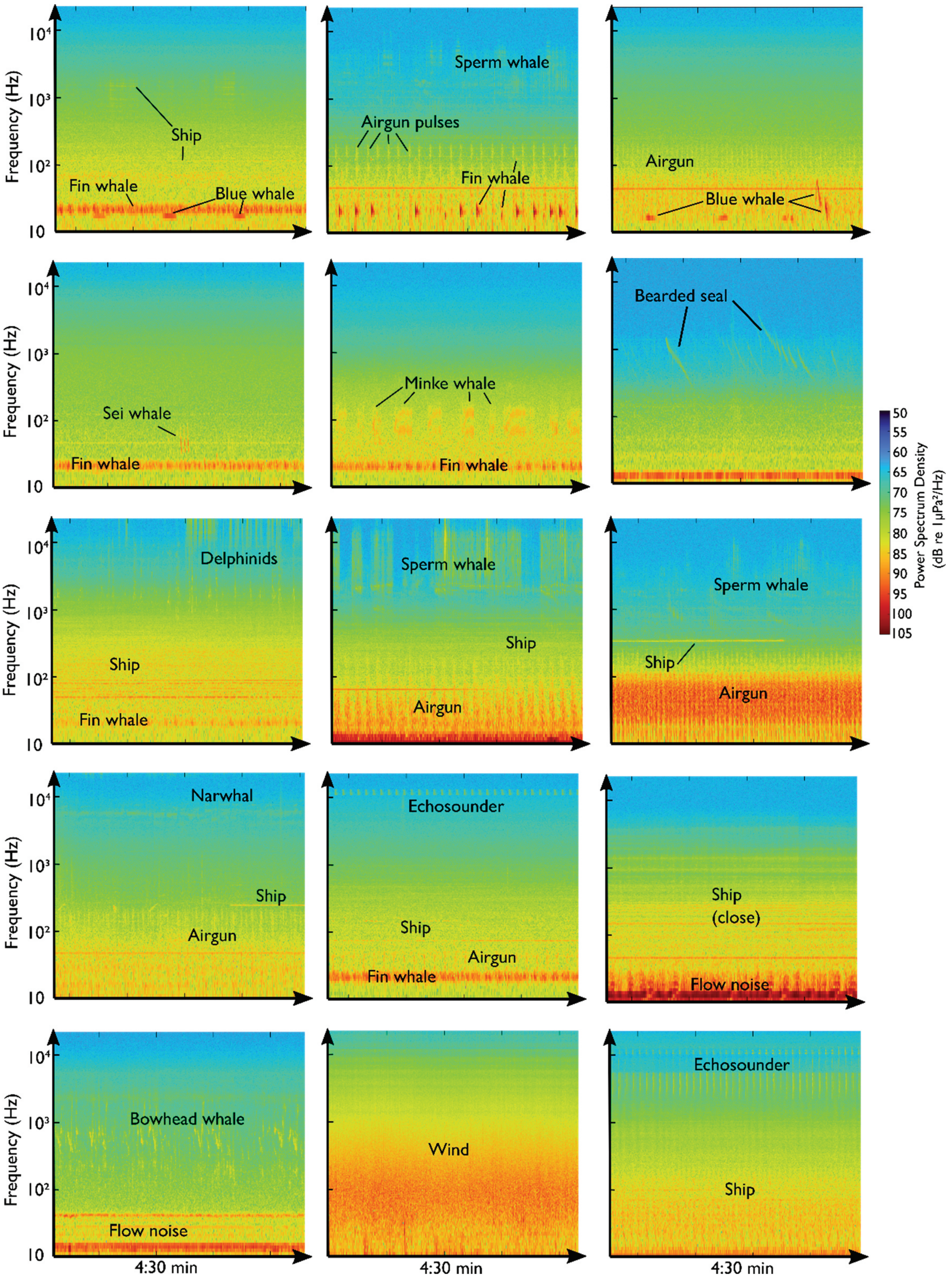

Fig. 7. Examples of soundscape variability found in the Fram Strait, Arctic Ocean. These example spectrograms indicate the variability in ambient sound levels but also show the spectro-temporal complexity created by the various sound source compositions. The y-axis shows the log10 frequency in Hz. All spectrograms show a time snippet of 4:30 minutes. Spectrograms taken and modified from OPUS (Open Portal to Underwater Soundscapes), Creative Commons CC-BY 4.0 Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research 2025, www.opus.aq, last accessed July 2025.

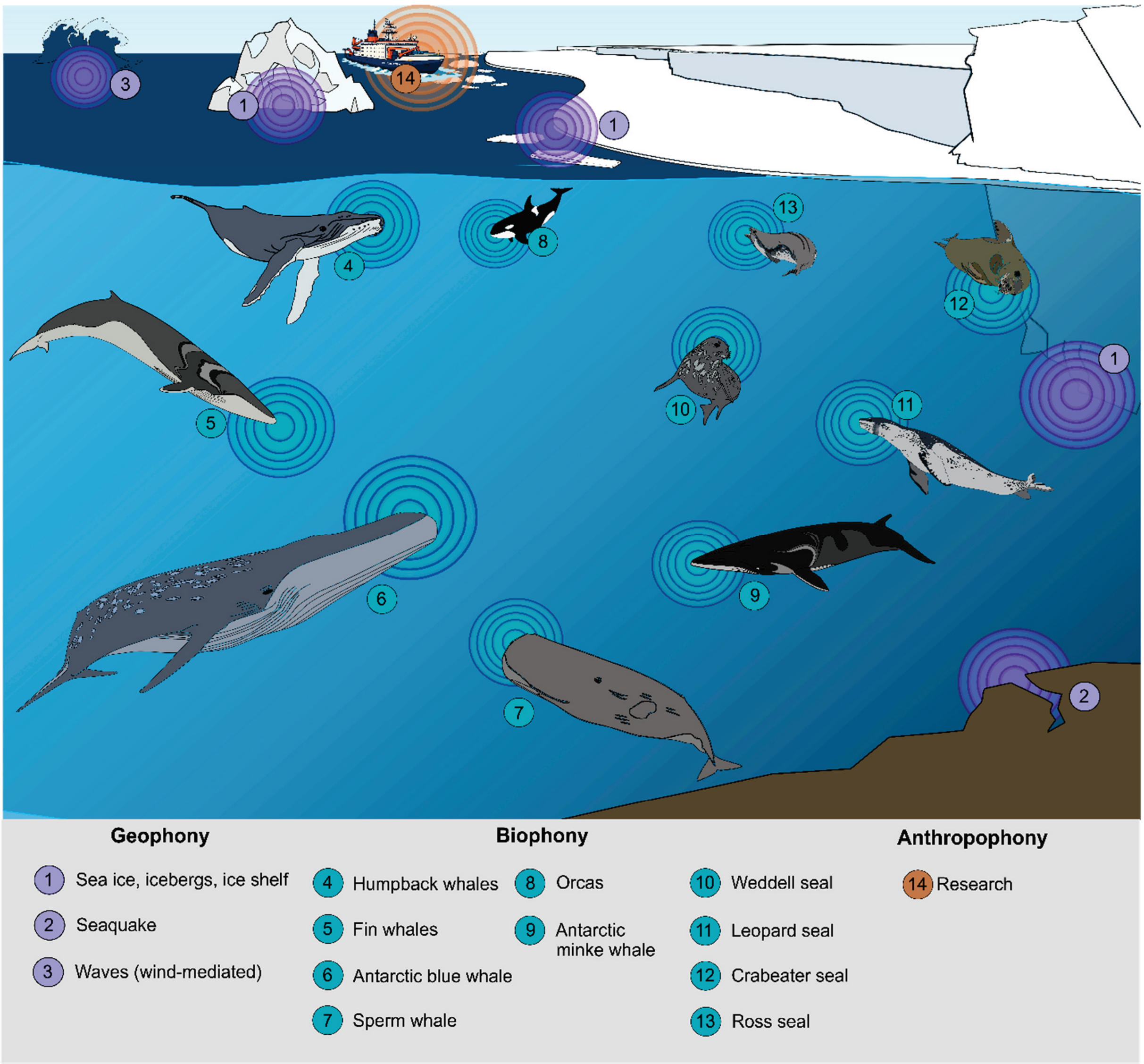

Fig. 8. Common and dominant sound sources characterising offshore soundscape of the Southern Ocean. This scheme shows some of the cetacean and one phocid species which are regularly acoustically detected in the Weddell Sea basin, Atlantic Sector of the Southern Ocean (Boebel, 2017; Van Opzeeland and Hillebrand, 2020). See Tab. 1 for scientific Latin names. Most of the Weddell Sea basin is free from anthropogenic activity, besides research activities, which are, limited to the summer months. The author of this dissertation designed the graphic. The ship icon was AI-generated with OpenAI's ChatGPT-4o (version July 2025).

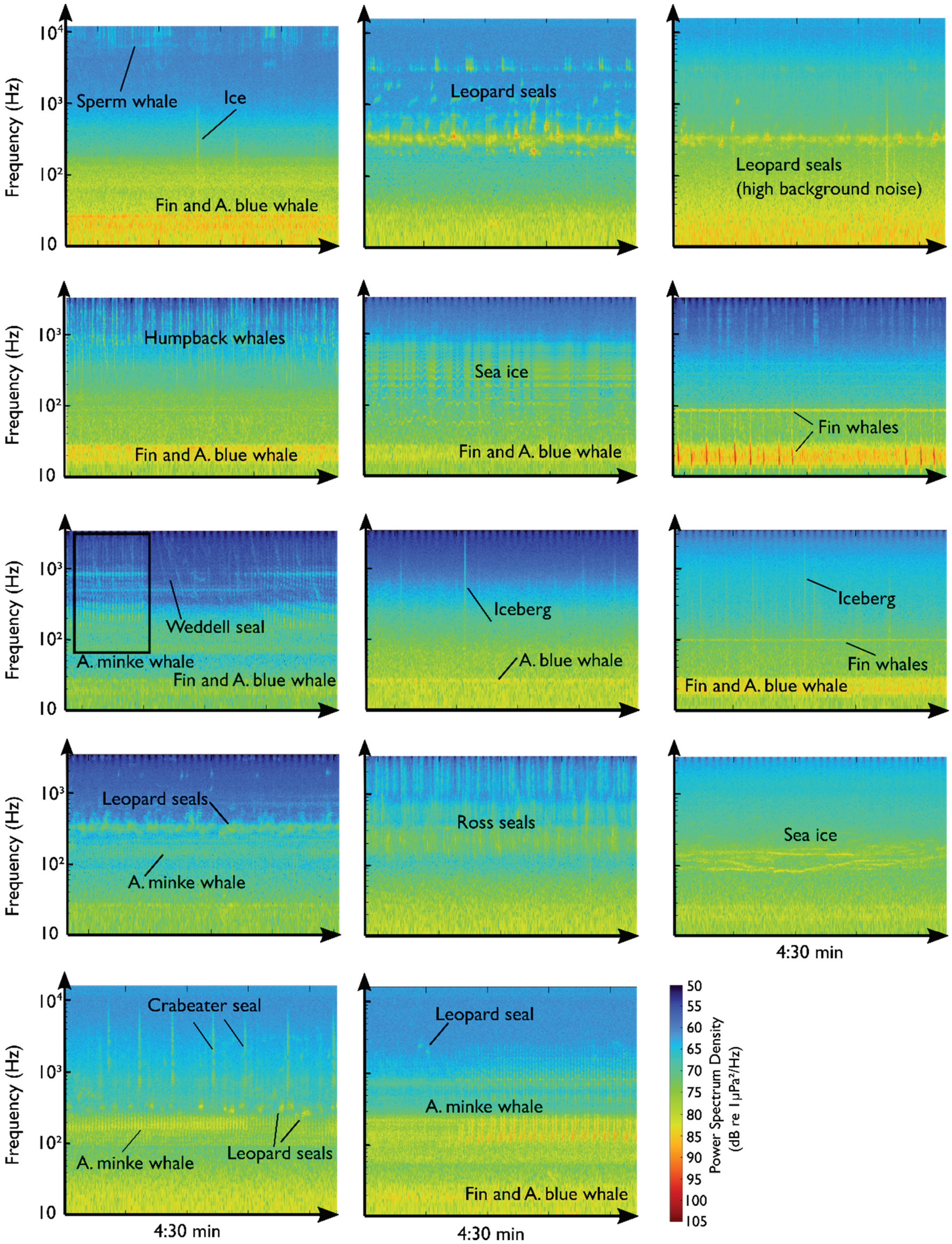

Fig. 9. Examples of soundscape variability found in the Weddell Sea, Southern Ocean. These example spectrograms indicate the variability in ambient sound levels but also show the spectro-temporal complexity created by the various sound source compositions. The y-axis shows the log10 frequency in Hz. All spectrograms show a time snippet of 4:30 minutes. Spectrograms taken and modified from OPUS (Open Portal to Underwater Soundscapes), Creative Commons CC-BY 4.0 Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research 2025, www.opus.aq, last accessed July 2025

The triple planetary crisis – ecological changes and consequences on soundscapes

The triple planetary crisis (UNFCCC, 2022) – climate change, biodiversity loss, and pollution – is irreversibly altering ecosystems around the world (Arias *et al.*, 2023; Hodapp *et al.*, 2023; Hatje *et al.*, 2024). Over the period of 2003 to 2013, 59% of our oceans experienced an increased pace of change due to increasing cumulative anthropogenic impacts (Halpern *et al.*, 2019). It is anticipated that cumulative impact levels on marine habitats double or might even triple by the middle of the 21st century (Halpern *et al.*, 2025). Thereby, the poles and coastal areas are among the regions anticipated to experience the most significant anthropogenic impacts in the future (Halpern *et al.*, 2025). As the triple planetary crisis irreversibly alters environments, the marine acoustic environment is subject to alterations and shifts, providing an acoustic perspective of ecosystem changes in the Anthropocene* (Rossi *et al.*, 2017; Duarte *et al.*, 2021).

A brief overview of ecological changes in polar oceans

Arctic Ocean: The Arctic is warming at an alarming rate, three to four times faster than the global average since 1979 (Rantanen *et al.*, 2022; Zhou *et al.*, 2024), which is discussed under the term 'Arctic Amplification' (Serreze and Barry, 2011; Wendisch *et al.*, 2023). The Arctic Ocean is expected to become virtually sea ice-free during summer by 2050 or even as early as in the current century (Jahn *et al.*, 2024). Additionally, the Arctic Ocean experiences Atlantification, the transition of Arctic waters to resemble Atlantic waters more closely (Ingvaldsen *et al.*, 2021; de Steur *et al.*, 2023), and drastic sea ice loss with severe ecological consequences (Stroeve and Notz, 2018; Serreze and Meier, 2019). Improved light conditions in the ocean as sea ice becomes thinner and vanishes cause an earlier increase in primary production (Lannuzel *et al.*, 2020; Ingvaldsen *et al.*, 2021). Moreover, borealization, the expansion of temperate and sub-Arctic species into higher latitude Arctic Ocean areas in response to warming waters, affects Arctic food webs (Polyakov *et al.*, 2020; Ingvaldsen *et al.*, 2021). The expansion of marine mammals further north has been observed for several temperate and sub-Arctic cetaceans (e.g., Ramp *et al.*, 2015; Storrie *et al.*, 2018; Moore *et al.*, 2019; Davis *et al.*, 2020; Bengtsson *et al.*, 2022). Additionally, changes in their timing of migration and overwintering at high latitude feeding grounds, likely following changes in prey distribution and increased food availability at higher latitudes, have also been recorded (e.g., Ramp *et al.*, 2015; Storrie *et al.*, 2018; Moore *et al.*, 2019; Davis *et al.*, 2020; Bengtsson *et al.*, 2022). By contrast, endemic marine mammals face accumulating challenges: habitat decline, changes in the food web, increased predation pressure, increased competition for resources, parasites and

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* In the Earth-system sciences, the Anthropocene denotes the epoch, since the mid-twentieth century, in which the Earth system is fundamentally altered by human actions (see Lewis *et al.*, 2015; Zalasiewicz *et al.*, 2024).

diseases (Kovacs *et al.*, 2011; Laidre *et al.*, 2015). This might cause distributional changes, range reductions, and population decline of pagophilic marine mammals of the Arctic Ocean (Laidre *et al.*, 2015).

Southern Ocean: Since the 1980s, the sea ice extent in the Southern Ocean has experienced a modest increase, peaking in 2012 and 2014. However, concerns arise that the Southern Ocean is experiencing rapid ecosystem change due to a rapid decline in sea ice extent and one record minimum following another since 2016 (Eayrs *et al.*, 2021; Raphael *et al.*, 2025). Regionally, the sea ice extent decreased by 80%, including the Weddell Sea and the Antarctic Peninsula (Eayrs *et al.*, 2021; Josey *et al.*, 2024; Raphael *et al.*, 2025). Such a fast-paced decline in sea ice cover can have severe biological impacts on Southern Ocean food-web structures that are highly dependent on the annual cycle of the sea ice. The biomass of pelagic algae, copepods, krill and fish is considered to decrease due to increasing temperatures and reduced sea ice duration (Swadling *et al.*, 2023). Specifically, the range and the biomass of Antarctic krill (*Euphausia superba*), the primary food sources of various marine mammals in the Southern Ocean, are declining and retracting poleward as a result of ocean warming and changes in sea ice dynamics (Kawaguchi *et al.*, 2023). Such shifts in prey resources can affect the recovery of whale populations (Kawaguchi *et al.*, 2023). Moreover, it is hypothesised that phocids may fail to respond to rapid drops in sea ice cover and that regularly occurring sudden drops will affect breeding phenology and might force phocids out of their breeding area (Roca *et al.*, 2023). Overall, the response of phocids to climate change will be highly species- but also region-specific, governed by prey distribution or depletion and competition with other higher trophic predators (Wege *et al.*, 2021a; Wege *et al.*, 2021b). Furthermore, humpback whales are assumed to respond to large-scale climate oscillations in the Southern Ocean such as ‘El Niño’ with changes in their distribution patterns following shifts in krill and sea ice distribution (Schall *et al.*, 2021). In addition, humpback whales off Australia have advanced their southbound migration by three weeks, likely in response to sea ice loss at their Antarctic feeding grounds (Dunlop *et al.*, 2025).

Soundscape alterations due to the triple planetary crisis

As soundscapes integrate ecological processes, the large-scale interference of humans with nature has caused significant structural changes to our planet's soundscapes, in both terrestrial and aquatic environments (Sueur *et al.*, 2019). Structural changes in the marine soundscapes are a consequence of cumulative effects of human impacts causing alterations in propagation ranges, ambient sound levels, degradations of environments, and the overall spectro-temporal assembly of sound types over regional to synoptic scales (Fig. 10). Because the factors that create and influence soundscapes act together rather than in isolation, a change in one condition can trigger multiple alterations across different levels, affecting various elements that shape the soundscape (see also again Fig. 1). For example, habitat degradation has been found to decrease the complexity of marine soundscapes along with changes in ambient noise levels due to regime shifts in environmental conditions and bioacoustic community composition (Rossi *et al.*, 2017; Gordon *et al.*, 2018). The following subsections will outline some possible changes in polar oceans in more detail.

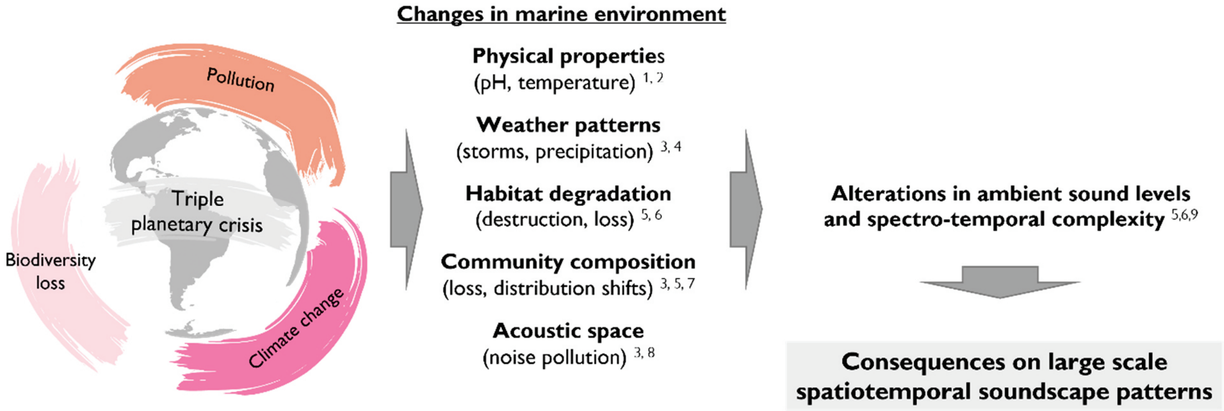


Fig. 10. Summary of changes in the environment caused by the triple planetary crisis that result in changes in the spectro-temporal complexity and ambient sound levels of the soundscape and consequently causes changes in large scale soundscape patterns. Example references indicated in the figure: (1) e.g., Ilyina et al. (2009), (2) e.g., Affatati et al. (2022), (3) e.g., Duarte et al. (2021), (4) e.g., Warren et al. (2021), (5) e.g., Rossi et al. (2017), (6) e.g., Gordon et al. (2018), (7) e.g., Davis et al. (2020), (8) e.g., Clark et al. (2009), (9) e.g., Sueur et al. (2019).

Changes in physical properties – pH and temperature: Changes in sound transmission are forecasted as a consequence of increased CO_2 emissions and global warming altering pH and temperature conditions (Ilyina *et al.*, 2009; Affatati *et al.*, 2022). Ocean acidification is expected to decrease transmission loss for sounds between ~100 Hz and ~10 kHz, particularly in high-latitude regions and in areas of deep-water formation, with the potential to increase the propagation range of anthropogenic noise (Ilyina *et al.*, 2009). Moreover, the Arctic Ocean, particularly the Greenland Sea, is considered one of the 'acoustic hotspots' (Affatati *et al.*, 2022), where variations of sound speed greater than 1.5% are expected by the end of the century due to increased ocean temperatures (Affatati *et al.*, 2022). It is assumed that this will increase the propagation range for low-frequency baleen whale calls and improve the communication among conspecifics (Affatati *et al.*, 2022). This also means that low-frequency anthropogenic noise propagates faster as ocean temperatures rise (Affatati *et al.*, 2022) increasing the potential of masking biological signals. Increased sound transmission, particularly of lower-frequency signals might cause a higher similarity of soundscapes across larger scales as they become increasingly acoustically connected.

Habitat degradation – shifts in sea ice conditions: In polar areas, shifts in ice regimes, such as towards younger, thinner, and more dynamic sea ice (Eayrs *et al.*, 2021; Sumata *et al.*, 2022; Gorodetskaya *et al.*, 2023) are expected to increase ambient sound levels, due to increased ice-generated sounds (Matsumoto *et al.*, 2014; Mo *et al.*, 2023). Additionally, due to increased sea ice loss, wind stress and wave height are considered to increase (Vavrus and Alkama, 2022; Casas-Prat *et al.*, 2024). Therefore, a prolonged open water period can cause increasing ambient sound levels, as the uncoupling effect of sea ice on wind-mediated sounds is lost (Matsumoto *et al.*, 2014; Halliday, 2021; Mo *et al.*, 2023). Lastly, an increase in the volume of small icebergs is expected in the Southern Ocean, which can cause an increase in ambient sound levels (Matsumoto *et al.*, 2014).

Shift in community composition: Changes in the distribution and behaviour of marine life in response to anthropogenic pressures are expected to have significant repercussions on spatiotemporal soundscape patterns (Rossi *et al.*, 2017; Gordon *et al.*, 2018; Sueur *et al.*, 2019; Duarte *et al.*, 2021). For example, the acoustic presence of seasonal migrating baleen whales in the Fram Strait, Arctic Ocean, has been recorded to shift further north and can be detected even through winter months as a result of sea ice loss (e.g., Nieukirk *et al.*, 2020; Meister *et al.*, 2024 Ahonen, 2017 #1396). In the Southern Ocean, specifically in the Weddell Sea, climate-related oscillations and changes in sea ice extent have been shown to drive basin-wide marine mammal acoustic distribution patterns (Schall *et al.*, 2021; Roca *et al.*, 2023). Changes in the acoustic marine mammal community dynamics in the polar ocean due to changes in species distribution and timing of migration have the potential to change soundscape patterns across various temporal and spatial scales. Furthermore, considering that marine mammals are a fundamental part of polar ocean soundscapes, commercial whaling must have severely altered the acoustic environment.

Noise pollution: The industrialisation of the ocean, especially the rise in commercial shipping, has led to a doubling of low-frequency (<150 Hz) ambient sound levels in the Northeast Pacific throughout the 20th century (McDonald *et al.*, 2006). Noise emissions from shipping are predicted to double every approximately 10-12 years, corresponding to a noise increase of above 3 dB per decade on a global scale and every three years in the Arctic Ocean (McDonald *et al.*, 2006; Jalkanen *et al.*, 2022). As the noise emissions in the Arctic Ocean are still relatively low, a doubling of shipping noise emissions can rather easily increase noise levels (Jalkanen *et al.*, 2022). Modelling of ship noise indicates an increase of noise levels between 5-20 dB re 1 μPa from 2013 to 2019 across the Arctic Ocean (Heaney *et al.*, 2024). Moreover, the opening of the Arctic will allow for transpolar shipping routes (Bennett *et al.*, 2020). Although the Southern Ocean is considered to be one of the last relatively pristine areas, fishing and touristic activities have nevertheless increased and will continue to increase sharply over recent and coming years, particularly along the Antarctic Peninsula (Savoca *et al.*, 2024; Senigaglia *et al.*, 2025; Trathan *et al.*, 2025). Ship and airgun noise can cause a variety of disturbances in marine mammals and their prey, including behavioural changes, masking of acoustic communication due to alterations of acoustic space, displacement, as well as health impacts and death (Clark *et al.*, 2009; McCauley *et al.*, 2017; Southall *et al.*, 2019a; Southall *et al.*, 2019b; Duarte *et al.*, 2021; Southall *et al.*, 2021; Vereide *et al.*, 2024). Such noise impacts on marine mammals can cause local to large scale repercussions on soundscape patterns as biophonic activity is lost or disperses.

The need for small to large-scale soundscape assessments and comparisons

As ecosystems shift and noise pollution increases, regional to large-scale soundscape monitoring and comparisons become crucial for understanding ecological processes, for example, to maintain acoustic connectivity across habitats (Van Parijs *et al.*, 2009; Flowers *et al.*, 2021; Napier *et al.*, 2024). Additionally, soundscape comparisons can inform marine management and stakeholders to improve protection of species and areas by identifying habitat importance, changes in distribution patterns, ecosystem shifts or degradation, and identify areas more or less strongly affected by noise (e.g., Van Parijs *et al.*, 2009; Radford *et al.*, 2014; Bittencourt *et al.*, 2020; Davis *et al.*, 2020; Ladegaard *et al.*, 2021).

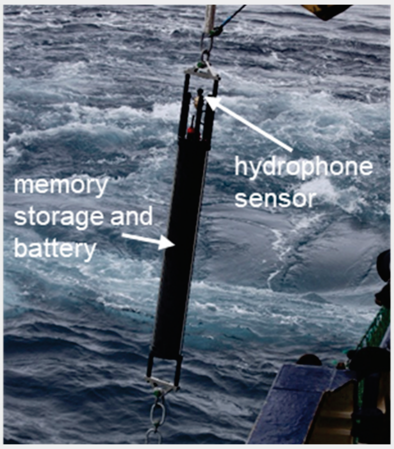
In the past soundscape investigations and comparisons were confined to a limited number of sites and shorter time scales as a result of affordability and accessibility of the available technology at that time, as well as logistical constrains in data sampling (Van Parijs *et al.*, 2009; Havlik *et al.*, 2022). Today, passive acoustic monitoring (PAM; BOX 1) is globally established as the technology of choice to monitor marine ecosystems (e.g., Havlik *et al.*, 2022; Tyack *et al.*, 2023; Darras *et al.*, 2025), ship noise (e.g., Haver *et al.*, 2021), biodiversity (e.g., Mooney *et al.*, 2020), and marine mammal ecology (e.g., Van Parijs *et al.*, 2009; Davis *et al.*, 2020). The nowadays numerous globally distributed PAM platforms (see Tyack *et al.*, 2023; Darras *et al.*, 2025), which have extensively collected soundscape data over the last two decades, present novel opportunities. It provides the means of soundscape analysis over large temporal and geographical scales, from local to synoptic (>2000 km) scales as well as from years to over decades. The extensive amount of collected PAM data provides the foundation to investigate natural soundscape dynamics in the context of large-scale environmental conditions, such as seasonal sea ice conditions and climate oscillations, as well as to understand large-scale changes driven by the triple planetary crisis.

In recent years, soundscape assessments across large temporal or spatial scales, or both have revealed climate-driven changes in marine mammal diversity (Van Opzeeland and Hillebrand, 2020) and distributional patterns (e.g., Davis *et al.*, 2020; Schall *et al.*, 2021; Roca *et al.*, 2023), enhancing our understating of both natural and anthropogenic caused variability of ecosystems. Studies at the regional scale are also relevant as indicator studies that can initiate large-scale investigations and monitoring efforts. For example, Roca *et al.* (2023) and Ahonen *et al.* (2021), using single and sparse recording locations, show climate-driven responses to sea ice loss in marine mammals. Davis *et al.* (2020) show, using multiple recording stations across the North Atlantic and over one decade, that the acoustic baleen whale distribution mirrors climatic shifts. Van Opzeeland and Hillebrand

(2020) used multiple recording stations and years spanning across the Weddell Sea basin, and show that acoustic marine mammal diversity strongly reflects seasonal patterns in sea ice conditions. Just recently, ZoBell *et al.* (2025), using recordings spanning over one decade and multiple recording sites across the Southern California Bight, show that soundscapes patterns correlate with large-scale oceanographic fluctuations and climatic patterns, as well as with economic factors.

BOX 1. - Passive acoustic monitoring (PAM)

PAM can provide long-term data on the ocean sonic context, producing a uniquely holistic and detailed picture of the underwater sound compositions. PAM is a remote-sensing, autonomous, cost-effective, non-invasive, easy-to-operate, and low-maintenance technology, which can record the soundscape over long periods (over multiple years). In remote offshore and polar areas, visual surveys are challenging to conduct due to their remoteness and seasonal restrictions caused by harsh weather conditions, sea ice cover, and polar nights. Therefore, PAM is an ideal tool to study vocally but visually elusive and cryptic species, such as pagophilic or endangered marine mammals also during sea ice cover and dark winter month (e.g., Filun et al., 2020; Thomisch et al., 2022), as well as providing insights into the polar ocean acoustic environments (e.g., Ahonen et al., 2017; Menze et al., 2017). BOX-Fig. 1 shows the deployment of a recording device used for PAM in the Weddell Sea.



BOX-Fig. 1 PAM device being deployed. Photo courtesy: Ocean Acoustics Group, Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research.

Despite the observed global ecological changes as well as technological and methodological advances, the diversity and dynamics in marine mammal community compositions and soundscape patterns in polar regions across varying spatial and temporal scales are still poorly understood and baseline levels are long overdue.

The primary focus of studying ecosystem changes in the Arctic is often concentrated towards higher latitude areas, such as the Svalbard Archipelago and Fram Strait, whereas lower latitude Artic areas are often neglected. However, lower-latitude Arctic areas may serve as sentinel areas for future ecosystem alterations in higher Arctic regions, as they are the first to experience warming, sea ice loss, and regime shifts. For example, increased sea ice decline off the coast of Southeast Greenland and warming water temperatures have already led to shifts in species composition, including increasing boreal summer abundance of humpback and fin whales (e.g., Jansen *et al.*, 2016; Hansen *et al.*, 2018; Heide-Jørgensen *et al.*, 2023). Nevertheless, knowledge about the year-round marine mammal community compositions of lower-latitude Arctic areas off Greenland is long missing. The cumulative response of the marine mammal community to seasonal dynamics of sea ice cover is poorly understood. Such information, however, is crucial to better understand shifts in migration patterns and distribution in response to climate change and sea ice loss, as well as to infer the contemporary status of the ecosystem. Moreover, studying (acoustic) species presence, distribution patterns, or migration of marine mammals in response to sea ice conditions, climate change, or climate oscillations often only take a single species (e.g., Thomisch *et al.*, 2016; Boye *et al.*, 2020; Schall *et al.*, 2021) or a specific group of species into consideration, for example just phocids (e.g., Roca *et al.*, 2023) or just baleen whales (e.g., Davis *et al.*, 2020). Studying sentinel species, such as marine mammals (Moore, 2008; Moore and Kuletz, 2019), as part of a community can enable the assessment of combined responses to environmental disturbances (Van Opzeeland and Hillebrand, 2020). Therefore, investigating holistic acoustic marine mammal community dynamics might foster the interpretation of responses to natural seasonal cycles and consequently in the context of ongoing environmental alterations (Van Opzeeland and Hillebrand, 2020). In the Weddell Sea, such an approach has shown a strong link between the seasonal acoustic marine mammal diversity and the seasonal cycle of sea ice conditions, indicating complete species turnover twice a year (Van Opzeeland and Hillebrand, 2020). However, such an assessment has so far been missing for the Arctic.

In the Southern Ocean, baseline information on ambient sound levels is scarce, limited to a few sites and years (e.g., Matsumoto *et al.*, 2014; Dziak *et al.*, 2015; Haver *et al.*, 2017; Menze *et al.*, 2017; Yun *et al.*, 2021). The assessment of baseline ambient sound levels in the Southern Ocean over large scales is crucial as anthropogenic noise is likely to increase, as fisheries and tourism are expanding (Savoca *et al.*, 2024; Senigaglia *et al.*, 2025). Similarly, ambient sound levels are lacking for several areas across the Arctic (Halliday, 2021). Given the increase in anthropogenic activities and the effects of climate change in the Arctic, it is important to monitor lower latitude Arctic areas as well as the Gateways to the central Arctic Ocean, e.g., the Fram Strait, to improve monitoring noise pollution across the Arctic.

Ambient sound levels, however, do not adequately reflect spectro-temporal soundscape complexity and thereby ignore the underlying soundscape structure created by the sound source composition. Soundscape complexity is considered an essential part in the decision-making process of marine species (Holles *et al.*, 2013; Gordon *et al.*, 2018; Lillis and Mooney, 2018). Hence, characterising marine soundscapes based simply on ambient sound levels limits the perspective on the acoustic environment (McKenna *et al.*, 2021). Assessing spectro-temporal complexity would provide additional information on the spatiotemporal variability in soundscape patterns (Bradfer-Lawrence *et al.*, 2025). To my knowledge, large-scale studies that integrate spectro-temporal soundscape complexity in their assessment of holistic soundscape variability are absent for polar regions.

Approaches to assess and compare holistic soundscape patterns and their spatiotemporal variability

Often, soundscapes are manually (visually and aurally) analysed. While manual scanning the soundscape for sound types or sound sources (e.g., for acoustic marine mammal presence) is often done for biodiversity assessments or sound source identification. Yet it can become tedious and time-consuming, limiting the comprehensiveness of studies to shorter temporal and smaller spatial scales. With the growing amount of available PAM data, holistic soundscape characterisation using traditional soundscape analysis methods is becoming increasingly challenging analytically (Roca and Van Opzeeland, 2019; Flowers *et al.*, 2021; Ladegaard *et al.*, 2021; Sethi *et al.*, 2023). Thus, approaches that quantify holistic soundscape patterns on a spatiotemporally coarser but scalable spatiotemporal resolution are needed to characterise large-scale structural variability and shifts in ecosystems acoustically (Sethi *et al.*, 2023). In this context, ecoacoustic metrics are discussed (see Sethi *et al.*, 2023; Bradfer-Lawrence *et al.*, 2025).

Ecoacoustic metrics

'Ecoacoustic metric' is an overarching term that summarizes specific mathematical functions that quantify acoustic information into single values and thereby report on acoustic properties, such as amplitude or the spectro-temporal variability in intensity distribution (complexity). To date, there are more than 60 different ecoacoustic metrics available (e.g., Buxton *et al.*, 2018; Pieretti and Danovaro, 2020; Minello *et al.*, 2021; Bradfer-Lawrence *et al.*, 2024). Ecoacoustic metrics can be categorised into two main groups: (i) **ecoacoustic intensity metrics**, which quantify the signal amplitude from the pressure waveform and provide information on how loud soundscapes are, and (ii) **ecoacoustic diversity metrics**, which quantify the spectro-temporal variability in intensity distribution, providing information on the spectro-temporal complexity of the soundscape.

i) Ecoacoustic intensity metrics to characterise ambient sound levels

Ocean ambient sound is fundamentally important to ocean acoustics, impacting a wide range of disciplines, including the performance of military technology, ocean exploration, and, most importantly, affecting animal behaviour and ecosystem structures (Wenz, 1962; Southall *et al.*, 2021; Deane, 2025). Assessing the ocean ambient sound levels is a standard method in ocean acoustics. It provide baselines for how loud oceans are, to monitor shipping noise, and to communicate impacts of anthropogenic activities on animals and ocean ecosystems to governments (MSFD, 2017; Southall *et al.*, 2021; Merchant *et al.*, 2022; Tyack *et al.*, 2023). Often sound levels are used to measure biological activity, for example of marine mammals or other marine species that form choruses (Menze *et al.*, 2017; McKenna *et al.*, 2021). Particularly, blue and fin whale acoustic presence is often derived from seasonal variations of sound levels measurements in specified narrow frequency bands, as these species are known to increase sound levels with their chorusing (e.g., Klinck *et al.*, 2012; Haver *et al.*, 2017; Menze *et al.*, 2017; Burkhardt *et al.*, 2021). In the Southern Ocean, leopard and crabeater seals as well as Antarctic minke whale chorusing, can also be measured through sound levels (Menze *et al.*, 2017; Yun *et al.*, 2021).

Ocean ambient sound is planned to be included in the Global Ocean Observing System as an 'essential ocean variable' and the International Quiet Ocean Experiment was established as an international scientific program to foster global ocean soundscape research (Tyack *et al.*, 2023). The International Quiet Ocean Experiment aims to provide recommendations on how ocean sound observations should be collected, analysed, managed, and reported (Tyack *et al.*, 2023). The primary goals of measuring underwater sound levels are to observe climate change, weather patterns, ocean health (ecosystem change and biodiversity loss), and to monitor direct threats (earthquakes/tsunamis, naval and military operations; Tyack *et al.*, 2023). Reporting ambient sound levels is also included in the European Union Marine Strategy Framework Directive (MSFD) in Descriptor 11: "Introduction of Energy, including underwater noise, is at levels that do not adversely affect the marine environment" (MSFD, 2017; Merchant *et al.*, 2022). This framework has been implemented for European waters but is also increasingly applied globally to report ambient sound levels in a standardised and comparable manner (e.g., Ainslie *et al.*, 2021; Haver *et al.*, 2021; Warren *et al.*, 2021). The measurement of sound pressure level (SPL, unit: dB re 1 µPa) for specified frequency bands is one of the most ubiquitous metrics used to characterise ambient sound levels (e.g., Merchant *et al.*, 2015; MSFD, 2017; Merchant *et al.*, 2022). The International Quiet Ocean Experiment recommends reporting ambient sound levels as sound pressure level measured across 1/3-octave level (TOL) bands (one tenth of a decade, therefore sometimes also referred to as decidecade band) and across 1 minute (Tyack *et al.*, 2023). Moreover, the MSFD precisely mentions measuring the sound pressure level within the TOL bands centred at 63 Hz and 125 Hz, which are considered to monitor shipping noise (Descriptor 11.2: continuous noise, (MSFD, 2017)). Besides these two specified bands, the TOL bands centred at 250 Hz and 500 Hz are also recommended to monitor broadband shipping noise (Merchant *et al.*, 2014; Merchant *et al.*, 2016).

However, marine mammals do not obey governmental regulations, and their vocalisations might interfere regionally with the intended purpose of the bands recommended by the MSFD. Notably, the vocalisation range of baleen whales spans these recommended TOL bands (see Erbe *et al.*, 2017; Van Opzeeland and Boebel, 2018; Southall *et al.*, 2019b; Duarte *et al.*, 2021). Particularly in coastal areas, Merchant *et al.* (2016) showed that the lower bands can be influenced by flow noise and might inadequately reflect the risk of acoustic masking through anthropogenic noise. Thus, it is imperative to acknowledge the soundscape context in this matter, as incorrect interpretation can affect the status classification of an ecosystem as 'noise-impacted' or 'natural'. Therefore, before applying these bands and considering them to reflect global anthropogenic noise, these bands should be tested regionally to determine if they truly reflect anthropogenic noise. The recommended bands to report ambient sound levels in the context of global shipping noise have previously been applied on the Atlantic Sector of the Arctic (e.g., Ahonen *et al.*, 2017; Ladegaard *et al.*, 2021), but they have not yet been applied to Southern Ocean soundscapes. Thus, to monitor global changes in noise pollution the assessment of baseline levels for the Southern Ocean is urgently required. Moreover, the question arises whether these recommended bands are actually suitable to indicate anthropogenic noise in the Southern Ocean or if they rather reflect marine mammal vocal activity or geophony.

ii) Ecoacoustic diversity metrics to characterise spectro-temporal soundscape complexity

Ecoacoustic diversity metrics were developed for terrestrial systems. Furthermore, they are based on the assumption that biophonic complexity increases with acoustic species richness due to an increased number of call types and amplitude-modulation within the species-specific acoustic space which will increase soundscape complexity (Boelman *et al.*, 2007; Sueur *et al.*, 2008; Pieretti *et al.*, 2011; Bradfer-Lawrence *et al.*, 2020; Alcocer *et al.*, 2022). In particular, ecoacoustic diversity metrics are developed based on the acoustic niche hypothesis (Krause, 1993; Sueur and Farina, 2015). This hypothesis suggests that species within the same environment adjust their calling across the frequency, time, and amplitude domain to avoid signal interference with other species or ambient sound by specialising to communicate in their species-specific acoustic space (Krause, 1993; Sueur and Farina, 2015). Indications for the support of the hypothesis are discussed for marine mammals (Mossbridge *et al.*, 1999; Van Opzeeland and Boebel, 2018; Erbe *et al.*, 2025b).

Over the last decade, ecoacoustic metrics have been increasingly applied for biodiversity assessments. However, they have shown variable success in assessing acoustic biodiversity from real-world soundscape data sets of terrestrial and marine environments, and have been highly debated ever since (Pieretti *et al.*, 2011; Mooney *et al.*, 2020; Mammides *et al.*, 2021; Llusia, 2024; Sugai and Costa-Pereira, 2025). One challenge using ecoacoustic diversity metrics for biodiversity metrics is the right interpretation of the values. The ecoacoustic diversity metrics are highly sensitive to changes in the signal-to-noise ratios (Alcocer *et al.*, 2022; Chen *et al.*, 2023). One issue thereby is the presence of environmental sounds and anthropogenic noise in real-world data sets (Depraetere *et al.*, 2012; Parks *et al.*, 2014; Towsey *et al.*, 2014; Dimoff *et al.*, 2021; Chen *et al.*, 2023). These continuous and broadband sounds can cause masking of acoustic biological activity, which interferes with the metrics' intended purpose to indicate biophonic activity. Particularly in the marine environment, the anthropophony often overlaps with the biophony, for example, with low-frequency baleen whale or fish vocalisations confounding acoustic biodiversity assessments (Parks *et al.*, 2014; Bolgan *et al.*, 2018; Duarte *et al.*, 2021; Ferguson *et al.*, 2023).

Changes in biophonic activity can additionally cause controversy in the interpretation of metrics, as the relationship of the metrics to call type and call abundance is not always straightforward and might also vary among the applied metrics, as shown for sounds of snapping shrimps and fish (Bohnenstiehl *et al.*, 2018; Bolgan *et al.*, 2018; Dimoff *et al.*, 2021; Mammides *et al.*, 2021). Consequently, species diversity might not equal acoustic richness, as the acoustic biophonic assemblage can be governed by the abundance of call types, variation in call rate, by species abundance and dominance, as well as the animal's distance to the recorder (Bolgan *et al.*, 2018). For example, fish chorusing can decrease temporal variability due to a decreased signal-to-noise ratios as single calls cannot be distinguished anymore, but might also increase spectral variability as energy becomes concentrated in species-specific frequency bands (Siddagangaiah *et al.*, 2019). Thus, caution should be taken when applying ecoacoustic diversity metrics on real-world aquatic soundscapes as they are far from being a proxy for rapid biodiversity assessments (Alcocer *et al.*, 2022). Therefore, it is recommended to ground-truth each study to understand what kind of soundscape patterns the metrics reflect (Bolgan *et al.*, 2018; Alcocer *et al.*, 2022; Bradfer-Lawrence *et al.*, 2023).

The various causes of changes in the signal-to-noise ratio can be problematic for biodiversity assessments. However, it can also become an important piece of information to capture holistic spatiotemporal dynamics in soundscape complexity and infer cumulative changes affecting the whole acoustic environment. Therefore, the variation in signal-to-noise ratios resulting from variability in wind and seasonal sea ice conditions and changes in the duration of open water conditions is as relevant as changes in the soundscape due to anthropogenic noise or biophony. The overall variability of the daily, seasonal or annual complexity of the soundscape can thus provide additional information on the variability in soundscape patterns created by all components of the soundscape. Besides the broad application of the ecoacoustic diversity metrics in acoustic biodiversity assessments, they have already been discussed at an early stage of their development to infer variability in landscape structures through variability in soundscapes (Pijanowski *et al.*, 2011a; Pijanowski *et al.*, 2011b; Villanueva-Rivera *et al.*, 2011; Sueur and Farina, 2015). Moreover, it has been argued that these metrics might be able to characterise acoustic variability and shifts across large temporal and spatial scales, provided that PAM data is becoming available that spans multiple areas and extended time frames (Pijanowski *et al.*, 2011a; Pijanowski *et al.*, 2011b; Villanueva-Rivera *et al.*, 2011) – which is nowadays the case. Unlike with ambient sound levels, there is currently no official recommendation on which of the many ecoacoustic diversity metrics should be used to infer or report soundscape complexity. Therefore, the question arises which ecoacoustic diversity metrics are suitable for quantifying soundscape patterns over broad spatial and temporal scales more holistically, particularly for polar oceans.

Multi-metric approaches to identify spatiotemporal variability of holistic soundscape patterns

Single-metric applications are not recommended to assess acoustic biodiversity or holistic soundscape patterns, as different metrics have different sensitivities toward specific sound types (Bradfer-Lawrence *et al.*, 2023). However, the application of several ecoacoustic metric simultaneously is considered to best explain variation in soundscape patterns across varying spatial and temporal scales (Bradfer-Lawrence *et al.*, 2019; Alcocer *et al.*, 2022; Bradfer-Lawrence *et al.*, 2023). Such multi-metric approaches have been shown to be valuable to assess acoustic biodiversity of avian (Towsey *et al.*, 2014) and marine mammal communities in the Southern Ocean (Roca and Van Opzeeland, 2019; Roca *et al.*, 2023) but also to differentiate between habitat types (e.g., Bradfer-Lawrence *et al.*, 2019; Roca and Van Opzeeland, 2019; Flowers *et al.*, 2021). For instance, (Bradfer-Lawrence *et al.*, 2019) could reveal variation in dial patterns across different terrestrial habitat types. Moreover, Flowers *et al.* (2021) demonstrated that clustering of multiple ecoacoustic metrics derived from terrestrial soundscapes can reveal unexpected similarities between otherwise ecologically different environments. In marine systems, such an approach could discriminate between various marine ecosystems, such as between healthy and degraded reefs (Williams *et al.*, 2022), deep-sea versus coastal reefs (Wilford *et al.*, 2023), and between noise polluted and less polluted areas (Bittencourt *et al.*, 2020). Lastly, Roca and Van Opzeeland (2019) showed that a multi-metric approach in combination with clustering indicates differences between on-shelf and pelagic Southern Ocean soundscapes. However, the primary focus of their study was to assess acoustic marine mammal community structures between habitats. Therefore, they did not consider whether the ecoacoustic metrics can indicate seasonal soundscape patterns or variability in temporal patterns across different polar habitats. Furthermore, they did not consider the variability of soundscapes due to environmental sounds or anthropogenic noise and how this would affect holistic spatiotemporal soundscape patterns. Consequently, this dissertation aims to determine whether multiple ecoacoustic metrics in combination with clustering can capture and explain the spatiotemporal variability of soundscapes in polar oceans and highlight similarity and dissimilarity in soundscape characteristics across basin scales.

Outline of this dissertation

In my dissertation I investigate polar ocean soundscapes across different spatial and temporal scales to shed light on the contemporary status of the variability in soundscape characteristics of polar oceans in the Anthropocene. Furthermore, I aim to provide baselines on soundscape patterns and properties to facilitate future comparisons in light of the triple planetary crisis. Therefore, I also explore different ecoacoustic metrics to facilitate the evaluation of extensive soundscape datasets for the analysis of soundscape patterns as well as spatial and temporal comparisons. In line with this, I address four primary aims. First, I investigate the contemporary ecological status of a lower-latitude Arctic region, with a particular emphasis on the spatiotemporal distribution, diversity, and community dynamics of marine mammals in relation to sea ice conditions. Second, I test whether a combination of multiple ecoacoustic metrics can be used to quantify the holistic variability in soundscape patterns created by all sound sources, and whether the selected metrics could serve as a standard for inferring and monitoring soundscape variations across different polar ocean ecosystems. Third, I explore the spatiotemporal similarity of soundscapes and their diversity in soundscape patterns across the Weddell Sea basin. Lastly, throughout my dissertation, I apply a suite of recommended and standardised metrics to measure and report baselines of ambient sound levels, contributing to the global assessment of ocean ambient sound levels.

Chapter 2

The study of this chapter explored the acoustic marine mammal community composition of a lower-latitude Arctic area to improve knowledge on current and future ecosystem shifts. Therefore, I investigated the coastal Tasiilaq area (Southeast Greenland) which is already experiencing an ecosystem shift and increasing baleen whale abundance in boreal summer. However, no year-round data on the contemporary marine mammal community dynamics was available for this critical area. Thus, the goal of the study was to assess and describe the contemporary seasonal and year-round acoustic marine mammal diversity and community dynamics, in conjunction with the local prevailing sea ice conditions. Therefore, year-round and multi-year PAM data of two stations in the Tasiilaq area were utilised and manually evaluated for daily acoustic marine mammal presence on which I applied statistical community composition analysis. I also aimed to explore similarity between the two stations to assess small scale variability.

Chapter 3

This chapter investigated the suitability of multiple ecoacoustic metrics to describe and reflect holistic soundscape characteristics of already disturbed and naturally intact polar offshore soundscapes. Furthermore, I evaluated if these metrics can serve as a standard to monitor the acoustic state of polar ocean environments quantitatively, contributing to the development of standardised sets of metrics for holistic ocean soundscape monitoring. Therefore, I employed a bipolar approach by comparing seasonal soundscape samples of the anthropogenic noise-impacted Fram Strait in the Arctic Ocean with the soundscape of the 'pristine' Weddell Sea in the Southern Ocean. This study, to my knowledge, is the first to measure ambient sound levels for recommended and standardized frequency bands for the Southern Ocean.

Chapter 4

This study was conducted to address the need to better understand large-scale spatiotemporal variation in soundscape patterns and dynamics in a relatively pristine polar ocean environment to facilitate a more comprehensive understanding of natural ecological dynamics and acoustic connectivity. Thus, this study aimed to provide a baseline understanding on how the acoustic environments across the Weddell Sea basin are temporally and spatially clustered into acoustically similar or dissimilar entities. I applied the established ecoacoustic metrics from Chapter 3 in combination with clustering to soundscape data comprising 18 stations across the Weddell Sea and over several years from 2008 to 2021. To my knowledge, this study is the first to apply clustering to an unlabelled soundscape dataset at the basin scale and over multiple years, providing a promising approach for simultaneously comparing multiple soundscapes to identify spatiotemporal soundscape similarity.

Chapter 5 – General discussion

In the last chapter I summarise and discuss the most important results of the previous three chapters. I elaborate on the prospects of future polar ocean soundscapes with respect to the triple planetary crisis. I outline the ecological consequences of soundscape alterations and noise pollution. Furthermore, I discuss the complexity of using ecoacoustic metrics and reflect on lessons learned regarding the study design and outline potential future research perspectives.

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Passive acoustic monitoring reveals year-round marine mammal community composition off Tasiilaq, Southeast Greenland

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JASA ARTICLE

Passive acoustic monitoring reveals year-round marine mammal community composition off Tasiilaq, Southeast Greenland[a)]

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ABSTRACT:
Climate-driven changes are affecting sea ice conditions off Tasiilaq, Southeast Greenland, with implications for marine mammal distributions. Knowledge about marine mammal presence, biodiversity, and community composition is key to effective conservation and management but is lacking, especially during winter months. Seasonal patterns of acoustic marine mammal presence were investigated relative to sea ice concentration at two recording sites between 2014 and 2018, with one (65.6°N, 37.4°W) or three years (65.5°N, 38.0°W) of passive acoustic recordings. Seven marine mammal species were recorded. Bearded seals were acoustically dominant during winter and spring, whereas sperm, humpback, and fin whales dominated during the sea ice-free summer and autumn. Narwhals, bowhead, and killer whales were recorded only rarely. Song-fragments of humpback whales and acoustic presence of fin whales in winter suggest mating-associated behavior taking place in the area. Ambient noise levels in 1/3-octave level bands (20, 63, 125, 500, 1000, and 4000 Hz), ranged between 75.6 to 105 dB re 1 μPa. This study provides multi-year insights into the coastal marine mammal community composition off Southeast Greenland and suggests that the Tasiilaq area provides suitable habitat for various marine mammal species year-round.
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I. INTRODUCTION

Located off Southeast Greenland, the Tasiilaq region is considered an area of "heightened ecological significance" providing critical habitat for endemic Arctic marine mammals and seasonally migrating cetaceans (AMAP/CAFF/SDWG, 2013). A total of 22 species of pinnipeds and cetaceans inhabit the waters of Greenland (Ugarte *et al.*, 2020), and 20 of these species have been sighted in or near the Tasiilaq region. However, knowledge on species diversity and on the spatial and temporal (seasonal and inter-annual) distributions of marine mammals in coastal Southeast Greenland are based on a handful of visual surveys (Heide-Jørgensen *et al.*, 2007; Boertmann *et al.*, 2009; Merkel *et al.*, 2010; Boertmann and Rosing-Asvid, 2014; Hansen *et al.*, 2019) and on subsistence hunting reports (e.g., Dietz *et al.*, 1994). These surveys and hunting reports are often strongly seasonally biased towards summer, reflecting the logistic constraints of accessing the area in winter. To date, year-round and multi-year data on the occurrence of marine mammals are lacking entirely for this critical ecological area off Southeast Greenland.

Passive acoustic monitoring (PAM) has become increasingly important to assess the distribution of acoustically active animals in remote (polar) areas and gain long-term insights into acoustic habitat and soundscape characteristics, especially in light of ongoing climatic changes (e.g., Davis *et al.*, 2020; Halliday *et al.*, 2020; Schall *et al.*, 2021). In this study, three years of PAM data were used to study intra- and inter-annual patterns in species diversity, community composition, and spatio-temporal distribution of marine mammals in the coastal waters off Southeast Greenland. Biodiversity measures were applied to explore the relationship between the acoustic marine mammal community composition and sea ice concentration.

Southeast Greenland has already lost a third of its winter sea ice cover, and the number of ice-free summer periods is increasing (Kern *et al.*, 2010; Onarheim *et al.*, 2018; Stroeve and Notz, 2018). The ecological consequences of sea ice loss are diverse and complex (e.g., Lannuzel *et al.*, 2020), including increased primary production (e.g., Lewis *et al.*, 2020), as well as poleward distributional shifts in

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species (e.g., Fossheim *et al.*, 2015; Davis *et al.*, 2020; Ershova *et al.*, 2021). For both marine mammals endemic to the Arctic and seasonally migrating species, habitat loss and changes in food availability drive northward distributional and temporal shifts in the occurrence on feeding grounds, with potential fitness implications (Kovacs *et al.*, 2011; Laidre *et al.*, 2015; Ramp *et al.*, 2015).

Distributional shifts of seasonally migrating baleen whales are increasingly reported for the (sub-)Arctic Ocean (for a review, see Moore *et al.*, 2019). In the Western North Atlantic Ocean, acoustic presence of sei (*Balaenoptera borealis*), fin (*B. physalus*), and blue whales (*B. musculus*) significantly increased in Davis Strait, indicating a northward distributional shift from the North American continental shelf within just one decade (Davis *et al.*, 2020). Blue whales seem to prolong their occurrence in Fram Strait by arriving almost a month earlier (mid-June) in 2015–2018 compared to 2008–2014 (Ahonen *et al.*, 2021). Similarly, sei whales were historically only occasionally observed north of ∼72°N, but recently, they were reported in Fram Strait (∼79°N) (Nieukirk *et al.*, 2020). Furthermore, the distribution of the North Atlantic right whale (*Eubalaena glacialis*) seems to have shifted to the northwest of their historic offshore whaling ground off South Greenland (Mellinger *et al.*, 2011). Moreover, along the continental shelf off Southeast Greenland, fin and humpback whales (*Megaptera novaeangliae*) are increasing in abundance, likely caused by progressing sea ice loss and changing prey distribution related to increasing sea surface temperatures (Jansen *et al.*, 2016; Hansen *et al.*, 2019). Spatial and temporal shifts in distribution of seasonally migrating marine species can affect local community compositions, potentially resulting in increased resource competition with endemic Arctic species (Kovacs *et al.*, 2011; Laidre *et al.*, 2015).

The ecological consequences of sea ice decline and ocean warming in lower Arctic regions such as the Tasiilaq region might reflect future scenarios for higher Arctic regions. Therefore, baseline information on the spatio-temporal distribution and local diversity of marine mammal species is crucial to observe, understand, and monitor shifts in species distribution, community composition, and ecosystem changes.

II. MATERIAL AND METHODS

A. Data collection

Between August 2014 and September 2018 AURAL-M2 recorders (Multi-Électronique, MTE, IN., Canada) were deployed at two sites off the coast of Tasiilaq (former Ammassalik), Southeast Greenland (Fig. 1). The first recording site was located close to the entry of the Sermilik fjord (hereinafter referred to as "SER"; 65.49°N, 38.02°W). The second recording site was located at the entry of Ammassalik fjord close to the village Kulusuk (hereinafter referred to as "KUL"; 65.59°N, 37.40°W). The distance between the recording sites was approximately 30 km. The SER recorders were deployed at a depth of 260 m (water depth: 276 m) and the KUL recorders were moored at 248 m depth (water depth: 338 m).

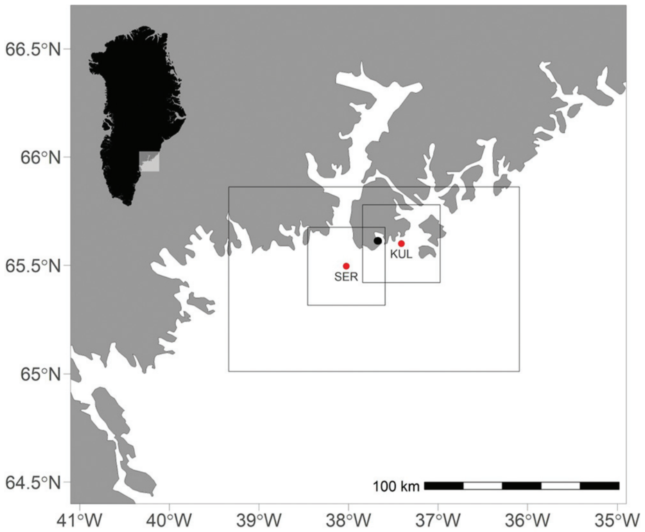

FIG. 1. The study area off Tasiilaq, Southeast Greenland. The red dots mark the recorder position SER (65.49°N, 38.02°W, Sermilik) and KUL (65.59°N, 37.40°W, Kulusuk). The black dot marks the town Tasiilaq. The rectangles around the recorders indicate the areas over which the daily sea ice concentration was averaged (40 × 40 km and 95 × 150 km).

At site SER, data were collected over three years from August 2014 to August 2015 (360 days) and from September 2016 to September 2018 (736 days). At recording site KUL, approximately one year (368 days) of recordings was collected from September 2016 to September 2017 (Table I). The recorders had a sampling rate of 32 768 Hz (effective frequency range: 10–16 384 Hz), 16-bit resolution, and a system peak clipping level of 151 dB re 1 μPa. The hydrophones (HTI-96-Min) had a sensitivity of −165 dB re 1 V/μPa with a flat frequency response from 2 Hz to 30 kHz (High Tech Inc., Long Beach, MS). The recorders were set to sample 30 consecutive minutes every four hours in the 2016/17 deployments and 30 consecutive minutes every two hours during all other deployment years giving a total of 3 and 6 h recorded per day, respectively (see also Table I for details).

A total of 35.3% of days (i.e., 517.4 days corresponding to 2783.5 h) of the overall recorded passive acoustic data (corresponding to 1463.8 days) were analyzed for the daily acoustic presence of marine mammal species (Table I).

Four recorders that were deployed could not be used for data analysis for various reasons and were omitted from the analysis here: SER-2015/16 and KUL-2014/15 ran out of battery and only recorded during a part of the deployment period. KUL-2015/16 showed irregularities in the duty cycle due to an unknown technical failure of the instrument, and KUL-2017/18 was lost, probably to an iceberg.

B. Daily acoustic marine mammal presence

Five-minute-long spectrograms were visually and aurally screened by a trained human operator to assess the daily acoustic presence of marine mammal species, using Raven Pro 1.5.0 (Hanning-window, 50% overlap, gray-scale; Bioacoustics Research Program 2014, Cornell Laboratory of

TABLE I. Overview of the analyzed acoustic data recorded by the AURAL-M2 acoustic recorders deployed off Tasiilaq. All recorders were set to a sampling rate of 32 768 Hz, 16-bit resolution, and preamplifier gain of 20 dB. SER, Sermilik; KUL, Kulusuk.

						Analyzed		
Recording site	Deployed years	Recording period	Duty cycle (min/min)	Days recorded	Analyzing scheme	Days	Hours	Proportion of data
SER (65.49 °N 38.02 °W)	2014/15	27.08.2014 – 21.08.2015	30/120	359.4	Every 7th day	52	312	14.5%
	2016/17	03.09.2016 – 15.09.2017	30/240	378	Every 7th day	54	162	14.3%
	2017/18	19.09.2017 – 12.09.2018	30/120	358.4	Every day	358.4	2150.5	100%
KUL (65.59 °N 37.40 °W)	2016/17	03.09.2016 – 05.09.2017	30/240	368	Every 7th day	53	159	14.4%

Ornithology). Only signals which were clearly distinguishable over ambient noise were considered. In this study, "daily acoustic presence" is defined to mean that at least one distinct signature (i.e., one call) attributed to a specific species or sound source was detected during the respective recording day that was analyzed.

For recordings of SER-2017/18, every recorded day was analyzed for marine mammal daily acoustic presence, while every seventh day was analyzed for SER-2014/15, SER-2015/16, and KUL-2016/17 (see Table I).

Detected call types and vocalizations were assigned to species level wherever possible based on species-specific call type characteristics (such as duration, frequency range, spectrographic shape, inter-call intervals, or complexity of songs) described in the literature, such as species-specific trills, moans, or sweeps for bearded seals (*Erignathus barbatus*) (Risch *et al.*, 2007), low-frequency clicks, buzzes, and pulsed calls for narwhals (*Monodon monoceros*) (e.g., Stafford *et al.*, 2012a; Ahonen *et al.*, 2019), regular, slow clicks and creaks emitted by sperm whales (*Physeter macrocephalus*) (e.g., Goold and Jones, 1995; Madsen *et al.*, 2002), and killer whale (*Orcinus orca*) pulsed calls and whistles (e.g., Deecke *et al.*, 2011). Furthermore, the acoustic presence of baleen whales was determined based on the 20 and 130 Hz calls of fin whales (e.g., Simon *et al.*, 2010), species-specific non-patterned calls, call sequences, and song fragments of humpback whales (e.g., Huang *et al.*, 2016; Kowarski *et al.*, 2019), and bowhead whale (*Balaena mysticetus*) simpler call sequences (e.g., Stafford *et al.*, 2012b). Given the similarities in humpback and bowhead whale vocalizations (overlapping frequency range, similar calling structure, and acoustic behavior, including annual changing songs and singing through winter) (e.g., Payne and McVay, 1971; Ljungblad *et al.*, 1982; Herman, 2017; Stafford *et al.*, 2018), we defined humpback whales as acoustically present when a detected call sequence was considered complex (i.e., call sequences consisting of three or more call types), whereas bowhead whales were considered present when the call sequence was simpler (i.e., call sequences consisting of one to two call types). Additionally, online sound databases were used to compare detected species-specific sound signals aurally: NOAA fisheries Sounds in the Ocean (2021), Discovery of Sound in the Sea (2021), and Voices in the Sea (2021).

Recordings were reviewed in a three-stage audio-visual screening process. First, the full frequency spectrum (10–16 384 Hz) was analyzed to capture higher frequency signals (fast Fourier transform, FFT: 8192, time resolution: 0.25 s, frequency resolution: 4 Hz, overlap: 50%). Secondly, the frequency range from 10 to 4000 Hz was screened for signals produced by seals and baleen whales (FFT: 8192, overlap: 50%). Finally, the spectrogram was screened for low-frequency signals using a frequency range from 10 to 500 Hz (FFT: 12 032, time resolution: 0.367 s, frequency resolution: 2.72 Hz, overlap: 50%). For each stage, these settings were kept constant throughout the screening process. If necessary, individual signals were examined for species identification by zooming into the spectrogram and optimizing the spectral display of the signal by adjusting the settings (brightness, contrast, and FFT).

Unidentified biological sound signals were classified into broader groups: unidentified toothed whales (UTW) and unidentified baleen whales (UBW). UTW signals included whistles, pulsed calls, and clicks of toothed whales that could not be assigned to species level. UBW signals mainly contain lower frequency sounds (<700 Hz) that could not be attributed to a species with certainty. UBW sounds were classified into sub-categories, based on the aural and visual appearance.

C. Acoustic community composition

We quantified the acoustic marine mammal diversity off Tasiilaq by estimating the monthly effective number of (acoustically active) species (ENS) for every recording period (following Van Opzeeland and Hillebrand, 2020). ENS is an index number of species within a community and provides the true species diversity relative to evenness: As long as all species are equally common, ENS reflects the total number of species in the community; when evenness decreases, so does ENS. However, the decrease is disproportional as rare species only account for a fraction and ENS is primarily influenced by common species. ENS is an ideal measure of diversity given that it is robust to fluctuations in sampling effort or sudden changes in species diversity (Chase and Knight, 2013). Although our data do not contain information on precise species abundance, the relative acoustic presence of species (the sum of days in a month a species was acoustically present divided by the number of days analyzed per month) can be used as a pseudo species abundance (see also Van Opzeeland and Hillebrand, 2020). Thereby, we assume that in a large population the probability of detecting an acoustically active individual is higher and that a larger population has a more consistent acoustic activity, leading to more days with acoustic presence compared to a small population (Van Opzeeland and Hillebrand, 2020). Additionally, the net change in acoustic species richness, as well as considering species identity, was calculated from month to month (Hillebrand *et al.*, 2018; Van Opzeeland and Hillebrand, 2020).

D. Ambient noise level metrics

To assess (relative) trends of ambient noise levels within the communication range of the detected marine mammal species off Tasiilaq, four 1/3-octave levels (TOL) bands centered at 20 Hz (range: 17–22 Hz), 500 Hz (445–561 Hz), 1000 Hz (890–1122 Hz), and 4000 Hz (3563–4489 Hz) were investigated. These bands were selected as they reflect (parts of) the communication range of the species detected in this study (Mellinger *et al.*, 2007; Southall *et al.*, 2008; Erbe *et al.*, 2017). Additionally, background noise levels were assessed within the 63 Hz (55–70 Hz) and 125 Hz (111–140 Hz) TOL bands, according to the recommendations of the Marine Strategy Framework Directive (Van der Graaf *et al.*, 2012). In this study, we use the term "ambient noise" to comprise all recorded sounds, including natural and anthropogenic sounds as well as acoustic self-noise, which is in addition to the ISO (2017) definition of "ambient noise" (ISO 18405:2017, 3.1.5.11) because not all TOL bands analyzed in the present study contained acoustic self-noise (ISO 18405:2017, 3.1.5.10).

For these six TOL bands, received levels were measured over 60 s time intervals using the Noise Band Monitor (filter: Butterworth; filter order: 5) of the software PAMGUARD 1.15.15. Received levels (dB re 1 μPa) were calculated using factory calibration settings of the Aural-M2 recorders, i.e., system sensitivity: -164.1 dB re 1 V/μPa; peak to peak voltage range: ± 2 V; preamplifier gain: 20 dB. For each TOL, the daily median sound pressure levels (SPL) were computed, as well as mean, median, 5% percentile, and 95% percentile of the SPLs for each recording period and site.

E. Sea ice concentration data

The daily sea ice concentration (SIC) was provided in a grid resolution of 3.125×3.125 km on a polar stereographic grid for South Greenland and obtained from the University of Bremen (Spreen *et al.*, 2008). The daily SIC was spatially averaged for three areas at the recording sites (see Fig. 1) using the R package "raster" by averaging over all pixels within and touched by the defined area boundaries (Hijmans, 2020; R 3.5.2, The R Foundation for Statistical Computing).

The size of the areas over which the daily SIC was averaged, was based on estimated detection ranges of the sounds produced by marine mammals. To our knowledge, there is no published information on local sound propagation characteristics or sound propagation modeling results available for the Tasiilaq region. We used previously published detection ranges for species from other (Arctic) locations (e.g., Cleator and Stirling, 1990; Madsen *et al.*, 2002; Stafford *et al.*, 2007; Ahonen *et al.*, 2021), although detection ranges may differ with site characteristics (such as oceanographic conditions, sea ice cover, bathymetry, ambient noise, and season) (e.g., Au and Hastings, 2008). Bearded seal trills and sperm whale echolocation clicks were assumed to propagate less than 20 km (Cleator and Stirling, 1990; Madsen *et al.*, 2002). Surmising similar and shorter propagation distances for other seal and toothed whale species, an area around the recording site with the size of 40×40 km was chosen. The low-frequency calls of baleen whales can propagate more than 100 km in deep water (Stafford *et al.*, 2007; Ahonen *et al.*, 2021). However, in shelf regions, the propagation range is assumed to be shorter, in particular when only distinct individual calls are considered. For bowhead whale calls in the Beaufort Sea, detection ranges were estimated to range up to 35 km (Bonnel *et al.*, 2014). In Fram Strait, close to the East Greenland shelf, the propagation distance for blue and fin whales was estimated to range between 30 and 60 km (Ahonen *et al.*, 2021). Therefore, we chose to average the daily sea ice concentration for a second larger area measuring 95×150 km, spanning both recording sites (Fig. 1) to represent the sea ice conditions vocalizing baleen whales recorded off Tasiilaq are likely to experience. Thereby, the southern, western, and eastern box boundary is 60 km from the nearest recorder position. We excluded the main Sermilik fjord, assuming the ice concentration within the fjord does not affect the species presence outside the fjord and that the species within the fjord are not acoustically detectable at the recording site SER.

Given the lower latitude of the Tasiilaq region and its lower sea ice concentrations compared to higher Arctic regions, we used SIC thresholds of $\leq$15% and $\geq$45% for this study to reflect open water and heavier sea ice conditions, respectively (following Laidre *et al.*, 2012). The average daily SIC is calculated as 7-day daily moving mean for all three SIC-area-boxes.

III. RESULTS

PAM off Southeast Greenland revealed the acoustic presence of three marine mammal species endemic to Arctic waters: bearded seals, narwhals, and bowhead whales. Further, four seasonally migrating cetaceans were acoustically present: killer, sperm, humpback, and fin whales. Bearded seals, sperm, humpback, and fin whales showed a strong seasonality in their acoustic presence linked to the seasonal SIC in the study area (Fig. 2). No seasonal trend was evident for narwhals, killer, and bowhead whales, due to their rare detections. In addition, several further (presumably) cetacean sounds were recorded, that could not be identified to species level with certainty.

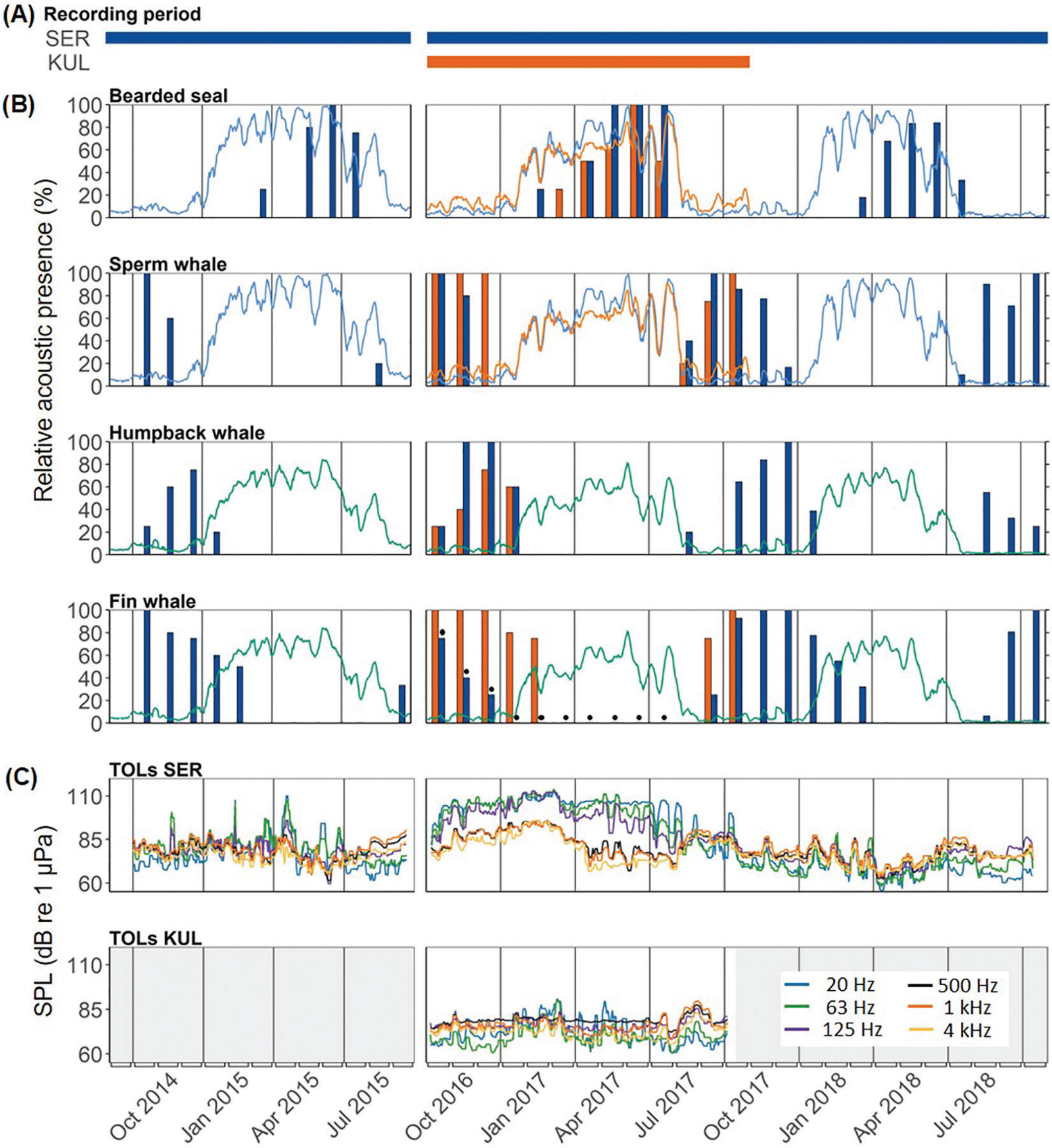

FIG. 2. (A) Recording periods analyzed in this study for site SER (blue horizontal bar) and site KUL (orange horizontal bar). (B) Monthly relative acoustic presence (proportion of days with acoustic presence per month on days analyzed, left *y*-axis) per species and recording site (vertical bars) relative to the SIC given as 7-day daily moving means (right *y*-axis). The blue and the orange line represent the SIC within 40 × 40 km boxes around site SER and site KUL, respectively, for the assumed propagation distance of sounds produced by the species. The SIC spanning the larger Tasiilaq area (95 × 150 km) is represented as the green line, after the assumed propagation distance of sounds produced by baleen whales. Black dots (in the fin whale panel) indicate times of intense mooring-generated strumming potentially masking fin whale 20 Hz pulses. Note that narwhals, killer, and bowhead whales are not represented here, due to their low acoustic presence. (C) SPLs (in dB re 1 μPa) within six 1/3-octave level (TOL) bands as a 7-day daily moving median. Gray shaded areas mark periods that were not analyzed (KUL-2014/15) or of lacking data (KUL-2017/18). The seasons are indicated by the vertical lines: autumn, September–November; winter, December–February; spring, March–May; summer, June–August.

A. Arctic marine mammal species

Bearded seals were acoustically present from January through June, following sea ice formation, with a peak in acoustic presence in May at both recording sites and all years [Fig. 2(b); Information on the total amount of days with species-specific acoustic presence per recording period is given in the supplementary material.[1]] Acoustic activity continued during sea ice retreat and ceased in June when the SIC was around 45%. Overall, 6% of days with bearded seal acoustic presence had open water conditions (≤15% SIC), while 73% of days with bearded seal acoustic presence exhibited heavier SICs (≥45% SIC) up to full sea ice coverage.

Narwhals were acoustically present only at site SER and were detected on two days in spring: on 20 May 2015 and 1 April 2017 when SICs were 86% and 89%, respectively.

Vocalizations (simpler call sequences) of bowhead whales were detected on three days in total. At site SER, bowhead whales were acoustically present on 21 January 2017 and 9 March 2018, when SIC were 30% and 61%, respectively. At KUL, acoustic presence was detected on 26 November 2016 when the SIC reached 45%.

B. Seasonally migrating marine mammal species

Killer whales were acoustically present only at site SER on 23 September 2017 during open water conditions.

Sperm whales were acoustically present from July to October or November, with a peak in acoustic presence in late summer and early autumn (August or September) at both recording sites and all years [Fig. 2(b)]. The acoustic presence of sperm whales slightly decreased in October 2016 at site SER but remained constant at site KUL. At site SER sperm whale acoustic presence was considerably lower in 2014/15 compared to other years. Overall, sperm whales appeared to prefer open water conditions [with 96% of days with sperm whale acoustic presence associated with open water conditions, Fig. 2(b)] but were occasionally acoustically present at SIC up to 37%. The acoustic presence of sperm whales ceased about one month before sea ice formation.

Humpback whales were acoustically present from July to late December and their acoustic presence peaked in October and November in all years and at both recording sites [Fig. 2(b)]. In summer, mainly non-song social calls, including calls associated with foraging, were detected. However, humpback whales were acoustically absent or rarely acoustically present during the summer months. Starting in September/October, song fragments remained present until December. (Vocalizing) humpback whales appeared to prefer open-water conditions [with 92% of days with humpback whale acoustic presence occurring during open water conditions; Fig. 2(b)]. Occasionally, however, humpback whales were acoustically present at SIC up to 45% (4% of days with humpback whale acoustic presence) and up to 75% (3% of days with humpback whale acoustic presence). Despite careful and conservative assessment of humpback whale acoustic presence, the possibility of accidentally misclassifying bowhead whale sounds as humpback whale sounds exists, given similarities in their vocal characteristics.

Of all species, fin whales were acoustically present during most days, displaying a pronounced seasonality in their acoustic presence from June to the end of February with a peak in autumn [Fig. 2(b)]. Their acoustic presence per recording period was similarly distributed over both recording sites and years, except for SER-2016/17, in which mooring-generated strumming noise was present below 100 Hz [Fig. 2(b)]. For fin whales, 75% of days with acoustic presence were during open water conditions [Fig. 2(b)]. Only 15% of days with fin whale acoustic presence were characterized by heavier sea ice concentrations (up to 78%).

C. Unidentified biological sound signals

The recordings made off Tasiilaq contained several signal types that could not be assigned to species-level with certainty and hence, were summarized within two groups: unknown toothed whale sounds (UTW) and unknown baleen whale sounds (UBW). Information on the total relative species-specific acoustic presence per recording period for the unidentified biological sound signals, on temporal patterns in their occurrence, and spectrographic examples are given in the supplementary material.[1]

The group UTW consists of clicks and whistles. The occurrence of UTW signals mainly peaked in autumn at both recording sites, but occasionally occurred in other seasons.

The group UBW includes a variety of sound signals, mainly at frequencies below 700 Hz, that were categorized into five sub-categories (C1–C5) based on their visual and aural characteristics. For calls of categories C1 (faint tonal calling pattern) and C2 (pulsed frequency-modulated downsweeps), a seasonal pattern in their presence was similar to humpback whales and fin whales, respectively. The presence of sounds categorized as C3 (simple sequences of short pulses) did not show a clear seasonal pattern, but these were detected in different seasons during the analyzed recording period. Calls summarized as C4 (frequency modulated arched downsweeps) infrequently occurred in autumn and winter months from 2016 to 2018 and occasionally in combination with calls of category C5 (low-frequency moans and grunts). C5 calls occurred during all seasons, but only at site SER. All other UBW sub-categories were detected at both recording sites.

D. Trends in ambient noise levels

Overall, the abiotic and anthropogenic components of the marine soundscape off Tasiilaq included sounds from sea ice and ships. Moreover, the recordings contained electronic self-noise, as well as mooring generated strumming (<100 Hz) and shackle-noise (i.e., broadband impact sounds).

The annual mean SPLs for each recording period and site ranged from 75.6 to 105 dB re 1 μPa across all TOL bands (Table II). The lowest annual mean SPLs were measured in SER-2017/18 and KUL-2016/17 across all TOL bands, while SER-2016/17 showed the highest annual mean SPLs, mainly reflecting intensive mooring-generated strumming and shackle-noise. Among the TOL bands analyzed here, the highest mean SPLs were always measured in the 20 Hz or 63 Hz TOL band.

No clear seasonal pattern reflecting species' acoustic presence was discernable in the TOLs, recording periods, and recording sites. All TOLs exhibit high intra-annual variability, with KUL-2016/17 and SER-2017/18 showing the lowest daily median SPLs, especially in the 20 and 63 Hz bands [Fig. 2(c), Table II]. Within the recording periods SER-2014/15, SER-2017/18, and KUL-2016/17, the daily median SPLs were similar for all TOLs [Fig. 2(c)]. Mooring-generated strumming noise persisted occasionally in SER-2014/15 and for almost the entire recording period of SER-2016/17. Furthermore, the SER-2016/17 data also contained shackle-noise from October to March.

TABLE II. Annual metrics of the SPL (dB re 1 μPa) of the 1/3-octave level (TOL) bands for each recording period and site.

		TOL bands					
	Recorder	20 Hz	63 Hz	125 Hz	500 Hz	1 kHz	4 kHz
Mean	SER-2014/15	96.1	96.8	95.2	82.9	83.2	79.2
	SER-2016/17	105	103.8	101.3	87.9	87.4	85.6
	SER-2017/18	77.8	84.3	83.4	79.2	80.3	77.8
	KUL-2016/17	83.7	80.6	81	80.7	79.4	75.6
Median	SER-2014/15	74.4	79.5	79.0	79.5	80.8	76.3
	SER-2016/17	105.0	100.9	95.7	85.0	84.9	81.2
	SER-2017/18	68.3	70.3	75.9	75.8	77.1	74.9
	KUL-2016/17	71.3	69.2	76.0	78.8	76.1	72.7
5% percentile	SER-2014/15	57.0	63.6	67.1	64.5	65.8	66.6
	SER-2016/17	70.9	75.8	79.1	71.0	69.9	67.0
	SER-2017/18	54.4	57.5	62.7	62.5	64.3	65.6
	KUL-2016/17	57.9	60.7	71.3	74.2	69.2	65.8
95% percentile	SER-2014/15	112.0	112.2	112.0	92.0	91.4	87.8
	SER-2016/17	111.8	112.8	112.4	96.8	95.9	96.4
	SER-2017/18	86.9	95.5	90.7	87.4	88.9	86.3
	KUL-2016/17	97.1	92.6	88.6	86.9	88.0	84.0

The strumming and shackle-noise are reflected by high SPLs in all TOL bands of SER-2016/17 [Fig. 2(c)].

E. Acoustic community composition

Overall, seven marine mammal species were identified to be acoustically present at site SER and five at site KUL between August 2014 and September 2018. A trend in seasonal variation in the monthly acoustic ENS can be distinguished at both recording sites (Fig. 3, black dots, gray line), particularly at the multi-year recording site SER. The monthly acoustic ENS at both recording sites shows a recurring peak in the autumn, having primarily two to three acoustically active species present, reflecting that the acoustic community is most diverse in autumn. Generally, acoustic marine mammal diversity was highest at both sites during open water conditions and was lowest during sea ice-covered periods when primarily bearded seals were present. The net change of acoustic species richness was fairly neutral over time (Fig. 3, open triangles, dashed gray line), and there was no explicit recurring seasonal cycle of gained or lost numbers of species to consecutive months.

There was no substantial difference in species diversity and community composition at site KUL (one year of available data) compared to the multi-year site SER. Interestingly, the marine mammal acoustic community composition changes completely on a semiannual basis following the sea ice breakup and formation (Fig. 4). In autumn, three species of seasonally migrating cetaceans (i.e., sperm, humpback, and fin whales) mainly constitute the acoustic marine mammal community composition at both recording sites. In winter, the acoustic community composition shifts towards an acoustic community dominated by bearded seals with incidental narwhal and bowhead whale acoustic presence. In summer, the acoustic community again turns over to be acoustically dominated in autumn by seasonally migrating cetacean species (Fig. 4).

IV. DISCUSSION

This study provides insights into the intra- and interannual patterns in marine mammal occurrence and community composition relative to the local SIC for the Tasiilaq area of Southeast Greenland. Such knowledge is of direct relevance to international and intergovernmental initiatives that aim to monitor the status of Arctic marine environments and to coordinate efforts on their protection and sustainable development, such as the Arctic Council, including CAFF (Conservation of Arctic Flora and Fauna), PAME (Protection of the Arctic Marine Environment), AMAP (Arctic Monitoring and Assessment Program), SDWG (Sustainable Development Working Group) or the IQOE (International Quiet Ocean Experiment).

In total, one pinniped species (bearded seal), three baleen whale species (bowhead, humpback, and fin whale), and three toothed whale species (narwhal, killer, and sperm whale) were found to contribute to the local marine soundscape between 2014 and 2018. Despite the small spatial

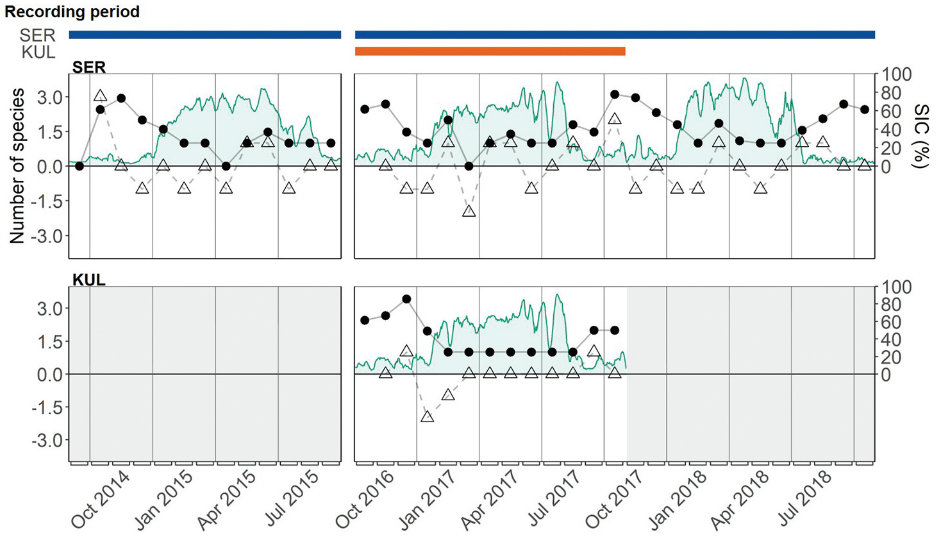

FIG. 3. Monthly acoustic species diversity (left y-axis) for recording site SER, and site KUL versus the 7-day daily moving mean SIC (%; green shaded area, right y-axis) of the larger area (95 × 150 km) off Tasiilaq. The monthly ENS (black dots, gray line) was calculated from the relative acoustic presence of all species (see Fig. 2). The net change in species richness (triangles, dashed gray line) from any month to the next month. Gray shaded areas mark periods that were not analyzed (KUL-2014/15) or lacking data (KUL-2017/18). The horizontal bars on top of the figure indicate the respective recording periods analyzed for site SER (blue) and site KUL (orange).

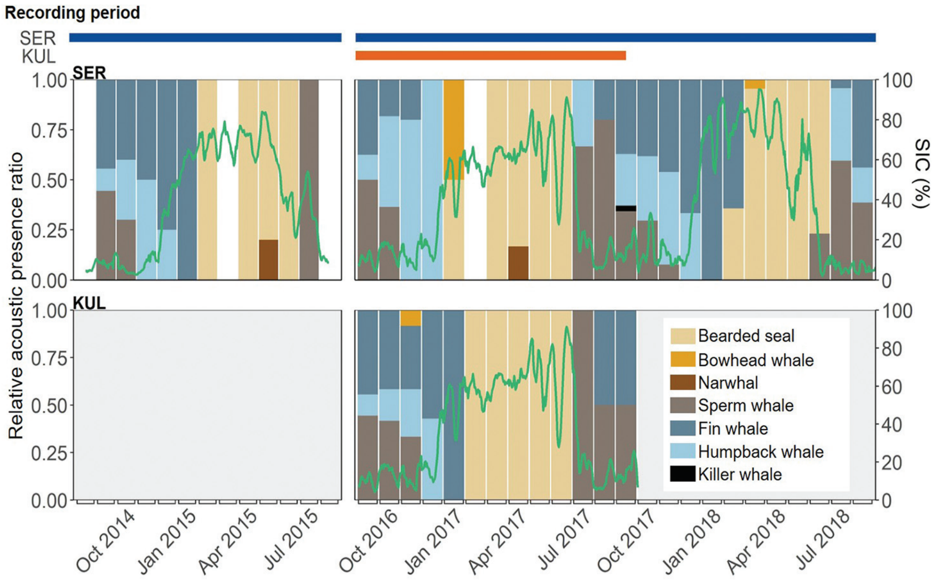

FIG. 4. Acoustic community composition of marine species acoustically present off Tasiilaq, as the relative acoustic presence of a species to the relative acoustic presence of any other species acoustically present within this month (left *y*-axis). The green line shows the 7-day daily moving mean SIC (%; right *y*-axis) of the greater area (95 × 150 km) off Tasiilaq. Gray shaded areas mark periods that were not analyzed (KUL-2014/15) or lacking data (KUL-2017/18). The horizontal bars on top of the figure indicate the respective recording periods analyzed for site SER (blue) and site KUL (orange).

scale of this study, our acoustic data captured 32% of the total marine mammal species richness described for all of Greenland (excluding polar bears, *Ursus maritimus*) (Ugarte *et al.*, 2020), implying the Tasiilaq area is a marine mammal hotspot.

Acoustic studies of marine mammal diversity rely on the species to produce sound and can be affected by the recorder set-up, recording period, and the analysis scheme (Mellinger *et al.*, 2007; Thomisch *et al.*, 2015). Furthermore, species detection is strongly dependent on both species-specific and individual acoustic behavior, such as the highly seasonal vocal activity of male pinnipeds (e.g., Van Parijs *et al.*, 2001; MacIntyre *et al.*, 2015) or context-dependent acoustic behaviors in cetaceans (e.g., Croll *et al.*, 2002; Stafford *et al.*, 2012b; Kowarski *et al.*, 2019). By choosing subsets of data (where applicable) that were evenly distributed over the respective recording period, we aimed to minimize the risk of biased detection results due to species-specific seasonal patterns in acoustic activity.

The effective frequency range of 10–16 384 Hz in this study hampered reliable detection and identification of species producing sounds that (partly) exceed the sampling frequency of the recorders (Mellinger *et al.*, 2007). Additionally, subsampling of data (applied in the recording or analysis process, or both) has been shown to affect the detection likelihood. Such duty cycle effects are most pronounced for species with low or temporally clustered vocal activity (Thomisch *et al.*, 2015), such as narwhals (Blackwell *et al.*, 2018; Ahonen *et al.*, 2019) or killer whales (Deecke *et al.*, 2005). The analysis scheme applied here, i.e., sampling every seventh day entirely, was selected to ensure we capture species that exhibit a diel pattern in their vocal activity. When comparing overall trends from a seventh-day subsampling scheme to the daily analysis, no substantial differences were found in acoustic diversity or seasonal patterns in species-specific acoustic presence, leaving it unlikely that our analysis scheme considerably underrepresents the daily acoustic presence of the different species.

A. Trends in ambient noise levels off Tasiilaq

Off Tasiilaq, the ambient noise levels measured for the TOL bands (centered at 20, 63, 125, 500, 1000, and 4000 Hz) did not show a pronounced reoccurring seasonal pattern in the daily median SPLs.

In Fram Strait, annual mean SPLs of the 63, 125, and 500 Hz TOL bands were higher, ranging from 85.3 to 95.9 dB re 1 μPa (Ahonen *et al.*, 2017). Lower SPLs in the Tasiilaq area, are likely caused by the absence of noise generated by seismic explorations, which contribute considerably to the SPLs in Fram Strait.

Overall, high noise levels can mask signals of interest by reducing the signals' detection ranges (Erbe *et al.*, 2016). Therefore, the actual detection range of vocalizing individuals likely was less for SER-2014/15 and SER-2016/17 than for SER-2017/18 and KUL-2016/17. In SER-2016/17 and occasionally in SER-2014/15, the TOL bands centered at 20, 63, and 125 Hz were affected by mooring-generated strumming noise (mainly below 100 Hz). In SER-2016/17, additionally, shackle-noise was prominent and affected the higher-frequency TOL bands centered at 500, 1000, and 4000 Hz. High SPLs in the 20 Hz TOL band in SER-2016/17 due to strumming noise likely masked 20 Hz fin whale calls, providing a possible explanation for the observed low acoustic presence of fin whales during this recording period. In SER-2014/15, however, strumming did not seem to mask fin whale calls and cause a subsequent underestimation of fin whale acoustic presence. The broadband but transient nature of the recorder shackle-noise allowed for detection of marine mammal vocalizations in the absence of shackle-noise and hence did not seem to compromise results on the overall daily acoustic presence of marine mammals.

B. Arctic marine mammal occurrence in the Tasiilaq area

Of the eight endemic Arctic seal and cetacean species occurring around Greenland (Ugarte *et al.*, 2020), three species were acoustically present in the Tasiilaq area: bearded seals, narwhals, and bowhead whales.

Bearded seal acoustic presence was strongly related to sea ice during winter and spring (from January to June), consistent with findings from other Arctic regions (Van Parijs *et al.*, 2004; MacIntyre *et al.*, 2015; Boye *et al.*, 2020). Male bearded seals are known to vocalize exclusively prior to and during the springtime breeding season (Cleator and Stirling, 1990; Van Parijs *et al.*, 2001). Our findings, therefore, highlight the relevance of the Tasiilaq area as breeding habitat for this species. Although most bearded seals are assumed to retreat into fjords during summer, some individuals remain present along Southeast Greenland (Boertmann and Rosing-Asvid, 2014). Hence, the Tasiilaq area may be of ecological importance for bearded seals year-round, serving as a breeding and molting ground. However, in light of increasing numbers of sea ice-free periods and earlier sea ice break-up, bearded seals might respond to changing sea ice conditions by using land for hauling out (Laidre *et al.*, 2008), using pieces of glacial ice during pupping season (Lydersen *et al.*, 2014), starting breeding earlier in the season, or (seasonally) migrating north into areas that still provide more stable sea ice cover (Kovacs *et al.*, 2011; Laidre *et al.*, 2015).

While Sermilik fjord is a known narwhal summering ground (Dietz *et al.*, 1994; Heide-Jørgensen *et al.*, 2010), narwhals were rarely acoustically detected in our data off Tasiilaq. The Tasiilaq area may be a transit area for narwhals, or they may occur at low densities such that they were not detected by our instruments. Additionally, the duty-cycled recording scheme (with duty cycles of 12.5% or 25%) and the chosen analysis schemes (with about 14% of data analyzed for most recording years) may have negatively affected the accuracy of acoustic presence estimates. Narwhal acoustic behavior is temporally clustered, e.g., they are known to vocalize more intensely during daytime and early evening, including long periods of vocal inactivity (Blackwell *et al.*, 2018; Ahonen *et al.*, 2019). Furthermore, narwhal high-frequency clicks are highly directional and range from about 18 up to 200 kHz (Stafford *et al.*, 2012a; Rasmussen *et al.*, 2015). This might have rendered them undetectable given our sampling rate of 32 768 Hz, thereby adding to an underestimation of narwhal acoustic presence.

The occasional acoustic presence of bowhead whales in our study supports previous observations that bowhead whales do not regularly inhabit the waters of Tasiilaq but move through the area occasionally (Heide-Jørgensen, 2019). Bowhead whales detected off Tasiilaq might belong to the Spitsbergen stock, which has been reported to migrate along the sea ice edge south to the "Southern Whaling Grounds" (70–75.5°N) of the Greenland Sea (Lydersen *et al.*, 2012; Kovacs *et al.*, 2020). In November, the acoustic presence of bowhead and humpback whales overlapped in the Tasiilaq area. Both whale species show similarities in their vocal behaviors, characterized by complex, annually changing songs (Payne and McVay, 1971; Ljungblad *et al.*, 1982; Herman, 2017; Stafford *et al.*, 2018). This might have caused an underestimation of bowhead whale acoustic presence.

C. Seasonally migrating cetacean occurrence in the Tasiilaq area

Four seasonally migrating cetaceans off Greenland were acoustically present. The regular seasonal occurrence of sperm, humpback, and fin whales during summer and autumn indicates summer feeding in the coastal waters of Tasiilaq.

Killer whales have been reported to regularly occur in the Tasiilaq area since 2009, with occurrences linked to sea ice loss in this region (Ugarte *et al.*, 2020). In this study, they were acoustically detected only on one single day in September 2017. Killer whales off Tasiilaq have been observed to prey on seals (Foote *et al.*, 2013). The low acoustic presence observed here may therefore reflect silent hunting strategies used by marine mammal-feeding killer whale ecotypes to avoid startling potential prey (Deecke *et al.*, 2005). Furthermore, the limited sampling rate, as well as duty-cycled sampling and analysis schemes may have affected the likelihood of detection for killer whale calls and highly directional clicks, which exhibit frequency ranges up to 75 kHz (Samarra *et al.*, 2010; Eskesen *et al.*, 2011).

Sperm whales are known to produce clicks for communication and prey localization year-round (e.g., Mellinger *et al.*, 2004), hence their acoustic absence likely reflects actual physical absence. In the Tasiilaq area deep trenches located at the fjord entries (about 400 to 900 m depth) (Sutherland *et al.*, 2014), provide suitable foraging habitats for these deep-diving predators (Watkins *et al.*, 1993). The pronounced seasonality of sperm whale acoustic presence in summer and autumn in the Tasiilaq area, with acoustic absence through winter and spring, contrasts observations of prolonged and year-round acoustic presence in eastern Fram Strait (Klinck *et al.*, 2012) and the Greenland Sea (De Vreese *et al.*, 2018). In contrast to recording sites in Fram Strait and the Greenland Sea, the Tasiilaq area exhibits seasonal sea ice cover, which may cause animals to leave the area in winter. Interestingly, sperm whale acoustic presence off Tasiilaq had already ceased one month before sea ice formation. Therefore, factors other than sea ice concentration alone (e.g., prey availability, changes in water temperature, or light conditions) are likely to trigger the onset of sperm whale departure (Shaw, 2016).

This study indicates that the Tasiilaq area serves as a suitable habitat for humpback and fin whales not only for summer feeding activities but also during winter. In general, both species are negatively associated with sea ice concentration, but fin whales seem to tolerate loose drift ice (Storrie *et al.*, 2018). In other (sub-)Arctic areas that were ice-free year-round, humpback and fin whales were acoustically present throughout winter and into spring (Magnúsdóttir *et al.*, 2014; De Vreese *et al.*, 2018; Fournet *et al.*, 2018). Ahonen *et al.* (2021) and Moore *et al.* (2012) detected fin whale 20 Hz calls in Western Fram strait in spite of sea ice cover. In Davis Strait, advancing sea ice seems to push singing fin whales to migrate further south (Simon *et al.*, 2010). In the Tasiilaq area, the seasonal sea ice cover can be quite variable due to currents and strong katabatic winds creating coastal polynyas (Oltmanns *et al.*, 2014). The presence of coastal polynyas possibly provides ice-free areas for marine mammals during winter and might explain fin whale singing off Tasiilaq until February. Later in the season, the persistent sea ice cover or changing prey availability may cause fin whales to move to sea ice-free areas further offshore (e.g., Irminger Sea, Davis *et al.*, 2020).

Similar to fin whale 20-Hz calls, humpback whale song fragments were recorded from late September into winter months. Songs of humpback whales and 20 Hz pulses of fin whales are most likely produced solely by males in a reproductive context (Croll *et al.*, 2002; Simon *et al.*, 2010; Herman, 2017). Humpback whale songs are mainly recorded at low-latitude breeding grounds, but also occur during migration and on high-latitude feeding grounds (Herman, 2017). Singing during migration and on feeding grounds is assumed to be connected to complex migratory behaviors, such as partial or staggered migration (Clark and Clapham, 2004; Geijer *et al.*, 2016). It also has been suggested as an opportunistic mating strategy of males to access females that failed to conceive during the breeding season or are skipping migration (Clark and Clapham, 2004). Our recordings of humpback whale song-fragments and fin whale 20 Hz pulses on a feeding ground during autumn and winter months thereby add to a growing body of evidence of complex migratory behaviors in baleen whales (Clark and Clapham, 2004; Simon *et al.*, 2010; Geijer *et al.*, 2016).

D. Unidentified biological sounds

The biological soundscape further contained several cetacean sounds that could often be attributed to family or genus but not to species level, including clicks, whistles, grunts, moans, frequency-modulated downsweeps, and simpler call sequences. The occurrence of these sounds might indicate a greater acoustic marine mammal diversity off Tasiilaq, potentially including white-beaked dolphin (*Lagenorhynchus albirostris*), blue, sei, and North Atlantic right whales.

Sounds of unknown origin, recorded at frequencies below 700 Hz, were recognized in all years in the waters off Tasiilaq. Some of these sounds, i.e., call categories C1 and C2, show similarities in the temporal patterns of acoustic presence to that observed for humpback and fin whales. Category C3 (simple call sequences of short pulses) occurred in winter and spring 2018 and might be produced by bowhead whales or by North Atlantic right whales, which have been reported and observed off Southeast Greenland (Mellinger *et al.*, 2011; AMAP/CAFF/SDWG, 2013). Both species produce spectrographically similar calls in the same frequency range (e.g., Laurinolli *et al.*, 2003; Stafford *et al.*, 2012b). However, the presence of C3 calls during heavier sea ice conditions might indicate that these calls are produced by bowhead whales. Calls categorized as C4 (frequency-modulated arched downsweeps) are known to be produced by blue (e.g., Mellinger and Clark, 2003; Schall *et al.*, 2020) and sei whales (e.g., Nieukirk *et al.*, 2020), and both species are reported to occur along Southeast Greenland (Heide-Jørgensen *et al.*, 2007; AMAP/CAFF/SDWG, 2013; Hansen *et al.*, 2019). Nieukirk *et al.* (2020) note that sei whale calls can be misidentified with similar calls of other baleen whales, requiring a highly conservative approach in confirming downsweeping vocalizations on species-level. Furthermore, the absence of the lower-frequency AB calls of blue whales (Mellinger and Clark, 2003), prevents an unequivocal assignment of the C4 calls to blue whales. Humpback whales tend to produce moans and grunts during feeding activities and social interactions (Dunlop *et al.*, 2008; Stimpert *et al.*, 2011). However, several baleen whales can produce such moans and grunts categorized here as C5, preventing an assignment to any specific species.

E. Acoustic community composition

In polar regions, strong seasonal fluctuations in environmental conditions, such as sea ice cover, are assumed to be reflected in species richness and community composition patterns (Van Opzeeland and Hillebrand, 2020). The acoustic species richness off Tasiilaq exhibited a highly seasonal dynamic, peaking during the sea ice-free late summer and autumn and dropping to mainly one species in winter when the sea ice concentration increased. Off Tasiilaq, a strong and complete semi-annual turnover and recovery of the acoustic species community composition linked to the seasonal sea ice cover was observed. Furthermore, there was no substantial difference in the acoustic species diversity and acoustic community composition at site KUL compared to site SER, even though only one year was analyzed for site KUL. Unidentified cetacean sounds, potentially reflecting the acoustic presence of additional species, were not included in the diversity analyses. In turn, the actual acoustic species richness and the acoustic community composition turnover off Tasiilaq might be higher and more complex than assumed.

With increasing sea ice loss, species turnover dynamics might change over time due to changing community composition and species dominance (Van Opzeeland and Hillebrand, 2020). Sea ice decline facilitates the occurrence of killer whales in the Tasiilaq area, potentially increasing the predation risk for seals and narwhals in the area (Westdal *et al.*, 2013; Breed *et al.*, 2017), which may add pressure to move to areas that still provide steady sea ice cover. With ongoing sea ice loss, seasonal migrants may arrive earlier on (sub-)polar summering grounds or extend their stay into winter (Ramp *et al.*, 2015; Ahonen *et al.*, 2021). Fin and humpback whales have a similar feeding ecology, foraging on the same pelagic prey species, such as euphausiids, copepods, and small schooling fish species (Aguilar and García-Vernet, 2018; Clapham, 2018). By trophic niche partitioning, however, they might avoid direct prey competition, possibly facilitating co-occurrence of these species in the Tasiilaq area (Gavrilchuk *et al.*, 2014).

V. CONCLUSION

Overall, the waters off Tasiilaq provide year-round habitat for endemic Arctic marine mammals and seasonally migrating cetaceans, supporting the classification of the region as an area of "heightened ecological significance" (AMAP/CAFF/SDWG, 2013). Strong seasonal dynamics in acoustic marine mammal richness and acoustic community composition linked to the local sea ice concentrations reflect the species-specific seasonal habitat suitability. Prospective PAM studies should consider recording continuously (rather than duty-cycled recording schemes) to gain insights into the habitat use of rare species or those exhibiting temporally clustered vocal activities, such as narwhal and killer whales, by increasing the likelihood of acoustically capturing these species. Furthermore, the availability of fully recorded call sequences and songs could greatly benefit the classification of the recorded sounds on species-level, e.g., by facilitating the distinction between bowhead and humpback whales.

Climate change-related, ongoing alterations in species distribution and community composition in the Arctic Ocean highlight the need for large-scale and long-term, internationally coordinated efforts to assess, understand and monitor the *status quo* of, as well as future trends in, already vulnerable Arctic environments.

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[1] See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0009429 for an overview of the total relative species-specific acoustic presence per recording period and for examples of unidentified biological sound signals and their temporal occurrence.

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Supplementary

Table SI. Relative acoustic presence per species, per recording period, and recording site in percent. The total amount of days with acoustic presence is given in brackets. Note that the recorder SER-2017/18 was analyzed based on a daily resolution while only every seventh day of the other recorders was analyzed. UTW = Unidentified toothed whales; UBW (categories) = Unidentified baleen whales.

	SER						KUL	
	2014/15		2016/17		2017/18		2016/17	
Number of days analyzed per recording period	54		54		359		53	
Bearded seal	22%	(12)	30%	(16)	24%	(87)	23%	(12)
Narwhal	2%	(1)	2%	(1)	0%	(0)	0%	(0)
Bowhead whale	0%	(0)	2%	(1)	0.3%	(1)	2%	(1)
Humpback whale	15%	(8)	30%	(16)	29%	(105)	17%	(9)
Fin whale	31%	(17)	15%	(8)	45%	(162)	45%	(24)
Sperm whale	15%	(8)	30%	(16)	29%	(104)	34%	(18)
Killer whale	0%	(0)	0%	(0)	0.3%	(1)	0%	(0)
UTW	13%	(8)	22%	(12)	9%	(33)	15%	(8)
UBW-C1	8%	(4)	7%	(4)	6%	(20)	4%	(2)
UBW-C2	13%	(7)	6%	(3)	14%	(52)	11%	(6)
UBW-C3	15%	(8)	13%	(7)	11%	(40)	13%	(7)
UBW-C4	0%	(0)	4%	(2)	7%	(25)	2%	(1)
UBW-C5	6%	(3)	13%	(7)	11%	(38)	0%	(0)

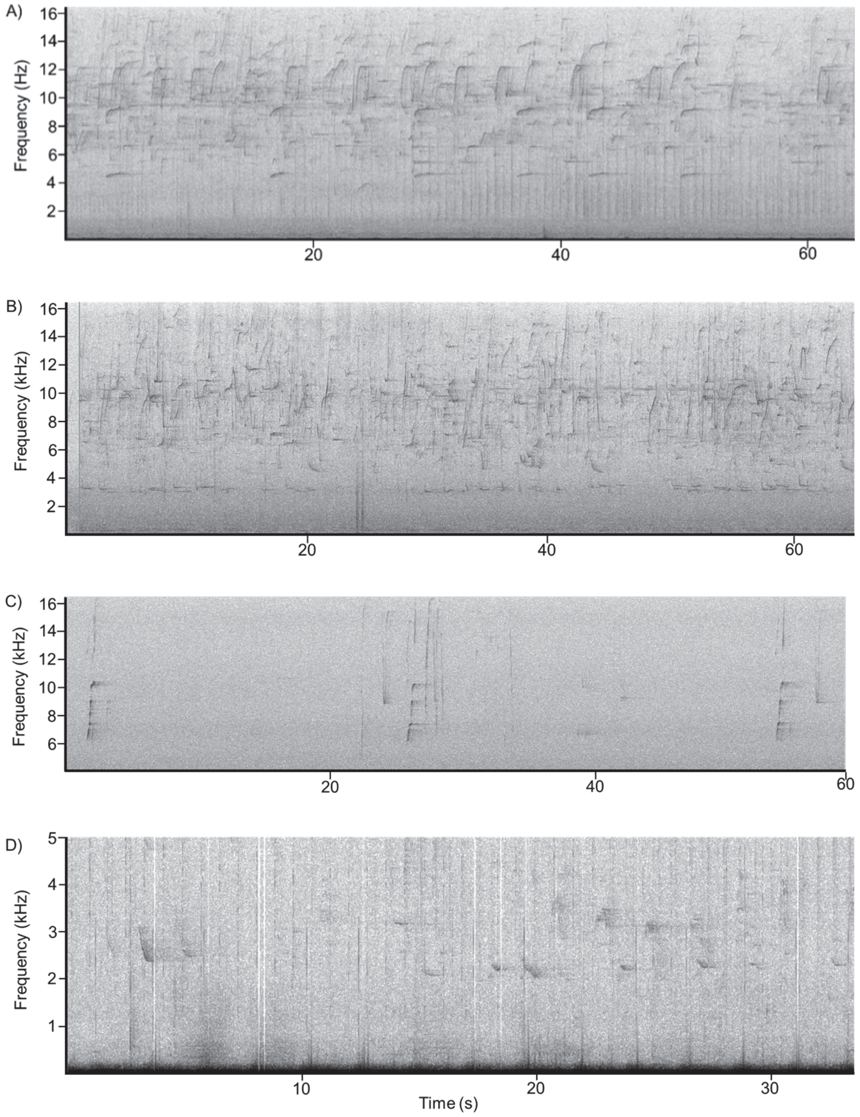

Fig. S1. Example spectrograms of unidentified toothed whale (UTW) whistles found in this study. Note the difference in the scaling of axes. A) high and mid-frequency whistles (8.10.2014 at SER; FFT: 2560). B) high and mid-frequency down- and steep upsweeping whistles (22.10.2017 at SER; FFT: 3328). C) Mid-frequency upsweeping whistles (10.11.2017 at SER; FFT: 3584). D) Lower frequency whistles (10.11.2016 at SER; FFT: 2811). For all spectrograms: 90% overlap and Hanning-window.

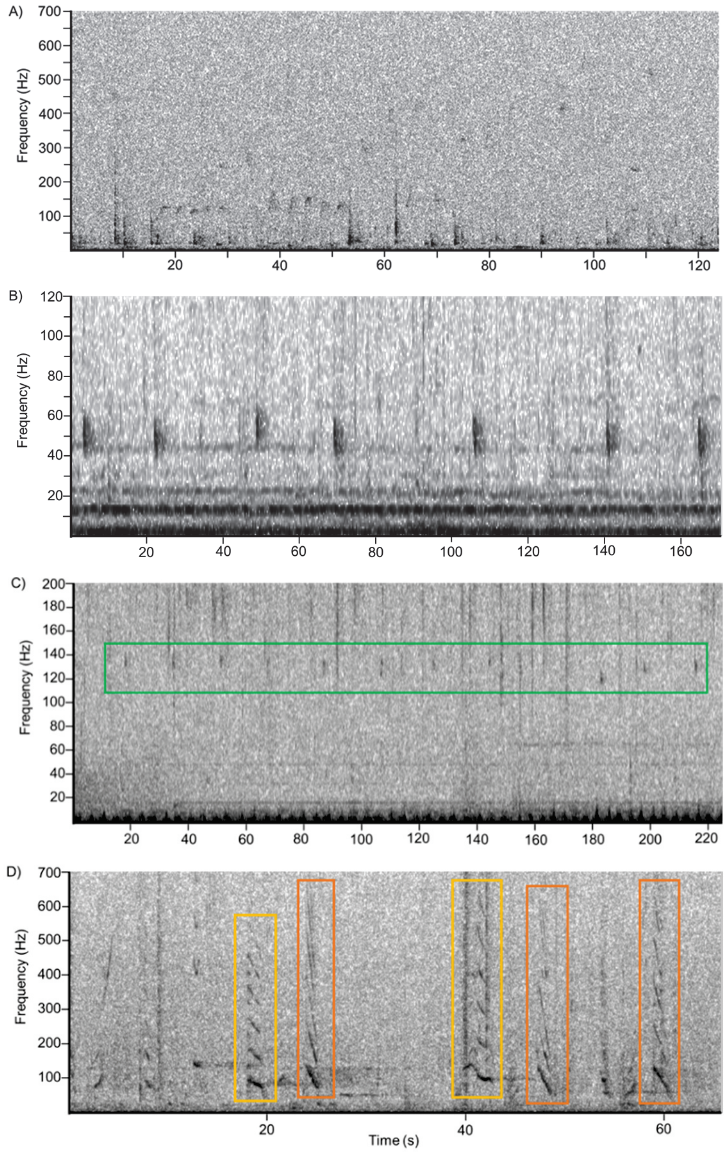

Fig S3. Example spectrograms of unidentified baleen whale (UBW) sounds. Note the difference in the scaling of axes. A) C1: low frequency faint tonal calling pattern (17.10.2017 at SER; FFT: 15738). B) C2: pulsed downsweeps with a bandwidth of about 20 Hz between approximately 60 to 40 Hz, but occasionally with broader bandwidth and up to 120 Hz and with varying inter-call-interval (24.07.2018 at SER; FFT: 22537). C) C3 (green box): Simple call sequences of short pulses with varying calling duration were detected at around 130 Hz or around 300 Hz (31.05.2018 at SER; FFT: 27900). D) C4 (orange box): signals summarizing frequency-modulated arched downsweeps between 120 to about 20 Hz; C5 (yellow box) signals contain low-frequency moans and grunts which can differ in their aural characteristic, but the spectral shape can look similar (14.10.2017 at SER; FFT: 1091). For all 90% overlap and Hanning-window.

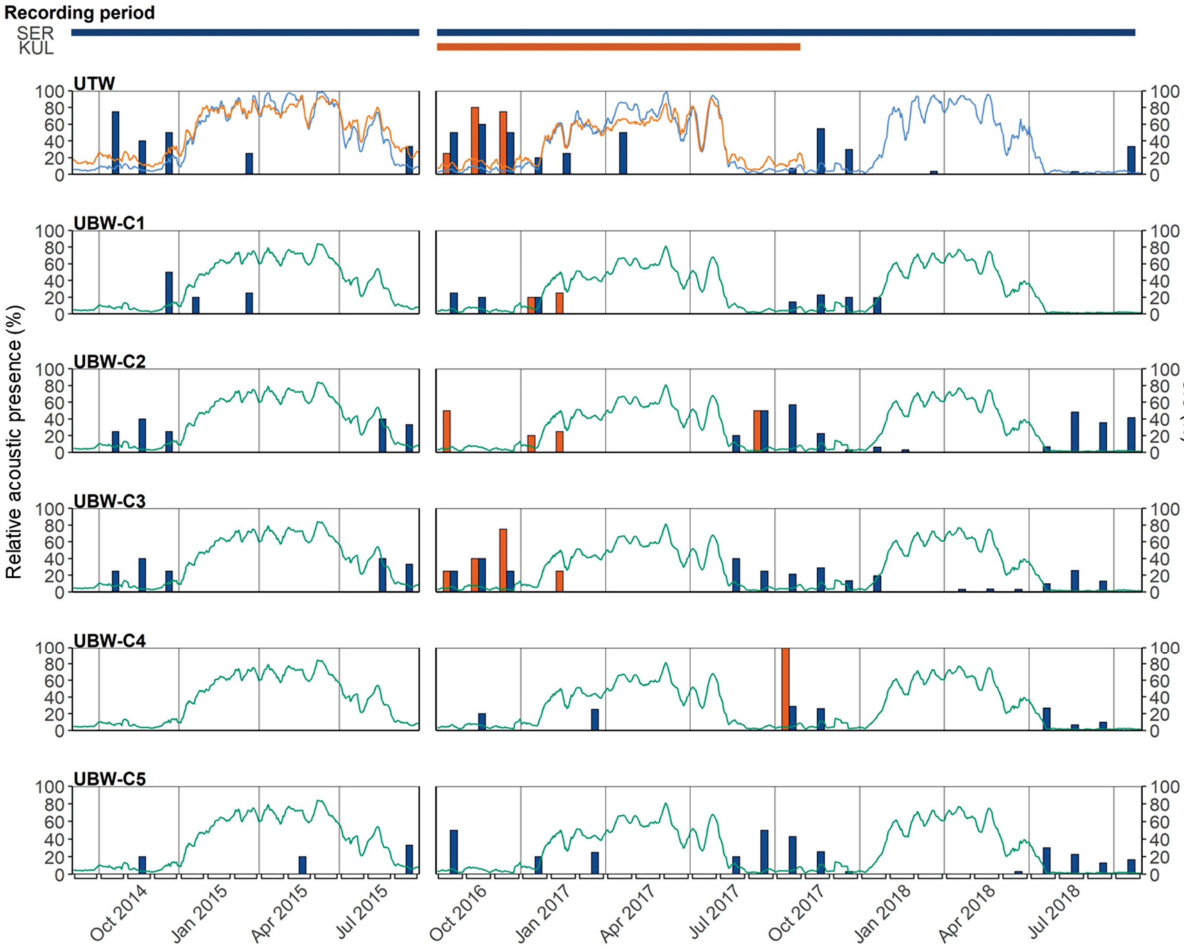

Fig. S3. Recording periods analyzed in this study for site SER (blue horizontal bars) and site KUL (orange horizontal bars). Monthly relative acoustic presence (proportion of days with acoustic presence per month on days analyzed, left y-axis) per unidentified calls and recording site (vertical bars) in relation to the sea ice concentration (SIC) given as 7-day daily moving means (right y-axis). The blue and the orange line represent the SIC within 40 x 40 km boxes around site SER and site KUL, respectively, for the assumed propagation distance of sounds produced by the species. The SIC spanning the larger Tasiilaq area (95 x 150 km) is represented as the green line, after the assumed propagation distance of sounds produced by baleen whales. The seasons are indicated by the vertical lines: autumn: September - November; winter: December - February; spring: March - May; summer: June - August.

3

Characterizing offshore polar ocean soundscapes using ecoacoustic intensity and diversity metrics

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Characterizing offshore polar ocean soundscapes using ecoacoustic intensity and diversity metrics

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Polar offshore environments are considered the last pristine soundscapes, but accelerating climate change and increasing human activity threaten their integrity. In order to assess the acoustic state of polar oceans, there is the need to investigate their soundscape characteristics more holistically. We apply a set of 14 ecoacoustic metrics (EAMs) to identify which metrics are best suited to reflect the characteristics of disturbed and naturally intact polar offshore soundscapes. We used two soundscape datasets: (i) the Arctic eastern Fram Strait (FS), which is already impacted by anthropogenic noise, and (ii) the quasi-pristine Antarctic Weddell Sea (WS). Our results show that EAMs when applied in concert can be used to quantitatively assess soundscape variability, enabling the appraisal of marine soundscapes over broad spatiotemporal scales. The tested set of EAMs was able to show that the eastern FS, which is virtually free from sea ice, lacks seasonal soundscape dynamics and exhibits low acoustic complexity owing to year-round wind-mediated sounds and anthropogenic noise. By contrast, the WS exhibits pronounced seasonal soundscape dynamics with greater soundscape heterogeneity driven in large part by the vocal activity of marine mammal communities, whose composition in turn varies with the prevailing seasonal sea ice conditions.

1. Introduction

Underwater acoustic environments (also referred to as 'soundscapes') are a complex assembly of all of the sounds produced by marine species (biophony), environmental conditions (geophony) and anthropogenic activities (anthropophony), which represent spatiotemporally unique soundscape patterns. While soundscapes represent a vital information resource for communication, orientation and foraging for a variety of marine organisms [1–3], many species are increasingly being affected and disturbed by soundscape alterations, owing to changes in environmental conditions and anthropogenic noise [4–6].

In polar areas, sea ice, icebergs and wind have a primary role in shaping ambient sound levels (e.g. [7–10]). However, in the Arctic Ocean (AO) the Arctic amplification, i.e. the rate of warming of this region which is almost four times the global average [11], has led to substantial changes and reductions in sea ice cover [11,12], resulting in higher ambient sound levels (e.g. [7]). The observed elevated ambient sound levels are primarily attributed to increased wind-mediated sounds owing to larger open water areas and cryonic sounds associated with unstable sea ice cover [7]. In the Southern Ocean (SO) increasing climate instability may lead to additional increases of sounds generated by breaking icebergs and glacier calving affecting ambient sound levels (e.g. [9]). This highlights the importance of considering the complex relationships among wind patterns and sea ice dynamics on overall soundscape characteristics in polar regions. In Arctic seas, sea ice decline promotes anthropogenic activities, including commercial shipping, fishing and tourism, as well as oil and gas exploration, which further increase underwater sound levels [13,14].

While the AO basin might still be considered acoustically pristine [15] as long as the sea ice cover remains some Arctic seas currently experience strong anthropogenic noise disturbance [14,16,17]. One example in the high Arctic is the Fram Strait (FS), which connects the AO basin with the Greenland Sea and is already experiencing seasonally dominating airgun and shipping noise (e.g. [18–20]), as well as annually increasing seasonal shipping activities [21]. By contrast, shipping noise in the SO is mainly connected to service traffic to research stations, while most of the SO stays traffic-free [14]. Tourism and fishing activities increase seasonally but are mainly concentrated off the Western Antarctic Peninsula [22]. Seismic airgun operations (scientific purpose only) also take place in the SO, albeit less frequently than in many Arctic regions (e.g. [20,23]). Marine mammals have formed on of the major sound sources in the SO that have always governed soundscape characteristics (e.g. [10,20]), when ignoring the major historical losses of cetaceans owing to commercial whaling [24], which must also have massively altered the underwater acoustic scene of the SO. Overall, the soundscape south of the Antarctic Convergence can currently still be considered relatively intact and quasi-pristine. In this regard, the SO could serve as a baseline to understand how intact polar marine soundscapes function, how they are composed and what characterizes them.

Recommendations of metrics to assess and monitor the *status quo* of marine soundscapes have focused mainly on ecoacoustic intensity metrics such as assessing the sound pressure level (SPL) of ambient sound (e.g. [20]), particularly in predefined frequency bands, such as within one-third-octave level (TOL) bands (e.g. [25–27]). However, characterizing marine soundscapes based solely on sound levels provides a one-dimensional view of the acoustic environment of a given habitat (e.g. [28]). Ecoacoustic diversity metrics, on the other hand, have the potential to capture the overall acoustic structure of the environment, i.e. the variability in the total spectro-temporal intensity distribution and complexity created by the ensemble of acoustic signals and how this is perceived.

To date, there are more than 60 different ecoacoustic metrics (EAMs) available, which extract and aggregate amplitude, time- and/or frequency-related variables into single values that are representative of intensity variability and complexity [29–32]. Of these, ecoacoustic diversity metrics have primarily been applied to investigate changes in terrestrial biodiversity patterns of acoustically active avian communities [33]. However, these metrics have yielded mixed results owing to the metrics' sensitivity to changes in the signal-to-noise ratio or acoustic masking (e.g. [30,34]). Their usefulness for assessing and quantifying biodiversity has therefore been under debate, in marine and terrestrial ecosystems (e.g. [30,33,35]). Nevertheless, for characterizing marine and terrestrial soundscapes, to discriminate between different habitat types and ecosystem status, and investigating temporal shifts in soundscape heterogeneity, uniformity and periodicity, the combination of various EAMs including ecoacoustic diversity metrics are increasingly applied and has proven valuable (e.g. [32,36–43]). In marine habitats, the application of combinations of EAMs has shown promising results to discriminate between various marine ecosystems, such as distinguishing healthy and degraded reefs [36], deep-sea versus coastal reefs [36–38], or polar pelagic and on-shelf habitats [39].

Here, we characterize soundscapes of the Arctic eastern FS as an example of an anthropogenically affected, and the Antarctic Weddell Sea (WS) as an example of a quasi-pristine polar soundscape by applying unsupervised machine learning and a combination of ecoacoustic intensity and diversity metrics on passive acoustic monitoring data collected between 2016 and 2018. We thereby evaluate the suitability of recommended intensity metrics [25,26] and of some of the most commonly applied diversity metrics (e.g. [29,31]) to describe and distinguish overall soundscape characteristics and to evaluate whether these metrics can serve as standards to monitor the acoustic states of polar offshore environments. We thereby hope to contribute towards the aim of the International Quiet Ocean Experiment (IQOE) and Global Ocean Observing System [44] regarding the development of standardized sets of metrics for holistic ocean soundscape monitoring.

2. Material and methods

2.1. Data acquisition

Acoustic data were collected in the eastern FS, AO, from 2016 to 2017 inclusive (herein referred to as FS station; figure 1) [46] and in the WS, Atlantic Sector of the SO, from 2017 to 2018 inclusive (herein referred to as WS station; figure 1) [47].

The FS recorder was attached to one of the oceanographic deep-sea moorings of the Frontiers in Arctic Marine Monitoring (FRAM) Ocean Observing System in the eastern FS [48]. This observatory is located in the pathway of the Atlantic Water inflow into the AO and West Spitsbergen Current [49]. The WS recorder formed part of a mooring within the Hybrid Antarctic Float Observation System (HAFOS) in the WS [50] within the Weddell Sea gyre [51]. Data for this study were selected to be offshore soundscape recordings from the eastern FS and the WS covering a similar period. The gain calibration differences of the hydrophones pre- and post-deployment were less than 1 dB for both recorders. Passive acoustic data were collected using autonomous acoustic Sono.Vault (Develogic GmbH, Hamburg) recorders with an omnidirectional hydrophone (RESON TC4037-3), set to sample continuously with a bit depth of 24 bits, storing the data in 10 min *.wav files (see table 1 for further details).

The eastern FS station was selected to represent a polar soundscape strongly affected by anthropogenic noise and low to no sea ice cover, thereby providing a potential baseline for future scenarios of polar soundscapes in Arctic regions that are still considered pristine. The WS station was selected as a baseline representation of a quasi-pristine and intact soundscape containing a high bioacoustic diversity and experiencing seasonal sea ice cover. Based on a pre-screening of long-term spectral averages of both datasets using the open portal to underwater soundscapes (OPUS; CC-BY 4.0 AWI 2023; [52]), we selected four months of data per recording site (table 1) to represent the seasonal soundscapes in terms of the typical sound sources present over the course of 1 year.

2.2. Ecoacoustic metrics

In total, 14 EAMs were applied, of which nine are intensity metrics and five are diversity metrics, to characterize variability in ambient sound and spectro-temporal intensity distribution, respectively.

2.2.1. Ecoacoustic intensity metrics

To compute the nine ecoacoustic intensity metrics (see electronic supplementary material, table S1 for an overview) in a standardized way, the MANTA (Making Ambient Noise Trends Accessible) software was used (v9.6.11 and v9.6.12, standalone version) [53]. MANTA computes the calibrated power spectral density (PSD; [54]) over 1-min time intervals (i.e. 10 data points per 10 min *.wav file) at a hybrid millidecade resolution [55,56]. The spectral probability density (SPD) [57,58] and the SPLs [59] were computed from the MANTA-derived PSD. The SPLs were computed for seven defined frequency bands: the broadband frequency range (10–3428 Hz, herein further referred to as broadband SPL) and six TOL bands, centred at 63, 125, 250 and 500 Hz, as recommended by the European Union Marine Strategy Framework Directive (MSFD; descriptor 11) [25] and Merchant *et al.* [26]. The sampling frequency of 6857 Hz was the smallest common denominator of the available frequency range for both

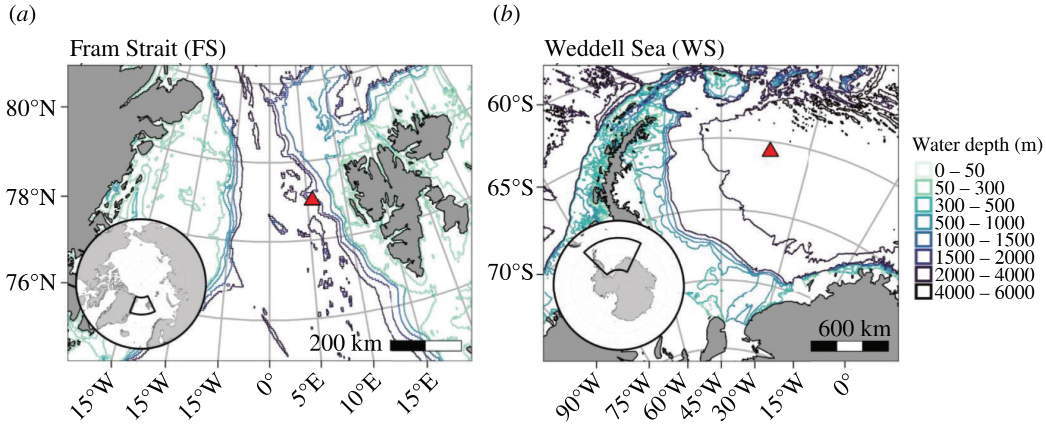

Figure 1. Geographic position of the recording stations. (*a*) FS, Arctic, recorder position 79 °N and 5.7 °E and (*b*) the WS, Antarctica, recorder position 65.7 °S and 36.7 °W. Maps were created with the R-package GGOCEANMAPS [45].

Table 1. Summary of the Sono.Vault recorder settings and deployment information.

region	deployment ID	position	recording period	months analysed	sampling rate (Hz)	recorder (water) depth (m)	pre- and post-calibration gain (dB)	sensor sensitivity (dB re 1 V µPa^{-1})
FS, AO	ARKF05-17 _SV1088	79 °N 5.7 °E	2016/07/23 –2017/07/18	August 2016 November 2016 February 2017 May 2017	48 000	808 (2100)	41.0/41.2	−193.1
WS, SO	AWI208-08 _SV1009	65.7 °S 36.7 °W	2017/01/19 –2018/05/02	May 2017 August 2017 November 2017 February 2018	6857	1032 (4766)	41.3/41	−192.5

datasets, which is why the SPL for the broadband frequency range was computed over 10–3428 Hz. Frequencies below 10 Hz were excluded to avoid a bias of low-frequency recorder-generated flow noise [60] on SPL measurements. The TOL bands were computed as decidecade bands as proposed by the IQOE [61]. To also describe the acoustic environment for species vocalizing at low frequencies (<50 Hz), such as fin whales (*Balaenoptera physalus*) and (Antarctic) blue whales (*B. musculus intermedia* and *B. musculus*), the 20 and 25 Hz TOL bands were included for the FS and WS stations, respectively.

The intensity metrics applied in our study are intended to characterize ambient sound [62], which is defined in our study as all sounds except for acoustic-self noise following the definition by the International Organization for Standardization (ISO) [63]. In this study, we apply the term ‘ambient sound’. We apply the term ‘noise’ when referring specifically to non-natural sounds, i.e. recorder-generated and anthropogenic signals.

2.2.2. Ecoacoustic diversity metrics

The five ecoacoustic diversity metrics to describe soundscape characteristics, such as spectro-temporal heterogeneity or uniformity (see electronic supplementary material, table S2 for an overview), were computed using the functions provided in the R-packages, i.e. TuneR [64], Seewave [65] and Soundecology [66]. For direct comparability of the computed diversity metrics between the FS and the

WS, the FS *.wav files were down-sampled (using the function 'downsample' of the package TuneR [64] in R) to a sampling rate of 6857 Hz, corresponding to the sample rate of the WS recordings. To avoid the aliasing of higher frequency signals on the one hand and to exclude frequencies below 10 Hz on the other hand, the audio data were band-pass filtered for 10–3428 Hz with a Finite Impulse Response filter (using the function 'fir' of the package SEEWAVE [65] in R, custom fitted to adhere to the original bit depth of 24) before down-sampling. All diversity metrics were computed for the broadband frequency range (10–3428 Hz) and for each 10 min *.wav file, resulting in one data point per 10-min file.

The Acoustic Complexity Index (ACI) measures intensity variation between two successive time bins and distinguishes high- from low-intensity variability, which are reflected as high and low ACI values, respectively [67]. The ACI has previously shown promise for distinguishing healthy from degraded reefs [36] and for data from the WS, for distinguishing on-shelf and pelagic soundscapes [39]. In our study, we consider increased ACI values to reflect greater temporal soundscape heterogeneity.

The Acoustic Evenness Index (AEI) and the Acoustic Diversity Index (ADI) indicate the degree of uniformity of the spectral intensity distribution by measuring intensity variation among frequency bins [68]. The AEI is based on the Gini coefficient, while the ADI is based on the Shannon's Diversity Index [68]. Both indices measure the intensity saturation within each frequency band, which reflects the degree of spectral uniformity. The AEI responds conversely to acoustic patterns compared with the ADI, meaning that with increasing acoustic uniformity the ADI increases towards 1 and the AEI decreases towards 0.

The total acoustic entropy index (HI) computes the Shannon evenness of the amplitude envelope and estimates the spectral and temporal uniformity of the intensity distribution across acoustic space [69]. The HI ranges between 0, indicating a heterogenous intensity distribution and 1, indicating a uniform intensity distribution. This index has shown promise in distinguishing healthy from degraded reefs [36] and on-shelf and pelagic habitats in the WS [39].

The Bioacoustic Index (BI) is intended to describe the saturation of acoustic space of a defined temporal range, by measuring the area under the mean spectral curve for sound levels greater than the minimum sound level between two frequency limits [70,71]. The BI was developed to measure avian abundance, with an increase in BI corresponding to increasing call rates and the intensity of choruses [70,72]. Therefore, in the context of our study, an increase in the BI reflects an increase in spectral heterogeneity.

2.3. Post-processing

The WS mooring contained an oceanographic sound source emitting RAFOS (ranging and fixing of sound; [73]) signals daily at 12:39 UTC. These signals are upsweeps that lasted 80s, ranged from 259 to 261 Hz and had a source level of 175 dB re 1 μPa. To prevent biases in the metrics' trends, the respective data points including the RAFOS signal were removed. For the ecoacoustic intensity metrics, the removal corresponded to four data points (each corresponding to a 1-min window) from 12:39 to 12:42 UTC. For the ecoacoustic diversity metrics, two data points (corresponding to two 10-min files) starting in the period of 12:28−12:42 UTC were discarded.

2.4. Environmental parameters

To interpret soundscape characteristics in the light of local environmental parameters known to affect polar soundscapes (e.g. [7,10]), data on the sea ice concentration (SIC) and wind speed were analysed for the recording positions. To spatially average the SIC and the wind speed across a defined area, the function 'extract' from the package RASTER [74] in R [75] was used, which averages across all pixels within the defined area boundaries.

2.4.1. Sea ice concentration

The daily SIC was obtained from the University of Bremen [76] at a grid resolution of 3.125 × 3.125 km on a polar stereographic grid for both the AO and SO. SICs of ≤15% were considered to indicate 'open water' conditions. The daily SIC was averaged for radii of 30, 50 and 100 km around the recording site. The size of the areas over which the daily SIC was averaged covers the assumed propagation range of high-, mid- and low-frequency signals of most pinnipeds and cetaceans (e.g. [77–79]).

2.4.2. Wind speed

The hourly east- and westward field components of wind speed 10 m above the Earth's surface were obtained from the European Centre for Medium-Range Weather Forecasts from the ERA5 dataset for re-analysis [80]. The hourly wind speed was spatially averaged across a radius of 0.25° latitude (corresponding to 27.75 km) around the recording sites.

2.5. Statistical analysis

To explore the influence of wind speed and SIC on the soundscape characteristics we fitted multiple regression models, assuming linearity (e.g. [7,10,81]) and fitting wind speed, SIC and the season as predictor variables and the hourly mean of ten EAMs (the broadband SPL, 63, 125, 250 and 500 Hz TOL band, ACI, AEI, ADI, HI and BI) as response variables. As the 20 and 25 Hz TOL bands were only measured for either the FS or the WS, and the 20 Hz band was strongly affected by flow noise, these TOL bands were excluded from further analysis. We included an interaction between wind speed and SIC to model the effect of sound generated by unstable sea ice moved by wind (e.g. [7]) and the effect of stable sea ice cover dampening the influence of wind on ambient sound levels (e.g. [10]). We differentiated between seasons to account for seasonal variation in the vocal activity of marine mammals and/or anthropogenic noise, which could cause deviation from the linear response of sea ice and wind speed on the metrics. For the broadband SPL, the 63 and 125 Hz TOL bands measured at the FS station a generalized linear gamma regression model using a log-link was applied. A general linear regression model was applied for the 250 and 500 Hz TOL band with a log link and an identity link, respectively, for the FS station. General linear models were fitted for the broadband SPL, 63, 250 and 500 Hz TOL band with an identity link and for the 125 Hz with a log-link at the WS station. A β-regression model, applying the 'betareg' function from the R package BETAREG [82] was applied for the AEI and the HI, as both metrics are bounded between 0 and 1. For the AEI, a log-link and for the HI a logit-link was applied. A generalized linear gamma regression with a log-link was fitted for the ACI and ADI for both regions, and for the BI for the FS only. In addition, the ADI of the WS was inverse transformed to follow a gamma distribution. A general linear model was fitted for the BI in the WS. General and generalized linear models were implemented using the 'glm' function in R [75].

To explore differences and similarities between the seasonal soundscape characteristics of the FS station and the WS station, we applied k-means clustering. The hourly mean of five intensity metrics, the broadband SPL, 63, 125, 250 and 500 Hz TOL band, and the hourly mean of the five-diversity metrics ACI, AEI, ADI, HI and BI, resulting in 5756 soundscape observations were used. As the 20 and 25 Hz TOL bands were only measured for either the FS or the WS, and the 20 Hz band was strongly affected by flow noise, these TOL bands were excluded. Before applying the k-means clustering, we tested for the cluster tendency of our dataset by applying Hopkins Statistics [83] using the function 'get_clust_tendency' from the R package FACTOEXTRA [84], which yielded a significant cluster tendency ($H > 0.9$). The data were then standardized by scaling to zero mean and unit variance by applying the 'decostand' function from the package VEGAN in R [85]. Following the approach by Roca and Van Opzeeland [39], we used the function 'cascadeKM' from the VEGAN package in R [85] to identify the number of clusters. We tested for 2–8 clusters (since we had two sites with four seasons each) and used the Simple Structure Index (SSI) [86] to determine the best number of clusters, as indicated by the highest SSI value. The SSI combines the maximum difference of each variable to a cluster prototype, the difference between the mean of variable values in each cluster prototype, and the overall mean of variable values for all clusters, which influences the cluster solution [86]. We then applied the k-means clustering algorithm on the hourly mean of the ten EAMs, applying the R built-in function 'kmeans' [75]. Furthermore, a principal component analysis (PCA) for feature selection using R's built-in function 'prccomp' [75] was applied to investigate that EAMs had the greatest explanatory power (contribution >10%) in explaining the variance of the clustered soundscape characteristics. To visualize the soundscape variation of the cluster analysis, we used a PCA biplot. All of the statistical analyses were conducted in R (v4.3.0) [75].

3. Results

3.1. Dominant sound sources

At the FS station, seasonal variation in the PSD and SPD was relatively low and could be attributed to the dominance of anthropogenic noise from seasonal (boreal summer, autumn and spring) airgun operations, as well as year-round ship noise and wind-mediated sounds (figure 2). However, airgun and ship noise were most pronounced in the PSD and SPD in the boreal summer and spring (figure 2*a,d*) and intense airgun and ship signals caused a high scattering of the SPD (figure 2*d*). In the boreal autumn, airgun noise was present only in the first week and had little effect on the seasonal PSD and SPD. Wind-mediated sounds increased the scattering of the SPD particularly in the higher frequencies (figure 2). The influence of biophonic sound sources (marine mammals) on the mean PSD was minimal (figure 2). The peaks in the lower percentiles (1–25%) and median PSD at 18 Hz and 20 Hz, from boreal summer to winter, indicated the acoustic presence of blue and fin whales, respectively (figure 2*a–c*). The peaks in the mean PSD from 12 to 25 Hz across all seasons were identified as flow noise (figure 2) and thus represent an acoustic artefact at the recorder and not a true component of the soundscape.

At the WS station, the year-round dominant sound sources were of natural origin (marine mammals, wind-mediated, sea ice and icebergs). The presence of anthropogenic sound sources was minimal, with seismic survey airgun pulses being detected only on a few days in the austral summer. Distinct peaks in the mean PSD curve revealed pronounced seasonal variation governed by the acoustic presence of five marine mammal species (figure 3): fin whales (20 Hz, across all months, as well as 86 and 99 Hz in the austral autumn and summer), Antarctic blue whales (28 Hz, across all months), Antarctic minke whales (*B. bonaerensis*; 60–1000 Hz in the austral autumn to spring), leopard seals (*Hydrurga leptonyx*; 300 Hz in the austral spring), and crabeater seals (*Lobodon carcinophaga*; 350–1000 Hz in the austral spring). The broader scattering of the SPD at frequencies above 250 Hz was likely a consequence of broadband sea ice and wind-mediated sounds (figure 3). In addition, in the austral summer, wind-mediated sounds increased the PSD in the absence of sea ice cover, and the plateau of the mean and median PSD in the range of 25–70 Hz likely reflected the interplay of airgun operations, Antarctic blue whale D-calls and supposedly iceberg sounds (figure 3*d*).

3.2. Ambient sound levels

At the FS station, the seasonal variability of the mean SPLs for all frequency bands was low, but the intra-seasonal variability of SPLs was high as indicated by the width of the interquartile range (figure 4, electronic supplementary material, table S3). Conversely, at the WS station, the mean SPLs for all frequency bands showed seasonality, while intra-seasonal variability of SPLs was generally low but increased for the 500 Hz TOL band (figure 4, electronic supplementary material, table S4).

The FS station exhibited higher annual median and mean SPLs for all of the investigated frequency bands compared with the WS station, with values of 107.6 and 112.5 dB re 1 μPa at the FS station, and 106.4 and 108.7 dB re 1 μPa at the WS station (figure 4), respectively. The median SPL measured in the austral summer at the WS station exceeded all of the seasonal median SPLs measured at the FS station in the 63 Hz TOL band. The lowest single broadband SPL was measured in the boreal summer at the FS station (93.8 dB re 1 μPa) and in the austral spring at the WS station (98.3 dB re 1 μPa). The highest single broadband SPLs were measured in the boreal spring in the FS (138.7 dB re 1 μPa) and in the austral summer at the WS station (142.2 dB re 1 μPa). At the FS station, the highest median SPLs for the 63 Hz TOL band were measured in the boreal spring (95.8 dB re 1 μPa) for the 125 Hz TOL band in the boreal autumn and winter (both, 93.3 dB re 1 μPa), and for the 250 and 500 Hz TOL band in the boreal winter (92.3 and 91.3 dB re 1 μPa, respectively). At the WS station, the highest median SPLs for the 63, 250 and 500 Hz TOL bands were measured in the austral summer (99.6, 90.7 and 89.6 dB re 1 μPa, respectively) and in the austral autumn for the 125 Hz TOL band (95.2 dB re 1 μPa).

At the FS station, the 20 Hz TOL band, which was applied to describe ambient sound levels within the communication range of fin and blue whales, was highly affected by flow noise (figure 2) and was therefore not interpretable. The 63 and 125 Hz TOL bands demonstrated sensitivity to airgun noise and the 250 Hz band was indicative of ship noise.

For the WS, the 25 Hz TOL band varied with the seasonal intensity variation of fin and Antarctic blue whale choruses (figure 4). In the austral summer in the WS, the 63 Hz TOL band was affected by Antarctic blue whale D-calls, airgun operations, and broadband bursts by supposedly distant iceberg sounds in austral summer. The 125 Hz band was also sensitive to the presence of airgun noise in

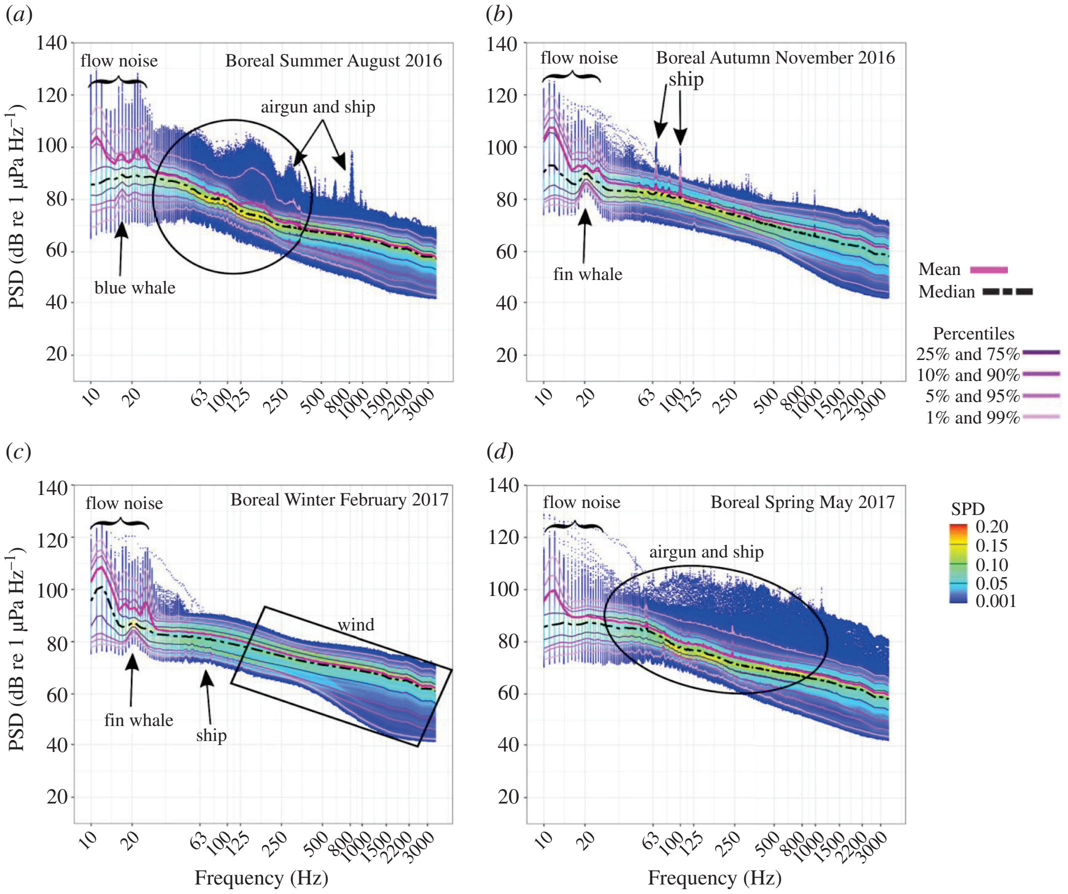

Figure 2. (*a–d*) Seasonal mean (pink line) and median (black-dashed line) power spectral density levels (PSD, dB re 1 µPa Hz^{-1}) and spectral probability density (SPD, colour scale) of the FS recordings. The main contributors to seasonal soundscape patterns are indicated by black arrows, boxes and circles. The indicated wind noise in *c* is exemplary and also applies to the other panels.

the austral summer. The 63, 250, 125 and 500 Hz TOL bands were sensitive to intensity fluctuations in Antarctic minke whale choruses from the austral autumn to spring. The 250 and 500 Hz bands reflected variation in the intensity of leopard and crabeater seal choruses during the austral spring.

The 500 Hz band best reflected temporal patterns in wind speed in both regions.

3.3. Spectro-temporal intensity variability

Overall, the ACI showed high temporal uniformity at the FS station and at the WS station across seasons but increased in response to repetitive impulsive broadband sounds such as clicks, pulses, cracking and squeaking or rubbing sounds. At the FS station, ACI peaks were related to the high-intensity click sequences of sperm whales (*Physeter macrocephalus*; boreal summer and autumn; see outliers in figure 5). At the WS station, the ACI responded to the chirps of Weddell seals (*Leptonychotes weddellii*; austral autumn), Antarctic minke whale pulses (in the austral autumn, winter and spring), and the cracking sounds of sea ice (in the austral autumn to spring; see outliers in figure 5).

Spectral heterogeneity (AEI) and uniformity (ADI) did not show pronounced seasonality at the FS station (figure 5). Here, both diversity metrics also had relatively low (AEI) and high (ADI) seasonal means (figure 5) reflecting the presence of continuous broadband wind-mediated sounds, ship and airgun noise. The AEI increased and the ADI decreased strongly in the presence of flow noise when wind-mediated sounds were absent. By contrast, in the WS, the AEI and the ADI showed a pronounced seasonal pattern (figure 5). The AEI decreased and ADI increased towards the austral spring as various marine mammal choruses saturated several frequency bands at the same time (figure 5). In the austral summer, the broadband wind-mediated sounds and sounds of icebergs caused a decrease in the AEI and an increase in the ADI.

At the FS station, broadband wind-mediated sounds, ship and airgun noise caused year-round high HI values (figure 5). Drops in the HI were mainly caused by the absence of broadband wind-mediated

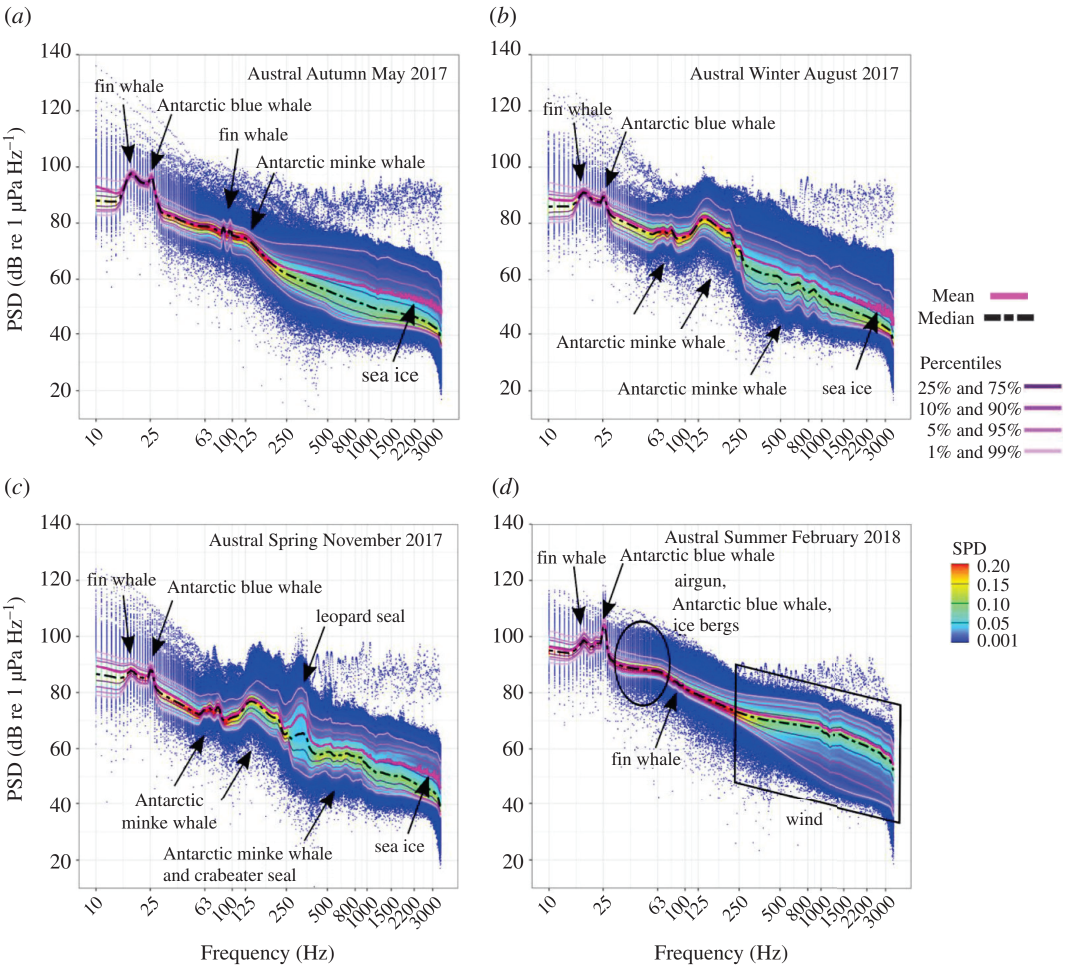

Figure 3. (*a–d*) Seasonal mean (pink line) and median (black-dashed line) power spectral density levels (PSD, dB re 1 µPa Hz^{-1}) and spectral probability density (SPD, colour scale) of the WS recordings. The main contributors to seasonal soundscape patterns are indicated by black arrows, boxes and circles.

sounds, while high-intensity sounds, e.g. from flow noise or a continuous fin whale chorus, were concentrated in the lower frequencies (i.e. 10–30 Hz). In the WS, marine mammal choruses simultaneously saturated multiple frequency bands resulting in high HI values.

The seasonal means of the BI were consistently low at the FS station (figure 5), which we attribute to broadband wind-mediated sounds, ship and airgun noise across seasons causing constant spectral uniformity. At the WS station, higher mean BI values indicated higher spectral heterogeneity and the observed seasonal variability (figure 5) was caused by variation in the spectral heterogeneity, attributed to the characteristics and intensity of the marine mammal choruses and wind-mediated sounds.

3.4. Environmental effects on the acoustic metric response

At both polar recording sites, no significant differences were found between the SIC around the recording site for the three investigated radii (30, 50 and 100 km), and therefore, only the SIC for the 50 km radius was further analysed.

At the FS station, sea ice was absent throughout the year (with the minor exception of two weeks at the end of boreal spring with SICs of 15–25%; electronic supplementary material, figure S1), while the WS station experienced open water conditions only in the austral summer but indicated a rather closed cover with SICs >79.7% in all of the other austral seasons (electronic supplementary material, figure S2).

At the FS station, the regression models indicate that increasing wind speed and the absence of sea ice cover influenced the SPLs of all frequency bands positively, with the greatest variation among seasons being found for the 500 Hz TOL band (electronic supplementary material, table S5 and figure

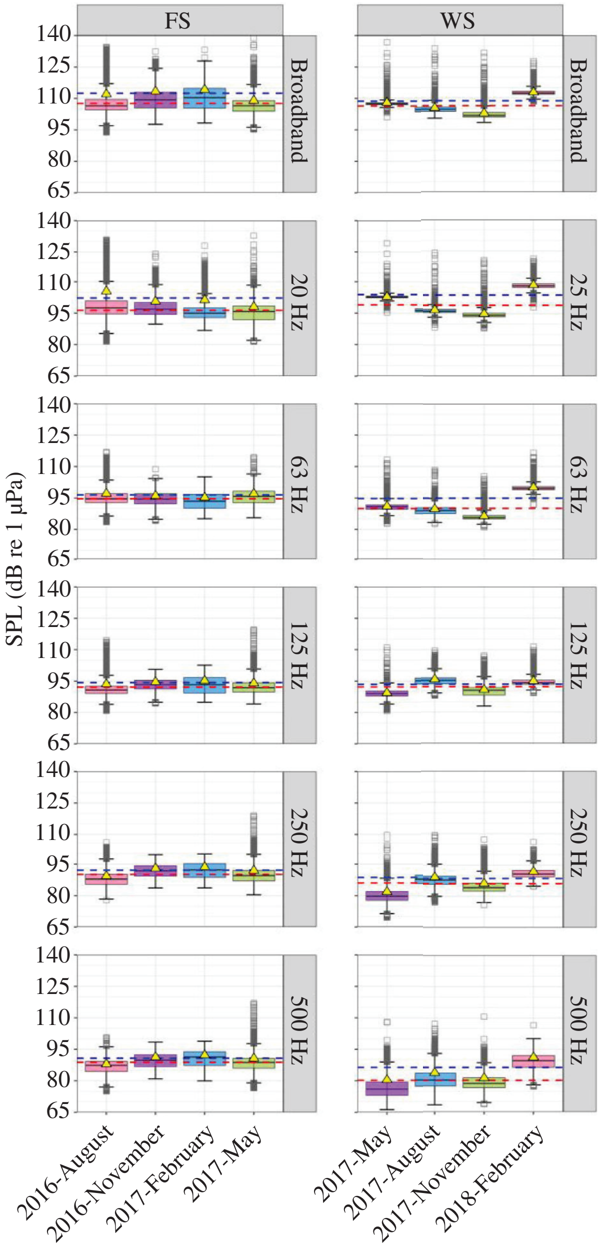

Figure 4. Ecoacoustic intensity metrics as SPLs for the broadband (10–3428 Hz) and TOL bands centred at 20 Hz (for the FS station), 25 Hz (for the WS station), and 63, 125, 250 and 500 Hz. The yellow triangles indicate the seasonal mean SPLs and the blue- and red-dashed lines indicate the annual mean and median SPLs, respectively. The box colours indicate the seasons: pink for summer, purple for autumn, blue for winter and green for spring. The lower and upper box borders show the interquartile range (25th to 75th percentiles) and the whiskers indicate the 5th and 95th percentiles. Seasonal medians are given by the inner black lines (see also electronic supplementary material, tables S3 and S4, for mean, median, maximum and minimum values for the FS station and the WS station, respectively).

S1). The low effect sizes ($R^2 \leq 0.3$, electronic supplementary material, table S5) for the broadband SPL, 63 and 125 Hz TOL band likely indicate a strong influence of anthropogenic noise in these bands, while the self-noise likely caused the low effect size ($R^2 = 0.153$) in the broadband SPL. By contrast to the SIC the wind speed affected the diversity metrics, but in different ways for each metric, and the effect sizes were generally low ($R^2 < 0.5$, electronic supplementary material, table S6). Moreover, seasonal variation was negligible for the diversity metrics at the FS station (electronic supplementary material, table S6 and figure S3). The ACI, AEI and BI were negatively, while the ADI and HI were positively associated with wind speed. Only the AEI, HI and BI were affected by the interaction of wind speed and sea ice, owing to the small increase of SIC in boreal spring (electronic supplementary material, table S6 and figure S3).

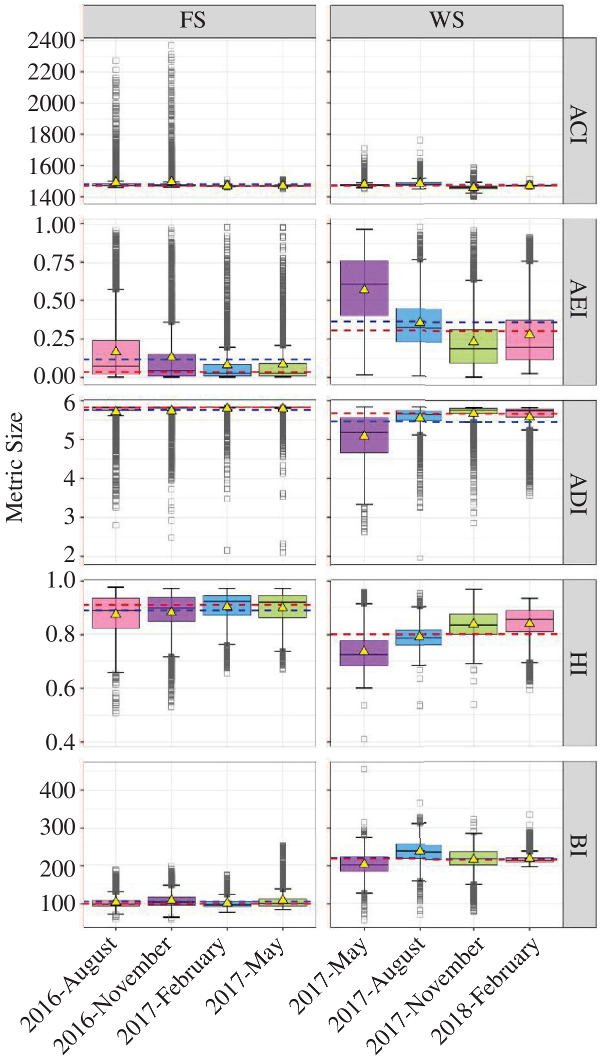

Figure 5. Ecoacoustic diversity metrics (ACI, AEI, ADI, HI and BI) for the FS and WS. The yellow triangles indicate the seasonal metric means and the blue- and red-dashed lines indicate the annual metric means and medians, respectively. The box colours indicate the seasons: pink for summer, purple for autumn, blue for winter and green for spring. The lower and upper box borders show the interquartile range (25th to 75th percentiles) and the whiskers indicate the 5th and 95th percentiles. Seasonal medians are given by the inner black lines.

At the WS station, the SPL of the 250 and 500 Hz TOL band were strongly influenced by the wind speed during absent sea ice cover in austral summer while sea ice cover dampened the influence of wind speed in the other seasons (electronic supplementary material, table S5 and figure S2). The low influence of wind speed in the remaining frequency bands is likely owing to interference with lower frequency (<200 Hz) marine mammal vocalizations and sound from breaking icebergs or calving glaciers. Interestingly, the SIC alone did not have a significant effect on the ACI but the interaction with wind speed did (electronic supplementary material, table S6 and figure S4). For the other metrics (AEI, ADI, HI and BI) high SIC dampened the effect of the wind speed on the metrics. Furthermore, the SIC in austral spring seemed to have only a weak or inverse influence on these metrics compared to the other sea ice-covered austral seasons (autumn and winter, electronic supplementary material, table S6 and figure S4).

3.5. Statistical comparison of soundscapes

The PCA for feature selection revealed that the first two principal components (PCs) explained 70% of the total variance in the soundscape characteristics (figure 6 and electronic supplementary material, table S7). The variance among the soundscape characteristics in the first two PCs was best explained by the AEI, HI, 500 Hz, 250 Hz, ADI, 63 Hz and broadband SPL (figure 6 and electronic supplementary material, figure S5). The 125 Hz, BI and ACI were deemed less important in explaining variance in the first two PCs. Moreover, k-means clustering using the SSI criteria identified four clusters that best explained the variation across regions and seasons in soundscape characteristics (figure 6 and table 2).

The soundscape observations of all boreal seasons of the FS were summarized within one cluster exhibiting high spectral uniformity caused by broadband wind-mediated sounds, airgun and ship noise. We consider the similarities in soundscape observations found between the FS and the WS in the cluster comprising mostly austral summer observations (table 2), to be an artefact explained by the low-frequency flow noise at the FS station causing a higher spectral heterogeneity in the data. Moreover, the k-means clustering did not seem to effectively distinguish anthropogenically affected periods in the austral summer in the WS, or variation in anthropogenic noise occurrence at the FS station (e.g. airgun noise versus ship noise in the boreal winter).

Seasonal differences in soundscape characteristics at the WS station are reflected by variation in three clusters separating the austral autumn, the austral summer and the combined austral winter and spring (table 2, figure 6). The cluster comprising mainly soundscape observations of the austral autumn reflects characteristics with spectral heterogeneity. These are governed by the absence of wind-mediated sounds due to sea ice cover, and variability in spectral intensity owing to the marine mammal choruses. The austral winter and spring cluster reflects characteristics with higher spectral uniformity and low sound levels. The similarity between these seasons is attributed to the absence of wind-mediated sounds linked to sea ice cover and the presence of a rich and diverse acoustic marine mammal community with relatively consistent chorus intensity. The austral summer cluster reflects soundscape characteristics with elevated sound levels governed by broadband wind-mediated sounds and intense vocalizations by fin whales and Antarctic blue whales in lower frequencies, additionally causing a lower spectral uniformity compared with the FS cluster.

4. Discussion

We applied a set of 14 ecoacoustic intensity and diversity metrics to characterize seasonal soundscapes of one recording site in the Arctic FS and one recording site in the Antarctic WS to investigate broad differences between anthropogenically affected and pristine polar offshore soundscape characteristics. We furthermore aimed to produce a baseline for understanding intact polar soundscapes. Moreover, we tested the suitability of a set of nine intensity and five diversity metrics in this context, and were able to show that this set of EAMs seems adequate to capture overall spatiotemporal differences in polar offshore soundscape characteristics and acoustic states. Our results suggest that soundscape characterization using a multi-metric approach including intensity and diversity metrics provides a valuable basis for assessing the acoustic *status quo* of remote polar offshore environments.

4.1. Differences between anthropogenically affected and pristine polar offshore soundscapes

One of our key findings with respect to how both regions differ acoustically was the pronounced seasonality of the soundscape characteristics of the WS station compared with the sea ice-free and anthropogenically affected FS station. Overall, the soundscape of the FS station exhibited relatively constant ambient sound levels and high spectro-temporal uniformity year-round governed by constant wind-mediated sounds and anthropogenic noise. The soundscape of the WS station exhibited pronounced seasonal soundscape characteristics with a higher degree of spectral heterogeneity and lower intra-seasonal variability in ambient sound levels compared with the station in the FS. The pronounced seasonal pattern was governed by the seasonal vocal activity of the marine mammal community composition causing varying saturation levels of the acoustic space linked to the seasonal sea ice patterns.

4.1.1. Overall ambient sound levels

At the FS station, the seasonal median SPLs for the 63–500 Hz TOL bands closely aligned with the annual median SPLs for the same TOL bands in the sea ice-covered western FS ranging from 83.9 to 94.6 dB re 1 μPa between 2008 to 2013 [18]. Similar to the western FS [18], we also found an effect of aigun pulses and distant fin whale calls on the PSD. Although we found no influence of bowhead whale (*B. mysticetus*) calls on the PSD at the eastern FS station compared with the western FS [18], a weak influence by blue whale calls in boreal summer was found to be similar to the observation of

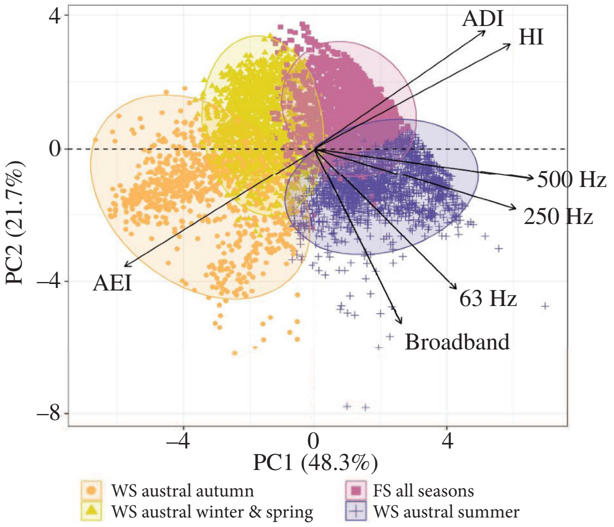

Figure 6. The PCA biplot for feature selection shows the clustered soundscape characteristics (table 2) explained by the combination of the hourly means (5756 soundscape observations) of the ten EAMs (broadband SPL, 63, 125, 250 and 500 Hz TOL band, ACI, AEI, ADI, HI and BI) along the first two principal components (PCs). Ellipses represent the 95% percentiles of cluster variables. The length of the arrows indicates the importance of the seven EAMs, which together explain approximately 70% of the variance in the first two PCs in differentiating among soundscape characteristics.

Table 2. Soundscape characteristics contributing to cluster formation. Clusters were obtained by applying k-means clustering on the hourly means of ten EAMs (broadband SPL, 63, 125, 250 and 500 Hz TOL band, ACI, AEI, ADI, HI and BI). The clusters are named according to their greatest contributors.

clusters		FS	WS		
		all seasons	austral autumn	austral winter and spring	austral summer
number of total soundscape observations		1731	765	1558	1702
FS	August 2016 (boreal summer)	30.2%	5.5%	2.2%	8.5%
	November 2016 (boreal autumn)	19.2%	5.9%	0.4%	19.7%
	February 2017 (boreal winter)	15.7%	2.2%	1.4%	21.2%
	May 2017 (boreal spring)	27.7%	2.9%	1.4%	13%
WS	May 2017 (austral autumn)	2.5%	66.1%	12.3%	0.1%
	August 2017 (austral winter)	0.2%	3.7%	41.7%	3.6%
	November 2017 (austral spring)	4.5%	1.7%	40.3%	0.1%
	February 2018 (austral summer)	0%	12%	0.2%	33.8%

Klinck *et al*. [19]. At the WS station, the median SPLs for the 63–500 Hz TOL bands ranged from 80.2 to 92.2 dB re 1 μPa. These values correspond to the range of values reported by Dziak *et al*. [87] for the Bransfield Strait, where sound levels from 70 to 90 dB re 1 Pa/Hz were documented for 51–90 Hz. The intra-seasonal variability within the measured frequency bands for each region in our study was also consistent with the observation of Haver *et al*. [20] that the variability of ambient sound levels at the FS station is higher owing to inconsistent changes in anthropogenic noise overlapping with other sound sources. By contrast, lower variability in ambient sound levels in the SO was caused by seasonally consistent marine mammal calling and weather patterns [20]. The annual median broadband SPL was similar between the two regions and was in the same range as the observations of Haver *et al*. [20], for the FS and the Bransfield Strait, SO, during 2009 and 2010. Together with our results, this suggests that the overall ambient sound levels in these two regions have not changed considerably over the last decade. For the FS, this seems surprising considering the increase in ships at Spitsbergen [21] and that global anthropogenic noise emissions are assumed to have doubled over the last decade [14] and increased even more quickly in shallow (sub-)Arctic areas (i.e. Norwegian, Barents and Kara Sea) [14].

However, with the opening of the Arctic likely leading to the establishment of the Trans-Polar Sea Route [21], ambient sound levels in the eastern FS will likely increase in the future.

The National Oceanic and Atmospheric Administration National Marine Fisheries Service [88] and Southall *et al*. [89] define a threshold of 120 dB re 1 μPa for continuous anthropogenic noise with the potential to harass marine mammals. Moreover, Halliday *et al*. [13] mention that wind-mediated sounds alone can increase ambient sound levels above 120 dB re 1μPa in the Arctic. At the FS station, ambient sound levels within the TOL bands of and over 63 Hz did not appear to surpass this threshold. However, even if this threshold is not reached or exceeded, this does not imply that the anthropogenic noise is not harming or disturbing for marine mammals in this region. At the WS station, occasional single SPL measurements, potentially stemming from earthquakes and icebergs [8,9,90], exceeded 120 dB re 1 μPa. The source level of fin and Antarctic blue whale vocalizations can reach 189 dB re 1 μPa @ 1 m [77] and therefore easily exceed this threshold when produced nearby. This means that anthropogenic noise-affected soundscapes are not necessarily characterized by high-amplitude ambient sound levels. Consequently, the intensity of natural, i.e. biophonic and geophonic, sounds should not be underestimated as a cause of high sound levels, and the interpretation of ambient sound levels requires sound source context.

4.1.2. Environmental sounds

The soundscape characteristics of both regions were significantly influenced by wind-mediated sounds but to different extents. Owing to a lack of year-round sea ice cover at the FS station, wind-mediated sounds caused increased and intra-seasonal variation in ambient sound levels as well as spectro-temporal uniformity year-round. At the WS station, soundscape characteristics were governed by the seasonal sea ice cover from the austral autumn to spring, and hence wind-mediated sounds only affected soundscape characteristics strongly in the sea ice-free austral summer. In addition, the sounds caused by breaking and collapsing icebergs increased ambient sound levels and spectral uniformity in the austral summer. In the austral winter, stable sea ice cover dampened wind-mediated sounds, while marine mammal vocalizations defined seasonal soundscape characteristics, consistent with the observation of Menze *et al*. [10]. However, corresponding to observations in sea ice-covered regions of the AO [7,18], strong winds during the freezing and melting seasons created cryonic sounds in the WS. These impulsive cracking or broadband abrasive sounds and harmonic tremors increased ambient sound levels, temporal heterogeneity (ACI) and spectral uniformity (AEI, ADI, HI and BI) at the WS station.

With ongoing climate change, sea ice regimes in the SO including the WS are expected to shift [91,92]. Annual ambient sound levels are therefore not only expected to rise in the AO but also in the SO as a consequence of unstable sea ice conditions, increased iceberg volume and extended periods of open water [7,9]. The increasing instability of the sea ice cover and the prolongation of open water periods might, furthermore, also change patterns of spectro-temporal uniformity owing to increasing effects of wind speed on soundscape characteristics.

4.1.3. Marine mammal acoustic presence

At the FS station, biophonic richness varied seasonally and was highest in the boreal summer and autumn, with blue and sperm whales and fin and sperm whales, respectively, being acoustically present (figure 2). In the boreal winter, only fin whales were detected (figure 2). This seasonal pattern of these species' acoustic presence corresponds to the results of Klinck *et al*. [19] from 2009 to 2010 and Ahonen *et al*. [93] from 2008 to 2018 in the FS, respectively. This consistency of acoustic presence patterns over the past decade supports previous observations (e.g. [93–95]) suggesting that the eastern FS provides a consistently seasonally suitable habitat for these species, likely as a result of the borealization of the AO (e.g. [93–96]). Linked to climate change and the borealization of the FS is the increasing period of open water and prey availability for seasonally migrating whales, including fin and blue whales, which has likely resulted in the observation of distributional changes north of 80°N and increases in the local abundance of these species [93–96]. Of the Arctic endemic marine mammals known to occur in the FS and around Spitsbergen (bearded seals (*Erignathus barbatus*), belugas (*Delphinapterus leucas*), narwhals (*Monodon monoceros*), and bowhead whales) [94,95,97] only bowhead whale vocalizations were acoustically identified with certainty at the FS station [98]. However, these vocalizations were not prominent at this recorder position [98] and hence unlikely to have significantly affected the overall soundscape characteristics.

In contrast to the FS station, biophonic richness at the WS station was highest during the austral winter. The WS station exhibited an overall richer biophony, with six marine mammal species contributing to seasonal soundscape characteristics (figure 3): two associated with open water conditions, i.e. fin and Antarctic blue whales, and four pagophilic species, i.e. Antarctic minke whales, leopard, crabeater and Weddell seals. Overall, their seasonal acoustic presence corresponds with the results of other PAM studies in the WS [10,99,100]. This suggests a basin-wide acoustic distribution of these species, and thereby, further highlights the year-round importance of the WS basin as a habitat for various marine mammals. All of these species, except for the sparse acoustic presence of Weddell seals detected by an increase in the ACI, affected and shaped the overall ambient sound levels and spectro-temporal uniformity.

Marine mammal choruses, had the strongest effect on the seasonal soundscape characteristics at the WS station, while the impact was weak at the FS station. In the WS, the year-round fin and Antarctic blue whale choruses with seasonal intensity variability are distinct soundscape characteristics, as also observed in other regions of the SO (e.g. [10,101]). The high intensity of these choruses is likely caused by higher species abundance or more localized presence at the WS recording site [101–103]. In the sea ice-covered seasons, the co-occurrence of intense choruses of Antarctic minke whales, leopard and crabeater seals in addition to the weaker but still prominent chorus of fin and Antarctic blue whales, saturated the temporal and spectral acoustic space. This caused a lower spectral heterogeneity (AEI, ADI and HI) over the course of the sea ice-covered seasons and aligns with previous terrestrial-based studies investigating the effect of high biophonic diversity and species richness on spectral uniformity [68,104]. Nevertheless, the rich biophonic diversity still maintains a higher degree of spectro-temporal heterogeneity in comparison to, for example, the presence of broadband and consistent wind-mediated sounds and additional anthropogenic noise such as at the FS station. This higher heterogeneity of co-occurring choruses can potentially be attributed to the hypothesis of species' unique acoustic spectro-temporal niche occupancy to avoid overlap of vocalizations [105]. In addition, the seasonal variability of ambient sound levels and spectro-temporal heterogeneity observed at the WS station, which is caused by the seasonal acoustic niche separation of these species, stands out as a key feature for an intact polar offshore soundscape.

In contrast, the FS station did not exhibit this chorus-driven effect on soundscape characteristics as blue and fin whale choruses were weak (figure 2) and the population size of both species is estimated to be low in the FS [94,95]. Furthermore, a potentially greater distance to the recorder may have limited the influence of fin and blue whales on the FS soundscape characteristics. Moreover, the sensitivity of the diversity metrics to changes in the signal-to-noise ratio, arising from wind-mediated sounds (e.g. [30,81]), the masking effect of anthropogenic noise (e.g. [34]), and the flow noise in the FS recordings, may have affected the influence of fin and blue whale choruses on the soundscape characteristics.

Distributional and compositional shifts in acoustic marine mammal communities owing to changes in sea ice regimes and prey availability are not only expected for the FS (e.g. [93,95,96]) but also in the WS [99,100]. Such sea ice-linked geographic shifts and changes in abundance may result in major modifications in the overall soundscape characteristics governed by changes in acoustic species composition and chorus intensity. In the AO, increases in fin and blue whale abundance might locally also result in more pronounced choruses, potentially increasing soundscape variability. Conversely, in the SO, reductions in sea ice habitats may potentially lead to geographic shifts in pagophilic marine mammals, which might result in a local weakening or loss of seasonal variability in soundscape characteristics as their choruses become locally fainter or are lost.

4.1.4. Anthropogenic noise

Our results imply that anthropogenic noise is present year-round in the eastern FS. The seasonal occurrence of airgun and ship noise aligns with the observations of Klinck *et al.* [19] and Haver *et al.* [20] for the same region. Moreover, airgun pulses probably contributed to intra-seasonal variation in ambient sound levels, which is also assumed by Haver *et al.* [20]. However, the merging of airgun noise also increased temporal uniformity, similar to the marine mammal choruses in the WS. Furthermore, anthropogenic noise contributed to a more stable spectral uniformity in the FS. This contrasts the findings of Wilford *et al.* [40], which were indicative of low uniformity for soundscapes containing airgun pulses. However, these pulses did not merge into a broad and continuous band such as the one observed at the FS station.

By contrast, the WS remains largely free from anthropogenic noise. Additionally, human activities in the SO are mostly limited to sea ice-free areas and seasons [20,22,23]. In this study, airgun pulses were also identified at the WS station but these were limited to a few days in the austral summer and did not seem to affect the soundscape characteristics of the WS. This might be explained by the similar impulsive characteristics of iceberg sounds and generally higher ambient noise levels attributed to wind-mediated sounds in the austral summer.

However, without appropriate adaptations of regulations governing human activities in polar oceans, further sea ice loss and resulting changes in ecosystem functions may lead to increasing anthropogenic activities not only in the last sea ice-covered and pristine regions in the AO but also in the SO [106].

4.2. Metric suitability for characterizing offshore polar soundscapes

4.2.1. Dominant characteristics

The PSD and the SPD are two metrics that are already widely applied and constitute a fundamental part of describing ocean soundscapes (e.g. [55–58]). In our study, the visual representation of the ambient sound in the context of the PSD along the SPD proved useful for identifying regional and seasonal salient sound sources (biophonic, geophonic and anthropophonic) and for visualizing seasonal soundscape characteristics. This seasonal visualization was valuable for understanding and interpreting the complexity of the diversity metrics. Moreover, it indicated that the set of selected metrics performed well in capturing seasonal soundscape characteristics. We, therefore, recommend the use of the PSD and SPD for visual investigation and interpretation of not only ambient sound levels but also of trends in the variability of spectro-temporal intensity distribution over large spatiotemporal scales.

4.2.2. Geophonic characteristics

Broadband wind-mediated and cryonic sounds affected SPLs (63, 125, 250, 500 Hz TOL bands and broadband SPL) and spectral uniformity (AEI, ADI, HI and BI) by increasing ambient noise levels and by lowering signal-to-noise ratios, which is consistent with previous studies (e.g. [7,10,30,81]). In both regions, the 500 Hz TOL proved to be the most robust indicator of broadband wind-mediated and cryonic sounds and may hold promise as a monitoring standard for changes in environmental conditions. In addition, the sensitivity of the ACI to cracking cryonic sounds could make this measure a valuable tool for studying changes in sea ice stability. Overall, the sensitivity of these intensity and diversity metrics to wind-mediated and cryonic sounds could therefore serve as a useful measure for studying changes in sea ice stability, sea ice patterns or increasing open water periods.

4.2.3. Biophonic characteristics

At the FS station, the weak acoustic presence of blue and fin whales was only indicated by small peaks at 18 and 20 Hz in the lower percentiles (1%–25%) of the PSD (figure 2). The respective TOL band did not properly reflect the presence of these species, owing to acoustic masking by flow noise and airgun noise. The sparse acoustic presence of sperm whales increased the ACI but did not affect the overall temporal heterogeneity of the soundscape.

At the WS station, the year-round fin and Antarctic blue whale choruses governed seasonal variation in ambient sound levels in the 25 Hz TOL band. In addition, peaks in the 63 Hz TOL band in the austral summer were in some cases indicative of Antarctic blue whale D-calls. During sea ice-covered conditions, the 125 Hz band was especially sensitive to intensity fluctuations in Antarctic minke whale choruses, while fluctuations in the 250 and 500 Hz TOL band in the course of austral spring were indicative of intensity variation in the leopard and crabeater seal choruses. Occasionally, high-intensity calls of Antarctic minke whales were also indicated by an increase in the ACI. Moreover, corresponding to previous studies (e.g. [68,104,107]), the AEI, ADI and HI indicated higher spectral uniformity for high call rates and rich acoustic biodiversity as the signal-to-noise ratio decreased owing to chorusing and more spectral niches becoming occupied. Siddagangaiah *et al.* [72] reported an increase in the ADI during fish chorusing, with harmonics occupying multiple frequency bands saturating the spectral acoustic space, similar to the call characteristics of Antarctic minke whales and the crabeater seals. Conversely, the presence of single high-intensity choruses such as fin and Antarctic blue whale choruses in the WS can decrease spectral uniformity. This observation aligns with other studies reporting a drop in the HI when chorus intensity increases and spectral uniformity is no longer given, as energy becomes concentrated into narrow bands [107,108]. This behaviour of the indices might be the key to the differentiation in soundscape characteristics between austral summer at the WS station and the FS station. In combination with the other diversity metrics, the BI could therefore be suitable as an indicator of soundscape patterns dominated by biophony forming spectral bands. This suggests that the diversity metrics along the TOL bands can function to monitor the influence of biophonic sources on shaping the characteristics and potential climatic-induced changes of the SO soundscape over large spatiotemporal scales.

4.2.4. Anthropophonic characteristics

We found that the TOL bands recommended by the MSFD [25] effectively captured the impact of airgun noise on sound levels in the FS. Among the two TOL bands recommended by Merchant *et al.* [26], the 250 Hz band appeared to be most indicative of ship noise while the 500 Hz TOL band was strongly influenced by wind-mediated noise in the FS. To our knowledge, our study is the first to apply the TOL bands recommended by the MSFD [25] and Merchant *et al.* [26] to characterize ambient sound levels for the Atlantic sector of the SO. However, these TOL bands mainly reflected the seasonal vocal activity of marine mammals (§4.2.3) and environmental sounds (§4.2.3), instead of shipping noise as envisioned by the MSFD recommendations and Merchant *et al.* [26]. Without critical review or previous knowledge of the soundscape, these metrics would have characterized this area as strongly impacted by ship noise during periods with sea ice cover. However, in austral summer, the 63 and 125 Hz TOL bands were able to indicate airgun noise. Therefore, these bands might still be effective for monitoring anthropogenic noise in sea ice-free regions of the SO. Our results, therefore, call for caution in defining and applying global standard metrics. For the SO, other bands with less marine mammal interference would need to be selected for monitoring current global shipping noise.

4.2.5. Identifying spatiotemporal soundscape patterns

In this study, metrics describing ambient sound levels (500, 250 and 63 Hz TOL band and broadband SPL) and spectral variability (AEI, ADI and HI) were most important in differentiating between seasonal and regional soundscape characteristics. The great importance of ambient sound levels is likely owing to seasonal variation in ambient sound levels at the WS station governed by the seasonality of marine mammal vocal activity and the dampening effect of sea ice cover. Our results in regards to the diversity metrics align with the study of Williams *et al*. [36] and Roca & Van Opzeeland [39] who reported the HI as one of the best-performing indices in differentiating between different marine habitat types (degraded, healthy, polar offshore and polar onshore). In contrast to our findings, these two studies found that the AEI and ADI were less important in discriminating between sites, while these studies considered the ACI and BI as most important [36,39]. Roca & Van Opzeeland [39] included soundscape observations from the SO with a higher abundance of Weddell seal calls, which might have resulted in a higher ACI variability among polar onshore and pelagic soundscapes. Consequently, the ACI might not have performed as well in our study for differentiating between seasonal and regional soundscape characteristics as both stations carried low or similar amounts of signals that the ACI responds to. This emphasizes that the importance of different metrics to differentiate soundscapes might vary with the spatiotemporal scale of the dataset in question (e.g. see also [32]), and a combination of multiple metrics provides a more robust monitoring standard for soundscapes spanning large spatial and temporal scales.

In our study, we used hourly mean values of EAMs to differentiate soundscape characteristics, which might have smoothed out more subtle soundscape variability but which provided a good overall representation of the overall spatiotemporal soundscape variability. However, we did not account for variability within soundscape properties, for example, the 95% confidence interval [40] or standard deviation [32], which has been shown to capture more subtle soundscape characteristics and improved characterization among different habitats [32]. Consequently, the interquartile range (25th to 75th percentile), which we used to indicate the intra-seasonal variability of ambient sound in at the FS station, might also be useful to include more subtle soundscape variation in the characterization of soundscapes.

Here, we focused on diversity metrics that emphasized spectral uniformity versus heterogeneity (AEI, ADI, HI and BI) and included lower-frequency TOL bands (maximum 500 Hz TOL band). The application of higher-frequency TOL bands will permit capturing additional local sound sources, and hence could improve soundscape characterization by including the full spectrum. Furthermore, including diversity metrics that emphasize temporal heterogeneity, such as temporal uniformity (Ht; [69]), or time-lagged autocorrelation of SPLs for quantifying periodicity [40], will likely also enhance the overall characterization of soundscapes. Wilford *et al*. [40] suggested incorporating further soundscape properties such as impulsiveness and recommended using kurtosis as a metric. They further applied the D-index, which supposedly better reflects the spectro-temporal uniformity in marine soundscapes compared with the HI [40]. In our study, however, we focused mainly on a suite of diversity metrics that have already been commonly applied (e.g. [29–31]). Nevertheless, Wilford *et al*. [40] recommended that standard metrics as well as other metric combinations are needed to determine the best set of EAMs to explore overall global soundscape characteristics and quantify the acoustic states.

5. Conclusions

Our results suggest that a combination of ecoacoustic intensity and diversity metrics is useful for investigating spatiotemporal soundscape characteristics in polar offshore regions in relation to anthropogenic noise and environmental conditions in order to assess the *status quo* of the marine acoustic environment. Our study uncovered differences in annual soundscape characteristics of our recording site in the Arctic FS strongly impacted by anthropogenic noise and the acoustically quasi-pristine Antarctic WS. It also provides a blueprint of a methodological approach to explore variations in polar acoustic offshore environments more holistically. Our results hence provide an essential baseline for further investigations of polar soundscape patterns on larger spatial and temporal scales, such as comparisons across the WS basin or the FS, which is particularly crucial in the light of climate change-induced alterations in soundscape regimes.

Ethics. The permission to deploy the recorder in the Weddell Sea was granted by the German federal environmental agency (UBA permit no. II 2.8-94033/137).

Data accessibility. The passive acoustic datasets analysed in this study are available through the PANGEA database: Thomisch *et al*. [46] (for data collected in the FS) and Thomisch *et al*. [47] (for data collected in the WS). The long-term spectrograms of the analysed recorders can be accessed via the Open Portal to Underwater Soundscapes (OPUS) accessible at (CC BY 4.0, AWI 2023 [52]).

Supplementary material is available online [109].

Declaration of AI use. The free version of OpenAI.ChatGTP (v3.4, 2023) was used by R.M.M. in the process of text editing within the writing process of the first draft to improve readability and language.

Authors' contributions. R.M.M.: Conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, visualization, writing—original draft, writing—review and editing; K.T.: conceptualization, data curation, methodology, resources, software, supervision, writing—original draft, writing—review and editing; J.I.H.: conceptualization, funding acquisition, project administration, supervision, writing—review and editing; I.V.O.: conceptualization, funding acquisition, methodology, project administration, resources, supervision, writing—original draft, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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Supplementary

Table S1. Overview of the ecoacoustic intensity metrics applied in this study to characterise ambient sound. Statistical evaluation was conducted in R (v4.3.0; R Core Team, 2023). TOL = 1/3-octave-level.

Metric	**Statistical evaluation and illustration**	**Computation**	**Setting**	**References**
Power spectral density level (PSD; dB re 1 µPa Hz^{-1})	Seasonal mean, median, and percentiles (1%, 5%, 25%, 75%, 95%, and 99%)	MANTA	Time interval: 1 min; Frequency resolution: hybrid millidecade	(Martin *et al.*, 2021b; a; Miksis-Olds *et al.*, 2021); widely applied
Spectral probability density (SPD)	Seasonal empirical probability distribution of PSDLs across frequencies	Derived from MANTA product	Histogram bin width for probability density: 0.1	(Merchant *et al.*, 2013; Merchant *et al.*, 2015); widely applied
Sound pressure level (SPL; dB re 1 µPa^2): - Broadband (10-3,428 Hz) - 20 Hz TOL band (FS) - 25 Hz TOL band (WS) - 63 Hz TOL band - 125 Hz TOL band - 250 Hz TOL band - 500 Hz TOL band	Seasonal mean, median, min, max, and percentiles (25%, 75%)	Derived from MANTA product	Time interval: 1 min Frequency resolution: broadband (10-3,428 Hz) and TOL bands	(Merchant *et al.*, 2016; MSFD, 2017); widely and increasingly applied

Table S2. Summary of the ecoacoustic diversity metrics selected to characterize the spectro-temporal intensity variability and the respective settings applied to compute these metrics over the broadband frequency range (10-3,428 Hz) and for each 10 min *.wav file. These metrics were computed using R (v4.3.0; R Core Team, 2023), and the R-packages tuneR (Ligges *et al.*, 2023), seewave (Sueur *et al.*, 2012), and soundecology (Villanueva-Rivera and Pijanowski, 2018).

Metric	**Short description**	**Intended soundscape characteristics to describe in this study**	**R-PACKAGE and Setting**	**Reference**
ACI (acoustic complexity index)	Intensity variation across time.	Temporal heterogeneity	SEEWAVE, Hanning-window; window lengths = 512 points; overlap = 50%; number of windows = 10	(Pieretti *et al.*, 2011)
AEI (acoustic evenness index)	Heterogeneity of intensity variation across frequency bands (Gini coefficient) and above a set power threshold.	Spectral heterogeneity	SOUNDECOLOGY, Size of frequency bands = 10 Hz; dB threshold = -50 dB	(Villanueva-Rivera *et al.*, 2011)
ADI (acoustic diversity index)	Evenness of intensity variation across frequency bands (Shannon's Diversity Index) and above a set power threshold.	Spectral uniformity	SOUNDECOLOGY, Size of frequency bands = 10 Hz; dB threshold = -50 dB	(Villanueva-Rivera *et al.*, 2011)
HI (total entropy)	Evenness of intensity variation across time and frequency above a set power threshold. (Shannon evenness of the amplitude envelop).	Spectral and temporal uniformity	SEEWAVE, Window lengths = 512 points, Hilbert amplitude envelop; smoothing = NULL	(Sueur *et al.*, 2008)
BI (bioacoustic index)	Area under the spectrum curve between two frequency limits.	Spectral heterogeneity	SOUNDECOLOGY, FFT (Fast Fourier Transformation) window size = 512 points	(Boelman *et al.*, 2007)

Table S3. Monthly (seasonal) and annual mean, median, percentile range, and minimum and maximum SPL (dB re 1 µPa) for the Fram Strait (FS) station. IQR= Inter quartile range

Frequency band	**Boreal summer (Aug. 2016)**	**Boreal autumn (Nov. 2016)**	**Boreal winter (Feb. 2017)**	**Boreal spring (May. 2017)**	**Annual**
	Mean (± standard deviation)				
10-3428 Hz	112.0 (±4.7)	113.3 (±5.3)	114.2 (±6.1)	109.0 (±3.9)	112.5 (±5.2)
20 Hz	105.4 (±5.6)	100.5 (±4.2)	101.2 (±5.1)	98.0 (±4.4)	102.2 (±5)
63 Hz	97.1 (±3.6)	96.1 (±3.6)	95.2 (±3.9)	97.0 (±3.6)	96.4 (±3.7)
125 Hz	93.5 (±3.3)	94.6 (±3.3)	95.2 (±4.3)	94.0 (±3.3)	94.3 (±3.7)
250 Hz	89.3 (±3.5)	93.0 (±3.3)	93.6 (±4.0)	92.0 (±3.8)	92.2 (±4)
500 Hz	87.9 (±3.8)	91.3 (±3.7)	92.2 (±4.4)	90.7 (±4.1)	90.7 (±4.3)
	Median				
10-3428 Hz	106.5	109.3	110.4	106.5	107.6
20 Hz	97.5	96.9	95.0	95.8	96.3
63 Hz	94.6	94.5	93.4	95.8	94.6
125 Hz	90.7	93.3	93.3	91.8	92.1
250 Hz	87.9	91.8	92.3	89.5	90.1
500 Hz	87.4	89.8	91.3	88.7	88.7
	Percentile range 25 - 75% (IQR)				
10-3428 Hz	104.5 - 109.5 (5)	105.4 - 113.0 (7.6)	105.3 - 114.8 (9.5)	103.9 - 109.0 (5.1)	104.7-111.4 (6.7)
20 Hz	94.6 - 100.9 (6.3)	94.4 - 100.1 (5.7)	92.9 - 97.5 (4.6)	91.9 - 98.5 (6.6)	93.5- 99.4 (5.9)
63 Hz	92.8 - 97.1 (4.3)	92.2 - 97.0 (4.8)	90.2 - 96.7 (6.5)	92.7 - 98.2 (5.5)	92.1-97.4 (5.3)
125 Hz	89.1 - 92.5 (3.4)	91.2 - 95.4 (4.2)	89.3 - 96.7 (7.4)	89.8 - 94.2 (4.4)	89.8-94.7 (4.9)
250 Hz	85.4 - 90.2 (4.8)	89.3 - 94.2 (4.9)	88.6 - 95.2 (6.6)	87.0 - 92.0 (5.0)	87.4-92.9 (5.5)
500 Hz	84.4 - 89.2 (4.8)	86.8 - 92.4 (5.6)	87.3 - 93.9 (6.6)	86.0 - 90.7 (4.7)	86.0-91.6 (5.6)
	Min. – Max. (range width)				
10-3428 Hz	93.8-134.6 (40.8)	97.7-132.4 (34.7)	98.3-133.2 (34.9)	95.2-138.7 (43.5)	93.8-138.7 (44.9)
20 Hz	81.4-131.0 (49.6)	89.7-124.1 (34.4)	86.8-128.0 (41.2)	81.4-132.8 (51.4)	81.4-132.8 (51.4)
63 Hz	83.5-117.0 (33.5)	84.1-108.7 (24.6)	85.1-105.1 (20.)	85.6-114.4 (28.8)	83.5-117.0 (33.5)
125 Hz	80.7-114.6 (33.9)	84.3-100.7 (16.4)	84.9-102.6 (17.7)	84.1-119.6 (35.5)	80.7-119.6 (38.9)
250 Hz	77.8-105.4 (27.6)	83.6-99.5 (15.9)	83.7-99.8 (16.1)	80.4-119.2 (38.8)	77.8-119.2 (41.4)
500 Hz	75.0-100.6 (25.6)	80.9-98.5 (17.6)	79.9-98.9 (19.0)	76.5-117.1 (40.6)	75.0-117.1 (42.1)

Table S4. Monthly (seasonal) and annual mean, median, percentile range, and minimum and maximum SPL (dB re 1 μPa) for the Weddell Sea (WS) station. IQR= Inter quartile range.

Frequency band	Austral autumn (May 2017)	Austral winter (Aug. 2017)	Austral spring (Nov 2017)	Austral summer (Feb. 2018)	Annual
	Mean				
10-3428 Hz	108.0 (±1)	105.3 (±1.7)	102.8 (±1.8)	112.8 (±1.2)	108.7 (±4.1)
25 Hz	102.8 (±0.9)	96.7 (±1.2)	94.9 (±1.5)	108.7 (±1.4)	103.9 (±5.6)
63 Hz	91.1 (±1.8)	89.7 (±2.2)	86.3 (±1.5)	100.0 (±1.3)	94.8 (±3.4)
125 Hz	89.4 (±1.9)	95.7 (±2.3)	90.8 (±2.4)	94.9 (±1.7)	93.5 (±3.4)
250 Hz	81.8 (±3.4)	89.2 (±3.2)	86.2 (±3.1)	91.9 (±2.4)	88.6 (±5.1)
500 Hz	80.4 (±4.9)	83.8 (±4.7)	81.3 (±3.8)	91.2 (±4.3)	86.4 (±6.4)
	Median				
10-3428 Hz	104.6	107.5	101.7	112.4	106.4
25 Hz	96.2	102.7	94.2	108.3	99.0
63 Hz	88.9	90.8	85.6	99.6	90.0
125 Hz	95.2	89.1	90.5	94.1	92.2
250 Hz	87.8	79.7	84.2	90.7	86.1
500 Hz	80.3	76.1	78.7	89.6	80.2
	Percentile range 25 - 75% (IQR)				
10-3428 Hz	103.6-105.7 (2.1)	107.0-107.9 (0.9)	100.9-103.0 (2.1)	111.8-113.3 (1.5)	103.4 - 108.9 (5.5)
25 Hz	95.6-97.1 (1.5)	102.2-103.1 (0.9)	93.4-95.2 (1.8)	107.5-109.3 (1.8)	95.5 - 103.7 (8.2)
63 Hz	87.5-90.4 (2.9)	89.6-91.7 (2.1)	84.9-86.6 (1.7)	98.9-100.4 (1.5)	86.9 - 93.5 (6.6)
125 Hz	93.6-96.5 (2.9)	87.8-90.4 (2.6)	88.2-91.7 (3.5)	93.4-95.3 (1.9)	89.7 - 94.6 (4.9)
250 Hz	85.8-89.7 (3.9)	77.7-81.9 (4.2)	82.5-86.3 (3.8)	89.4-92.4 (3.0)	82.0 - 89.7 (7.7)
500 Hz	77.4-83.6 (6.2)	73.0-79.4 (6.4)	76.6-81.4 (4.8)	86.4-92.1 (5.7)	76.5 - 85.8 (9.3)
	Min. – Max. (range width)				
10-3428 Hz	100.4-133.8 (33.4)	101.0-142.2 (41.2)	98.3-131.7 (33.4)	108.3-127.8 (19.5)	98.3 - 142.2 (43.9)
25 Hz	88.3-124.2 (35.9)	95.3-129.2 (33.9)	88.0-120.6 (32.6)	98.0-121.3 (23.3)	88.0 - 129.2 (41.2)
63 Hz	82.5-108.4 (25.9)	82.6-113.3 (30.7)	80.9-105.3 (24.4)	91.7-116.6 (24.9)	80.9 - 116.6 (35.7)
125 Hz	87.9-109.6 (21.7)	80.8-111.1 (30.3)	83.0-107.1 (24.1)	89.2-114.4 (25.2)	80.8 - 111.4 (30.6)
250 Hz	77.0-109.3 (32.3)	69.6-109.7 (40.1)	75.8-107.2 (31.4)	84.8-106.1 (21.3)	69.6 - 109.7 (40.1)
500 Hz	68.4-107.3 (38.9)	66.3-108.0 (41.7)	68.8-110.6 (41.8)	77.2-106.5 (29.3)	66.3 - 110.6 (44.3)

Table S5. Statistical results for the linear regression models to assess the influence of wind speed (m/s) and the sea ice concentration (SIC; %), and differences between seasons, on the SPL of defined frequency bands for the Fram Strait (FS) station and the Weddell Sea (WS) station. The wind speed, SIC, and season were applied as fixed terms on the hourly means (2879 and 2877 observations in total for the FS station and the WS stations, respectively) of the SPLs, we also included an interaction term of wind speed and SIC. For the broadband SPL and the 63, and 125 Hz TOL bands at the FS station a generalized linear gamma regression model using a log-link was applied. A general linear regression model was fitted for the 250 and 500 Hz TOL band with a log-link and an identity-link, respectively, for the FS station. General linear models were fitted for the broadband SPL, 63, 250, and 500 Hz TOL band with an identity-link and for the 125 Hz with a log-link at the WS station. At the FS station the seasons correspond to the boreal summer (2016-Aug), spring (2017-Feb), autumn (2017-Nov), and winter (2017-Feb) and at the WS station to austral summer (2018-Feb), autumn (2017-May), winter (2017-Aug), and spring (2017-Nov). Statistical evaluation was conducted in R (v4.3.3; R Core Team, 2023).

Generalized model equation:

$y = \beta + \beta_1 \times \text{WindSpeed} + \beta_2 \times \text{SIC} + \beta_3 \times \text{Autumn} + \beta_4 \times \text{Winter} + \beta_5 \times \text{Spring} + \beta_6 \times \text{WindSpeed:SIC}$

	Fram Strait				**Weddell Sea**			
Broadband SPL								
Predictors	*Estimates*	*std. Error*	*Conf. Int (95%)*	*p*	*Estimates*	*std. Error*	*Conf. Int (95%)*	*p*
(Intercept)	105.62	0.26	105.11 – 106.13	**<0.001**	111.26	0.14	110.99 – 111.54	**<0.001**
WindSpeed	1.00	0.00	1.00 – 1.00	**<0.001**	0.19	0.02	0.15 – 0.22	**<0.001**
SIC	1.00	0.00	1.00 – 1.00	**<0.001**	0.03	0.01	0.02 – 0.04	**<0.001**
Autumn	1.02	0.00	1.01 – 1.02	**<0.001**	-7.44	0.70	-8.80 – -6.07	**<0.001**
Winter	1.02	0.00	1.02 – 1.03	**<0.001**	-10.20	0.70	-11.56 – -8.83	**<0.001**
Spring	0.97	0.00	0.97 – 0.98	**<0.001**	-12.56	0.67	-13.88 – -11.24	**<0.001**
WindSpeed×SIC	1.00	0.00	1.00 – 1.00	**0.020**	-0.00	0.00	-0.00 – -0.00	**<0.001**
	Pseudo R^2 = 0.153				R^2 = 0.885			
63 Hz TOL								
(Intercept)	92.36	0.18	92.01 – 92.70	**<0.001**	98.87	0.16	98.56 – 99.17	**<0.001**
WindSpeed	1.00	0.00	1.00 – 1.00	**<0.001**	0.14	0.02	0.10 – 0.18	**<0.001**
SIC	1.01	0.00	1.00 – 1.01	**<0.001**	-0.01	0.01	-0.03 – 0.00	0.148
Autumn	0.99	0.00	0.98 – 0.99	**<0.001**	-8.10	0.79	-9.64 – -6.55	**<0.001**
Winter	0.97	0.00	0.97 – 0.97	**<0.001**	-9.75	0.79	-11.30 – -8.21	**<0.001**
Spring	0.98	0.00	0.98 – 0.99	**<0.001**	-12.75	0.76	-14.24 – -11.26	**<0.001**
WindSpeed×SIC	1.00	0.00	1.00 – 1.00	**<0.001**	-0.00	0.00	-0.00 – 0.00	0.937
	Pseudo R^2= 0.220				R^2 = 0.915			
125 Hz TOL								
(Intercept)	87.62	0.16	87.31 – 87.94	**<0.001**	4.53	0.00	4.52 – 4.53	**<0.001**
WindSpeed	1.01	0.00	1.01 – 1.01	**<0.001**	0.00	0.00	0.00 – 0.00	**<0.001**
SIC	1.00	0.00	1.00 – 1.00	**0.012**	-0.00	0.00	-0.00 – -0.00	**<0.001**
Autumn	1.02	0.00	1.01 – 1.02	**<0.001**	0.01	0.01	-0.01 – 0.03	0.407
Winter	1.01	0.00	1.00 – 1.01	**<0.001**	0.08	0.01	0.06 – 0.10	**<0.001**
Spring	1.00	0.00	1.00 – 1.01	0.482	0.02	0.01	0.00 – 0.04	**0.049**
WindSpeed×SIC	1.00	0.00	1.00 – 1.00	0.767	-0.00	0.00	-0.00 – -0.00	**<0.001**
	Pseudo R^2 = 0.314				R^2 = 0.689			
250 Hz TOL								
(Intercept)	83.36	0.14	83.09 – 83.64	**<0.001**	86.50	0.27	85.97 – 87.02	**<0.001**
WindSpeed	1.01	0.00	1.01 – 1.01	**<0.001**	0.63	0.03	0.56 – 0.69	**<0.001**
SIC	1.00	0.00	1.00 – 1.00	**<0.001**	0.07	0.01	0.05 – 0.10	**<0.001**
Autumn	1.04	0.00	1.03 – 1.04	**<0.001**	-15.06	1.35	-17.71 – -12.41	**<0.001**
Winter	1.03	0.00	1.02 – 1.03	**<0.001**	-7.28	1.35	-9.92 – -4.63	**<0.001**
Spring	1.02	0.00	1.02 – 1.03	**<0.001**	-9.85	1.30	-12.40 – -7.30	**<0.001**
WindSpeed×SIC	1.00	0.00	1.00 – 1.00	**<0.001**	-0.00	0.00	-0.01 – -0.00	**<0.001**
	R^2 = 0.538				R^2 = 0.713			

< Table S5. Continued >

500 Hz TOL								
(Intercept)	80.06	0.13	79.81 – 80.31	**<0.001**	79.93	0.37	79.21 – 80.66	**<0.001**
WindSpeed	0.90	0.01	0.87 – 0.93	**<0.001**	1.25	0.05	1.16 – 1.33	**<0.001**
SIC	-0.26	0.03	-0.32 – -0.19	**<0.001**	0.09	0.02	0.05 – 0.13	**<0.001**
Autumn	2.04	0.12	1.81 – 2.28	**<0.001**	-15.17	1.85	-18.80 – -11.54	**<0.001**
Winter	1.50	0.13	1.26 – 1.75	**<0.001**	-11.12	1.85	-14.75 – -7.49	**<0.001**
Spring	1.91	0.16	1.59 – 2.22	**<0.001**	-12.05	1.79	-15.56 – -8.55	**<0.001**
WindSpeed×SIC	0.03	0.00	0.02 – 0.03	**<0.001**	-0.01	0.00	-0.01 – -0.01	**<0.001**
			$R^2 = 0.709$				$R^2 = 0.659$	

Table S6. Statistical results for the linear regression models to assess the influence of wind speed (m/s) and the sea ice concentration (SIC; %), and differences between seasons, on the diversity metrics for the Fram Strait (FS) station and the Weddell Sea (WS) station. The wind speed, SIC, and season were applied as fixed terms on the hourly means (2874 observations in total for each recording site) of the diversity metrics, we also included an interaction term of wind speed and SIC. A beta-regression was applied for the AEI and the HI. For the AEI a log-link and for the HI a logit-link was applied. A generalized linear gamma regression with a log-link was applied on the ACI and ADI for both regions, and the BI for the FS station. A general linear model was fitted for the BI for the WS station. Additionally, the ADI was inverse transformed to follow a gamma distribution. At the FS station the seasons correspond to the boreal summer (2016-Aug), spring (2017-Feb), autumn (2017-Nov), and winter (2017-Feb) and at the WS station to austral summer (2018-Feb), autumn (2017-May), winter (2017-Aug), and spring (2017-Nov). Statistical evaluation was conducted in R (v4.3.3; R Core Team, 2023).

Generalized model equation:

$y = \beta + \beta_1 \times \mathrm{WindSpeed} + \beta_2 \times \mathrm{SIC} + \beta_3 \times \mathrm{Autumn} + \beta_4 \times \mathrm{Winter} + \beta_5 \times \mathrm{Spring} + \beta_6 \times \mathrm{WindSpeed{:}SIC}$

	Fram Strait				**Weddell Sea**			
ACI								
Predictors	*Estimates*	*std. Error*	*Conf. Int (95%)*	*p*	*Estimates*	*std. Error*	*Conf. Int (95%)*	*p*
(Intercept)	1524.64	2.78	1519.21 – 1530.09	**<0.001**	1474.67	1.42	1471.89 – 1477.46	**<0.001**
WindSpeed	1.00	0.00	1.00 – 1.00	**<0.001**	1.00	0.00	1.00 – 1.00	0.378
SIC	1.00	0.00	1.00 – 1.00	0.435	1.00	0.00	1.00 – 1.00	0.353
Autumn	1.01	0.00	1.00 – 1.01	**0.002**	1.00	0.00	0.99 – 1.01	0.485
Winter	0.99	0.00	0.99 – 0.99	**<0.001**	1.00	0.00	0.99 – 1.01	0.630
Spring	0.98	0.00	0.98 – 0.99	**<0.001**	0.98	0.00	0.97 – 0.99	**<0.001**
WindSpeed×SIC	1.00	0.00	1.00 – 1.00	0.051	1.00	0.00	1.00 – 1.00	**<0.001**
Pseudo R^2			0.132				0.406	
AEI								
(Intercept)	0.41	0.02	0.38 – 0.45	**<0.001**	0.98	0.03	0.91 – 1.04	0.463
WindSpeed	0.87	0.00	0.86 – 0.88	**<0.001**	0.84	0.00	0.83 – 0.85	**<0.001**
SIC	1.06	0.01	1.04 – 1.08	**<0.001**	0.99	0.00	0.98 – 0.99	**<0.001**
Autumn	0.88	0.03	0.81 – 0.95	**0.001**	2.95	0.55	2.05 – 4.26	**<0.001**
Winter	0.81	0.03	0.75 – 0.88	**<0.001**	1.89	0.35	1.31 – 2.73	**0.001**
Spring	0.58	0.03	0.52 – 0.65	**<0.001**	1.19	0.21	0.83 – 1.69	0.343
WindSpeed × SIC	0.99	0.00	0.99 – 1.00	**<0.001**	1.00	0.00	1.00 – 1.00	**<0.001**
Pseudo R^2			0.464				0.504	
ADI								
(Intercept)	5.54	0.01	5.57 – 5.52	**<0.001**	4.99	0.03	5.05 – 4.93	**<0.001**
WindSpeed	1.00	0.00	1.00 – 1.00	**<0.001**	1.01	0.00	1.02 – 1.01	**<0.001**
SIC	1.00	0.00	1.00 – 1.00	0.197	1.00	0.00	1.00 – 1.00	**0.001**
Autumn	1.00	0.00	1.00 – 1.00	0.950	0.87	0.03	0.92 – 0.82	**<0.001**
Winter	1.01	0.00	1.01 – 1.00	**0.003**	0.95	0.03	1.01 – 0.90	0.128
Spring	1.02	0.00	1.02 – 1.01	**<0.001**	0.99	0.03	1.05 – 0.93	0.642
WindSpeed×SIC	1.00	0.00	1.00 – 1.00	0.431	1.00	0.00	1.00 – 1.00	**<0.001**
Pseudo R^2			0.121				0.444	

< Table S6. Continued >

HI								
(Intercept)	0.77	0.02	0.76 – 0.78	**<0.001**	0.65	0.02	0.64 – 0.67	**<0.001**
WindSpeed	0.53	0.00	0.52 – 0.53	**<0.001**	0.54	0.00	0.53 – 0.54	**<0.001**
SIC	0.48	0.00	0.48 – 0.49	**<0.001**	0.50	0.00	0.50 – 0.50	**<0.001**
Autumn	0.50	0.01	0.48 – 0.51	0.454	0.33	0.05	0.27 – 0.40	**<0.001**
Winter	0.51	0.01	0.50 – 0.53	**0.025**	0.40	0.06	0.33 – 0.47	**0.004**
Spring	0.59	0.02	0.58 – 0.61	**<0.001**	0.49	0.07	0.42 – 0.56	0.788
WindSpeed × SIC	0.50	0.00	0.50 – 0.50	**<0.001**	0.50	0.00	0.50 – 0.50	**<0.001**
Pseudo R²	0.444				0.602			
BI								
(Intercept)	124.39	0.93	122.59 – 126.22	**<0.001**	240.28	2.40	235.58 – 244.98	**<0.001**
WindSpeed	0.97	0.00	0.97 – 0.98	**<0.001**	-2.91	0.29	-3.49 – -2.34	**<0.001**
SIC	1.01	0.00	1.00 – 1.01	**0.001**	-0.29	0.13	-0.53 – -0.04	**0.022**
Autumn	1.08	0.01	1.06 – 1.09	**<0.001**	8.10	12.05	-15.51 – 31.71	0.501
Winter	1.04	0.01	1.03 – 1.06	**<0.001**	43.02	12.05	19.40 – 66.64	**<0.001**
Spring	1.04	0.01	1.02 – 1.06	**<0.001**	19.33	11.62	-3.45 – 42.11	0.096
WindSpeed×SIC	1.00	0.00	1.00 – 1.00	**0.001**	0.01	0.00	-0.00 – 0.01	0.147
Pseudo R²	0.393				0.284			

Table S7. Loadings of the used hourly means of ten ecoacoustic metrics (broadband SPL, 63, 125, 250, 500 Hz TOL band SPL, ACI, AEI, ADI, HI, BI) on the first two principal components. The highest positive or negative loadings are highlighted in bold.

Ecoacoustic metric	**PC1**	**PC2**
500 Hz	**0.435**	-0.090
250 Hz	0.400	-0.180
HI	0.390	0.308
AEI	-0.380	-0.350
ADI	0.340	0.349
63 Hz	0.282	-0.415
BI	-0.266	-0.146
125 Hz	0.244	-0.382
Broadband	0.172	**-0.517**
ACI	-0.003	-0.112

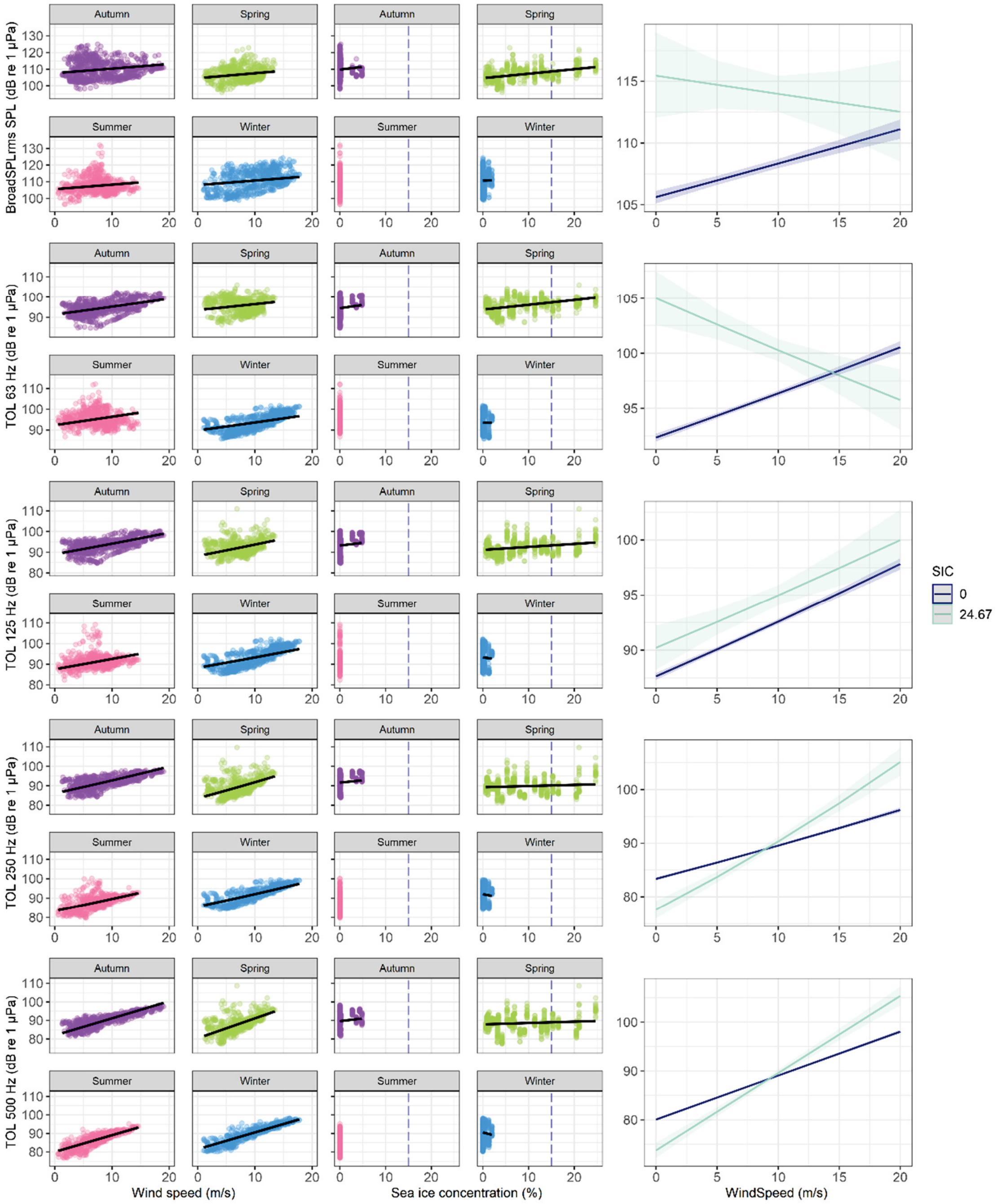

Figure S1. General and generalized linear regression models (black line) for the SPLs measured at the Fram Strait (FS) station corresponding to Table S5. The wind speed (m/s), and sea ice concentration (SIC, %), and season were applied as fixed terms on the hourly means (2758 observations in total; points show true data) of the SPLs, we also included an interaction term of wind speed and SIC. For the broadband SPL and the 63, and 125 Hz 1/3-octave level (TOL) bands a generalized linear gamma regression model using a log-link was applied. A general linear regression model was fitted for the 250 and 500 Hz TOL band with a log-link and an identity-link, respectively. The plots in the right panel show the interaction prediction of the marginal mean effect size of wind speed and SIC on the SPLs. The seasons correspond to boreal summer (2016-Aug, pink), boreal spring (2017-Feb, green), boreal autumn (2017-Nov, purple), and boreal winter (2017-Feb, blue). The dashed vertical blue line in the middle panel indicates the SIC threshold for open water conditions (SIC ≤15%).

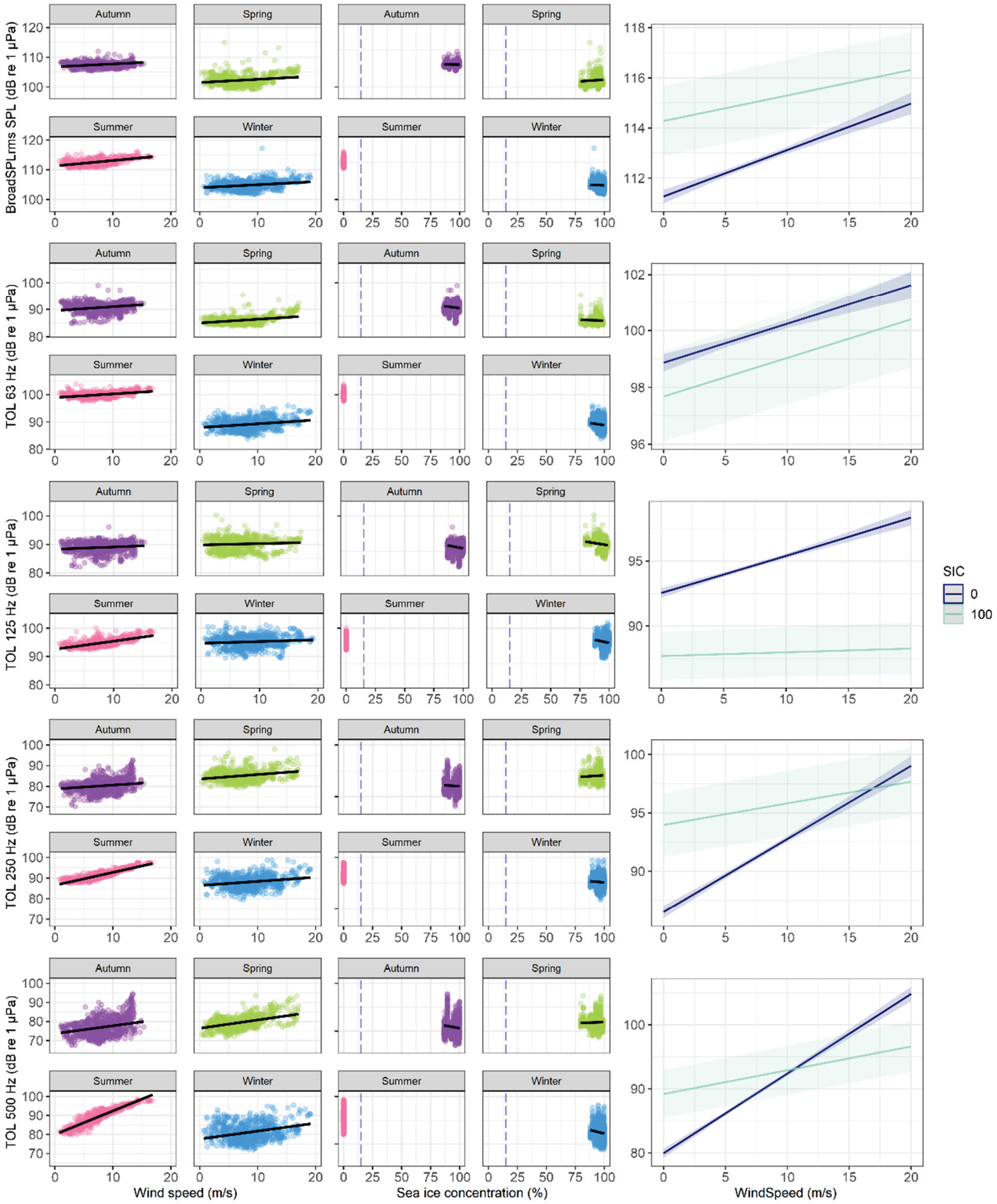

Figure S2. General linear regression models (black line) for the SPLs measured at the Weddell Sea (WS) station corresponding to Table S5. The wind speed (m/s), and sea ice concentration (SIC, %), and season were applied as fixed terms on the hourly means (2758 observations in total; points show true data) of the SPLs, we also included an interaction term of wind speed and SIC. General linear models were fitted for the broadband SPL, 63, 250, and 500 Hz TOL band with an identity-link and for the 125 Hz with a log-link. The plots in the right panel show the interaction prediction of the marginal mean effect size of wind speed and SIC on the SPLs. The seasons correspond to austral summer (2018-Feb, pink), austral autumn (2017-May, purple), austral winter (2017-Aug, blue), and austral spring (2016-Nov, green). The dashed vertical blue line in the middle panel indicates the SIC threshold for open water conditions (SIC ≤15%).

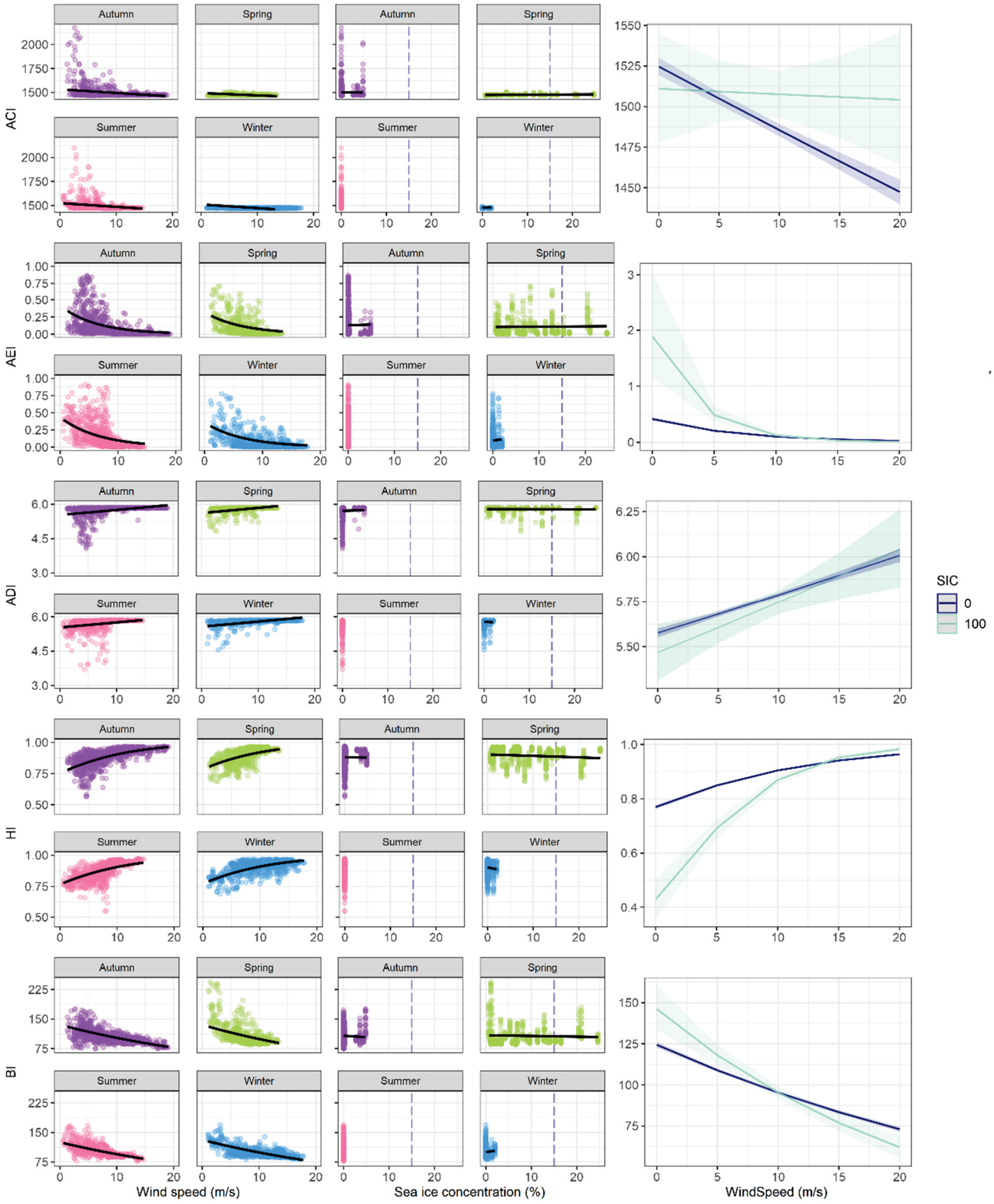

Figure S3. Generalized and beta linear regression models (black line) for the ecoacoustic diversity metrics measured at the Fram Strait (FS) station corresponding to Table S6. The wind speed (m/s), and sea ice concentration (SIC, %), and season were applied as fixed terms on the hourly means (2760 observations in total; points show true data) of the diversity metrics, we also included an interaction term of wind speed and SIC. A beta-regression was applied for the AEI and the HI. For the AEI a log-link and for the HI a logit-link was applied. A generalized linear gamma regression with a log-link was applied on the ACI, ADI, and BI. Additionally, the ADI was inverse transformed to follow a gamma distribution. The plots in the right panel show the interaction prediction of the marginal mean effect size of wind speed and SIC on the SPLs. The seasons correspond to boreal summer (2016-Aug, pink), boreal spring (2017-Feb, green), boreal autumn (2017-Nov, purple), and boreal winter (2017-Feb, blue). The dashed vertical blue line in the middle panel indicates the SIC threshold for open water conditions (SIC ≤15%).

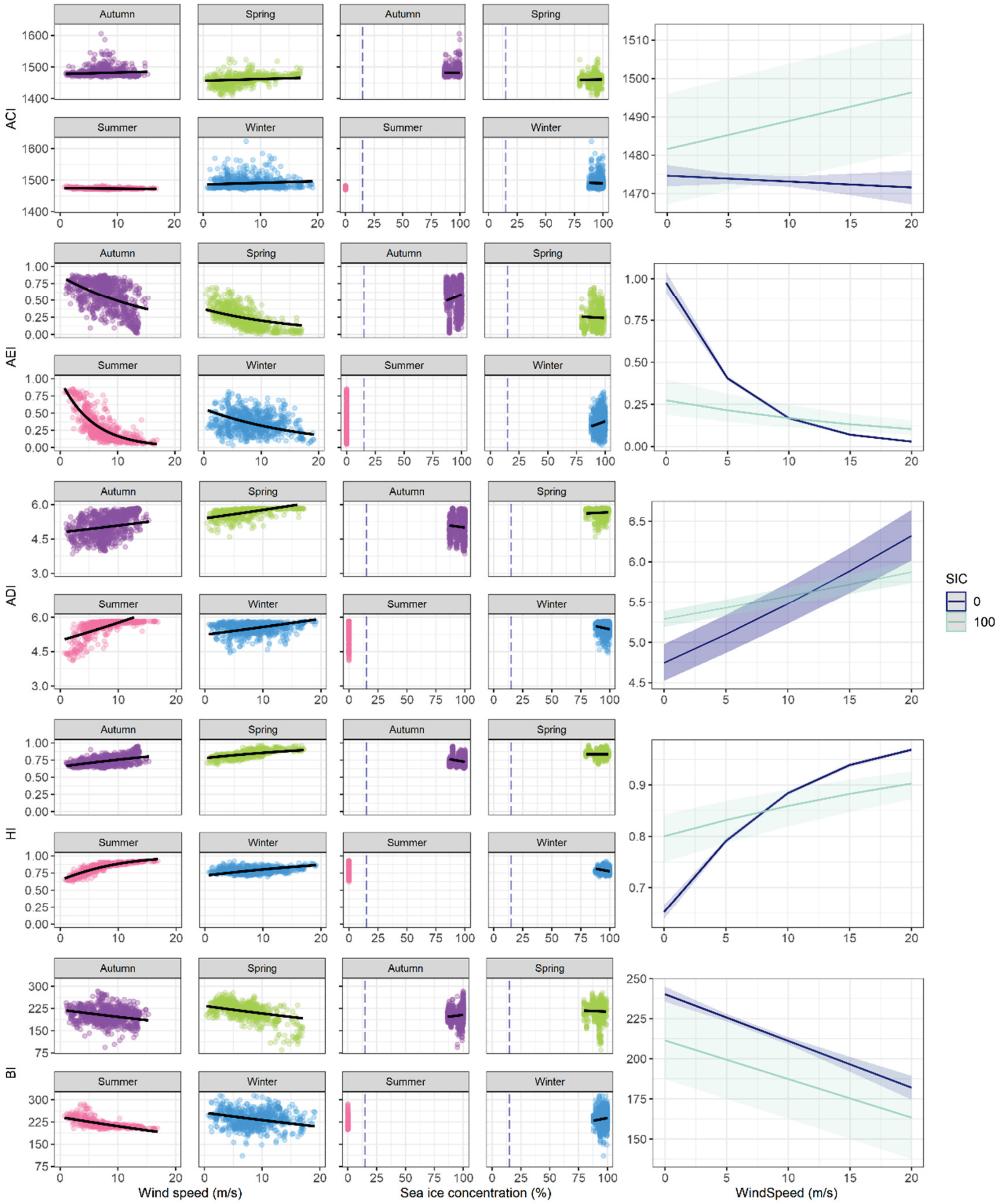

Figure S4. Generalized and beta linear regression models (black line) for the ecoacoustic diversity metrics measured at the Weddell Sea (WS) station corresponding to Table S6. The wind speed (m/s), and sea ice concentration (SIC, %), and season were applied as fixed terms on the hourly means (2760 observations in total; points show true data) of the diversity metrics, we also included an interaction term of wind speed and SIC. A beta-regression was applied for the AEI and the HI. For the AEI a log-link and for the HI a logit-link was applied. A generalized linear gamma regression with a log-link was applied on the ACI and ADI. A general linear model was fitted for the BI. Additionally, the ADI was inverse transformed to follow a gamma distribution. The plots in the right panel show the interaction prediction of the marginal mean effect size of wind speed and SIC on the SPLs. The seasons correspond to austral summer (2018-Feb, pink), austral autumn (2017-May, purple), austral winter (2017-Aug, blue), and austral spring (2016-Nov, green). The dashed vertical blue line in the middle panel indicates the SIC threshold for open water conditions (SIC ≤15%).

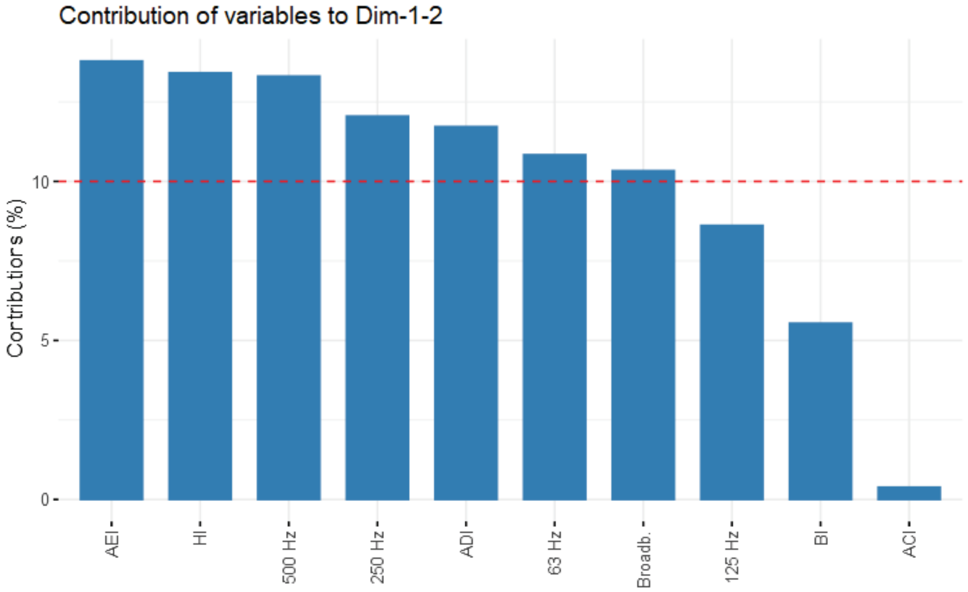

Figure S5. The contributions of the ten ecoacoustic metrics explaining 70% of the variance in the first two principal components. A principal component analysis (PCA) for feature selection was applied using the hourly mean of ten ecoacoustic metrics (broadband SPL, 63 Hz, 125 Hz, 250 Hz, 500 Hz TOL band, ACI, AEI, ADI, HI, BI). The contributions with more than 10% were regarded as the metrics with the highest explanatory power in describing overall soundscape characteristics and influencing cluster forming.

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4

Soundscape regimes and diversity across the Weddell Sea basin, Antarctica

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Abstract

The triple planetary crisis has consequences for the spatiotemporal patterns of soundscapes. Pristine soundscapes still prevail in the Southern Ocean (SO), shaped by environmental gradients and marine mammal vocalisations. The evaluation of large-scale patterns of spatiotemporal soundscape diversity is therefore important for establishing contemporary baselines and estimating future changes in pristine acoustic environments. Underwater soundscapes of 11 stations and 18 deployments across the Weddell Sea (WS) and off Elephant Island (EI) between 2008 and 2021, were characterised. A total of 22 ecoacoustic metrics, including acoustic intensity and diversity metrics, were applied to quantify soundscape properties. Cluster analysis, in combination with traditional α- and β-diversity measures, was applied to the computed set of soundscape properties to identify soundscape regimes and quantify diversity in soundscape patterns across the WS and off EI. We identified four distinct regimes, which were separated mainly by recording depth and overall water depth. The shallow-water soundscape off EI was less diverse in contrast to the deep-water soundscapes of the WS. In the WS, epi- and mesopelagic soundscapes were more diverse than bathypelagic soundscapes, and their diversity was strongly linked to seasonal sea-ice cover. Soundscapes were more diverse during sea-ice-covered periods and less diverse during the open-water period. We conclude that intact SO acoustic environments have a high spatiotemporal diversity in soundscape patterns. The assessment of soundscape diversity therefore has the potential to be an important tool for assessing the acoustic integrity of marine ecosystems over large spatiotemporal scales, contributing essential knowledge for ecosystem management and conservation.

Introduction

Our planet's ecosystems, including our oceans, have been irreversibly altered due to anthropogenic pressures causing changes in climate (IPCC, 2023), pollution (Hatje *et al.*, 2024), and biodiversity loss (Hodapp *et al.*, 2023). This triple planetary crisis (UNFCCC, 2022) has increased global efforts for more holistic ecosystem monitoring, e.g., the Global Ocean Observing System. In this regard, remote-sensing, autonomous, and non-invasive passive acoustic monitoring (PAM) methods have become a valuable and cost-effective tool across realms for the acoustic investigation of biodiversity and ecosystem change in the Anthropocene (Mooney *et al.*, 2020; Napier *et al.*, 2024; Darras *et al.*, 2025).

Significant structural changes to our planet's soundscapes, both terrestrial and aquatic, are expected and already observed as a response to direct, indirect, and cumulative anthropogenic ecosystem disturbances (Sueur *et al.*, 2019). Local and large-scale structural changes in marine soundscape patterns can be direct or indirect consequences of changes in physical properties as a result of global warming (Affatati *et al.*, 2022), such as the forecasted level of future ocean acidification, which will allow for an increased propagation range of lower frequency sounds (Ilyina *et al.*, 2010). Moreover, changes in weather patterns, such as increases in precipitation, storms, sea states, and currents can alter acoustic properties such as ambient noise levels in the ocean (Duarte *et al.*, 2021). In regions of the polar oceans, shifts in seasonal sea-ice regimes and the loss of sea-ice (Eayrs *et al.*, 2021; Gorodetskaya *et al.*, 2023; Sumata *et al.*, 2023) can lead to increased ambient sound levels, as the attenuation effect of sea-ice on wind-mediated sounds is lost (Menze *et al.*, 2017; Mo *et al.*, 2023). Additionally, the industrialisation of the ocean, particularly increased commercial shipping, has already caused a doubling of low frequency (<150 Hz) ambient sound levels in the Northeast Pacific in the late 20th century (1965-2003) (McDonald *et al.*, 2006). Noise emissions from shipping are predicted to double approximately 12 years on a global scale and every three years in the Arctic (Jalkanen *et al.*, 2022). Moreover, habitat degradation has been found to decrease the complexity of marine soundscapes along with changes in ambient noise levels due to regime shifts in environmental conditions and bioacoustic community composition (Rossi *et al.*, 2017; Gordon *et al.*, 2018). Lastly, changes in the distribution and behaviour of marine life in response to anthropogenic pressures (Hodapp *et al.*, 2023) are expected to have significant repercussions for spatiotemporal soundscape patterns (Rossi *et al.*, 2017; Gordon *et al.*, 2018; Duarte *et al.*, 2021).

The Southern Ocean (SO) is considered to be one of the last relatively pristine acoustic environments with the least number of anthropogenic activities on a global scale due to its extensive seasonal sea-ice cover and remoteness (Halpern *et al.*, 2008). Overall, the soundscapes of the SO are strongly characterized throughout the year by the underwater vocalizations of resident and endemic marine mammal species as well as by ice and wind-mediated sounds (Dziak *et al.*, 2015; Menze *et al.*, 2017). Acoustic anthropogenic contribution is mainly limited to the sea-ice-free austral summer months and a few transit areas to research stations (Breitzke, 2014; Erbe *et al.*, 2019; Jalkanen *et al.*, 2022). Fishing and touristic activities have nevertheless increased and will continue to increase sharply over recent and coming years, particularly along the Antarctic Peninsula (Savoca *et al.*, 2024; Senigaglia *et al.*, 2025). Furthermore, the Antarctic Peninsula is already experiencing strong impacts of climate change, with rising temperatures leading to changing weather patterns, and the retreat of glaciers, ice shelves, and sea-ice with consequences on marine food webs (Gorodetskaya *et al.*, 2023; Ferreira *et al.*, 2024). Recent observations also showed that the Weddell Sea (WS) is among the SO regions with the strongest sea-ice decline, with sea-ice concentrations (SIC) being reduced up to 80% (Eayrs *et al.*, 2021; Josey *et al.*, 2024), with severe and diverse further biological impacts (Wege *et al.*, 2021b; Kawaguchi *et al.*, 2023; Swadling *et al.*, 2023).

Large-scale assessments of the acoustic environment, e.g., of the SO, are therefore essential, as this can facilitate a more comprehensive understanding of ecological dynamics and acoustic connectivity over wide areas and diverse habitats (Van Parijs *et al.*, 2009; Flowers *et al.*, 2021; Napier *et al.*, 2024). Traditionally in soundscape research, acoustic features and sound sources are often investigated in isolation, neglecting their cumulative effects on soundscape patterns and the acoustic properties created by the whole ecosystem. Moreover, with the growing amount of available PAM data, holistic soundscape characterisation using traditional soundscape analysis methods is becoming increasingly challenging analytically (Flowers *et al.*, 2021; Ladegaard *et al.*, 2021; Sethi *et al.*, 2023). Thus, approaches that incorporate holistic soundscape structures on a spatiotemporally coarser but scalable resolution are needed to characterise large-scale structural shifts in soundscape patterns (Sethi *et al.*, 2023).

Here, we build on earlier work by Mattmüller *et al.* (2024) and will incorporate holistic soundscape structures on a spatiotemporally scalable resolution enabling the characterisation of large-scale structural shifts in SO soundscape patterns. The investigation of our planet's last still relatively pristine environment, the SO and its diversity in soundscape patterns is crucial for establishing an acoustic baseline to better understand how intact marine polar soundscapes are composed and function. The large-scale approach furthermore illuminates the spatiotemporal scales of polar underwater acoustic environments and their acoustic connectivity. Hence, we have two objectives. We aim to assess the diversity of soundscape patterns over large spatiotemporal scales across the WS basin in comparison to the prevailing wind and sea ice conditions. Furthermore, we assess the spatiotemporal similarities of the soundscape diversity to identify soundscape regimes on a basin scale. To achieve this, we draw from the basin-wide HAFOS (Hybrid Antarctic Float Observation System) mooring network in the WS which forms a long-term backbone for passive acoustic observations (Rettig *et al.*, 2013). It has provided unprecedented data and insights on marine mammal occurrence and distribution in relation to climate-related oscillations affecting, e.g., sea-ice extent (Schall *et al.*, 2021; Roca *et al.*, 2023). From this HAFOS PAM data set, we utilised PAM data collected at 11 stations during 18 deployments between Mar. 2008 – Feb. 2021. We apply ecoacoustic metrics, clustering analysis, as well as traditional α- and β-diversity metrics on the selected PAM data set.

Material and Methods

Data acquisition

PAM data were collected at 11 stations during 18 deployments across the central Weddell Sea basin (CWS), Atlantic Sector of the SO, along the Greenwich Meridian (GM), and off Elephant

Island (EI, Antarctic Peninsula), between March 2008 and February 2021 (Fig. 1 and Table 1). The PAM deployments were part of HAFOS serviced by RV Polarstern (Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, 2017) and deployed within the Weddell Sea gyre (Vernet *et al.*, 2019).

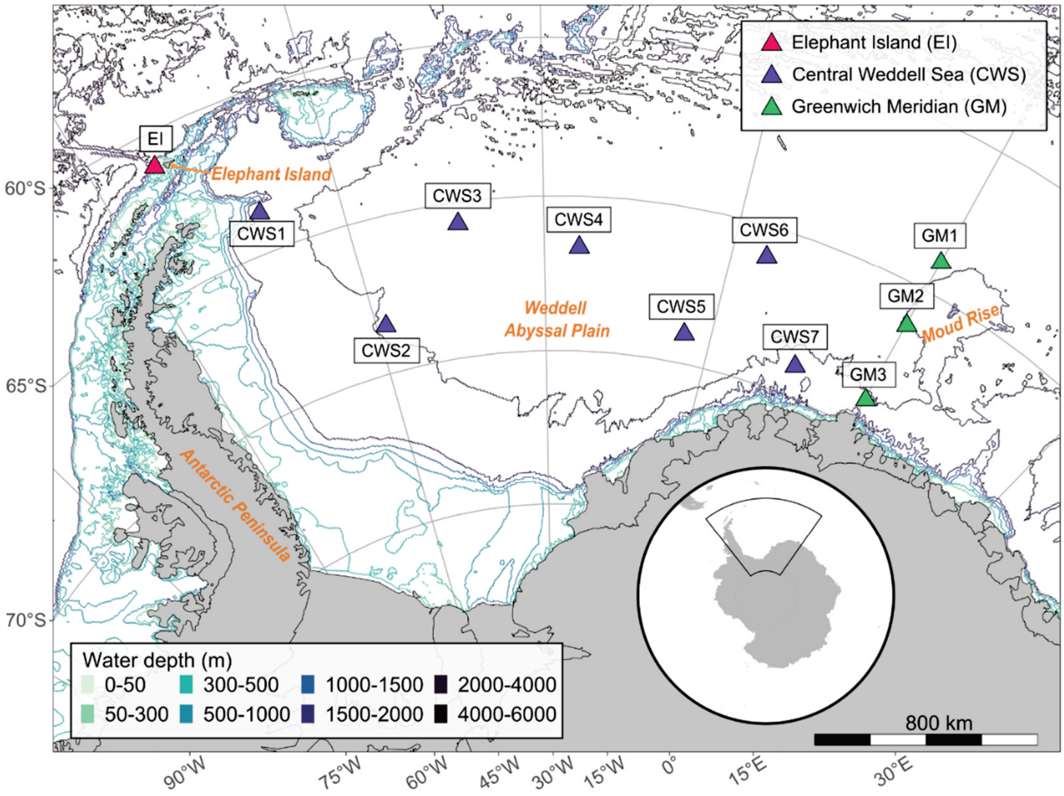

Fig. 1. Map of the WS basin showing the geographic location of the recording stations.

PAM data were collected using 10 autonomous acoustic Sono.Vault (Develogic GmbH, Hamburg, Germany) recorders with an omnidirectional hydrophone (RESON TC4037-3), set to sample continuously with a bit depth of 24 bits, storing the data in 10 min *.wav files. This Sono.Vault data set was selected based on the recorder pre- and post-deployment gain calibration deviations for the recorders amounting to less than 1 dB (see supplementary Table S1). Additionally, PAM data were collected using three AURAL-M2 (Multi Électronique, Rimouski, Canada) recorders with an omnidirectional hydrophone (HTI-96-Min, High Tech, Inc.). These were set to different duty cycles varying per deployment, with a nominal gain of 22 dB provided by the manufacturer, and a bit depth of 16 bits. Sampling rates differed per deployment and ranged between 6857 Hz and 32768 Hz. Table 1 lists the recording details and supplementary Fig. S1 provides a graphical data overview. In total, the combined recording duration of all recordings included in the study totalled 14.6 years (24.2 TB) of data.

Table 1. Summary of the deployed Sono.Vault (SV) and AURAL (AU) hydro-acoustic recorder settings and deployment information. The analyzed recording period starts 24 hours after deployment. The duty cycle is given as sampling effort by sampling interval. For the pre- and post-calibration gains and sensor sensitivity for each recording system see supplementary Table S1.

Station	Deployment ID_Recorder ID	Position	Analyzed recording period	Sampling rate (Hz)	Recorder/ water depth (m)	Duty cycle in minutes (Effort)
EI	AWI251-01_AU0231	61° 0′ 53″ S 55° 58′ 32″ W	2013/01/17 - 2016/02/09	32768	210/320	5/120 (4.2%)
	AWI251-02_AU0231*		2017/01/30 - 2018/02/04	32768	212/330	7/60 (11.7%)
	AWI251-02_SV1013*		2017/01/30 - 2017/04/29	6857	216/330	continuous (100%)
	AWI251-03_AU0085*		2019/02/02 - 2021/02/04	32768	179/335	6/60 (10%)
	AWI251-03_SV1002*		2019/02/02 - 2020/04/25	24000	181/335	continuous (100%)
CWS1	AWI207-08_AU0085	63° 43′ 4″ S5 0° 49′ 54″ W	2011/01/12 - 2014/02/05	32768	219/2500	4.5/180 (2.5%)
CWS2	AWI250-02_SV1003	68° 27′ 50″ S 44° 8′ 43″ W	2017/01/22 - 2018/11/11	6857	1036/4737	continuous (100%)
CWS3	AWI208-08_SV1009	65° 41′ 47″ S 36° 41′ 0″ W	2017/01/20 - 2018/05/02	6857	1032/4766	continuous (100%)
CWS4	AWI209-06_AU0086	66° 36′ 42″ S 27° 7′ 18″ W	2010/12/30 - 2012/12/31	32768	207/4830	4.5/180 (2.5%)
CWS5	AWI245-05_SV1014	69° 3′ 38″ S 17° 23′ 29″ W	2019/01/09 - 2020/07/03	24000	300/4734	continuous (100%)
CWS6	AWI248-03_SV1012	65° 58′ 8″ S 12° 13′ 51″ W	2019/01/08 - 2020/04/23	24000	350/4950	continuous (100%)
CWS7	AWI244-05_SV1057	69° 0′ 19″ S 6° 59′ 34″ W	2017/01/02 - 2018/09/14	6857	1044/2946	continuous (100%)
GM1	AWI229-11_SV1057	64° 0′ 19″ S 0° 0′ 13″ W	2014/12/18 - 2016/05/19	6857	970/5165	continuous (100%)
GM2*	AWI230-06_AU0085	66° 1′ 8″ S 0° 4′ 46″ E	2008/03/09 - 2010/12/15	32768	189/3322	5/240 (2.1%)
	AWI231-11_SV1058	66° 30′ 42″ S 0° 1′ 31″ W	2014/12/20 - 2016/05/28	6857	973/4472	continuous (100%)
	AWI231-13_SV1056		2018/12/28 - 2020/05/20	24000	303/4580	continuous (100%)
GM3	AWI232-09_AU0086	64° 0′ 19″ S 0° 0′ 13″ W	2008/03/12 - 2010/12/18	32768	206/3225	5/240 (2.1%)
	AWI232-12_SV1059		2015/01/08 - 2015/08/24**	6857	999/3360	continuous (100%)

*AWI230 and AWI231 are treated jointly as one station named GM2 due to their relatively close proximity (~55 km).
** Two data gaps existed for AWI232-12_SV1059 from 2015-01-26 22:59:21 UTC to 2015-02-14 10:52:23 UTC and 2015-02-21 10:20:18 UTC to 2015-03-04 22:03:25 UTC.

AWI251-02_AU0231 and AWI251-02_SV1013 as well as AWI251-03_AU0085 and AWI251-03_SV1002 were placed in the same mooring and recorded overlapping periods: 2017-01-30 15:36:00 to 2017-04-29 16:49:46 and 2019-02-02 18:30:00 to 2020-04-25 03:25:15, respectively. Therefore, the time overlap of AWI251-02_AU0231 and AWI251-03_AU0085 was removed to avoid a temporal overrepresentation of these stations for the lower frequency range ≤6857 Hz. For the higher frequency sampling rates of 24000 Hz, only the time overlap of AWI251-03_AU0085 was removed.

Post-deployment, PAM data were prepared for display in the OPUS (Open Portal to Underwater Soundscapes, www.opus.aq) following the AWI's Ocean Acoustic Group's standard operating procedures for PAM data (Thomisch *et al.*, 2023b; Thomisch *et al.*, 2023a). This includes storing the data in a standardized format and structure, checking the integrity of the metadata, and correcting the sampling rate of Sono.Vaults prior to 2019.

PAM data analysis

We investigated three frequency ranges: 12-840, 840-3428, and 3428-12000 Hz. The analysis was limited to 12 kHz as the AURAL recorders reached the recorder noise floor for the frequencies above. The frequency range 12-840 Hz was selected to capture the vocalizations of marine mammal species found in the WS-Basin (Van Opzeeland and Boebel, 2018), as well as environmental sounds from earthquakes, ice shelf, sea-ice, icebergs, and wind mediated-sounds (Dziak *et al.*, 2015; Menze *et al.*, 2017). Additionally, this band captures anthropogenic noise and natural sounds that propagate over large distances (up to >50 km) (Sirovic *et al.*, 2007; Van Opzeeland and Boebel, 2018; Duarte *et al.*, 2021). The frequency range 840-3428 Hz reflects the smallest common denominator of the sampling rate recorded across all 18 deployments. The frequency range 3428-12000 Hz reflects the next cut-off sampling rate across the data set and was applied to eleven of the 18 deployments, respectively. The latter two bands capture more local soundscape components (<30 km), for example, vocalizations of pinnipeds and odontocetes (Van Opzeeland and Boebel, 2018).

Ecoacoustic metrics

Building on previous work (Mattmüller *et al.*, 2024) highlighting the usefulness of ecoacoustic metrics to assess seasonal and spatial variability in polar ocean soundscape characteristics, we applied a similar set of ecoacoustic metrics and processing steps.

Acoustic intensity metrics – ambient sound levels:

To characterize the ambient sound levels, ten intensity metrics were computed: the broadband sound pressure levels (SPL) for all four frequency bands and the SPL for one-third octave level (TOL) bands centred at 63, 125, 250, 500 Hz, and 1, 2, 5 kHz. The first four TOL bands are recommended by the European Union Marine Strategy Framework Directive (Descriptor 11; Dekeling *et al.*, 2014; MSFD, 2017) and Merchant *et al.* (2015) as indicators of good environmental status. Additionally, the TOL bands centred at 1, 2, and 5 kHz were computed to improve the investigation of SPL variability at higher frequencies. The broadband SPLs are abbreviated as ‘SPL 840 Hz’, ‘SPL 3428 Hz’, and ‘SPL 12000 Hz’, for the frequency ranges 12-840 Hz, 840-3428 Hz, and 3428-12000 Hz, respectively.

SPLs were computed from power spectral densities (PSD) derived by processing the PAM data with the MANTA software (Making Ambient Noise Trends Accessible; v9.6.11 to v9.6.15, standalone version) (Miksis-Olds *et al.*, 2021). MANTA computes calibrated PSDs over 1-min time intervals (i.e., 10 data points per 10-min audio file) at a hybrid millidecade resolution (Martin *et al.*, 2021b; a). Frequencies below 12 Hz were excluded to minimise low-frequency recorder-generated flow noise (ISO, 2017) on SPL measurements. The TOL bands were computed as decidecade bands (Miksis-Olds *et al.*, 2021).

Acoustic diversity metrics – complexity of spectro-temporal patterns:

Four acoustic diversity metrics were computed for each frequency range to capture the overall complexity of spectro-temporal intensity variability within the soundscapes (Fig. 2): acoustic complexity index (ACI, temporal heterogeneity; Pieretti *et al.*, 2011), acoustic evenness index (AEI, spectral heterogeneity; Villanueva-Rivera *et al.*, 2011), total acoustic entropy (HI, spectro-temporal homogeneity; Sueur *et al.*, 2008), and bioacoustic index (BI, spectral heterogeneity and temporal homogeneity; Boelman *et al.*, 2007).

Acoustic diversity metrics were computed across the length of each audio file, resulting in one data point per audio file, and separately for each frequency band. The applied function and settings of each acoustic diversity metric and frequency band are shown in supplementary Table S2. For direct comparability of the computed acoustic diversity metrics among recordings with different sampling rates, any recordings exceeding the maximum frequency of the investigated frequency range were down-sampled (see supplementary Table S3, for the down-sampling scheme for each data set).

Post-processing

Some of the recordings contained upsweeps that were emitted by an oceanographic sound source (RAFOS; Ranging and Fixing of Sound; Rossby *et al.*, 1986) on a daily basis, lasting 80s and ranged from 259-261 Hz with a source level of 175 dB re 1 µPa (Van Opzeeland and Boebel, 2018). To prevent biases in trends of the acoustic intensity and diversity metrics, the respective data points including these RAFOS signals were removed (supplementary Table S4 shows the amount of removed data points).

Before further analysis, the daily means for each ecoacoustic metric were computed. We used the daily mean for metric calculation, to reduce the impact of sparser, less dominant, acoustic features and thereby to weigh metrics according to the actual acoustic contribution to the soundscape. Moreover, the frequency ranges 12-840 Hz and 840-3428 Hz were merged as the sampling rate of 6857 Hz was the smallest common denominator across all 18 PAM data sets. Therefore, all of the ecoacoustic metrics computed for the frequency range 12-840 Hz and 840-3428 Hz were combined into a lower-mid frequency band called LMF-B, which is now described by 16 ecoacoustic metrics: nine ecoacoustic metrics describe the frequency range 12-840 Hz and seven ecoacoustic metrics describe the frequency range 840-3428 Hz. The high-frequency range of 3428-12000 Hz is described by seven ecoacoustic metrics and is further referred to as the high-frequency band (HF-B), respectively. Fig. 2 describes the computation and processing workflow of the ecoacoustic metrics.

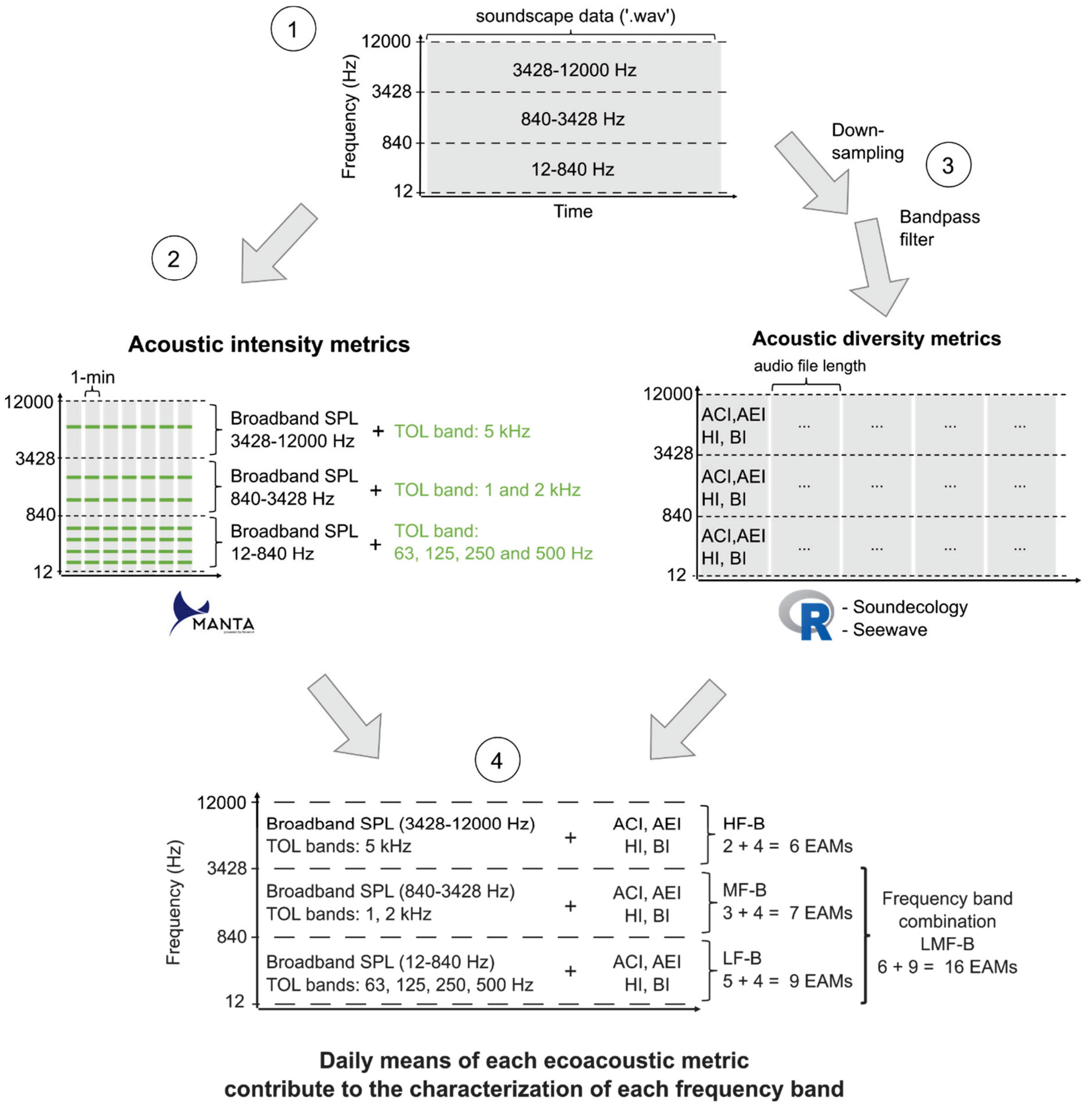

Fig. 2. Workflow of the ecoacoustic metric computation. 1) the soundscape data set was separated into three frequency ranges. 2) the audio data was processed to compute the intensity metrics for each frequency range on a 1-min basis. 3) the audio file was down-sampled when necessary and a band pass filter was applied before computing the four acoustic diversity metrics for each frequency range. 4) Removal of the data points containing RAFOS signals and computation of the daily means of each computed ecoacoustic metric (EAM).

Assessing scenes, regimes, and diversity

Clustering

To uncover the spatiotemporal partitioning of soundscape patterns and regimes, we applied two clustering methods. First, we identified soundscape clusters that summarize daily soundscape characteristics with similar acoustic properties described by the combination of the ecoacoustic metrics. For this, we introduce the term soundscape 'scene' to refer to the resulting clusters from here on. Second, we applied hierarchical clustering on the relative number of scene observations per deployment to explore spatiotemporal regimes.

Clustering to uncover soundscape scenes

We applied hybrid hierarchical k-means clustering ('hkmeans' of the R-package 'factoextra'; Kassambara and Mundt, 2020) on the daily means of the computed ecoacoustic metrics for the LMF-B and HF-B to identify scenes. We used 'ward.D2' as the agglomeration method, the 'euclidean distance' as the distance measure, and set the maximum iteration for k-means to 1000. Before clustering we applied z-score normalization on the daily means of the measured ecoacoustic metrics. To specify the optimal number of clusters, we applied the function 'NbClust' from the identically named R-package (Charrad *et al.*, 2014) set to compute all available indices. Considering that we had 18 different deployments for the LMF-B, we tested for up to 18 clusters, spanning the possibility of clustering into seasonal, monthly, and spatial scenes. Because only eleven deployments sampled the HF-B, we only tested up to 12 clusters, considering clusterability into monthly scenes but also spanning the possibility to cluster spatially across stations. The optimal number of clusters recommended was three for the LMF-B and for the HF-B. Further inspection of the recommended clusters or scenes revealed that these were mainly based on the presence and absence of wind-mediated sounds, linked to the seasonal sea-ice cover. To reveal more complex spatiotemporal patterns, we explored higher-level clustering based on the second most recommended number of clusters (supplementary Fig. S2). To investigate the characteristics of the scenes and the variation among scenes, we used a principal component analysis (PCA) to visualize and interpret the positions of the scenes along the gradients of the ecoacoustic metric values.

Soundscape β-diversity: spatiotemporal similarities in scene compositions

The relative number of scene observations per deployment was obtained by correcting the number of scene observations for the sampling effort per deployment. This was done by dividing the number of daily scene observations per deployment by the maximum number of days recorded per deployment. The obtained relative scene composition per deployment was then used to compute the Bray-Curtis dissimilarity, using the function 'vegdist' from the R-package 'vegan' (Oksanen *et al.*, 2022). To identify regimes, we then applied hierarchical clustering, using the R in build function 'hclust' with 'average linkage', on the Bray-Curtis dissimilarity matrix.

Soundscape α-diversity

To quantify scene diversity per deployment, regimes, and for different sea-ice conditions, we assessed the standing scene richness (number of scenes) and effective number of scenes (ENS). The standing scene richness provides the true number of scenes, disregarding their rate of occurrence. The ENS provides the Hill-number of the Simpson diversity taking abundance into account, putting more weight on common scenes relative to rarer scenes (Chase and Knight, 2013). To calculate richness and ENS, we applied the function 'renyi' of the R-package 'vegan' (Oksanen *et al.*, 2022) on the relative number of scene observations per deployment and sea-ice condition. To obtain the richness and ENS, for each identified regime, the arithmetic means across the richness and ENS for each deployment were calculated for each regime. The ENS for each deployment was computed using the relative number of scene observations per deployment. The ENS for the sea-ice conditions was computed separately once for the EI station and once for the CWS and GM stations using the relative number of scene observations per deployment and sea-ice condition. The relative number of scene observations per deployment and sea-ice condition was calculated by dividing the number of daily scene observations per deployment and sea-ice conditions by the days recorded per deployment and sea-ice conditions. Sea-ice conditions were defined as 'open-water' for a SIC of <15% and 'sea-ice covered' for SIC ≥15%.

Environmental parameters

To interpret scenes and regimes in the context of local environmental parameters, time-series data for wind speed, SIC, distance to sea-ice edge, and the marginal sea-ice zone were extracted for each recording station. Additionally, the distance to the nearest coast or ice shelf was measured.

Wind speed and SIC

The hourly east- and westward field components of wind speed (10 m above the earth's surface in m/s) were retrieved by the European Centre for Medium-Range Weather Forecasts from the ERA5 data set for re-analysis (Hersbach *et al.*, 2023).

The daily SIC (in %) was obtained from the Sea-ice Remote Sensing Platform at the University of Bremen at a grid resolution of 3.125 km on a polar stereographic grid (Spreen *et al.*, 2008). The AMSR-E (Advanced Microwave Scanning Radiometer for EOS) instrument failed from 5.11.2011 to 22.07.2012. This data gap only corresponds with data recorded at stations CWS1 and CWS4. Missing SIC data of this period were complemented by using the daily SIC retrieved by the SSM/IS instrument (Special Sensor Microwave Imager/Sounder) and obtained from the Ocean and Sea Ice Satellite Application Facility (OSI SAF) at a grid resolution of 10 km (OSI SAF, 2017).

To spatially average the wind speed and the SIC across a defined area, the function 'extract' from the R-package 'raster' (Hijmans, 2020) was used, which averages across all pixels within the defined area boundaries. The hourly wind speed was spatially averaged across a radius of 0.25° latitude (corresponding to 27.75 km) around the recording sites, to account for wind-mediated sounds relatively close to the stations, and daily means were computed. The SIC was spatially averaged across a radius of 100 km around each recording site, covering the assumed call propagation range of most local marine mammals (Sirovic *et al.*, 2007; Miksis-Olds *et al.*, 2016).

Distance to sea-ice zone boundaries, coast, and ice shelf

The marginal sea-ice zone is defined as the sea-ice zone between 15% and 80% SIC (Horvat, 2021; Vichi, 2022). For this study, the sea-ice edge is defined by a SIC threshold of 15%, and we defined a SIC threshold of 80% as the boundary to the closed pack-ice zone.

Daily SIC data obtained from the IFREMER/CERSAT (Ezraty *et al.*, 2007) were used to compute distances to the sea-ice zones (in kilometres). The dataset is derived from the Special Sensor Microwave/Imager (SSM/I) and SSM/IS, gridded onto a polar stereographic projection (true at 70°N) with a spatial resolution of 12.5 × 12.5 km. The SIC data were retrieved using the ARTIST Sea-ice (ASI) algorithm applied to the 85 GHz channels, which offer higher spatial resolution compared to lower frequency channels (Kaleschke *et al.*, 2001; Spreen *et al.*, 2008). To reduce atmospheric noise and short-term variability, a 5-day median filter was applied to the SIC data, following the methodology described by (Kern *et al.*, 2010). Distances to the sea-ice edge were subsequently calculated using the 'distance_transform_edt' function from the scipy.ndimage module in the SciPy library (Virtanen *et al.*, 2020).

The distance to the coast or ice shelf was computed using the function 'dist2land' from the R-package ggOceanMaps (Vihtakari, 2023) on the land and Antarctic Ice Shelves data set with a 1:10 m scale from Natural Earth (www.naturalearth.com).

Results

The clustering of the soundscape properties described by the ecoacoustic metrics revealed that the standing soundscape diversity in the LMF-B was characterised by 14 scenes and the standing soundscape diversity of the HF-B was characterised by four scenes. Table 2 shows that some scenes occurred more often than others, for both of the investigated frequency bands. The ENS across the LMF-B data set was 10.2 and 3.1 for the HF-B.

Table 2. The number and percentage of daily acoustic observations assigned to each scene for each frequency band. The effective scenes, based on the ENS, are indicated by a grey background.

LMF-B						
1LMF	**2LMF**	**3LMF**	**4LMF**	**5LMF**	**6LMF**	**7LMF**
1207 (11.44%)	1175 (11.14%)	418 (3.96%)	82 (0.78%)	1295 (12.27%)	608 (5.76%)	1579 (14.97%)
8LMF	**9LMF**	**10LMF**	**11LMF**	**12LMF**	**13LMF**	**14LMF**
593 (5.62%)	938 (8.89%)	88 (0.83%)	926 (8.78%)	1037 (9.83%)	273 (2.59%)	332 (3.15%)
Total: 10551 (100%)						

HF-B			
1HF	**2HF**	**3HF**	**4HF**
3084 (40.77%)	1943 (25.68%)	2183 (28.86%)	355 (4.69%)
Total: 7565 (100%)			

Fig. 3 shows that the variance of the scenes along the soundscape properties described by the ecoacoustic metrics in the LMF-B and HF-B data set was highly complex. The identified scenes were not particularly distinct and transitions between scenes were fluent. The SPLs were the major acoustic properties explaining most of the variance across the LMF-B scenes along the first dimension, whereas the acoustic diversity metrics explained most of the variance among the LMF-B scenes along the second dimension, of which the temporal and spectral heterogeneity (the ACI and AEI) of both frequency ranges had the highest impact (Fig. 3A, supplementary Fig. S3). For the HF-B, the explained variance of the scenes was governed mainly by the SPLs and spectro-temporal homogeneity (HI) along the first dimension, but temporal heterogeneity (ACI) contributed most to the overall variance (Fig. 3B, supplementary Fig. S4).

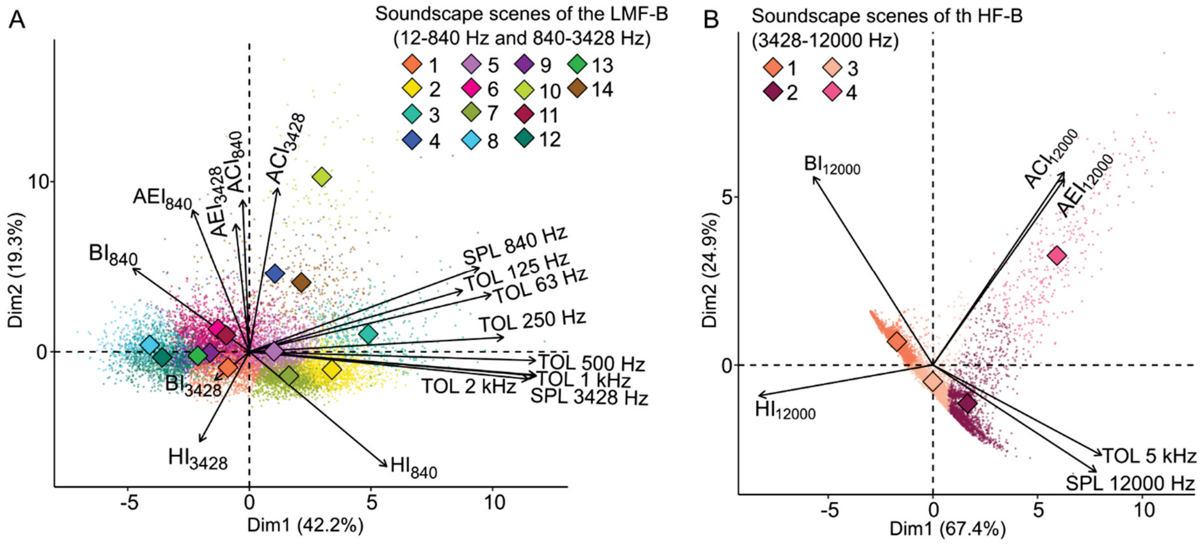

Fig. 3. PCA biplot to visualize the variance across the scenes explained by the ecoacoustic metrics for the two investigated frequency bands. A) The first four dimensions of the PCA explain 84% of the variance for the combined LMF-B. B) The first two dimensions of the PCA explain 92.3% of the variance for the HF-B. The large coloured diamonds indicate the scene centres, and the small points indicate the true daily soundscape observations used in the clustering method and assigned to each scene by colour. The scene centre parameters are provided in supplementary Table S5 and S6.

We considered the scenes 10_{LMF}, 14_{LMF}, and 4_{HF} as outliers. These scenes were characterized by a high spectro-temporal heterogeneity (AEI and ACI) and SPLs (Fig. 3). Moreover, inspection of daily spectrograms associated with the scenes revealed that these recordings were affected by strong periodic strumming and impulsive broadband shackle noise likely due to strong tidal movements at this station (see supplementary Fig. S5 for an example). Hence, these outlier-scenes for the LMF-B and HF-B are excluded from the computation of the soundscape diversity and regimes.

The loudest scenes were 3_{LMF}, 2_{LMF}, 4_{LMF}, and 2_{HF} and the quietest ones were scenes 8_{LMF}, 12_{LMF}, 13_{LMF}, and 1_{HF} (Fig. 3). The variability of the broadband SPLs across the scenes was highest for the

SPL 3428 Hz (scene centres ranging between 80 and 102.9 dB re 1 μPa), followed by the SPL 840 Hz (104.5 to 125.2 dB re 1 μPa), and lowest for the SPL 12000 Hz (76.9 to 89.1 dB re 1 μPa) (supplementary Table S5).

The order of the scenes for the LMF-B along a gradient of the spectro-temporal intensity variability was not as straightforward as it was for the SPLs. The values of the acoustic diversity metrics were rather variable across the measured frequency ranges, particularly for the HI and BI (Fig. 3A, supplementary Table S5). However, the BI seems to have played a minor role (Fig. 3A, supplementary Fig. S4). Overall, scene 4_{LMF} was the scene with highest spectro-temporal heterogeneity (high ACI, AEI, and low HI values), while scene 8_{LMF} was spectro-temporally heterogeneous (low HI, higher AEI and ACI) in the lower but homogenous (high HI, and low AEI and ACI) in the higher frequency ranges. Scene 2_{LMF} and 7_{LMF} were the most spectro-temporally homogenous scenes (high HI, low AEI and ACI) across both frequency ranges.

Similar to the variance explained across scenes for the LMF-B, the BI played a minor role in the overall explained variance for the HF-B scenes (Fig. 3B, supplementary Fig. S5). Scene 1_{HF} was the scene with highest spectro temporal homogeneity (high HI, low AEI and ACI), whereas scene 2_{HF} was comparatively spectro-temporally heterogenous (high HI, low AEI and ACI; Fig 3B, supplementary Table S6). However, the HI values increased with increasing frequency ranges to >0.9, indicating an increase in spectro-temporal homogeneity with increasing frequencies (supplementary Table S5 and S6).

Low-mid frequency band

The clustering in regimes revealed that spatial variation in scene composition and regime formation is driven mainly by two factors relating to depth (Fig. 4 and supplementary Fig. S6). First, regimes were separated by vertical zonation along the water column based on the recording depths of ~200 m, ~300 m, and ~1000 m, and classified into, epipelagic, mesopelagic, and bathypelagic zones, respectively. Second, regimes were grouped by water depth at the deployment station, such as shallow-water (~330 m) or deep-water (≥2500 m). Therefore, four main regimes were identified in total for the LMF-B (Fig. 4): shallow-water-epipelagic, deep-water-epipelagic, deep-water-mesopelagic, and deep-water-bathypelagic.

Moreover, there was also a tendency for the stations to be separated or grouped based on their distance from the coast or ice shelf (supplementary Fig. S6). The stations closest to the coast, station CWS1, and ice shelf, station GM3, were separated within the deep-water-epipelagic and station GM3 was also separated within the deep-water bathypelagic. Stations GM2 and CWS4 within the deep-wate-epipelagic and stations CWS7 and CWS2, as well as stations CWS3, GM2, and GM1, within the deep-water-bathypelagic, were grouped as they were more distant from the coast or ice shelf (Fig. 4).

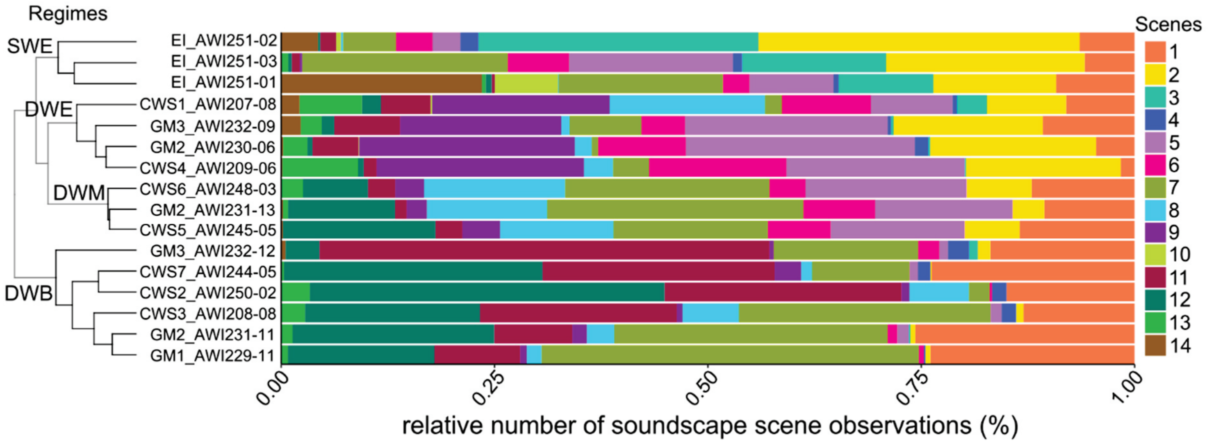

Fig. 4. Regimes obtained by the hierarchical clustering of the relative proportion of scene observations for the LMF-B. The dendrogram on the left correspond to the four identified regimes: shallow-water-epipelagic (SWE), deep-water-epipelagic (DWE), deep-water-mesopelagic (DWM), and deep-water-bathypelagic (DWB).

Fig. 4 shows that the proportion of scenes can be a unique feature for regime identification but also that scenes were shared between regimes. Moreover, the proportion and identity of the scenes shifted with increasing recording depth (Fig. 4). The proportion of scene 2_{LMF} decreased with increasing recording depth, whereas the proportion of scene 1_{LMF} increased with depth (Fig. 4). Additionally, the medium loud scenes 5_{LMF}, 6_{LMF}, and 9_{LMF} become replaced by the medium to quiet scenes 11_{LMF} and 12_{LMF} within the deep-water-bathypelagic regime (Fig. 4). High proportions of scene 8_{LMF}, which represents the quietest scene, was found in the deep-water-mesopelagic regime and not the deep-water-bathypelagic regime. The deep-water-epipelagic regime is on average 4.8 dB re 1µPa louder than the deep-water-bathypelagic regime. At the same time, the deep-water-epipelagic regime is on average 5.1 dB re 1 µPa quieter than the shallow-water-epipelagic regime (supplementary Table S7). In contrast, the acoustic diversity metrics did not indicate a considerable overall change in the complexity of spectro-temporal patterns with increasing depth in the water column or between shallow-water and deep-water regimes, except for the BI for the frequency range 12-840 Hz (supplementary Table S7). In contrast, the acoustic diversity metrics did not indicate a considerable change in the complexity of spectro-temporal patterns with increasing depth in the water column or between shallow-water and deep-water regimes, except for the BI for the frequency range 12-840 Hz (supplementary Table S7).

Pooling the deployments by the identified regimes showed that effective soundscape diversity was highest for the deep-water-mesopelagic and -epipelagic regimes, followed by the shallow-water-epipelagic, and finally by the deep-water-bathypelagic regime (Table 3). Table 3 shows that the effective soundscape diversity was higher for sea-ice-covered conditions for the deep-water regimes, whereas for the shallow-water-epipelagic regime the open-water period was effectively more diverse.

The temporal distribution of the scene observations per deployment indicated that the soundscape scene identity and diversity of the deep-water deployments were linked to seasonal sea-ice conditions (Fig. 5). Additionally, Fig. 5 indicates that shared scenes followed a different seasonal pattern in each regime in relation to increasing recording depth (e.g., scene 1_{LMF}, 5_{LMF}, 6_{LMF}, 7_{LMF}), and can therefore characterise different environmental conditions in each regime (Fig. 5 and 6).

Overall, the scenes most often associated with open-water conditions across all regimes (scene 7_{LMF}, 2_{LMF}, 5_{LMF}; Fig. 6) were louder and comparatively spectro-temporally homogenous. Additionally, scenes 2_{LMF} and 7_{LMF} were strongly characterised by wind-mediated sounds (Fig. 6). Moreover, sea-ice cover was absent most of the year at the EI station and therefore, wind conditions played a major role in characterising soundscape diversity in shallow-water regimes (Fig. 6). In contrast, the scenes that characterised soundscapes most often during sea-ice covered conditions (scene 1_{LMF}, 12_{LMF}, and 8_{LMF}) also characterised the soundscape south of the closed pack-ice zone across all deep-water regimes (Fig. 6), which are heavy sea-ice covered soundscapes that were quieter and comparatively spectro-temporally heterogeneous. The scenes that characterize the sea-ice-covered soundscape of the deep-water regimes (scenes 1_{LMF}, 12_{LMF}, and 8_{LMF}) did not effectively capture the prevailing wind conditions (Fig. 6).

Table 3. Soundscape diversity by deployment and regime as defined by the standing soundscape diversity (richness) and effective soundscape diversity (ENS).

		Richness						ENS					
		Whole recording period		Open-water conditions		Sea-ice covered		Whole recording period		Open-water conditions		Sea-ice covered	
Deployment	**Regime**	**total**	**mean**	**total**	**mean**	**total**	**mean**	**total**	**mean**	**total**	**mean**	**total**	**mean**
EI_AWI251-02	**Shallow-water-epipelagic**	10	10.7	10	10.3	6	6	3.5	4.3	3.6	4.7	1.9	3.7
EI_AWI251-03		11		10		4		5.4		5.2		4.9	
EI_AWI251-01		11		11		8		5.4		5.2		4.2	
CWS1_AWI207-08	**Deep-water-epipelagic**	12	11.8	5	5.8	12	11.8	7.8	6.3	2.2	2.0	7.2	5.8
GM3_AWI232-09		12		8		12		6.3		2.2		6.5	
GM2_AWI230-06		12		6		12		5.2		2.2		4.7	
CWS4_AWI209-06		11		4		11		5.8		1.8		5.3	
CWS6_AWI248-03	**Deep-water-mesopelagic**	10	9.7	7	7.3	9	9	6.6	6.7	3.4	3.3	4.0	4.3
GM2_AWI231-13		10		8		9		5.8		3.2		4.1	
CWS5_AWI245-05		9		7		9		7.2		4.1		4.6	
GM3_AWI232-12	**Deep-water-bathypelagic**	10	10	3	6.2	10	9	2.9	3.8	2.3	2.2	2.7	3.2
CWS7_AWI244-05		10		8		9		4.2		3.4		3.5	
CWS2_AWI250-02		9		3		9		3.6		2.3		3.5	
CWS3_AWI208-08		10		8		8		4.9		2.1		3.8	
GM2_AWI231-11		11		8		10		4.3		2.4		3.3	
GM1_AWI229-11		10		7		8		3.4		1.9		3.1	

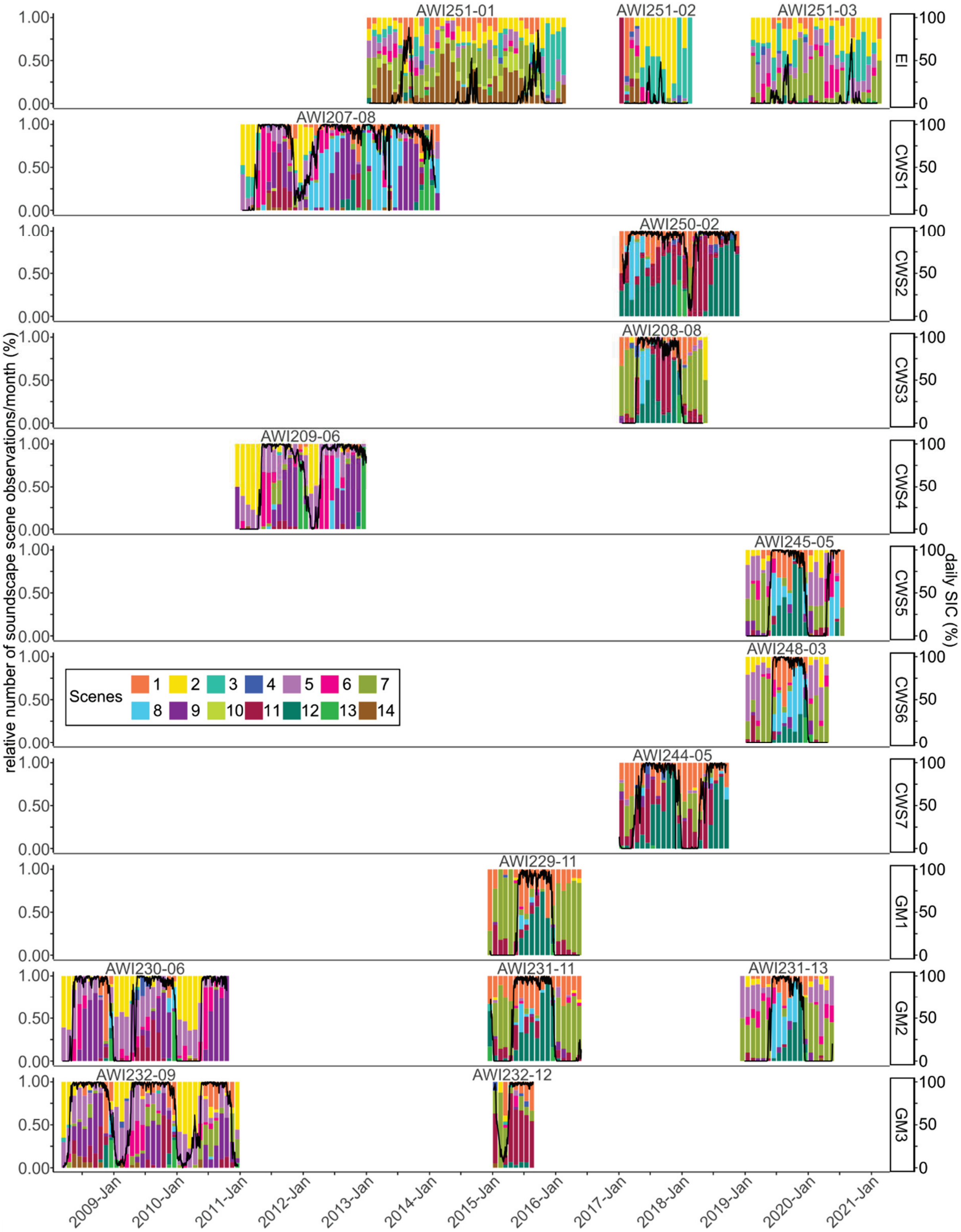

Fig. 5. Relative proportion of scene observations by month and deployment for the LMF-B in relation to the daily mean SIC (black line, right-y-axis). The number of scenes by deployment and month was corrected for sampling effort by month.

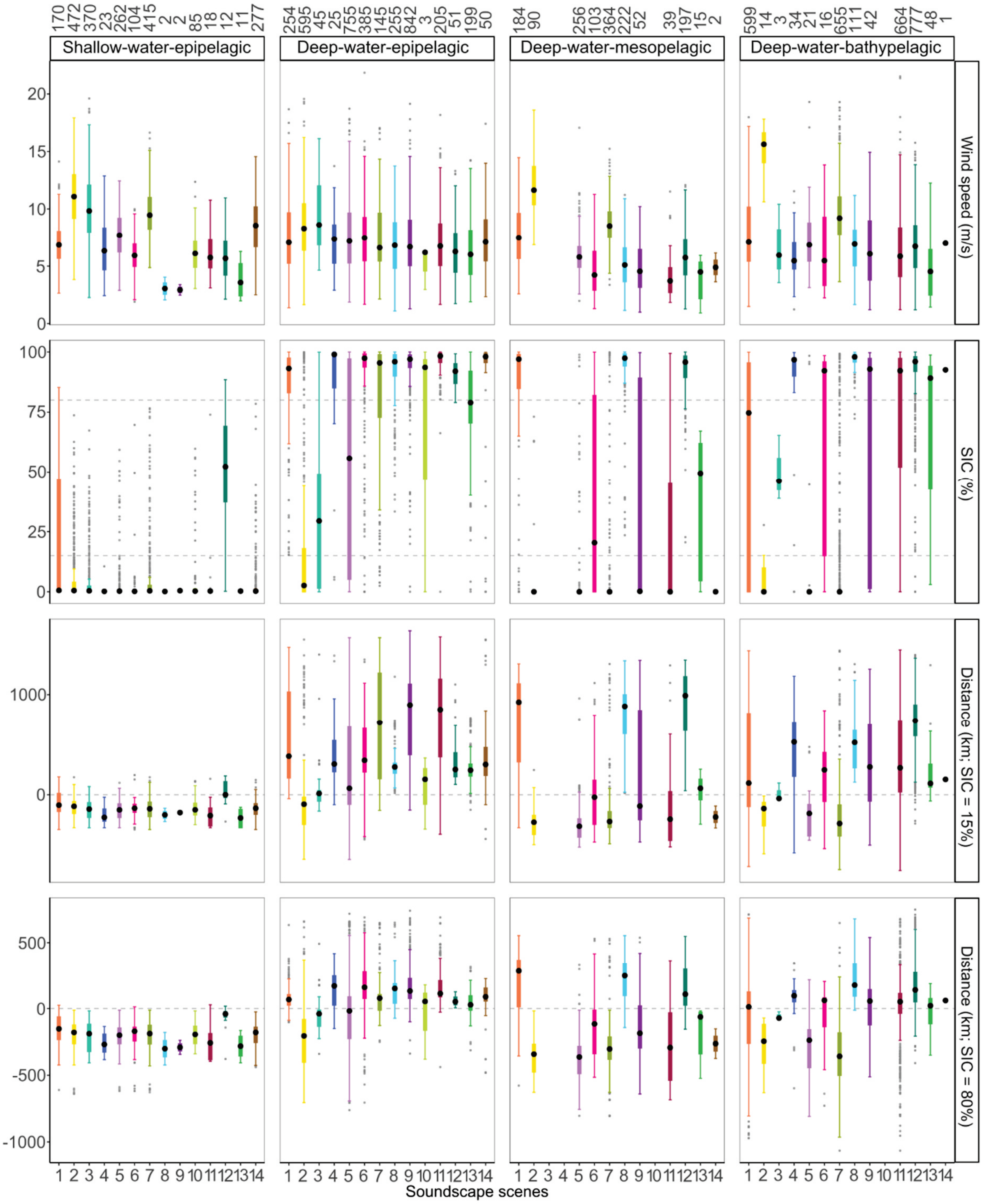

Fig. 6. Boxplots of the scene observations partitioned by environmental conditions and identified regimes for the LMF-B. The large black points indicate the medians. The numbers on top of the first panel represent the daily acoustic observation of each scene. The dashed lines in the second panel represents the SIC threshold for 'open-water' and 'closed pack-ice' conditions, with a SIC of 15 and 80%, respectively. The dashed lines in the lower two panels represent the corresponding ice boundaries, with positive values indicating that the station was south of the respective sea-ice boundary, south of the sea-ice edge, and south of the closed pack-ice zone.

High-frequency band

The proportion of scenes per deployment in the HF-B revealed two regimes separated by the water depth at the station, similar to the MF-B regimes: shallow-water, EI deployments, and deep-water, CWS and GM deployments (Fig. 7A). The deep-water regime showed a tendency towards further partitioning. Station CWS1 was separated, whereas the other stations were grouped and further sub-partitioned. This resulted in the grouping of station GM2 (deployment AWI213-13) and CWS6, both of which recorded a deep-water-bathypelagic soundscape. Furthermore, soundscapes of stations CWS4 and CWS5, as well as GM3, and GM2 (deployment AWI230-06) were grouped from west to east and across different recording depths.

The shallow-water and deep-water regimes were characterised by the same three scenes, but the proportions of these scenes differ greatly (Fig. 7). The shallow-water regime is characterised mainly by scenes 2_{HF} and 3_{HF}, whereas the deep-water regime is characterized mainly by scenes 1_{HF} and 3_{HF}. The HF-B for the shallow-water regime is on average 4.5 dB re 1 µPa louder than the deep-water regime (supplementary Table S8). The acoustic diversity metrics indicate similar spectro-temporal intensity variability between the regimes, as the values are quite similar and the HF-B was overall spectro-temporally homogenous with HI values ≥0.94 (see supplementary Table S8).

Across both regimes, scenes 2_{HF} and 3_{HF} were linked to open-water conditions, and characterized the open-water soundscape as loud (Fig. 8B). In addition, scene 1_{HF} mainly characterised soundscapes during high SICs, south of the closed pack-ice boundary, while it was less characterised by wind-mediated sounds (supplementary Fig. S7). Therefore, scene 1_{HF} characterised the quiet sea-ice-covered soundscape. In contrast, scene 2_{HF} was characterised by wind-mediated sounds and characterised soundscapes during open-water conditions and far away from the sea-ice edge, whereas scene 3_{HF} characterised soundscapes closer to the sea-ice edge and was less affected by wind-mediated sounds (supplementary Fig. S7). In contrast to the LMF-B soundscape, the HF-B soundscape was characterized by two scenes during the open-water conditions and mainly by one scene during sea-ice-covered conditions.

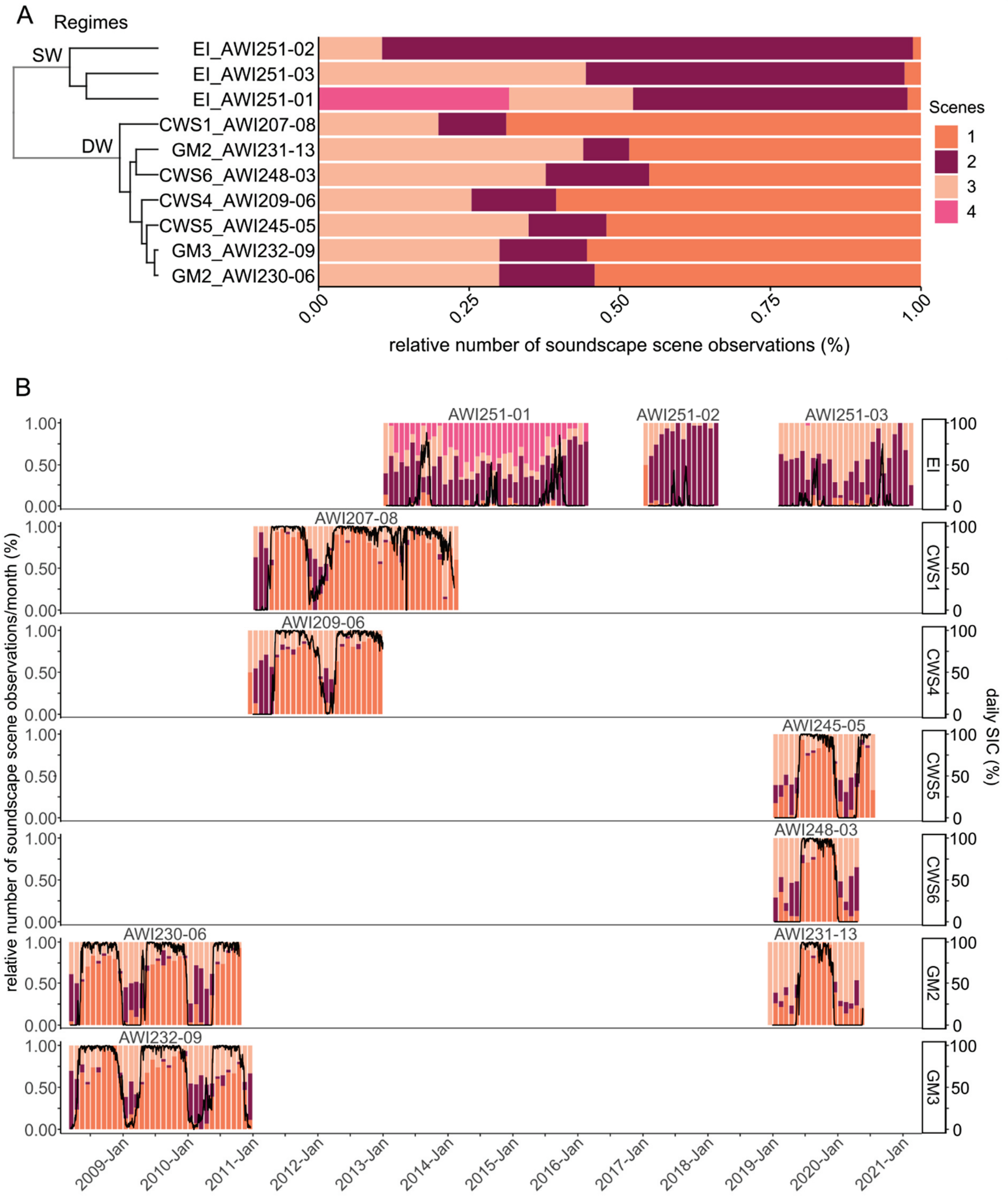

Fig. 7. A) Regimes obtained by the hierarchical clustering of the relative proportion of scene observations for the HF-B. The dendrogram on the left correspond to the identified HF-B regimes, shallow-water (SW) and deep-water (DW), respectively. B) Relative proportion of scene observations by month and deployment for the HF-B in relation to the daily mean SIC (black line, right-y-axis). The number of scenes by deployment and month was corrected for sampling effort by month.

Discussion

This study was motivated by the need to better understand the diversity of the acoustic component of remote and pristine underwater environments. To our knowledge, our work is the first to compare such large-scale spatiotemporal patterns in soundscape diversity, revealing different soundscape regimes across an ocean basin scale. Understanding how the acoustic environment of large-scale ecosystems is temporally and spatially clustered into acoustic regimes, is critical to improve our knowledge of underwater soundscape dynamics. Such baseline knowledge is relevant, also in the light of climate change, which is affecting the spatiotemporal distribution of sound sources and underwater sound propagation, causing regime shifts, disrupt and alter soundscape patterns, and affects basin-wide and synoptic scale acoustic connectivity of marine habitats.

Spatial diversity across the WS basin

Geographical comparisons of soundscapes can reveal acoustic connections across environments through biological, environmental or anthropogenic factors over local to larger scales, comprising both terrestrial (Sethi *et al.*, 2020; Flowers *et al.*, 2021) and marine environments (Bittencourt *et al.*, 2020; Wilford *et al.*, 2023; Mattmüller *et al.*, 2024). Regimes revealed spatiotemporal similarities of acoustic environments driven mainly by similarities in recording depth, water depth, and sea-ice cover, whereas the distance to the coast or ice shelf was less relevant. We found a greater similarity between the epi-and mesopelagic recorded soundscapes despite different water depths and sea-ice conditions across the stations, whereas the deep-water-bathypelagic regime was unique.

The type and number of sound sources, e.g., marine mammals, and their spatiotemporal distributions are key drivers for ecoacoustic metric variability in the WS (Menze *et al.*, 2017; Roca and Van Opzeeland, 2019) and thereby contribute to shaping the spatiotemporal soundscape diversity and regimes. Most sound sources in the SO are found at the sea surface or within the upper meters of the water column. Most baleen whale species in the SO, such as fin (*Balaenoptera physalus*), Antarctic blue (*Balaenoptera musculus intermedia*), and Antarctic minke whales (*Balaenoptera bonaerensis*), vocalize at comparatively shallow depths (down to approximately 40 m; Risch *et al.*, 2014; Stimpert *et al.*, 2015; Bouffaut *et al.*, 2021). Weddell seals (*Leptonychotes weddellii*) are estimated to vocalize mainly between 10-35 m below the sea-ice (Moors and Terhune, 2005). Similar vocalization depths might hold for the other pagophilic pinnipeds, such as leopard (*Hydrurga leptonyx*), crabeater (*Lobodon carcinophaga*), and ross seals (*Ommatophoca rossii*) found in the SO (Rogers, 2003; Van Parijs, 2003). Moors and Terhune (2005) described that ice sounds are less prevalent with increasing depth and that seals benefit from an improved signal-to-noise ratio below 20 m of the ice surface. Additionally, signals generated at shallow water layers may create a highly ensonified polar surface duct, above 60 to 500 m, also during sea-ice-covered periods (Jensen *et al.*, 2000; Alexander *et al.*, 2016). This might explain the higher effective soundscape diversity of the louder soundscapes recorded at shallower depth layers (i.e., ~200 m and ~300 m) and the distinct separation of the quieter deep-water-bathypelagic regime. The presence of an ensonified polar surface duct might also explain the differences between the deep-water-epi and mesopelagic soundscapes that our analysis showed. Consequently, this suggests that vertical zonation plays a crucial role in comparing and defining acoustic environments. Nevertheless, we cannot exclude the potential effect of the subsampling scheme that was applied when collecting the deep-water epipelagic data, causing these deployments to lack temporally clustered events (Thomisch *et al.*, 2015). The subsampling might have affected the daily means and hence clustering of the deep-water-epipelagic-regime, which might otherwise have been classified as more similar to the deep-water mesopelagic regime.

In our study, the distance to the coast or ice shelf appeared to only have a weak influence on the deep-water regimes, but stations more distant to the coast or ice shelf showed a higher soundscape similarity. It has been shown that the offshore pelagic soundscapes are acoustically different from the on-shelf soundscapes of the WS (Roca and Van Opzeeland, 2019). This was hypothesized to reflect a higher amount of transiting marine mammal species at the offshore pelagic sites, while sites closer to the shelf might provide more reliable access to food resources, and consequently more resident pagophilic marine mammal species (Roca and Van Opzeeland, 2019). Higher acoustic similarity of the offshore stations might also be explained by the long transmission ranges (up to 200 km; Sirovic *et al.*, 2007) of the low-frequency (<120 Hz) vocalizations of fin and Antarctic blue whales (Thomisch *et al.*, 2016; Wöhle *et al.*, 2025). These two species prefer open-water conditions and characterize the WS soundscape year-round (Thomisch *et al.*, 2016; Menze *et al.*, 2017; Wöhle *et al.*, 2025). Therefore, these species area able to acoustically connect soundscapes across the WS basin. For the pagophilic marine mammals on the other hand, the species-specific preference of sea-ice conditions and foraging strategies cause their distribution within the WS to be more clustered (Wege *et al.*, 2021a; Wege *et al.*, 2021b; Roca *et al.*, 2023). Additionally, their vocalizations transmit over much shorter scales (up to 30 km; Terhune and Ronald, 1986; Filun *et al.*, 2020), limiting their contribution to the soundscape to more local scales. Similarly, the likelihood of most ice-related sounds affecting other than local soundscapes might considerably decrease with increasing distance from the Antarctic shelf. Furthermore, stations located farther away from the Antarctic shelf are likely to experience shorter periods of sea-ice cover and therefore more wind-mediated sounds as the sea-ice seasonally extends and retreats. This suggests that the horizontal variation in soundscape diversity that we observed for the deep-water regimes was driven not only by acoustic marine mammal distribution but also by seasonal variation of environmental sounds changing with distance from the coast or ice shelf. To better resolve horizontal partitioning, we recommend that recorders ideally be deployed at the same depth in the water column to eliminate the confounding effects of vertical regimes.

Temporal soundscape diversity of the deep-water regimes is linked to sea-ice cover

We observed that the deep-water-regimes had higher effective soundscape diversity and a pronounced seasonal pattern, in contrast to the shallow-water-epipelagic regime. In accordance with a previous study (Mattmüller *et al.*, 2024), our study demonstrates that a higher and seasonal soundscape diversity is associated with a pristine SO ecosystem. Consequently, these results corroborate the observations that healthy ecosystems tend to be acoustically complex (Rossi *et al.*, 2017; Gordon *et al.*, 2018). Moreover, our results suggest that temporal soundscape diversity patterns are shaped by a combination of the annual cycle of the sea-ice cover, distance to the sea-ice boundary, wind-mediated sounds, and the acoustic ecology of marine mammal species.

The seasonal acoustic ecology of the WS basin is tightly linked to the prevailing seasonal sea-ice cover not only due to the dampening effect of the ice-cover shielding wind-mediated sounds, or sea-ice generated sounds but also due to the highly sea-ice adapted (acoustic) ecology and community dynamics of the SO marine mammal species (Menze *et al.*, 2017; Van Opzeeland and Hillebrand, 2020). Hence, the higher soundscape diversity during the sea-ice-covered periods found in our study can at least in part most likely be explained by the exclusion of wind-mediated sounds causing higher signal-to-noise ratios of marine mammal vocalizations (Chen *et al.*, 2023; Mattmüller *et al.*, 2024). In addition, ecoacoustic metrics are sensitive to variations in call abundance (Bohnenstiehl *et al.*, 2018; Mammides *et al.*, 2021), which might have contributed to the observed higher soundscape diversity during sea-ice-covered periods. The vocalizations of the pagophilic marine mammal species, are characteristic of the sea-ice-covered period (Van Opzeeland *et al.*, 2010; Filun *et al.*, 2020). Due to the long transmission range of the vocalizations of fin and Antarctic blue whales these species also contribute to the under-ice diversity of sea-ice-covered soundscapes (Thomisch *et al.*, 2016; Menze *et al.*, 2017; Wöhle *et al.*, 2025). Earlier work in the WS basin also showed that the marine mammal acoustic community composition is most diverse during sea-ice cover periods (Van Opzeeland and Hillebrand, 2020) and that a multi-metric approach was a good approximation of acoustic marine mammal species richness and identity (Roca and Van Opzeeland, 2019). Our study's findings are in line with these and suggest that observed soundscape diversity during sea-ice-covered periods mimics marine mammal acoustic community dynamics.

The lower soundscape diversity of the open-water period of the deep-water regimes can be attributed to the increased contribution of broadband and continuous sounds, such as wind-mediated sounds and icequakes from icebergs (Dziak *et al.*, 2015). These sound sources increase

SO ambient sound levels, particularly in the lower frequency range, during open water conditions (Dziak *et al.*, 2015; Menze *et al.*, 2017; Mattmüller *et al.*, 2024). The increased ambient sound levels lower the signal-to-noise ratio and can weaken or mask biological acoustic features, such as the chorusing of fin and Antarctic blue whales, during the austral summer months, thereby increasing spectro-temporal homogeneity (Mattmüller *et al.*, 2024).

We also showed that some scene observations followed a different temporal pattern within different regimes. This reflects that a scene does not necessarily characterize a distinct soundscape pattern but that a consistent dominant factor must drive similarities in soundscape properties across seasons. Similar Mattmüller *et al.* (2024) observed that the August and November soundscape of one station in the WS are characterized by similar acoustic properties, as both seasons were strongly sea-ice-covered reducing the effect of wind-mediated sounds. Both seasons also contained a diverse acoustic community composition with relatively consistent chorus intensity (Mattmüller *et al.*, 2024). For our study this might mean, that a soundscape recorded in the bathypelagic during open-water conditions, where wind-mediated ambient sound levels are reduced, may have similar acoustic properties to a soundscape recorded in epipelagic under sea-ice conditions or under weak wind conditions also reflecting low ambient sound conditions. In contrast, at shallower recording depths, soundscapes are predominantly characterised by fluctuations in the impact of wind-mediated sounds on the soundscape characteristics which contributes to higher soundscape diversity.

The shallow-water-epipelagic regime off EI

We anticipated the separation of the shallow-water-epipelagic soundscape off EI from the other soundscapes since it is the only station that exhibits a low water depth, virtually no seasonal sea-ice cover, and records relatively close to the coast. However, unlike the deep-water bathypelagic regime, the shallow-water-epipelagic-regime was not unique but was grouped with the other soundscapes recorded at shallow depths within the deep-water regimes. This grouping was likely caused by the seasonal (austral-summer) similarities of loud and relatively high spectro-temporally homogenous scenes. Therefore, the most influential factors at this site are presumably the sound sources producing broadband and (virtually) continuous sounds and/or high ambient sound levels.

Off EI, a high seasonal (acoustic) abundance of fin whales was reported (Burkhardt *et al.*, 2021; Herr *et al.*, 2022; Wöhle *et al.*, 2025). This high abundance of nearly continuously vocalizing fin whales might contribute to the high ambient sound levels of the shallow-water-epipelagic regime. Additionally, the waters off EI hosts a high acoustic marine mammal diversity (Van Opzeeland and Hillebrand, 2020), including Antarctic blue whales (Van Opzeeland and Hillebrand, 2020; Burkhardt *et al.*, 2021), which presumably also contributed to high ambient sound levels at this station. Moreover, broadband and loud icequakes from calving or breaking of icebergs strongly characterize the soundscape off the Antarctic Peninsula contributing to increased ambient sound levels in austral summer (Dziak *et al.*, 2015). Additionally, the Antarctic Peninsula including EI is, in contrast to the deep-water regime, comparatively strongly impacted by anthropogenic noise, due to research, tourism and fishing (Breitzke, 2014; Erbe *et al.*, 2019). The lack of sea-ice therefore causes a two-folded lack of a pronounced seasonal pattern in soundscape diversity at this station due to the year-round presence of wind-mediated sounds as well as anthropogenic presence. Moreover, there is prominent shore noise at this station, which can periodically increase ambient sound levels in the lower frequency range with the potential to weaken or mask biological acoustic soundscape features, such as fin whale calls (Burkhardt *et al.*, 2021).

A difference in methodology likely explains the fact that the soundscape diversity off EI, in the current study was found to be lower compared to deep-water-epipelagic regimes of the WS, which is in contrast to the findings by Van Opzeeland & Hillebrand (2020). Van Opzeeland and Hillebrand (2020) based their analyses on manually perused daily acoustics presence-absence records of marine mammal species. By contrast, our study used ecoacoustic metrics to holistically assess the acoustic properties of soundscape patterns created by all sound sources (bio-, geo-, and anthropophonic) in order to evaluate diversity in soundscape patterns and not specifically focus on evaluating acoustic marine mammal species diversity. Therefore, we suspect that the discrepancy between those studies is caused by the sensitivity of the acoustic diversity metrics to decreased signal-to-noise ratios of biological acoustic features (Bohnenstiehl *et al.*, 2018; Mooney *et al.*, 2020; Chen *et al.*, 2023) caused by wind-mediated sounds, icequakes, shore noise, and anthropogenic noise.

Diversity across frequency range

In the WS basin, a high number of sound sources is known to occupy the lower frequency ranges (Dziak *et al.*, 2015; Van Opzeeland and Boebel, 2018). We suspect, that this higher soundscape diversity found in the LMF-B, is not only due to the higher number of sound sources but also due to the higher attenuation of high-frequency sounds. This, in turn, might also explain the increasing spectro-temporal homogeneity for higher frequency ranges, and lower soundscape diversity during sea-ice-covered periods for the HF-B of the deep-water regime. However, the HF-B showed a higher soundscape diversity during the open-water period. This might be explained by the fluctuation between weak and strong wind conditions, and the associated change in ambient sounds, during the open-water period.

The observed differences in soundscape diversity found between the LMF-B and the HF-B might be biased by the fact that the LMF-B is described by the combination of two frequency ranges, which might have increased the likelihood of capturing higher soundscape diversity. We applied the daily mean for clustering, however, this means that dominant and continuous soundscape features, such as choruses, wind-mediated sounds, and persistent repetitive impulsive signals, such as strumming and shackle noise, are directing the clustering, whereas sparse calling or temporally clustered events do not have a strong impact on the scene clustering, e.g., higher frequency clicks of sperm whales or Weddell seal calls (Madsen *et al.*, 2002; Moors and Terhune, 2004).

Future implications

Our study showed, that the regime off the ice-free EI station exhibited a lack of pronounced seasonal soundscape diversity and that open-water periods exhibit lower soundscape diversity. This supports (Mattmüller *et al.*, 2024), suggesting that, with a decreasing sea-ice cover, the soundscape of the WS basin is likely to become acoustically less diverse and louder as wind-mediated sound and anthropogenic noise increase, masking biological acoustic patterns of acoustics marine mammal community dynamics, in analogy to what has already been observed and postulated for the Arctic Ocean (Mo *et al.*, 2023; Mattmüller *et al.*, 2024). Hence, the soundscapes off EI and off the Antarctic Peninsula might provide an outlook to what future Antarctic coastal soundscapes could sound like, if ongoing changes continue to proceed at the present rate.

The SO offshore soundscapes, most distant to the Antarctic shelf, might likely be the first to become increasingly acoustically homogenous and louder, as open-water periods prolong (Eayrs *et al.*, 2021). Also, marine mammals might migrate southwards, following the receding sea-ice extent and prey availability (Rogers *et al.*, 2020; Hodapp *et al.*, 2023; Roca *et al.*, 2023). Apart from changing species distribution patterns, marine mammals will need to optimize their acoustic strategies, such as calling frequency, timing, or intensity, to cope with the changing acoustic environments (Tyack, 2008; Duarte *et al.*, 2021) with possible implication on soundscape patterns. The recovering populations of fin and Antarctic blue whales (Tulloch *et al.*, 2019), with their loud and far-reaching vocalizations (Charif *et al.*, 2002; Sirovic *et al.*, 2007), may have a significant influence on shaping future SO soundscape patterns, if their population continue to recover despite climate-induced changes and increases in other anthropogenic impacts, such as ship-generated underwater noise and krill fishery (Tulloch *et al.*, 2019; Teschke *et al.*, 2021).

Conclusion

In the context of the tripe planetary crisis, which is causing ongoing alterations to marine soundscapes, it is essential to monitor large-scale spatio-temporal acoustic dynamics and connectivity of quasi-pristine marine ecosystems in relation to environmental gradients. This will provide a fundamental understanding of natural soundscape patterns in space and time. In this context, clustering approaches are increasingly being used to assess soundscape variation among different acoustic environments, both terrestrial and aquatic (Roca and Van Opzeeland, 2019; Bittencourt *et al.*, 2020; Flowers *et al.*, 2021; Parcerisas *et al.*, 2023; Sethi *et al.*, 2023; Wilford *et al.*, 2023; Mattmüller *et al.*, 2024). Our study is, to the best of our knowledge, the first to apply clustering on a basin-scale, real-world data set comprising approximately 127896 h of unlabelled acoustic data. We showed that local to basin-wide assessments of spatiotemporal soundscape diversity and regimes in relation to environmental parameters can reveal isolation and similarities among soundscapes. We captured changes along, increasing recording depth, water depth, and distance to the coast or ice shelf reasonably well. Moreover, our approach captured the wind and sea-ice-driven seasonality of the soundscape diversity, which we additionally linked to the acoustic ecology of the acoustically dominant marine mammals of the SO. Therefore, our study might provide a starting point to explore and compare basin-wide soundscapes and to uncover spatiotemporal patterns in soundscape diversity to boost a more holistic understanding of soundscapes. Lastly, this approach supports the urgently needed monitoring of ongoing large-scale climate-induced changes in the acoustic environment in the WS basin (Schall *et al.*, 2021; Roca *et al.*, 2023).

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Ethics

The permission to deploy the recorders in the WS-Basin was granted by the German federal environmental agency (UBA, Umweltbundesamt). Following UBA permits were granted: I 3.5 – 94003-3/286, I 3.5 – 94003-3/255, II 2.8 – 94003-3/385, II 2.8 – 94033/137, II 2.8 – 94003-3/324, I 2.4 – 94003-3/207. The permit information for each individual deployment can be found in the metadata for each data set (see data accessibility statement).

Data accessibility

The passive acoustic data sets analysed in this study are published under a CC-BY 4.0 license at the PANGAEA data repository (www.pangaea.de; Data Publisher for Earth & Environmental Science; Felden *et al.*, 2023) through the following references for each recording: AWI207-08_AU0085 (Thomisch *et al.*, 2025e), AWI208-08_SV1009 (Thomisch *et al.*, 2023c), AWI209-06_AU0086 (Thomisch *et al.*, 2024e), AWI229-11_SV1057 (Thomisch *et al.*, 2025f), AWI230-06_AU0085 (Thomisch *et al.*, 2024c), AWI231-11_SV1058 (Thomisch *et al.*, 2024f), AWI232-09_AU0086 (Thomisch *et al.*, 2024d), AWI232-12_SV1059 (Thomisch *et al.*, 2024g), AWI245-05_SV1014 (Thomisch *et al.*, 2024b), AWI248-03_SV1012 (Thomisch *et al.*, 2024a), AWI250-02_SV1003 (Thomisch *et al.*, 2025b), AWI251-01_AU0231 (Thomisch *et al.*, 2024h), AWI251-02_AU0231 (Thomisch *et al.*, 2025a), AWI251-02_SV1013 (Thomisch *et al.*, 2025c), AWI251-03_AU0085 (Thomisch *et al.*, 2025d). Furthermore, the following datasets have been submitted to the PANGAEA data repository and are currently under editorial review for publication: AWI251-03_SV1002, AWI244-05_SV1057, AWI231-13_SV1056.

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Supplementary

Table S1. Information on the pre- and post-calibration gain and sensor sensitivity for each recording system.

Station	**Deployment ID_Recorder ID**	**Pre- and post-calibration gain (dB)**	**Sensor sensitivity (dB re 1 V µPa^{-1})**
EI	AWI251-01_AU0231	manufacturer calibration	-164
	AWI251-02_AU0231	manufacturer calibration	-164
	AWI251-02_SV1013	41.2/40.2	-192.4
	AWI251-03_AU0085	manufacturer calibration	-164.6
	AWI251-03_SV1002	41.3/40.5	192.5
CWS1	AWI207-08_AU0085	manufacturer calibration	-165
CWS2	AWI250-02_SV1003	41.5/41	-193.2
CWS3	AWI208-08_SV1009	41.3/41	-192.5
CWS4	AWI209-06_AU0086	manufacturer calibration	-164
CWS5	AWI245-05_SV1014	44.3/44.1	-192.5
CWS6	AWI248-03_SV1012	44.4/44.5	-192.5
CWS7	AWI244-05_SV1057	41.7/41.3	-193
GM1	AWI229-11_SV1057	44.65/45	-192.5
GM2*	AWI230-06_AU0085	manufacturer calibration	-164.3
	AWI231-11_SV1058	44.53/44.9	-193
	AWI231-13_SV1056	44.5/44.7	-193
GM3	AWI232-09_AU0086	manufacturer calibration	-164.6
	AWI232-12_SV1059	44.67/44.7*	-193

*Post calibration is not available why the manufacturer pre-deployment gain calibration is used

Table S2. Summary of the ecoacoustic diversity metrics selected to characterize the complexity of the spectro-temporal intensity variability and the respective settings applied to compute these metrics over each frequency range and over the full file length. x = audio file ('.wav'). R version 4.2.2 was used (R Core Team, 2023). See also Bradfer-Lawrence et al., (2024) for a more detailed explanation on these acoustic diversity metrics.

Metric	Short description		Reference
ACI (acoustic complexity index)	Complexity of intensity variation across time. High values indicate higher temporal heterogeneity.	Temporal heterogeneity	(Pieretti *et al.*, 2011; Sueur *et al.*, 2012)
R implementation: **SEEWAVE:: ACI(x, wl, ovlp , nbwindows, lim, "hanning")** ACI$_{840}$ (12-840 Hz): wl = 512, ovlp = 50, nbwindows = 1, lim = c(0.012, 0.84) ACI$_{3428}$ (840-3428 Hz): wl = 2024, ovlp = 50, nbwindows = 1, lim = c(0.84, 3.428) ACI$_{12000}$ (3428-12000 Hz): wl = 6084, ovlp = 50, nbwindows = 1, lim = c(3.428, 12)			
AEI (acoustic evenness index)	Heterogeneity of intensity variation across frequency bands (Gini coefficient) and above a set power threshold relative to full scale. Value between 0 and 1, whereas values close to 0 represent spectral homogeneity and values close to 1 spectral heterogeneity	Spectral heterogeneity	(Villanueva-Rivera *et al.*, 2011; Villanueva-Rivera and Pijanowski, 2018)
R implementation: **SOUNDECOLOGY::acoustic_evenness(x, max_freq, freq_step, db_threshold)$aei_left** AEI$_{840}$ (12-840 Hz): max_freq = 840, freq_step = 10, db_threshold = -50 dBFS AEI$_{3428}$ (840-3428 Hz): max_freq = 3428, freq_step = 34, db_threshold = -50 dBFS AEI$_{12000}$ (3428-12000 Hz): max_freq = 12000, freq_step = 120, db_threshold = -50 dBFS			
HI (total acoustic entropy)	Evenness of intensity variation across time and frequency. Value between 0 and 1, whereas values close to 0 represent spectro-temporal heterogeneity and values close to 1 spectro-temporal homogeneity.	Spectro-temporal homogeneity	(Sueur *et al.*, 2008; Sueur *et al.*, 2012)
R implementation: **seewave::th(SEEWAVE::env(x)) * SEEWAVE::sh(SEEWAVE::meanspec(x, wl, ovlp, "hanning"))** HI$_{840}$ (12-840 Hz): wl = 512, ovlp = 50 HI$_{3428}$ (840-3428 Hz): wl = 2024, ovlp = 50 HI$_{12000}$ (3428-12000 Hz): wl = 6084, ovlp = 50			
BI (bioacoustic index)	Area under the spectrum curve between two frequency limits. Higher values represent high spectral heterogeneity and temporal homogeneity (banding)	Spectral heterogeneity and temporal homogeneity	(Boelman *et al.*, 2007; Villanueva-Rivera and Pijanowski, 2018)
R implementation: **SOUNDECOLOGY::bioacoustic_index(x, min_freq, max_freq)$left_area** BI$_{840}$ (12-840 Hz): min_freq = 12, max_freq = 840 BI$_{3428}$ (840-3428 Hz): min_freq = 840, max_freq = 3428 BI$_{12000}$ (3428-12000 Hz): min_freq = 3428, max_freq = 12000			

Table S3. Processing and down-sampling scheme for the computation of the diversity metrics by investigated frequency range. Given is the frequency range for the applied bandpass filter for each of the main four applied frequency bands. We applied the function 'downsample' of the R-package 'TuneR' (Ligges et al., 2023), including a bandpass filter, using the function 'fir()' from the R-package 'seewave' (Sueur et al., 2012), to avoid aliasing prior to down-sampling. Before computing the acoustic diversity metrics for each frequency range, a bandpass filter adjusted for the width of each frequency range was applied.

		Step 1: Frequency band to investigate:		
		FB840	**FB3428**	**FB12000**
		Step 2: Anti-aliasing bandpass filter before down-sampling:		
		10-840 Hz	**10-3428.5 Hz**	**10-12000 Hz**
		Step 3: Down-sampling sampling frequency (Nyquist frequency):		
Station	**Deployment ID_Recorder ID**	**2000 Hz (1000 Hz)**	**6857 Hz (3428.5 Hz)**	**24000 Hz (12000 Hz)**
EI	**AWI251-01_AU0231**	Down-sampled	Down-sampled	Down-sampled
	AWI251-02_AU0231	Down-sampled	Down-sampled	Down-sampled
	AWI251-02_SV1013	Down-sampled	Not applied	Not available
	AWI251-03_AU0085	Down-sampled	Down-sampled	Down-sampled
	AWI251-03_SV1002	Down-sampled	Down-sampled	Not applied
CWS1	**AWI207-08_AU0085**	Down-sampled	Down-sampled	Down-sampled
CWS2	**AWI250-02_SV1003**	Down-sampled	Not applied	Not available
CWS3	**AWI208-08_SV1009**	Down-sampled	Not applied	Not available
CWS4	**AWI209-06_AU0086**	Down-sampled	Down-sampled	Down-sampled
CWS5	**AWI245-05_SV1014**	Down-sampled	Down-sampled	Not applied
CWS6	**AWI248-03_SV1012**	Down-sampled	Down-sampled	Not applied
CWS7	**AWI244-05_SV1057**	Down-sampled	Not applied	Not available
GM1	**AWI229-11_SV1057**	Down-sampled	Not applied	Not available
GM2	**AWI230-06_AU0085**	Down-sampled	Down-sampled	Down-sampled
	AWI231-11_SV1058	Down-sampled	Not applied	Not available
	AWI231-13_SV1056	Down-sampled	Down-sampled	Not applied
GM3	**AWI232-09_AU0086**	Down-sampled	Down-sampled	Down-sampled
	AWI232-12_SV1059	Down-sampled	Not applied	Not applied
		Step 4: Bandpass filter applied before computing the diversity metrics:		
		12-840 Hz	**840-3428 Hz**	**3428-12000 Hz**

Table S4. Excluded data due to RAFOS signal. Data was only removed for the time period the RAFOS signal was received by that recorder. The audio file length reflects the on period of the duty cycle. RAFOS-A = Of the RAFOS source within the deployment; RAFOS-B = Received from another deployment; C = Total removed data points (percentage removed relative to total data within that deployment).

Station	**Deployment ID_Recorder ID**	**Time of RAFOS signal reception (UTC)**		**Acoustic intensity metric (1 data point reflects 1 minute)**			**Acoustics diversity metric (1 data point reflects one audio file)**			**File length**
				Removed time period (UTC)		**C**	**Removed time period (UTC)**		**C**	
		RAFOS-A	**RAFOS-B**	**RAFOS-A**	**RAFOS-B**		**RAFOS-A**	**RAFOS-B**		
CWS2	AWI250-02_SV1003	13:30:00 (until 2017/07/11)	13:10:00 (Throughout whole recording)	13:29:00 -13:31:00	13:09:00 -13:11:00	2468 (0.26%)	13:20:00 - 13:40:00	13:00:00 -13:20:00	1647 (1.75%)	10 min
CWS3	AWI208-08_SV1009	12:40:00 (throughout whole recording)	-	12:39:00 -12:41:00	-	1370 (0.21%)	12:29:00 - 12:51:00	-	1014 (0.02%)	10 min
CWS4	AWI209-06_AU0086	01:00:00 (until 2012/02/07)	-	00:59:00 -01:01:00	-	2020 (8.05%)	All 01:00 am files	-	404 (8%)	4.5 min
CWS7	AWI244-05_SV1057	12:42:00 (until 2017/05/14)	-	12:40:00 -12:44:00	-	595 (0.07%)	12:30:00 - 12:54:00	-	306 (0.35%)	10 min
GM2	AWI231-11_SV1058	13:00:00 (throughout whole recording)	-	12:59:00 -13:01:00	-	1416 (0.21%)	12:49:00 - 13:10:00	-	1074 (1.46%)	10 min

Table S5. Ecoacoustic metric parameter profiles for each scene centre for the LMF-B. The table provides the mean and the standard deviations. Colour scale from green to red indicates lowest to highest values for each ecoacoustic metric, respectively. Scenes 10$_{LMF}$ and 14$_{LMF}$ are considered outlier scenes.

Scene	ACI$_{840}$	AEI$_{840}$	HI$_{840}$	BI$_{840}$	SPL 840 Hz	TOL 63 Hz	TOL 125 Hz	TOL 250 Hz	TOL 500 Hz	ACI$_{3428}$	AEI$_{3428}$	HI$_{3428}$	BI$_{3428}$	SPL 3428 Hz	TOL 1 kHz	TOL 2 kHz
1$_{LMF}$	123.59 (±1.49)	0.046 (±0.03)	0.861 (±0.03)	389.84 (±67.24)	108.64 (±3.02)	94.7 (±3.52)	92.467 (±2.96)	89.75 (±3.01)	87.17 (±2.36)	446.54 (±5.42)	0.245 (±0)	0.941 (±0)	286.16 (±16.99)	88.03 (±2.31)	83.25 (±2.42)	78.42 (±2.54)
2 $_{LMF}$	123.24 (±1.32)	0.041 (±0.04)	0.879 (±0.03)	358.53 (±63.09)	118.23 (±2.88)	105.59 (±3.24)	101.39 (±2.6)	99.63 (±2.43)	98.38 (±2.38)	443.80 (±4.3)	0.242 (±0)	0.945 (±0)	300.45 (±12.65)	99.5 (±2.5)	94.65 (±2.5)	89.58 (±2.61)
3 $_{LMF}$	123.92 (±2.53)	0.128 (±0.08)	0.861 (±0.03)	481.94 (±83.4)	125.25 (±3.72)	115.32 (±4.51)	109.76 (±3.42)	107.11 (±3.93)	104.08 (±4.03)	447.9 (±8.38)	0.246 (±0.01)	0.94 (±0)	277.07 (±21.46)	102.86 (±4.23)	98.41 (±4.24)	92.16 (±4.31)
4 $_{LMF}$	129.14 (±4.72)	0.124 (±0.08)	0.853 (±0.04)	501.53 (±117.1)	117.56 (±7.09)	104.82 (±7.86)	105.41 (±8.61)	105.32 (±9.37)	102.53 (±9.14)	469.84 (±18.23)	0.296 (±0.03)	0.924 (±0.01)	248.66 (±42.19)	99.49 (±8.5)	95.99 (±8.67)	86.6 (±7.61)
5 $_{LMF}$	123.77 (±1.82)	0.093 (±0.06)	0.838 (±0.03)	477.84 (±82.83)	115.82 (±2.93)	102.3 (±3.5)	99.67 (±3.32)	96.3 (±3.02)	92.06 (±2.48)	446.22 (±6.01)	0.244 (±0)	0.943 (±0)	288.64 (±17.73)	91.94 (±2.49)	87.22 (±2.46)	81.81 (±2.79)
6 $_{LMF}$	124.41 (±2.7)	0.261 (±0.1)	0.771 (±0.03)	554.69 (±104.6)	116.43 (±3.15)	102.13 (±4.13)	98.69 (±4.28)	91.14 (±3.1)	86.64 (±3.17)	446.24 (±5.32)	0.244 (±0)	0.945 (±0)	299.62 (±20.91)	86.55 (±3.64)	81.79 (±3.69)	76.58 (±3.68)
7 $_{LMF}$	123.08 (±1.16)	0.026 (±0.02)	0.889 (±0.03)	304.98 (±59.67)	112.17 (±2.44)	98.71 (±2.45)	95.67 (±2.31)	94.37 (±2.25)	93.61 (±2.23)	444.17 (±4.46)	0.243 (±0)	0.941 (±0)	286.07 (±13.18)	95.13 (±2.23)	90.27 (±2.18)	85.35 (±2.28)
8 $_{LMF}$	124.21 (±1.6)	0.231 (±0.1)	0.762 (±0.03)	515.88 (±62.76)	109.01 (±3.31)	92.09 (±2.81)	89.59 (±3.47)	82.92 (±3.37)	79.32 (±3.04)	445.05 (±2.52)	0.243 (±0)	0.948 (±0)	322.81 (±17.65)	80 (±3.14)	74.38 (±3.26)	70.94 (±3.08)
9 $_{LMF}$	125.58 (±2.98)	0.079 (±0.04)	0.835 (±0.02)	553.17 (±62.7)	109.67 (±2.3)	94.02 (±3.71)	98.99 (±3.7)	93.69 (±3.44)	84.51 (±2.63)	446.36 (±4.53)	0.243 (±0)	0.946 (±0)	296.172 (±19.8)	83.98 (±2.48)	79.25 (±2.72)	73.99 (±2.47)
10 $_{LMF}$	143.04 (±7.21)	0.371 (±0.13)	0.76 (±0.05)	475.28 (±84.94)	129.51 (±5.47)	115.38 (±6.31)	107.74 (±5.37)	97.85 (±3.91)	94.56 (±3)	547.08 (±27.3)	0.277 (±0.02)	0.928 (±0.01)	297.97 (±17.1)	96.07 (±2.84)	89.41 (±3.3)	87.72 (±3.47)
11 $_{LMF}$	125.87 (±3.11)	0.069 (±0.05)	0.85 (±0.03)	478.22 (±90.08)	110.21 (±3.17)	95.94 (±3.94)	98.37 (±4.52)	94.89 (±4.75)	87.28 (±3.54)	451.56 (±7.74)	0.254 (±0.01)	0.935 (±0)	252.66 (±18.82)	86.43 (±3.79)	82.28 (±3.96)	75.63 (±3.82)
12 $_{LMF}$	124.93 (±2.03)	0.073 (±0.04)	0.834 (±0.03)	443.19 (±76.27)	104.49 (±2.9)	90.29 (±3.18)	90.76 (±3.76)	83.83 (±3.31)	79.85 (±2.59)	448.12 (±4.46)	0.248 (±0.01)	0.942 (±0)	284.12 (±18.46)	80 (±2.72)	74.94 (±2.74)	70.46 (±2.8)
13 $_{LMF}$	122.18 (±3.23)	0.118 (±0.06)	0.848 (±0.02)	697.69 (±110.86)	109.53 (±2.96)	92.08 (±4.06)	86.89 (±3.02)	97.67 (±4.24)	89.88 (±4)	447.35 (±5.82)	0.249 (±0.01)	0.943 (±0)	337.83 (±24.39)	85.21 (±3.83)	79.44 (±3.98)	75.76 (±3.63)
14$_{LMF}$	132.95 (±5.54)	0.237 (±0.13)	0.804 (±0.05)	415.8 (±91.01)	125.68 (±6.27)	111 (±7.14)	103.53 (±5.53)	96.48 (±3.81)	94.67 (±3.48)	484.45 (±16.67)	0.253 (±0.01)	0.938 (±0)	295.19 (±17.64)	95.53 (±4.11)	90.17 (±4.07)	86.03 (±4.53)

Table S6. Ecoacoustic metric profiles by scene centre for the scenes of the HF-B. Provided is the mean and the standard deviation. Colour scale from green to red indicate lowest to highest values for each ecoacoustic metric, respectively. The * indicates the outlier scenes.

Scene	**ACI$_{12000}$**	**AEI$_{12000}$**	**HI$_{12000}$**	**BI$_{12000}$**	**SPL 12000 Hz**	**TOL 5 kHz**
1$_{HF}$	1260.99 (±8.24)	0.281 (±0.001)	0.948 (±0.001)	41.22 (±3.685)	76.88 (±1.81)	69.31 (±1.94)
2$_{HF}$	1274.24 (±37.55)	0.286 (±0.012)	0.939 (±0.003)	24.83 (±5.393)	89.07 (±2.75)	82.51 (±2.75)
3$_{HF}$	1262.89 (±15.67)	0.282 (±0.005)	0.944 (±0.002)	30.03 (±4.152)	82.64 (±2.21)	75.61 (±2.32)
***4$_{HF}$**	1548.69 (±129.64)	0.364 (±0.031)	0.926 (±0.009)	30.96 (±4.887)	91.85 (±3.21)	87.4 (±3.52)

Table S7. Mean values and standard deviation (±) in brackets of the ecoacoustic metrics by identified soundscape regime for the LMF-B. Colour scale from green to red indicate lowest to highest values for each ecoacoustic metric, respectively. The outlier scenes values were removed before computing the average statistics by regime.

Regime	ACI_{840}	AEI_{840}	HI_{840}	BI_{840}	SPL 840 Hz	TOL 63 Hz	TOL 125 Hz	TOL 250 Hz	TOL 500 Hz	ACI_{3428}	AEI_{3428}	HI_{3428}	BI_{3428}	SPL 3428 Hz	TOL 1 kHz	TOL 2 kHz
Shallow-water-epipelagic	123.62 (±1.98)	0.105 (±0.104)	0.867 (±0.047)	387.85 (±102.61)	120.43 (±6.22)	109.68 (±6.97)	103.97 (±6.63)	101.66 (±6.04)	99.16 (±5.27)	447.44 (±8.21)	0.245 (±0.009)	0.943 (±0.005)	289.49 (±17.05)	98.43 (±5.13)	93.99 (±4.96)	87.90 (±4.74)
Deep-water-epipelagic	124.63 (±2.83)	0.093 (±0.087)	0.835 (±0.043)	508.87 (±107.31)	114.63 (±4.23)	101.05 (±6.40)	100.15 (±5.8)	97.35 (±5.33)	93.67 (±6.02)	446.61 (±6.29)	0.243 (±0.005)	0.945 (±0.005)	298.2 (±28.56)	94.13 (±6.43)	89.35 (±6.59)	84.09 (±6.39)
Deep-water-mesopelagic	123.19 (±1.06)	0.098 (±0.092)	0.835 (±0.044)	419.51 (±113.44)	111.48 (±4.61)	98.45 (±4.42)	94.69 (±4.16)	91.9 (±6.13)	90.23 (±6.35)	444.04 (±2.98)	0.244 (±0.004)	0.944 (±0.003)	292.6 (±18.21)	92.122 (±7.01)	87.08 (±7.21)	82.34 (±6.88)
Deep-water-bathypelagic	124.3 (±2.3)	0.05 (±0.052)	0.855 (±0.038)	406.88 (±107.22)	109.35 (±3.98)	95.95 (±4.63)	94.74 (±4.15)	91.02 (±4.99)	88.94 (±5.87)	447.29 (±5.99)	0.249 (±0.009)	0.939 (±0.004)	276.76 (±21.48)	90.29 (±6.61)	85.19 (±6.65)	80.74 (±6.67)

Table S8. Mean values and standard deviation (±) in brackets of the ecoacoustic metrics by identified soundscape regime for the HF-B. Colour scale from green to red indicate lowest to highest values for each ecoacoustic metric, respectively. The outlier scene values were removed before computing the average statistics by regime.

Regime	ACI_{1200}	AEI_{1200}	HI_{1200}	BI_{1200}	SPL 12 kHz	TOL 5 kHz
Shallow-water	1277.76 (±39.3)	0.287 (±0.012)	0.940 (±0.003)	25.86 (±5.16)	87.29 (±4.169)	80.96 (±4.34)
Deep-water	1260.71 (±8.86)	0.281 (±0.002)	0.947 (±0.003)	36.06 (±7.48)	83.2 (±4.6)	76.12 (±4.86)

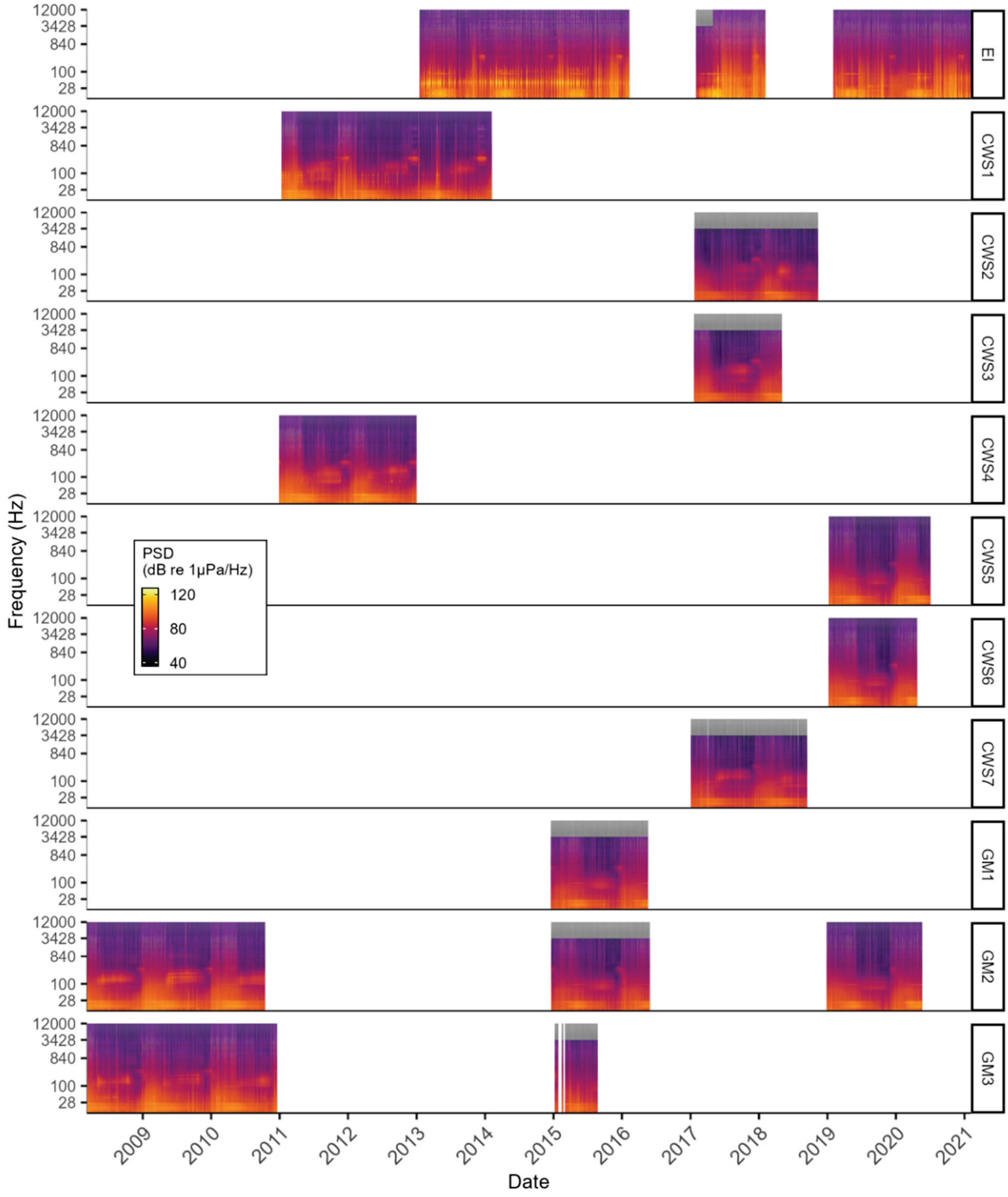


Fig. S1. Long term spectral averages of the investigated recording periods. The 1-min time frames were averaged over one day and the frequency scale is log transformed and provided as hybrid millidecade resolution (1 Hz bins for the frequency range of 12-434 Hz and millidecade bands for frequencies above 435 Hz (Martin et al., 2021b; a). The maximum sampling rate sampled across all investigated deployments is 32768 Hz. However, this frequency range was not sampled by all deployed recorders. Hence, the grey area indicates the frequency range which was not sampled due to lower sampling rates applied in the individual recorder deployment. Higher frequencies for the deployments AWI251-02_AU0231 for the overlapping time frames with AWI251-02_SV1013 are not shown. Higher resolution long term spectral averages can also be accessed via OPUS (Open Portal to Underwater Soundscapes, www.opus.aq, CC BY 4.0, AWI 2023 (Thomisch et al., 2021).

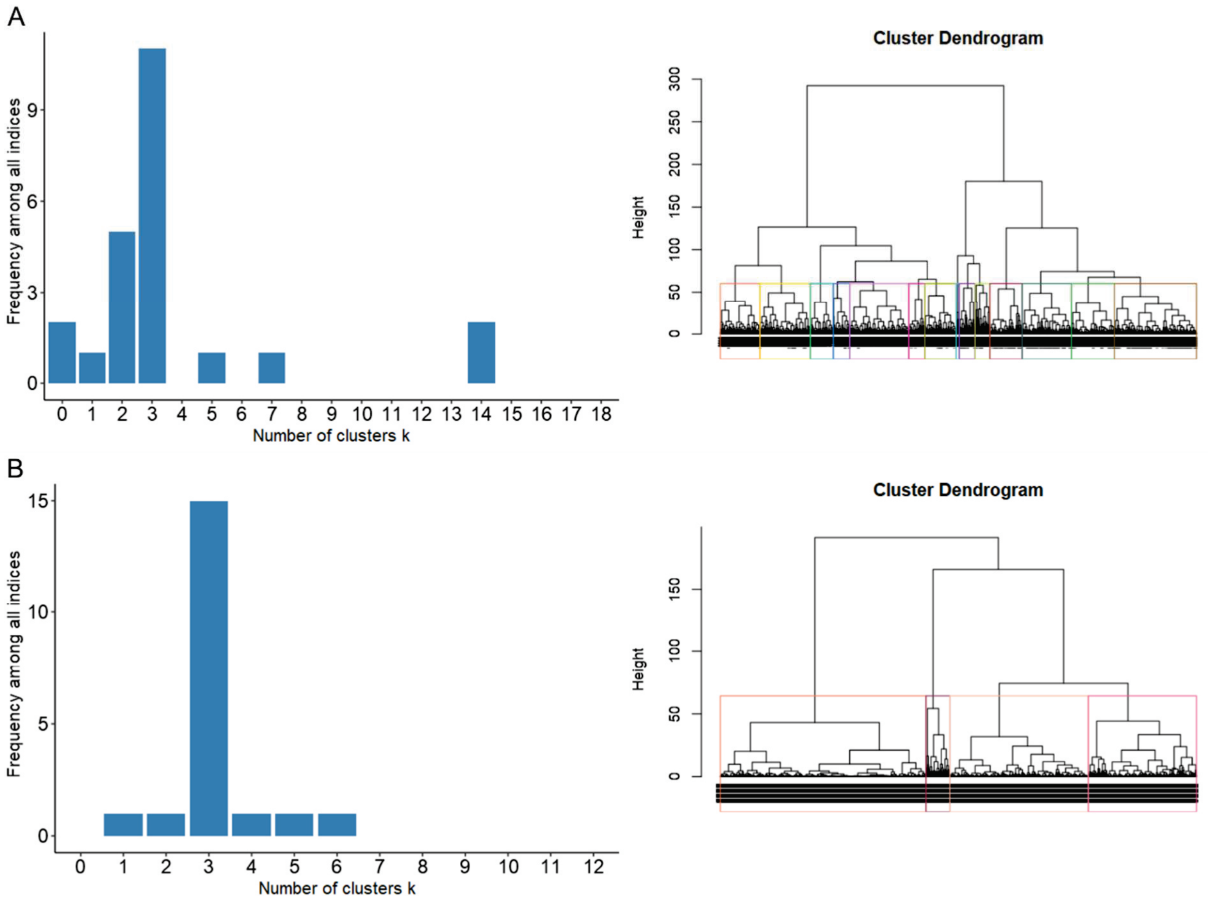


Fig. S2. Results of the proposed numbers of clusters for the suit of the daily means of the EAM with the resulting hierarchical k-means dendrogram with the applied selected numbers of clusters. A) For the LMF-B the selected second recommended optimal number of clusters is 14. B) For the HF-B there is no clear second recommended optimal number of clusters why we decided to go only one level up and applied four clusters.

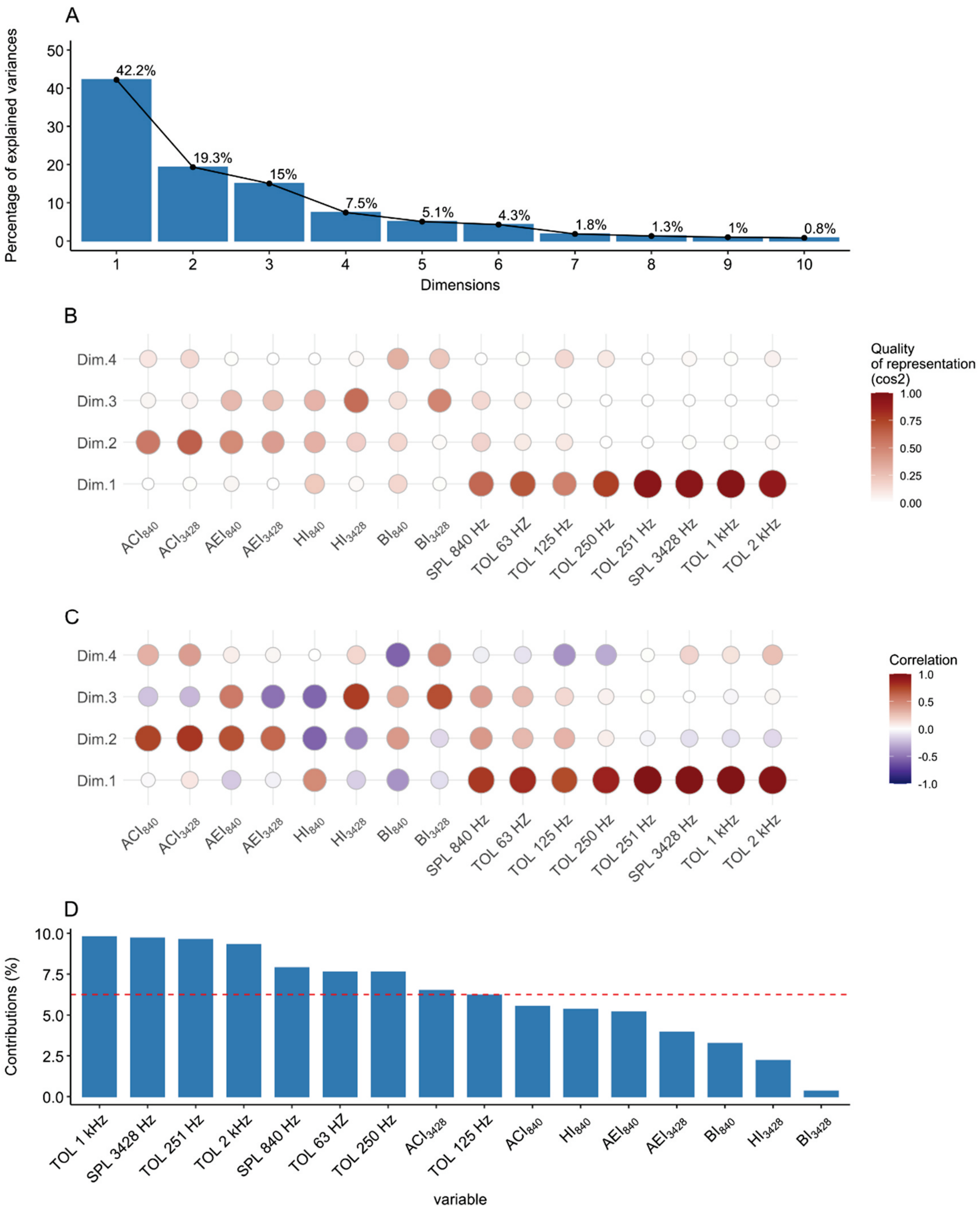


Fig. S3. Representation and correlation of the combination of the ecoacoustic metrics for the LMF-B with the dimensions of the PCA. A) Percentage of explained variance by dimension. B) Quality of the representation of the variables along the dimensions, C) correlation of the variables with the dimensions, and D) contribution of the scene variance in the first two dimensions.

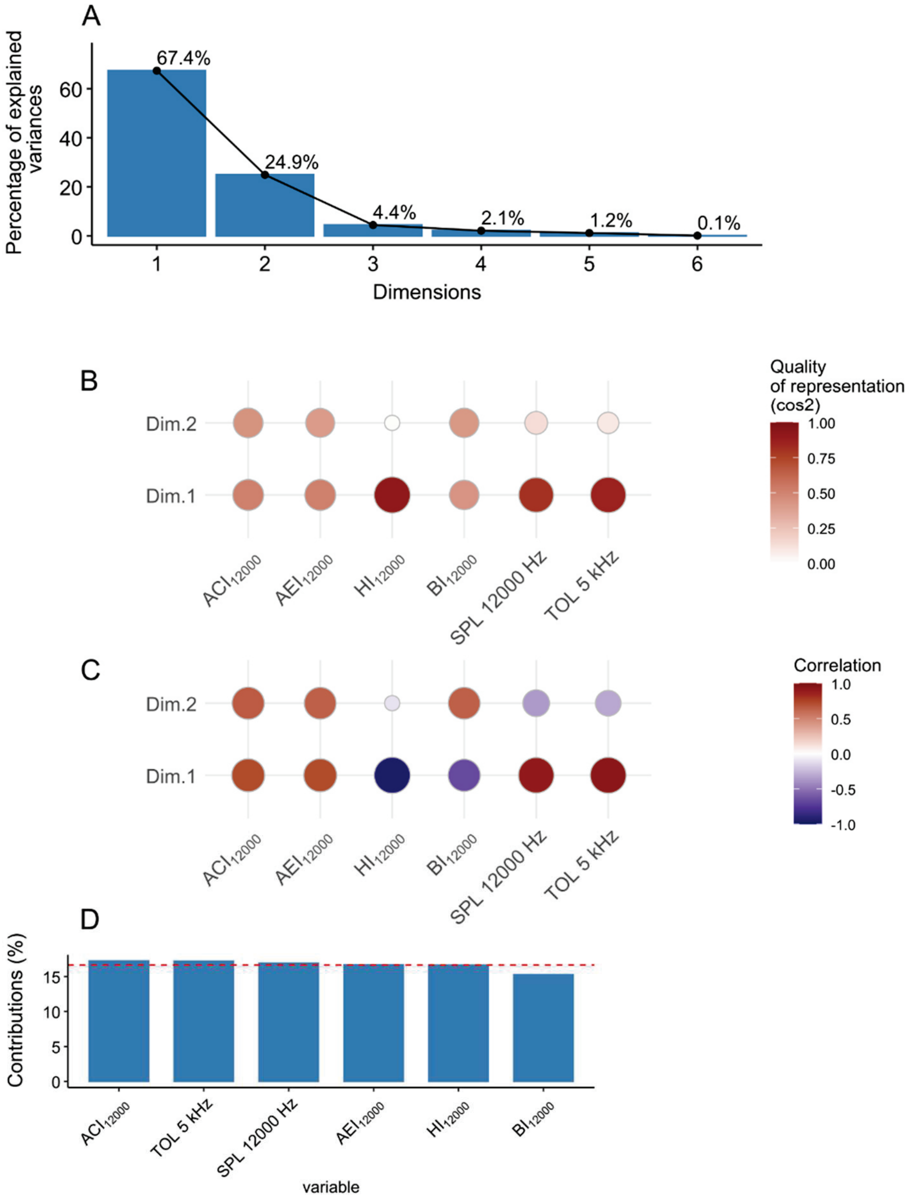
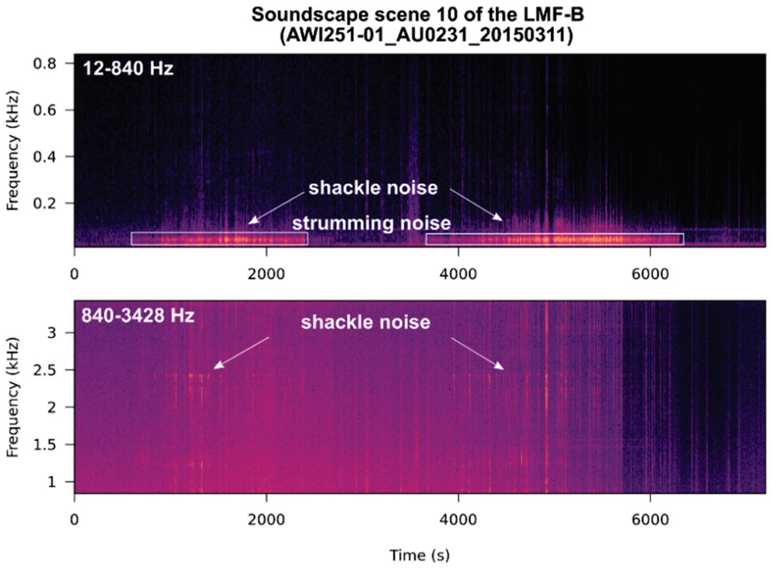
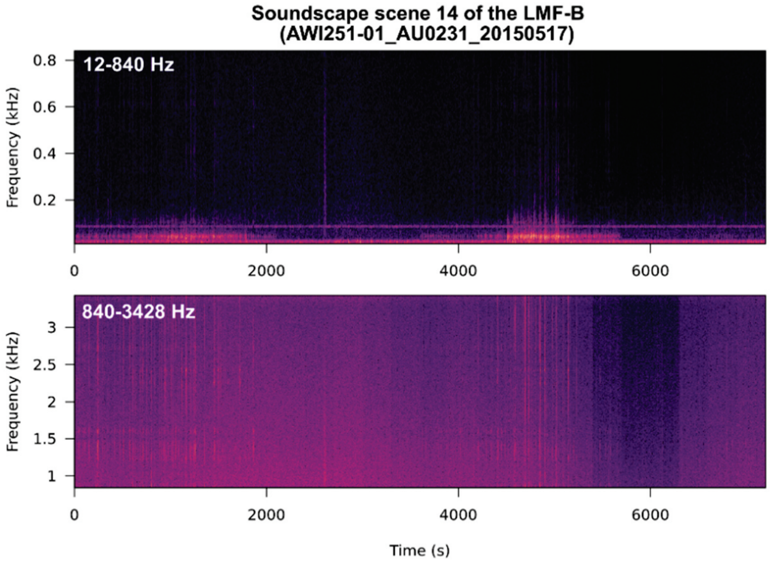


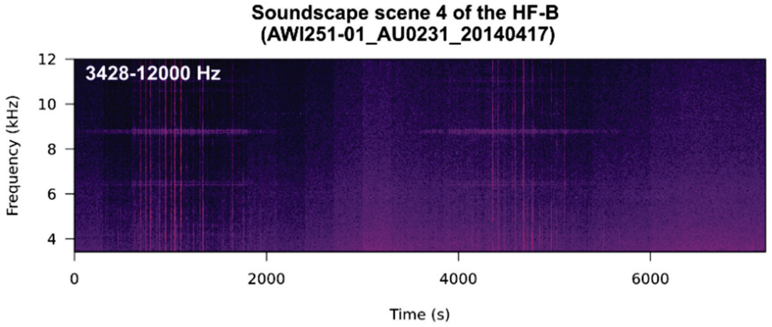
Fig. S4. Representation and correlation of the combination of the ecoacoustic metrics for HF-B with the dimensions of the PCA. A) Percentage of explained variance by dimension. B) Quality of the representation of the variables along the dimensions, C) correlation of the variables with the dimensions, and D) contribution of the scene variance in the first two dimensions.



Soundscape scene 10 of the LMF-B (AWI251-01_AU0231_20150311)



Soundscape scene 14 of the LMF-B (AWI251-01_AU0231_20150517)



Soundscape scene 4 of the HF-B (AWI251-01_AU0231_20140417)

Fig. S5. Daily Lon-term-spectral averages (LTSA). The LTSA are computed across all audio files recorded on one day (subsampling gaps are ignored). Example day which was found closest to the respective soundscape scene centre.

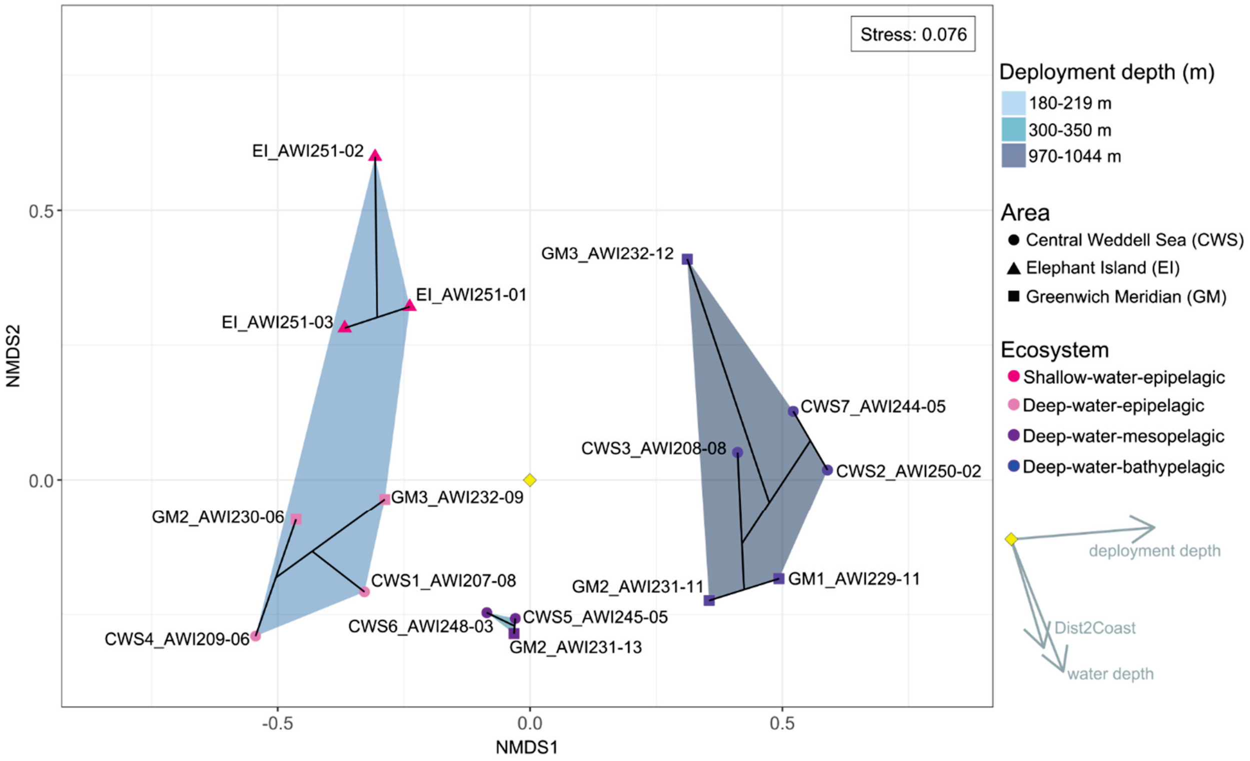


Fig. S6: Non-metric multidimensional scaling (NMDS) to investigate the effect of static environmental conditions, such as the depth zone (deployment depth; m), water depth at the station (m), and distance from the station to the coast or ice shelf (Dist2Coast, km) on the soundscape regimes. The lines represent the structure of the dendrogram (Fig. 4, main article). The NMDS was applied on the Bray-Curtis dissimilarity computed on the relative proportion of soundscape scenes of the LMF-B by deployment. The arrows indicate the direction of separation of clusters by environmental conditions and correspond to the yellow diamond at the axis intercept in the plot. The NMDS was applied using the function 'metaMDS()' from the R-package 'vegan' using the default settings and the Bray-Curtis dissimilarity as dissimilarity index (Oksanen et al., 2022).

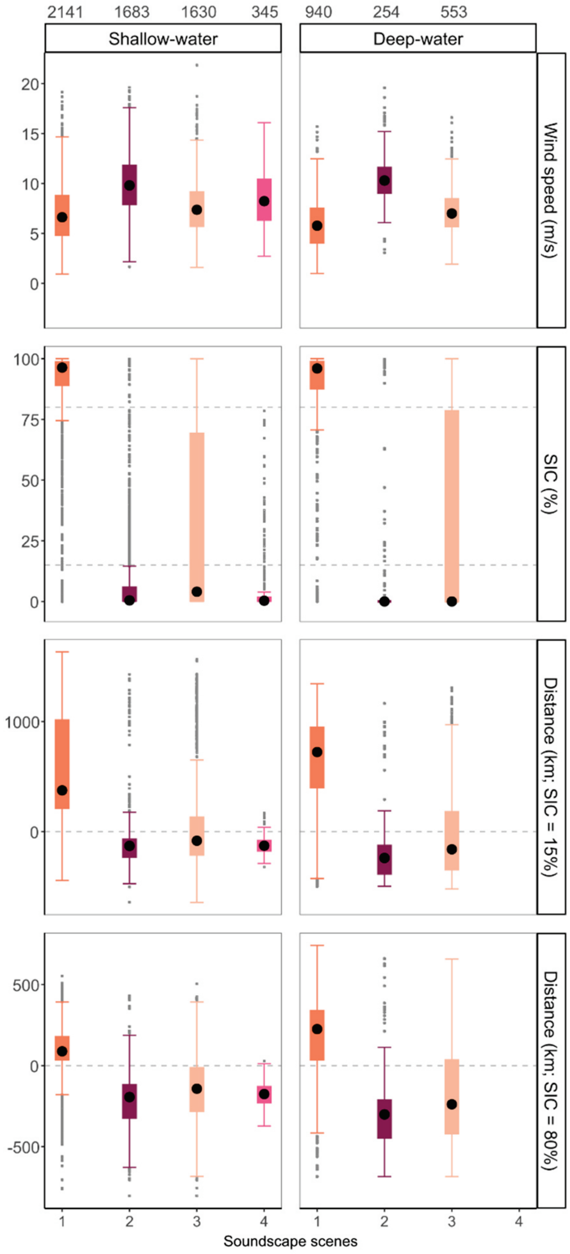


Fig. S7. Soundscape scene observations by environmental conditions and by identified soundscape regime for the HF-B. The big black dot indicates the median. The numbers in the last panel represent the true scene observations by identified regime. The dashed line in the second panel represents the SIC threshold for 'open-water' and 'closed pack-ice' conditions, with a SIC of 15% and 80%, respectively. The dashed line in the lower two panels represent the corresponding ice boundary and positive values indicate that the acoustic observation was recorded during sea-ice covered conditions above the applied SIC threshold used to define the respective ice-zone boundary.

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5

GENERAL DISCUSSION

In the following sections, first, I briefly reiterate the scope and aims of my dissertation. Second, I summarise and discuss the most important results of the three studies I conducted in the context of this dissertation and elaborate on the prospects of future polar ocean soundscape with respect to the triple planetary crisis based on my findings. Furthermore, I delineate possible ecological consequences of impoverished soundscapes and noise pollution. Third, with regard to methodological advances, I discuss the approach of using multiple ecoacoustic metrics and clustering to identify spatiotemporal soundscape patterns. I also address the pitfalls, complexity, and the suitability of using ecoacoustic metrics. Fourth, I discuss the lessons learned regarding the design of passive acoustic monitoring (PAM) sampling and its impact on the comparisons of soundscapes and the assessment of soundscape regimes. Finally, I present my thoughts on potential further research avenues.

Study aims at a glance

In the last two decades, the collection of ocean PAM data advanced profoundly (see Havlik *et al.*, 2022; Tyack *et al.*, 2023; Darras *et al.*, 2025) and nowadays, ocean soundscape data are available that not only span multiple sites across ocean basins but also timescales of multiple years to decades (e.g., Davis *et al.*, 2020; Ladegaard *et al.*, 2021; ZoBell *et al.*, 2021; and Chapter 4 of my dissertation). The extensive datasets now provide the opportunity to investigate ecosystem variability in the context of large-scale environmental conditions, climate oscillations, and the triple planetary crisis from an acoustic perspective (e.g., Davis *et al.*, 2020; Schall *et al.*, 2021; Roca *et al.*, 2023; ZoBell *et al.*, 2025). Previous ocean soundscape studies have hitherto mainly focused on assessing soundscape components individually or solely focused on ambient sound levels, as well as seasonal or large-scale spatiotemporal dynamics, paying less attention to cumulative response patterns (e.g., Haver *et al.*, 2017; Davis *et al.*, 2020; Ladegaard *et al.*, 2021; Schall *et al.*, 2021; Roca *et al.*, 2023). For example, little attention has been given to alterations in the dynamics of the overall acoustic species composition (see Van Opzeeland and Hillebrand, 2020) and of the holistic soundscape patterns created by the full suite of local soundscape components in response to seasonal fluctuations or large-scale environmental alterations. Thus, in my dissertation, I aimed to evaluate the contemporary status of the variability in soundscape characteristics, patterns, and dynamics of polar oceans in the Anthropocene across different temporal and spatial scales. My analyses included the assessment of the acoustic marine mammal community composition. Furthermore, my underlying aim was to thereby establish data on the baseline levels of the acoustic environment in polar oceans for future reference. Specifically, I applied a bi-polar approach which encompassed soundscapes of the Arctic, off Southeast Greenland and the eastern Fram Strait, and of the Southern Ocean, the Weddell Sea basin. In my dissertation, the Arctic soundscapes functioned as references for acoustic environments that are already anthropogenically impacted, whereas I considered the Southern Ocean soundscapes as references for relatively pristine acoustic environments. As soundscape datasets expand over time, there is an increasing need for scalable methods that enable comprehensive insights into the variability of soundscapes over large temporal and geographic scales. I therefore explored the use of multiple ecoacoustic metrics and clustering to establish an approach that allowed me to evaluate and intercompare multiple soundscapes in order to identify similarities in soundscape patterns across large temporal or geographical scales.

Polar ocean soundscape characteristics, patterns, and dynamics

Dynamics of an acoustic marine mammal community in an anthropogenically impacted Arctic coastal area

Climate change causes shifts in the spatiotemporal distributions of marine species, including marine mammals (Hodapp *et al.*, 2023). Many seasonally migrating baleen whale species have extended their range northward, further into the Arctic or shifted their timing of migration in response to warmer waters, sea ice loss, and shifting prey distribution (e.g., Ramp *et al.*, 2015; Hansen *et al.*, 2018; Moore *et al.*, 2019; Davis *et al.*, 2020; Nieukirk *et al.*, 2020; Ahonen *et al.*, 2021; Bengtsson *et al.*, 2022). Off Southeast Greenland, ecosystem shifts, including an increasing abundance of fin (*Balaenoptera physalus*) and humpback whales (*Megaptera novaeangliae*) in boreal summer as a response to warmer waters, increased sea ice loss, and shifting prey distribution have already been reported (e.g., Jansen *et al.*, 2016; Hansen *et al.*, 2018; Heide-Jørgensen *et al.*, 2023). Despite the already observed ecosystem shift off Southeast Greenland, information on the year-round and multi-year (acoustic) marine mammal community composition and dynamics in this area has been largely lacking. Such information on lower-latitude Arctic areas is crucial, as it provides important baselines that can serve as a reference point for future sea ice-free scenarios of higher Arctic areas. Thus, Chapter 2 aimed to contribute important information towards filling this knowledge gap and provided the first insights into the year-round and multi-year acoustic marine mammal community composition off Tasiilaq, an ecologically important coastal area for many marine mammals (AMAP/CAFF/SDWG, 2013). In Chapter 2, I showed that the acoustic marine mammal community composition experiences a semi-annual turnover linked to the local sea ice patterns: from pagophilic to seasonal migrants and from seasonal migrants to pagophilic marine mammals (Chapter 2, Fig. 3 and Fig. 4). Moreover, acoustic marine mammal diversity peaks in boreal summer and autumn, due to the seasonally migrating cetaceans. The results of Chapter 2 support the assumption made by Van Opzeeland and Hillebrand (2020) that acoustic marine mammal turnover dynamics in polar areas may be subject to alterations over time due to changing acoustic community composition and species dominance as a consequence of sea ice loss. As outlined in Chapter 2, increasing sea ice loss in this area might lead to a change in the acoustic community dynamics towards seasonal migrants as pagophilic species might follow the receding sea ice extent. However, the pattern of semi-annual turnover in the acoustic species composition observed in the Tasiilaq area is bound to change, as the boreal winter period becomes sea ice-free and the seasonal migrants may become acoustically dominant year-round. Nevertheless, similar assessments observing cumulative dynamics of sentinel species, such as marine mammals (Moore, 2008; Moore and Kuletz, 2019), are missing for other Arctic regions. Thus, assessing the combined response of the Arctic ecosystem towards climate change through cumulative (acoustic) marine mammal community dynamics would boost our understanding of current Arctic ecosystem changes. Additionally, it would facilitate to monitor tipping points as acoustic community compositions start to drift. However, most Arctic pagophilic marine mammals do not have a pan-Arctic distribution and show a more clustered distribution due to species-specific habitat preferences (Hamilton *et al.*, 2021; Hamilton *et al.*, 2022). Therefore, recording in different Arctic locations will likely capture different species compositions (e.g., De Vreese *et al.*, 2018; Halliday *et al.*, 2019; Stafford *et al.*, 2022; Llobet *et al.*, 2023) and reveal different acoustic marine mammal community dynamics. Cumulative acoustic marine mammal response patterns to ecosystem shifts might therefore be highly site specific in the Arctic and are likely to require monitoring at different locations to fully capture ecosystem change across the Arctic.

Holistic soundscape patterns of anthropogenically impacted *vs.* relatively pristine acoustic environments

Global warming, sea ice loss, and prolonged open water periods (Eayrs *et al.*, 2021; Rantanen *et al.*, 2022; Jahn *et al.*, 2024; Raphael *et al.*, 2025) affect species spatiotemporal distribution (e.g., Moore *et al.*, 2019; Hodapp *et al.*, 2023). In addition, anthropogenic activities are increasing (e.g., Bennett *et al.*, 2020; Savoca *et al.*, 2024; Senigaglia *et al.*, 2025). The alteration of polar ocean ecosystems impacts their acoustic environment. Nevertheless, baseline data on the contemporary state of soundscape characteristics and patterns are lacking for many ocean areas, including Arctic and Southern Ocean areas. However, such knowledge is vital for improving our understanding of the dynamics of acoustic environments of polar marine ecosystems to subsequently be able to assess and monitor (further) ecosystem transformations. In Chapter 3, I showed that the already disturbed and noise-polluted polar ocean soundscape of the eastern Fram Strait lacks a pronounced seasonal soundscape pattern and exhibits low acoustic complexity due to year-round wind-mediated sounds and anthropogenic noise, as this area is sea ice-free throughout the year. The intra-seasonal variability of ambient sound levels in the Fram Strait on the other hand was high and was explained by the inconsistent changes in anthropogenic noise overlapping with other sound sources (Chapter 3), similar to the observation of Haver *et al.* (2017).

In contrast, the soundscape of the Weddell Sea which is still considered one of the planet's most 'pristine' underwater acoustic environment, exhibits pronounced seasonal soundscape patterns. The seasonal dynamics in ambient sound levels and spectro-temporal complexity are characteristic and are linked to the seasonal sea ice cover and acoustic marine mammal community composition (Chapter 3). Moreover, I found a low intra-seasonal variability in ambient sound levels for the Southern Ocean, which I linked to the consistent marine mammal vocal behaviour and environmental conditions (Chapter 3), as also previously reported by Haver *et al.* (2017). Corresponding to Chapter 3, Chapter 4 highlighted, that the diversity in soundscape patterns across the deep waters of the Weddell Sea basin is highly seasonal and linked to the seasonal sea ice cover. I suggested in Chapter 3 and Chapter 4 that this highly seasonal pattern, along with higher soundscape complexity and diversity, forms a key feature of an intact polar ocean acoustic environment. The observation that healthy ecosystems are acoustically complex (see Rossi *et al.*, 2017; Gordon *et al.*, 2018) is also supported by my dissertation.

Polar ocean soundscape patterns in the light of the triple planetary crisis

How the acoustic environments of polar oceans will change in the future is one of the crucial questions in the context of the triple planetary crisis. Soundscape alterations are highly complex to investigate from a holistic perspective, as soundscape patterns are shaped by numerous interacting factors and drivers (see again Chapter 1 Fig. 1; Pijanowski *et al.*, 2011a; Bradfer-Lawrence *et al.*, 2025). In the Arctic Ocean, one of the more obvious expectations is the increase of ambient sound levels due to ice-generated sounds as a result of unstable sea ice cover and an increase in wind-mediated sounds as a result of prolonged open water periods (Halliday, 2021; Mo *et al.*, 2023). Beyond that, Arctic Ocean ambient sound levels are considered to rise as anthropogenic activities increase (Bennett *et al.*, 2020; Jalkanen *et al.*, 2022; Heaney *et al.*, 2024). Year-round wind-mediated sounds and anthropogenic noise are already masking biophonic patterns in the sea ice-free Arctic, causing a higher spectro-temporal uniformity and weak seasonal patterns (Chapter 3). Although populations of seasonal migrants might increase at high latitudes due to northward shifts or recovery despite anthropogenic threats (Storrie *et al.*, 2018; Bengtsson *et al.*, 2022; Stewart *et al.*, 2025), this is a trend that is likely to persist in the Arctic. Wind-wave conditions are strengthening (Vavrus and Alkama, 2022; Casas-Prat *et al.*, 2024) and anthropogenic activities are increasing as the climate changes and the Arctic is opening up (Bennett *et al.*, 2020).

In Chapter 3 and Chapter 4, I argued that the future Southern Ocean offshore soundscapes might undergo local weakening or loss of seasonal soundscape variability and diversity, becoming less complex and more homogenous, as well as louder if open-water periods prolong. Such weakening of seasonal patterns is based on the observation that the soundscape of the sea ice-free austral summer of the Weddell Sea is the loudest and most homogenous (Chapter 3, Fig. 4 and Fig. 5). As wind-mediated sounds increase with the decrease in sea ice cover, the increasing ambient sound levels are likely to mask biophonic patterns, similar to what I observed in the year-round sea ice-free eastern Fram Strait (Chapter 3) and at Elephant Island (Chapter 4). As sea ice habitat shrinks, pagophilic marine mammals may shift their distribution (e.g., Wege *et al.*, 2021; Roca *et al.*, 2023). In turn, seasonal soundscape variability can weaken or might be lost as choruses grow faint or vanish (Chapter 3). Seasonal migrants and residents preferring open water conditions might extend their range further southward, following the receding sea ice edge and prey availability (e.g., Rogers *et al.*, 2020; Hodapp *et al.*, 2023), analogous to the northward extension of seasonal migrants in the Arctic (Hansen *et al.*, 2018; Bengtsson *et al.*, 2022). This could lead to a weakening of biophonic patterns further offshore. Lastly, an increase of anthropogenic noise in the Southern Ocean will likely increase ambient sound levels and cause higher soundscape homogeneity through masking of biophonic patterns, similar to the patterns I observed for the eastern Fram Strait (Chapter 3).

In Chapter 4, I also discussed that, marine mammals may alter their acoustic strategies to cope with changing acoustic environments (Tyack, 2008; Duarte *et al.*, 2021), which can consequently reshape acoustic niches and patterns. Furthermore, I discussed that it remains uncertain how recovering fin and Antarctic blue whale (*Balaena musculus intermedia*) populations (Tulloch *et al.*, 2019), whose vocalisation are loud and far-reaching (Charif *et al.*, 2002; Širović *et al.*, 2007), shape future Southern Ocean soundscapes. On the other hand, despite the recovering of whale populations from commercial whaling, they are threaten by climate-driven changes and increasing anthropogenic pressures, including tourism and krill fishery, particularly along the Antarctic Peninsula (Savoca *et al.*, 2024; Senigaglia *et al.*, 2025; Stewart *et al.*, 2025; Trathan *et al.*, 2025).

In conclusion, soundscapes of the last 'pristine' areas of the polar oceans are likely to gradually transform, reflecting the increasing impact of noise pollution and changes in sea ice conditions, species distributions, and acoustic dominance as polar ecosystems shift. If species fail to adapt their acoustic behaviour, for example are not able to adjust their call intensity or frequency (Tyack, 2008), polar ocean soundscapes may eventually become less complex as the biophony is masked or ultimately silenced. However, only the continuation of large-scale monitoring of polar ocean soundscapes will show how the acoustic environment will transform in response to increasing anthropogenic impacts and shifting ecosystems.

Ecological consequences of impoverished soundscapes and noise pollution

In my dissertation I showed that polar oceans soundscape patterns and dynamics are shaped by the spatiotemporal variation in environmental conditions and the acoustic marine mammal community composition. Additionally, I showed that anthropogenic noise can affect soundscape patterns. I discussed that the polar ocean, particularly the Southern Ocean, soundscape is likely to transform as a result of habitat degradation and noise pollution. However, soundscapes reflect not only ecosystem processes and alterations, but may also functions as positive or negative feedback mechanism on the spatial distribution of species that govern ecosystem shifts (Rossi *et al.*, 2017, see also again Chapter 1 Fig. 1).

The loss of an intact soundscape as an acoustic cue is proposed to have far-reaching ecological consequences as the recovery of ecosystems is hampered, as key-stone species are not directly attracted (Rossi *et al.*, 2017). Impoverished soundscapes, characterised by low acoustic complexity and ambient sound levels due to reduced biophonic activity from habitat degradation, lose acoustic cues which are important for the spatial orientation of marine species (Rossi *et al.*, 2017). For example, fish and invertebrate orient towards biophonic complex soundscapes but are less attracted by impoverished soundscapes (Gordon *et al.*, 2018; Lillis *et al.*, 2018; Williams *et al.*, 2022b; Solé *et al.*, 2023). Anthropogenic noise might cause a similar effect due to acoustic masking hampering perception of acoustic cues, which can disrupt the recruitment of fish and invertebrate larvae (Gordon *et al.*, 2018; Lecchini *et al.*, 2018; Williams *et al.*, 2024) or impede the communication and likely also the orientation of marine mammals (Erbe *et al.*, 2016). Moreover, anthropogenic noise can have severe negative consequences on their behaviour and physiology, and can cause injury or death of marine invertebrates and fish (Cox *et al.*, 2018; Solé *et al.*, 2023) with potential implications on marine food-webs. Anthropogenic noise can also cause temporary or permanent behavioural and physiological effects, as well as lead to injury and death in marine mammals (Southall *et al.*, 2021). The direct consequences of anthropogenic noise for Antarctic marine mammals and their vulnerability are considered poorly understood (Darias-O'Hara *et al.*, 2025). Polar populations require particular attention as they are considered more susceptible to anthropogenic noise owing to their lower exposure to human activities to date (Darias-O'Hara *et al.*, 2025; Halliday *et al.*, 2020). In the Arctic, ship and airgun noise caused narwhals (*Monodon monoceros*) to change their behaviour, avoiding deep-dives and reducing foraging, which causes a reduction in feeding-related vocal activity, which might be a response to accommodate travelling to avoid exposure (Tervo *et al.*, 2023). Moreover, bowhead whales (*Balaena mysticetus*) avoid areas with seismic airgun operations and alter their call rate and surface behaviour when exposed to airgun pulses (Ahonen *et al.*, 2017, references therein). Consequently, short-term or permanent loss of acoustic cues, recruitment failure, displacement, and habitat avoidance due to impoverished soundscapes and anthropogenic noise exposure may not only have negative repercussions on individual fitness, but also on population and community levels, and may also disrupt trophic dynamics and local ecosystem functions (see also Kok *et al.*, 2023 for a review). How altered soundscapes and noise pollution, may affect the distribution of polar marine species across various trophic levels and how these effect polar ocean ecosystem dynamics and functions are important open research questions.

Ecoacoustic metrics in practice

Ecoacoustic metrics have become attractive as a scalable method to assess the acoustic state and coarser patterns in soundscapes. In the light of extensively growing soundscape datasets, ecoacoustic metrics allow holistic acoustic evaluation, without the need for detailed and tedious detection of soundscape components (e.g., Merchant *et al.*, 2015; Sethi *et al.*, 2023; Wilford *et al.*, 2023; Llusia, 2024; Bradfer-Lawrence *et al.*, 2025). Nonetheless, particularly ecoacoustic diversity metrics are highly debated in terrestrial (e.g., Mammides *et al.*, 2021; Alcocer *et al.*, 2022) and marine systems (e.g., Bohnenstiehl *et al.*, 2018; Mooney *et al.*, 2020; Dimoff *et al.*, 2021; Williams *et al.*, 2022a) as they have shown mixed results in biodiversity assessments. See again Chapter 1 and the following section for a more in-depth discussion on this matter. However, several studies show that a combination of multiple ecoacoustic metrics, including ecoacoustic diversity metrics, and clustering can aid the interpretation and comparisons of spatiotemporal soundscape patterns and infer the status of the acoustic environment (e.g., Roca and Van Opzeeland, 2019; Bittencourt *et al.*, 2020; Flowers *et al.*, 2021; Wilford *et al.*, 2023; Bradfer-Lawrence *et al.*, 2025). Therefore, in my dissertation, I aimed to determine whether multiple ecoacoustic metrics, involving ecoacoustic intensity and ecoacoustic diversity metrics, in combination with clustering, can capture the spatiotemporal variability of polar ocean soundscapes and their acoustic state. In Chapter 3, I tested the suitability of several ecoacoustic metrics to holistically characterise spatiotemporal soundscape patterns of acoustically contrasting polar ocean soundscapes: of the anthropogenically impacted eastern Fram Strait, Arctic Ocean, and the ‘pristine’ Weddell Sea, Southern Ocean.

I showed that a multi-metric approach of a variety of ecoacoustic metrics combined with clustering can capture the spatiotemporal variation of soundscape characteristics. It captured patterns between the two different polar ocean soundscapes as well as indicated their acoustic similarities (Chapter 3, Fig. 6, Table 2). Chapter 3, thereby, provided a methodological foundation for assessing the contemporary acoustic state of remote polar offshore environments across large spatial and temporal scales. However, I found that the ecoacoustic diversity metrics I identified as most suitable to characterise the spatiotemporal soundscape variation of the eastern Fram Strait and Weddell Sea did not completely align with the study of Roca and Van Opzeeland (2019). That study applied a similar set of ecoacoustic diversity metrics to describe the geographic variation of soundscapes in the Weddell Sea, but found a different set of ecoacoustic metrics suitable to distinguish pelagic from on-shelf soundscapes. Differences in the soundscape content between both studies, such as different signal types, might have caused a different weighting of the importance of ecoacoustic metrics. Therefore, as discussed in Chapter 3, increasing the spatial and temporal scales of soundscape studies may shift the importance of specific ecoacoustic metrics in differentiating the soundscapes of the dataset in question (see also Bradfer-Lawrence *et al.*, 2019). Thus, I concluded in Chapter 3 that a combination of multiple metrics characterising a variety of soundscape properties provides a more robust monitoring for polar ocean soundscapes spanning large spatial and temporal scales. In general, the use of a suite of ecoacoustic metrics is advised as each ecoacoustic metric captures only a single aspect of the soundscape (Bradfer-Lawrence *et al.*, 2019; Alcocer *et al.*, 2022; Bradfer-Lawrence *et al.*, 2023).

After I laid out the methodological foundation in Chapter 3, I applied the set of ecoacoustic metrics to assess the spatiotemporal variability of soundscape patterns over several years and multiple sites across the Weddell Sea. I only removed the acoustic diversity index (ADI) for Chapter 4, as this metric informs about the same soundscape property (spectral heterogeneity) and responds conversely to the acoustic evenness index (AEI; Sueur, 2018). To my knowledge, the study I presented in Chapter 4 is the first to apply this combination of ecoacoustic metrics and clustering to a real-world unlabelled ocean soundscape dataset at the basin scale and across multiple years (comprising in total 14.61 years of audio data). I argue that Chapter 4 provides a promising approach for simultaneously comparing multiple soundscapes to identify large-scale spatiotemporal variability in soundscape patterns. This approach is based on identifying temporally and spatially similar acoustic entities (or 'soundscape scenes' as referred to in Chapter 4) within the data. These similarities are based on measuring spectro-temporal acoustic properties over pre-defined time spans using multiple ecoacoustic metrics. I applied two clustering approaches as well as statistical α- and β-diversity measures to identify effective soundscape diversity (Chapter 4, Fig. 5, Table 2, Table 3) and spatiotemporal similarity ('soundscape regimes') of the soundscapes (Chapter 4, Fig. 4). Chapter 4 was thereby based on the assumption that the variation of cluster proportions indicates dissimilarity or similarity across soundscapes (see also Flowers *et al.*, 2021).

In Chapter 4, I demonstrated, that the spatiotemporal variability in soundscape diversity reflects the seasonal and geographical variability in sea ice cover (Chapter 4, Fig. 5). Moreover, it potentially reflects seasonal variation in the acoustic behaviour of the dominant marine mammal species and their acoustic community composition, as the soundscape diversity was highest during sea ice cover (Chapter 4, Table 3) aligning with the peak in acoustic marine mammal species richness in the Weddell Sea (Van Opzeeland and Hillebrand, 2020). Thus, my results support the assumption of Flowers *et al.* (2021), applying a similar approach to terrestrial soundscape data. They stated that the proportion of each cluster ('soundscape scene') might be the factor defining location-specific soundscapes. Measuring shifts in cluster proportions and characteristics may therefore provide a new tool for monitoring soundscape transformation over time. Furthermore, the approach applied in Chapter 4 therefore may provide a simple and coarser but scalable method of exploring soundscapes at various temporal and geographical scales. Subsequently, such exploratory studies can be followed up by more detailed ecological studies, as also emphasised by Sethi *et al.* (2023).

Flowers *et al.* (2021) discuss how ecoacoustic metrics, specifically acoustic diversity metrics, may also provide a basis for storing data in a more sustainable manner, as storing raw-PAM data is memory-demanding. However, before acoustic diversity metrics can replace the raw acoustic data, there needs to be an agreement on a standardised application, as there are many pitfalls (e.g., Bohnenstiehl *et al.*, 2018; Dimoff *et al.*, 2021; Metcalf *et al.*, 2021; Bradfer-Lawrence *et al.*, 2024; Jarrett *et al.*, 2025; Kemp *et al.*, 2025).

The complexity of using ecoacoustic diversity metrics:

The application and interpretation of ecoacoustic diversity metrics for measuring soundscape complexity is as complex as the soundscape itself. Within the scientific community, there is a heated debate about the practicality of using them to infer ecological information (e.g., Llusia, 2024; Bradfer-Lawrence *et al.*, 2025). This section discusses some of the debated issues in the application and interpretation of the ecoacoustic diversity metrics and how they might be related to my dissertation (Chapter 3 and Chapter 4).

Ecoacoustic diversity metrics are highly influenced by call type, signal-to-noise ratios, selected settings and study design, including sampling rate and spectro-temporal resolution, software, hardware, and filters (Bohnenstiehl *et al.*, 2018; Dimoff *et al.*, 2021; Metcalf *et al.*, 2021; Chen *et al.*, 2023; Bradfer-Lawrence *et al.*, 2024; Jarrett *et al.*, 2025; Kemp *et al.*, 2025). Thus, the sensitivity of the acoustic diversity metrics across different aspects (wanted or unwanted) of the data strongly adds to the debate of the actual usefulness of ecoacoustic diversity metrics for biodiversity assessments (e.g., Buxton *et al.*, 2018; Mooney *et al.*, 2020; Alcocer *et al.*, 2022; Llusia, 2024; Sugai and Costa-Pereira, 2025). Therefore, guidelines have emerged in recent years to assist researchers in correctly applying and interpreting these metrics in line with their study's objective (see Bradfer-Lawrence *et al.*, 2023; Bradfer-Lawrence *et al.*, 2024; Kemp *et al.*, 2025). In general, they all recommend to not apply them blindly but develop prior knowledge on the soundscape, becoming familiar with soundscape patterns and signal types in order to select appropriate ecoacoustic metrics and parameter settings (Bradfer-Lawrence *et al.*, 2023). Furthermore, it is recommended to explicitly ground-truth ecoacoustic diversity metrics to known ecological patterns in the soundscape and to test their robustness across different spectro-temporal settings and audio duration, in order to evaluate whether they truly reflect the perceived soundscape patterns and are sensitive enough to capture ecologically relevant changes (Bradfer-Lawrence *et al.*, 2023; Kemp *et al.*, 2025). This should ensure that the ecoacoustic diversity metrics accurately characterise the intended soundscape properties and effectively address the study's objective, such as biodiversity assessment or the detection of strong trends in spatiotemporal soundscape patterns (Bradfer-Lawrence *et al.*, 2023). In line with these recommendations, in Chapter 3, I examined how the ecoacoustic metrics respond to polar ocean soundscape characteristics and evaluated how well they capture the soundscape patterns of the two contrasting acoustic environments. I also ensured that the assessment included the dominant and common sound sources of the Weddell Sea.

Signal-to-noise ratios:

As previously mentioned in Chapter 1, ecoacoustic diversity metrics are sensitive to changes in the signal-to-noise ratio (Chen *et al.*, 2023) caused by variation in call rates: from distinct calls to chorusing (e.g., Bohnenstiehl *et al.*, 2018; Bolgan *et al.*, 2018; Siddagangaiah *et al.*, 2019; Dimoff *et al.*, 2021), and by wind or anthropogenic activity (Parks *et al.*, 2014; Bohnenstiehl *et al.*, 2018; Siddagangaiah *et al.*, 2019). However, the variation of the signal-to-noise-ratio, caused by the geo- or anthropophony, as well as the variability in the call rate, is also a fundamental information on the state of the acoustic environments along temporal and geographical gradients (Pijanowski *et al.*, 2011b; Roca and Van Opzeeland, 2019; Flowers *et al.*, 2021). Therefore, I exploited this sensitivity of the ecoacoustic diversity metrics as the foundation in Chapter 3 and Chapter 4, as I aimed to capture the variability and differences in holistic soundscape patterns and dynamics along environmental gradients and anthropogenic activities.

Spectral and temporal settings:

In my dissertation, I addressed how ecoacoustic metrics characterise dominant polar ocean soundscape features in Chapter 3. However, in Chapter 4, I applied a coarser temporal resolution but higher frequency resolution in contrast to Chapter 3. The spectral and temporal resolution over which the ecoacoustic diversity metrics are measured has also been shown to introduce a bias in the acoustic diversity metrics (e.g., Bohnenstiehl *et al.*, 2018; Bradfer-Lawrence *et al.*, 2024; Kemp *et al.*, 2025). Thus, the change of the spectro-temporal resolution might have smoothed out short impulsive characteristics in Chapter 4, while spectral variability might have become weighted stronger. Considering that I focused on coarser soundscape patterns caused by acoustically dominant soundscape characteristics such as choruses, the effect of choruses on the soundscape patterns would not have been affected by the differences in spectro-temporal resolution between both chapters. It remains unclear whether the ecoacoustic diversity metrics have correctly captured higher frequency signals, which tend to have short impulsive characteristics and do not form prominent choruses, such as sperm whale (*Physeter macrocephalus*) clicks (e.g., Madsen *et al.*, 2002), and (ultrasonic) vocalisations of phocids (e.g., Cziko *et al.*, 2020) or delphinids (Schall and Van Opzeeland, 2017). Therefore, the diversity in soundscape patterns might have been underestimated, particularly for the higher frequencies (3428-12000 Hz) I investigated in Chapter 4. Studies following up on this approach should thus, as recommended by Bradfer-Lawrence *et al.* (2023) and Kemp *et al.* (2025), test the capability of the selected metrics and settings to capture ecologically relevant patterns, particularly for the higher frequency ranges. Despite these limitations, I still consider that the approach applied in Chapter 4 to be valid, particularly for the lower frequency ranges (Chapter 3 and Chapter 4, Fig. 4 and Fig. 5), as I was able to uncover seasonal patterns and variation in soundscape diversity corresponding to seasonal sea ice cover. I argue that the found pattern in soundscape diversity in Chapter 4, also seems to reflect the acoustic marine mammal community dynamics in the Weddell Sea (Van Opzeeland and Hillebrand, 2020). Thus, I reason that Chapter 4 provides guidance for further exploration of the underlying sound sources and signal types shaping these soundscape patterns and acoustic similarities between the investigated recording stations.

Audio duration:

The audio duration over which the ecoacoustic diversity is measured has also been shown to introduce a bias (Bradfer-Lawrence *et al.*, 2024; Kemp *et al.*, 2025). With an increase in the audio duration, more temporal frames are considered by the metric (Bradfer-Lawrence *et al.*, 2024; Kemp *et al.*, 2025). The length of the saved audio files by the AURALs was shorter (4.5-7 min) than for the Sono.Vaults (10 min). However, I did not find a distinct separation of the AURAL recordings based solely on their measurement (Chapter 4, Figure 3) but only by the overall soundscape diversity (Chapter 4, Figure 4), which I linked to depth of the recorder in the water column. Therefore, I think it is unlikely that the different audio lengths introduced a strong bias affecting the overall results. Nevertheless, to avoid potential bias in future studies, the audio duration over which the ecoacoustic diversity metrics are measured should either be adapted to the shortest available audio duration or be standardised, e.g., to one minute, as it is also recommended for the computation of ambient sound levels (Miksis-Olds *et al.*, 2021; Tyack *et al.*, 2023).

In Chapter 3 and Chapter 4, I focussed on assessing coarser, larger-scale variability in soundscape patterns, which is why I used the hourly (Chapter 3) and daily means (Chapter 4) of the acoustic properties computed with the ecoacoustic metrics. This might have smoothed out biases from the audio duration. Additionally, as discussed in the corresponding chapters, using hourly or daily means might have also smoothed out temporally clustered or sparse sounds which do not form choruses, for example vocalisations from Weddell seals (*Leptonychotes weddellii*) or sperm whales (Madsen *et al.*, 2002; Moors and Terhune, 2004). The propagation ranges of odontocete and phocid vocalisations are estimated to propagate over more local scales (from 6 to 30 km; e.g., Cleator *et al.*, 1989; Madsen *et al.*, 2002). Applying a higher temporal resolution might facilitate the identification and understanding of more localised soundscape patterns. Perspectively, a follow-up study, might use shorter audio durations and averaging to provide more insight into ecological details at higher frequencies and could increase understanding of the ecosystem's response to environmental alterations more comprehensively. However, the coarser approach of hourly and daily means likely provides a more feasible solution for very large datasets and to assess large-scale spatiotemporal soundscape patterns and dynamics in the context of synoptic scale environmental conditions, climate-oscillations or climate change.

The complexity of using ecoacoustic intensity metrics

Unlike for the ecoacoustic diversity metrics, the recommendations regarding which ecoacoustic intensity metrics should be applied to report ocean ambient sound levels in a standardised and comparable manner are more tangible (Merchant *et al.*, 2016; MSFD, 2017; Merchant *et al.*, 2022; Tyack *et al.*, 2023). Particularly, the application of the TOL bands centred at 63 Hz, 125 Hz, 250 Hz, and 500 Hz is recommended to measure shipping noise (MSFD, 2017; Merchant *et al.*, 2022). To my knowledge, Chapter 3 and Chapter 4 represent the first values for these recommended bands to characterise ambient sound levels of the Southern Ocean in a standardised and comparable manner. In Chapter 3, I showed that these bands mainly captured the influence of marine mammal vocalisations and environmental sounds on the soundscapes, but were also able to indicate anthropogenic noise in the sea ice-free period. I discussed in Chapter 3 that these bands would have characterised the Southern Ocean as noise-polluted from shipping even during the sea ice-covered period due to the loud vocalisations of the pagophilic marine mammals interfering with these bands. I argued that other bands with less interference from marine mammals should be selected for monitoring current global shipping noise in the Southern Ocean. At the same time, they might still be effective for monitoring shipping noise in sea ice-free periods and regions of the Southern Ocean. In the Arctic, the 50 Hz band was correlated with airgun noise (Klinck *et al.*, 2012) and ship noise is also reported to peak at higher frequency bands, such as 200 Hz or 2 kHz in coastal areas (Picciulin *et al.*, 2016; Mustonen *et al.*, 2019; Merchant *et al.*, 2022). How these frequency bands perform to indicate ship noise in the Arctic and Southern Ocean could be tested in a follow-up study. Furthermore, this highlights that single ecoacoustic metrics are not ideal to study spatiotemporal soundscape patterns or the status of the acoustic environment but that the combinations of metrics, as I applied in Chapter 3 and Chapter 4, provide a more suitable approach which is as also discussed by Alcocer *et al.* (2022) and Bradfer-Lawrence *et al.* (2019). The potential for the combination of ambient sound levels measured in different frequency bands to serve as an indicator of anthropogenic noise pollution in the Southern Ocean could be tested by correlating these levels with audio files in which anthropogenic noise has been detected. Parallel analysis with ship-traffic data retrieved from Automatic Identification Systems would provide additional correlation and validation data.

Further challenges using ecoacoustic metrics for soundscape assessments

In the context of improving and standardising soundscape assessments on a global scale, the selection of an appropriate set of ecoacoustic metrics to capture variations in soundscape properties in an ecologically meaningful way is a crucial task. A standardised set of metrics would facilitate inter-comparability between regions and studies as well as foster reporting the acoustic state of the ecosystem to regulators and stakeholders. In Chapter 3, I discussed that there is a wealth of possible ecoacoustic metrics (Buxton *et al.*, 2018; Pieretti and Danovaro, 2020; Minello *et al.*, 2021) which could be used to characterise and compare soundscape properties. Throughout, Chapter 3 and Chapter 4, I measured soundscape properties focusing on the overall amplitude and spectro-temporal homogeneity or heterogeneity. Nevertheless, there are further soundscape properties such as periodicity and impulsivity (see Wilford *et al.*, 2021; Wilford *et al.*, 2023) which could be explored. Therefore, expanding and testing the wealth of ecoacoustic metrics might provide further insights into polar ocean soundscape properties, characteristics, diversity, and soundscape regimes. The exploration of a set of ecoacoustic metrics that can universally capture different soundscape properties would be beneficial to the International Quiet Ocean Experiment and the Global Ocean Observing System, as they aim to identify a standardised set of metrics for holistic ocean soundscape monitoring (Tyack *et al.*, 2023). Furthermore, to improve global standardisation, ecoacoustic metrics should be tested using a global example of marine soundscape data to make sure the selected set of metrics responds to a large variety of soundscape characteristics and correctly assigns defined soundscape properties. Such a test dataset should span soundscapes of polar areas, as well as different offshore and reef habitats, and vertical regimes ranging from the deep sea to the epipelagic to characterise the full picture of soundscape variabiltiy caused by different sound source assemblages and signal types. Conversely, it may be challenging to identify a set of metrics that can be universally applied to assess marine soundscapes on a global scale because acoustic environments are very versatile due to a high variation in sound sources Moroever, besides the high variation of sound sources between ecoystems, the bathymetry can affect the way signals manifest in soundscapes through absorption, reverbration, and dispersion (Erbe *et al.*, 2025). As a result, coastal and offshore areas may exhibit different soundscape properties even when the sound source and signals are the same. Thus, tailoring ecoacoustic metrics to specific ecosystems may be more feasible, enabling the set to capture ecosystem-specific soundscape characteristics and to assess patterns and dynamics more efficiently. Therfore, an ecosystem-specific set of ecoacosutic metrics might also improve the sensetivity of assessing the contemporary state of the ecosystem and assessing shifts in the acoustic environment.

Lessons learned using a diverse set of PAM deployments

In Chapter 4, I aimed to identify geographic variation of soundscapes across the Weddell Sea, however, this was hampered by the soundscapes being recorded at different depths in the water column, resulting in summarising the similarities in soundscapes based on the recording depth rather than geographical acoustic similarities. However, the applied approach in Chapter 4 could still indicate that soundscapes more distant from the coast or ice shelf within the deep-water regimes of the Weddell Sea basin have a greater similarity in soundscape patterns. To better identify geographical variation across the Weddell Sea basin or in other ocean regions, the study design should ensure that recording devices are deployed across consistent depth in the water column to avoid separation into vertical zones if the bathymetry allows.

Additionally, the AURAL recorders were set to a subsampling scheme. The subsampling, as discussed in Chapter 4, might additionally govern the separation of the regimes. Subsampling has been shown to negatively affect the accuracy of detecting marine mammals that vocalise sparsely or in clusters (Thomisch *et al.*, 2015). Thus, subsampling might not only have biased the acoustic detection of marine mammals in Chapter 2, but might have also caused a failure to detect acoustic events in Chapter 4, which might have influenced holistic soundscape patterns and consequently the formation of soundscape regimes. Therefore, I stress that continuous data collection is not only beneficial to monitor the acoustic species presence but also to assess diversity in soundscape patterns and regimes.

Future directions for polar ocean soundscape monitoring and research

One of the main aims of my dissertation was the analysis of large-scale spatiotemporal variation in the soundscape patterns of the Southern Ocean, with comparatively less emphasis on large-scale variation in the Arctic Ocean soundscapes. Consequently, this means that a continuation of my research, particularly of Chapter 4, would be ideal as a follow-up for the Arctic Ocean. Ideally, such soundscape comparisons for the Arctic Ocean should cover a variety of Arctic ecosystems. They should cover vulnerable areas important for Arctic endemic marine mammals from lower (Chapter 2) and higher Arctic latitudes (see Hamilton *et al.*, 2022). Such studies should include soundscapes across environmental gradients and ecosystem transitions: from coastal waters and the shelf slope to open-ocean offshore areas, marginal sea ice zones, and year-round heavy sea ice-covered areas, such as the central Arctic Ocean basin. Knowledge of the central Arctic Ocean's acoustic environment is particularly limited as recordings from this area are largely absent (Halliday, 2021). The Atlantic-Arctic Distributed Biological Observatory[*] is planned as a comprehensive marine observing network for climate and environmental research within the Atlantic Sector of the Arctic. The Atlantic-Arctic Distributed Biological Observatory has already identified some areas for standardised long-term monitoring. This network does not yet fully extend along East Greenland. However, the gateways to the Arctic Ocean, such as the Fram Strait, might provide a good opportunity to start. Fortunately, pan-Arctic PAM networks[†] are already established by different institutions, including PAM platforms across the Fram Strait, providing soundscape data

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[*] A-DBO, https://arcticpassion.eu/adbo/, last accessed 09.09.2025

[†] 'Listen, Connect and Conserve' – A Pan-Arctic Passive Acoustic Monitoring Network (CAFF 2020). https://experience.arcgis.com/experience/ce814a59aa8e4b70a7c4d03f2dc64003, last visited 12.08.2025

across several ice conditions and multiple years (e.g., Klinck *et al.*, 2012; Nieukirk *et al.*, 2020; Ahonen *et al.*, 2021; Ladegaard *et al.*, 2021; Meister *et al.*, 2024).

Within the Southern Ocean, I have primarily focused on the Weddell Sea soundscape, but exploring other Southern Ocean basins, for example the Ross Sea, would improve our understanding of the large-scale implications of climate oscillations or climate change on the Southern Ocean ecosystem. Moreover, Chapter 4 only included one station closer to the shore (Elephant Island) and mainly deep-water environments within the Weddell Sea basin. Monitoring ecological changes in the Southern Ocean, however, needs to involve a higher variability of ecosystems to better monitor and understand distribution shifts of marine mammals as a response to sea ice loss and climate oscillations, as has already been observed (Schall *et al.*, 2021; Roca *et al.*, 2023; Dunlop *et al.*, 2025). Therefore, a circumpolar soundscape comparison would benefit in monitoring the Southern Ocean ecosystem and changes in response to the triple planetary crisis. However, a Southern Ocean circumpolar PAM network has not yet been established.

Nevertheless, efforts have been made to propose a circumpolar PAM network (van Opzeeland *et al.*, 2013). Potentially, the upcoming international Antarctica InSync (International Science & Infrastructure for Synchronous Observation) program[*] could provide a great opportunity for addressing such efforts. A pan-Antarctic distribution of PAM could contribute to two core scientific themes of Antarctica InSync: (i) 'improving knowledge and protection of the unique Antarctic life' and (ii) 'anthropogenic signatures'. It might also contribute to 'rapid sea ice decline and its causes and consequences'. Based on the findings of my dissertation, I would recommend deployments and comparisons to include higher and lower latitude soundscapes, e.g., along presumed migration routes of baleen whales from their summering to wintering grounds (e.g., Marcondes *et al.*, 2021; Herr *et al.*, 2022; Dunlop *et al.*, 2025). Such an expansion of stations can aid a more comprehensive understanding of soundscape alterations through changes in the phenology and migration pattern of baleen whales and endemic pagophilic marine mammals in response to sea ice loss. Additionally, it would allow to test the hypothesis I established that Southern Ocean offshore soundscapes become more homogenous and louder when sea ice declines. Moreover, more stations at the ice shelf or the Antarctic coast should be included, particularly along the Antarctic Peninsula. Lastly, established and prospective fishing (Savoca *et al.*, 2024) and tourist zones (Senigaglia *et al.*, 2025) are crucial areas to monitor and to incorporate into comparisons to advance knowledge on the scale and impact of noise pollution in the Southern Ocean.

Throughout my dissertation, I focused on sea ice conditions to study environmental drivers of soundscape patterns, diversity, and regimes as sea ice strongly shapes polar ocean ecosystems (Post

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[*] https://www.antarctica-insync.org/about/, last accessed 18.09.2025

et al., 2013; Schofield *et al.*, 2024). However, several other environmental factors could also be explored to provide insights into large-scale soundscape dynamics, diversity, and regimes. Such environmental factors could include climatic oscillation indices governing large-scale oceanographic fluctuations that have shown effects on baleen whale acoustic presence (Schall *et al.*, 2021; ZoBell *et al.*, 2025), such as the Southern Annual Mode, the Oceanic Niño Index, the Pacific Decadal Oscillation, the North Pacific Gyre Oscillation, and the North Atlantic Oscillation. In the Southern Ocean, the acoustic presence of humpback whales correlated with the Southern Annual Mode and Oceanic Niño Index (Schall *et al.*, 2021). In the North Pacific, low-frequency sound levels associated with fin and blue whale acoustic presence correlated with the Oceanic Niño Index, Pacific Decadal Oscillation, and North Pacific Gyre Oscillation, indicating a distributional shift of baleen whales as a response to a marine heatwave off the coast of California (ZoBell *et al.*, 2025). For the Atlantic Sector of the Arctic Ocean, the North Atlantic Oscillation and Arctic Oscillation (also referred to as Northern Annular Mode) could be considered to investigate soundscape dynamics in response to climate oscillations. To my knowledge, these two climate indices have not been applied to investigate or explain changes in soundscape characteristics or acoustic marine mammal presence. However, the North Atlantic Oscillation has been shown to affect zooplankton and North Atlantic right whale (*Eubalaena glacialis*) abundance in the Gulf of Maine (Ganley *et al.*, 2022). Moreover, sea surface temperature and net primary production might also be valuable parameters to investigate climate-driven soundscape variability, as they have been shown to correlate with marine mammal acoustic behaviour (Barlow *et al.*, 2023). Off Aotearoa New Zealand, the acoustic presence of the pygmy blue whales (*B. m. brevicauda*) correlated with sea surface temperature and net primary production, indicating that these whales fell silent due to a decline in fitness in response to the ecological effects of a marine heatwave (Barlow *et al.*, 2023). Marine heatwaves are expected to intensify in the Arctic Ocean, with severe ecological implications (Gou *et al.*, 2025).

The correlation with other environmental parameters, such as the amount and volume of icebergs (Matsumoto *et al.*, 2014; Dziak *et al.*, 2015), might provide additional insights and support interpretations into the variability of polar ocean soundscape patterns driven by geophonic influences. Lastly, correlations with the amount of ship traffic and economic fluctuations, derived from Automatic Identification System (e.g., ZoBell *et al.*, 2025), or the amount and duration of airgun surveys (e.g., Haver *et al.*, 2017; Warren *et al.*, 2021), will significantly enhance our understanding of the effect of anthropogenic activities on our current and future polar ocean soundscape patterns and dynamics.

Polar and coastal marine habitats are projected to face significant cumulative impacts in the future and the impacts may surpass the capacity of the ecosystem to cope with environmental alterations (Halpern *et al.*, 2025). Ocean warming and poorly managed fishery are considered the most impactful pressures experienced by marine ecosystems globally (Halpern *et al.*, 2025). However, Halpern *et al.* (2025) did not consider noise pollution in their assessment as global data is deficient. However, incorporating noise pollution could improve the assessment of cumulative anthropogenic impacts on ecosystems. In addition, spatial modelling of noise pollution focused on polar areas is, to my knowledge, so far only applied to the Arctic (Heaney *et al.*, 2024) but is lacking for the Southern Ocean. Monitoring, assessing, and modelling noise pollution across the Southern Ocean and the Arctic are therefore necessary to understand contemporary and future cumulative anthropogenic pressures on polar ocean ecosystems.

The methodological approach which I introduced in Chapter 4, despite its limitations, is able to capture basin-wide holistic soundscape dynamics in correlation with environmental factors. I argue that the approach might also be applied to other marine ecosystems, as well as in ecosystem management and conservation. Furthermore, the temporal and geographical scalable and comparable concept of soundscape diversity and soundscape regimes can highlight differences between seemingly similar ecosystems. Consequently, the identification of differences in soundscape diversity patterns might indicate which areas are eco-acoustically different or might be experiencing ecological shifts and are at risk. Identified areas could then be studied more closely to better resolve and understand the underlying cause(s) of differences in soundscape patterns.

Given the far-reaching ecological consequences the triple planetary crisis and impoverished soundscapes can have on marine ecosystems, it is essential to improve our understanding of the rate of change in soundscape patterns. In Chapter 2, I assessed turnover dynamics of the acoustic marine mammal community using the net change of species richness (see also Hillebrand *et al.*, 2018; Van Opzeeland and Hillebrand, 2020). Van Opzeeland and Hillebrand (2020) additionally applied an abundance and richness-based species exchange ratio to quantify the rate of change in the acoustic marine mammal community over time (see also Hillebrand *et al.*, 2018). Community compositions analysis (e.g., Hillebrand *et al.*, 2018) could be applied on soundscape scenes as identifed in Chapter 4 to estimate rates of change in soundscape patterns. Building on this, a soundscape turnover index could be developed to serve as an indicator for ecosystem change through cumulative anthropogenic pressures from an acoustics perspective. Quantifying the rate of soundscape change would also provide a valuable tool for communitcating ecosystem alterations to regulators and stakeholders.

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Contribution Statement

The present dissertation has been the result of a collaborative effort with several researchers, who have contributed as co-authors throughout the different research chapters. The following section details my (**Ramona M. Mattmüller**) contribution to the conceptualization, data acquisition, formal analysis, and writing of each chapter. The present declaration has been signed by the co-authors, who thereby confirm that they have read the contribution statement and agree that the chapters and statements in which they are named are accurate.

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Declaration of authorship

I herewith formally declare that this work, submitted in fulfilment of the requirements for the doctoral degree (Dr. rer. nat.), has been developed and written by myself and I have not used any sources without declaration in the text. Any citations and references are marked as such. I am aware of the doctoral regulations of the biological faculty of the University Bielefeld and I certify that the work is original and that I have not submitted this thesis, in whole or parts, or any other essay in support of a doctoral degree or other qualification from this or any other university. I confirm that no third party has earned monetary benefits, direct or indirect, for any work related to this thesis.

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