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# Anthropogenic noise is a dominant component of the shallow-water soundscape of the eastern Ionian Sea

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## Abstract

The eastern Ionian Sea is an important area for marine fauna, but it is also a region of substantial overlap between human activities and natural ecosystem components. Using data from a fixed passive acoustic monitoring station deployed over a 7-month period (July 2022 – January 2023), this study describes the near-shore marine soundscape of northern Kefalonia Island and documents elevated noise levels associated with coastal and offshore anthropogenic activities. Underwater noise from recreational speedboats exhibited a prominent diel pattern during the summer months that was absent in winter. In contrast, diffuse low-frequency noise from offshore shipping traffic was persistent throughout the monitoring period. Additionally, offshore oil and gas seismic surveys conducted at the end of 2022 had a major acoustic footprint on the coastal soundscape. During the first two weeks of December 2022, sustained seismic airgun activity resulted in broadband (10–2000 Hz) received sound pressure levels of 114.4 dB re 1 μPa (Root-Mean-Square), with maximum daily zero-peak levels ranging from 140 to 147 dB re 1 μPa. Continuous soundscape monitoring in these waters is essential for informing underwater noise management and mitigation measures under the European Union Marine Strategy Framework Directive, particularly in light of ongoing hydrocarbon exploration efforts in the eastern Ionian Sea and the establishment of the Ionian National Marine Park, which is primarily aimed at the conservation of marine mammals.

**Keywords:** passive acoustic monitoring; underwater noise; moored hydrophone; marine soundscape; Cephalonia; Mediterranean Sea.

## Introduction

The eastern Ionian Sea is an important area for Mediterranean marine fauna (Frantzis *et al*., 2003, 2014; Bearzi *et al*., 2005; Coll *et al*., 2010; Papazekou *et al*., 2024), but it is also a region of substantial overlap between human activities and natural ecosystem components (Bearzi *et al*., 2006, 2008; Issaris *et al*., 2012). This ecoregion (*sensu* UNEP-MAP-RAC/SPA, 2010) hosts the National Marine Park of Zakynthos for the protection of the loggerhead sea turtle *Caretta caretta* (Margaritoulis, 2005), includes multiple marine sites of the Natura 2000 network, and has been identified as a priority conservation area for key Mediterranean habitats such as *Posidonia oceanica* meadows, coralligenous formations, and marine caves (Giakoumi *et al*., 2013). Further highlighting its prime ecological importance for marine megafauna, large sections of the eastern Ionian Sea have been designated as Important Marine Mammal Areas – IMMAs (IUCN-MMPATF, 2017a, 2017b) and Areas of Special Importance for cetaceans in the ACCOBAMS region (ACCOBAMS, 2010). In 2025, the Ionian National Marine Park was declared in these waters, covering an area of about 17000 km$^2$, in line with the "30 by 30" target (KMGBF, 2022) of the Kunming-Montreal Global Biodiversity Framework.

Central to this ecoregion is Kefalonia, the largest of the Ionian Islands in western Greece. This island is bordered to the west by the steep depressions of the deep (>2000 m) Hellenic Trench (Brooks & Ferentinos, 1984) and to the south by the Zakynthos submarine canyon (Hasiotis *et al*., 2005). To its east, waters of 200 m depth lead to the semi-enclosed Patraikos Gulf, which is connected to Korinthiakos Gulf through the narrow Rio-Antirio

Strait. The coastal waters of Kefalonia host several key habitat types listed in the EU Habitats Directive 92/43/EEC, including seagrass beds (Topouzelis *et al*., 2018), rocky reefs, sandbanks, and marine caves (Gerovasileiou & Bianchi, 2021). The island is also important for cetaceans (Bearzi *et al*., 2005; Frantzis, 2009; Gnone *et al*., 2023), Mediterranean monk seals (*Monachus monachus*) (Panou *et al*., 1993, 2023) and loggerhead turtles (Margaritoulis *et al*., 2003, Casale *et al*., 2018), and almost half its coastline is currently part of the Natura 2000 marine network (site codes: GR2220004, GR2220005, GR2220007). However, as in most parts of the Inner Ionian Archipelago, commercial and recreational activities in the waters adjacent to Kefalonia exert cumulative pressures on threatened biodiversity, often with detrimental impacts (Bearzi *et al*., 2006, 2008; Issaris *et al*., 2012; Papazekou *et al*., 2024).

Most human activities in the marine environment introduce acoustic energy underwater, and anthropogenic noise (Hildebrand, 2009) is a key pressure pertaining to this high-use region (Maglio *et al*., 2016; Fakiris *et al*., 2023). Over the last 50 years, underwater noise associated with shipping (<1 kHz) has been steadily increasing in the oceans (Ross, 1976; Andrew *et al*., 2002; Walkinshaw, 2005) at an alarming average rate of 3 dB per decade (Hildebrand, 2009). Maritime traffic and recreational boats can also increase background noise in coastal settings (Buscaino *et al*., 2016; Pine *et al*., 2016; Heenehan *et al*., 2017; Corrias *et al*., 2023), depending on temporal patterns of traffic density, proximity to shipping routes, and acoustic propagation conditions (Dahl *et al*., 2007). Due to its geographic position, Kefalonia is exposed to continuous low-frequency noise from cargo shipping lanes that densely run along the Hellenic Trench (Frantzis *et al*., 2019) and across Korinthiakos Gulf, as well as from passenger ferry routes that regularly connect the island to mainland Greece. Coastal, leisure marine traffic is also heavy during the summer season, and includes a variety of speedboats, jet-skis and daily excursion boats that mostly launch from tourism hotspot ports like Fiskardo and Agia Efimia.

The area is also exposed to impulsive noise, i.e., high-energy, short-duration broadband sounds with a rapid onset, such as those produced by explosions, sonars, and seismic surveys. Maglio *et al*. (2016) compiled all available information on impulsive noise sources in the ACCOBAMS area and identified the eastern Ionian Sea, and Kefalonia specifically, as a primary noise-cetacean interaction hotspot in the eastern Mediterranean. This issue has further been highlighted by several atypical mass stranding events of Cuvier's beaked whales (*Ziphius cavirostris*) linked to the use of naval active sonar (Frantzis, 1998, 2004; Podestà *et al*., 2016). The eastern Ionian Sea also hosts offshore oil and gas reservoirs, as indicated by well-documented oil seeps and surface oil shows that have historically occurred in the region (Rigakis *et al*., 2007; Karakitsios, 2013). While few and isolated exploitation efforts have been attempted since 1995, recent years have seen a rapid growth in interest for detailed mapping (through geophysical seismic surveys) and industry-scale exploitation of the Ionian hydrocarbon reservoirs. Currently, many deep-sea regions of the eastern Ionian Sea (and southwest of Crete Island) are delineated as areas ("blocks") available for licensing to explore and extract offshore hydrocarbons (see Anastasopoulou *et al.,* 2022 for a review). The introduction of more impulsive noise in the marine environment (through pile driving) is also expected to increase in the foreseeable future, given that the National Energy and Climate Plan of Greece involves a surge in offshore wind farm development in the Ionian and Aegean Seas (Law 4964/2022, GGI A' 150/30.07.2022 of the Hellenic Parliament).

The adverse effects of anthropogenic noise on marine biota (Richardson *et al*., 1995; Nowacek *et al*., 2007; Clark *et al*., 2009; Slabbekoorn *et al*., 2010; Celi *et al*., 2015) highlight the global need for noise monitoring and mitigation (Chou *et al*., 2021). In the European Union (EU), the Marine Strategy Framework Directive – MSFD (EU, 2008) explicitly addresses underwater noise pollution (Descriptor 11: Energy, including underwater noise), promoting low noise levels as a criterion for Good Environmental Status (GES). The MSFD requires Member States to monitor and report on the spatial distribution, temporal extent, and levels of impulsive (Criterion D11.1) and continuous low-frequency underwater noise (D11.2, in the 1/3-octave frequency bands centred at 63 and 125 Hz). Contrary to other European regions however (e.g., Picciulin *et al*., 2023; Basan *et al*., 2024), underwater noise monitoring in Greek waters is scarce (Nystuen *et al*., 2015; Prospathopoulos *et al*., 2017; Diogou *et al*., 2019; Fakiris *et al*., 2023; Fuentes Rivera Escalante *et al*., 2025), while descriptions of near-shore underwater soundscapes (e.g., Buscaino *et al*., 2016; Corrias *et al*., 2023) are lacking.

In an effort to characterise the soundscape of a high-use area in the eastern Ionian Sea, we installed a seafloor-mounted passive acoustic monitoring (PAM) station off northern Kefalonia Island for a 7-month period (July 2022 – January 2023). This deployment captured temporal variability in multiple anthropogenic noise sources, including coastal recreational vessel traffic during summer and offshore seismic surveys during winter. These seismic surveys, associated with hydrocarbon exploration, were conducted in the final months of 2022 across the offshore areas known as "Block 2" and "Ionian Block". Combined, these offshore blocks extend from north-western Corfu Island to southern Lefkada Island, *i.e.* about 15 km north of our acoustic station. Here, we describe the principal acoustic sources and their frequency of occurrence, report on long-term underwater noise measurements using 1/3-octave band sound levels (TOLs, dB re 1 μPa), and identify the dominant contributors to the underwater soundscape. The observed elevated noise levels are discussed in the context of the ecological importance of this area and the anticipated expansion of industrial marine activities in the eastern Ionian Sea.

## Materials and Methods

### *Passive acoustic monitoring station*

An autonomous fixed acoustic recorder was installed in the Fiskardo area, North Kefalonia (Fig. 1A). This location is a popular tourist destination, hosting extensive recreational marine activities during the summer months (June–September) and heavy offshore shipping traffic throughout the year, mainly associated with a shipping lane located approximately 4 km to the north (Fig. 1B). The fixed PAM station utilized an LS1 underwater acoustic recorder from Loggerhead Instruments. This device was equipped with an HTI-96-min hydrophone sensor (sensitivity -170 dB re 1V/μPa), and it stored acoustic data in 16-bit uncompressed audio (WAV) format. The acoustic recorder was moored using a custom-built concrete base, weighing approximately 30 kg in air, thereby ensuring stability on the seafloor. An INOX rod was fixed into the concrete base for mounting the PVC housing in an upright position, using heavy-duty plastic cable ties (Fig. 1C).

The acoustic recorder was deployed at 20 m depth on July 1st, 2022, inside the Natura 2000 site GR2220005. The seafloor surrounding the recorder's location (38.476° N, 20.564° E) was covered by *Posidonia oceanica* meadows and patchily distributed rocky reefs.

### *Acoustic data collection*

Throughout this study, the PAM station was configured to record at a 48 kHz sampling rate with 2 dB gain. Its operational protocol (Table 1) was initially set to continuous recording from the moment of initial deployment until 06-10-2022. Subsequently, considering the anticipated lack of station maintenance during the winter months, its schedule was modified to a duty cycle of 10 minutes recording followed by 10 minutes of sleep mode. A gap in the acoustic data collection occurred from 25-08-2022 to 11-09-2022 due to battery malfunction.

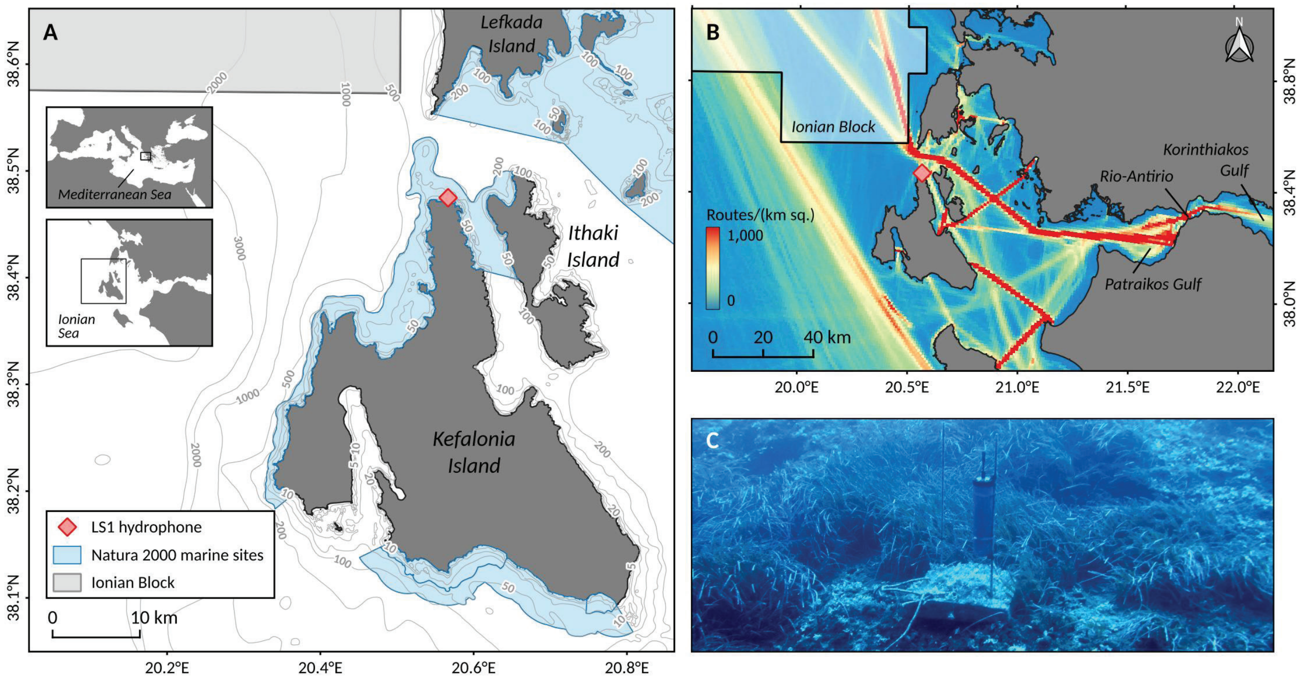


***Fig. 1:*** A) Map of the study area (Kefalonia Island, eastern Ionian Sea), illustrating the fixed acoustic station, the Natura 2000 marine sites, and part of the "Ionian Block" designated for oil and gas exploration. B) Density of marine traffic in the vicinity of Kefalonia Island (all vessel types) for the year 2022 (source: EMODnet, https://emodnet.ec.europa.eu, accessed 12 February 2024). C) Underwater photograph of the LS1 autonomous acoustic recorder used in this study.

**Table 1.** Summary of passive acoustic data collected in this study; only dates with usable data are listed, excluding station maintenance and downtime periods. Non-continuous duty cycle (10/10) denotes minutes recording / minutes sleep. Recorder gain was 2 dB for all data sets, clip level (peak-to-peak): 1.58 V, hydrophone sensitivity: -170 dB re 1V/μPa.

| Acoustic recorder | Recording dates | Duty cycle | Sampling rate (kHz) | File format |
|---|---|---|---|---|
| **LS1** | 01-Jul-2022 to 21-Aug-2022 | Continuous | 48 | WAV, 16-bit |
| | 11-Sep-2022 to 06-Oct-2022 | Continuous | 48 | WAV, 16-bit |
| | 06-Oct-2022 to 15-Jan-2023 | 10/10 | 48 | WAV, 16-bit |

### *Acoustic data analysis*

The acoustic station produced a dataset comprising 18294 WAV files (978 GB) during its recording period. As a first processing step, raw acoustic waveforms were run through a discrete Fast Fourier Transform (FFT) algorithm using Raven Pro software v1.6 (K. Lisa Yang Center for Conservation Bioacoustics, 2023), and spectrograms were produced with a $N_{FFT}$ = 1024-sample Hamming window and 50% overlap. These spectrograms and corresponding waveforms were manually inspected in Raven Pro with a time window of 30 to 60 s. This initial inspection provided an understanding of the dataset contents and helped to identify temporal patterns in recurring acoustic events, e.g., fish choruses during night, speedboat noise from leisure activities in summer, and pulse trains from seismic surveys in winter. Data clean-up was also conducted during this phase to exclude artifacts such as SCUBA noise during station maintenance or waveform spikes resulting from direct animal contact with the hydrophone's sensor. Notes of cetacean detections (for presence/absence information) were also logged during the manual scan. Specifically, for each dolphin (Delphinidae spp.) whistle identified in the spectrogram, its fundamental ($1^{st}$) harmonic was manually marked in Raven Pro by drawing an annotation box that tightly encompassed the sound of interest. Delphinid clicks or buzzes were not marked individually, but grouped into a single annotation box if their inter-call interval was less than 5 s.

Having an informed qualitative description of the soundscape, the second step in our analysis was to examine the two large temporal blocks emerging from the dataset. These were the summer months (July to September) characterised by intense recreational speedboat traffic, and the winter recordings (October to January) where noise from offshore seismic surveys dominated the soundscape. To reduce computational needs and provide a synoptic view of the acoustic attributes of each period, July and December were selected as representative months of summer and winter, respectively. July was chosen because it falls within the peak tourist season and was the only summer month that lacked recording downtime. December was also recorded without downtime and featured elevated impulsive noise during its first two weeks; the stop of airgun pulses during its second half offered additional ground for visualising the acoustic footprint of seismic surveys.

Next, we used the MATLAB version of the open source PAMGuide software (Merchant *et al*., 2015) to produce calibrated spectrograms (dB re 1 μPa) of selected characteristic soundscape components such as fish choruses, speedboat instances or airgun pulses. We created Long-Term Spectral Average (LTSA) plots with 60 s averaging window for the months of July and December, in order to assess important contributors to the soundscape over such broad temporal scales. For the period of non-continuous recording duty cycle (10/10 minutes on/off during winter), the "off" intervals were omitted from plotting. Furthermore, to obtain insight into the power spectral density of speedboats specifically, a 7-day period was selected (13-19 August 2022) which was typical of the increased anthropogenic leisure activities in the summer months. Notwithstanding some overlapping occurrences, all unique speedboat instances identified in the spectrograms were manually marked in Raven Pro and exported as separate WAVs. The PAMGuide software was then used to compute the Power Spectral Density (PSD) of these samples.

Subsequently, noise level metrics were computed for the full seven-month period of our PAM installation in 1/3-octave frequency bands. Subsampling was conducted to reduce the computational needs of this task. Specifically, the first minute of each hour of the day was automatically isolated and saved as a separate WAV file with an appropriate timestamp; no modification was done in the waveform. Each of these 1-min WAVs was considered representative of the originating hour of the day, and Root-Mean-Square (RMS), Sound Exposure Level (SEL), and zero-peak noise measurements at 1/3-octave bands were performed on these subsamples. The noise metrics for these subsamples were calculated using PAMGuard (Gillespie *et al*., 2009), applying a Butterworth filter to isolate each TOL, centred at their nominal base-10 frequency (e.g., 50, 63, 79, 100, 125 Hz). Sound Exposure Levels (dB re 1 $\mu Pa^2/s$) were computed with 60 s measurement interval and 120 s integration time.

Finally, the July and December 1-min subsamples were visually re-examined as spectrograms in Raven Pro. The prominent acoustic presence of vessels (irrespective of their type and number and disregarding instances of other anthropogenic sounds such as sonars and airgun pulses) was empirically logged on a binary scale (1: present, 0: absent). Despite the absence of a consistent signal-to-noise threshold, this was a practical way to empirically parse the convoluted character of the acoustic data, which simultaneously contained diffuse shipping noise, overlapping speedboat passages and bottom trawlers in winter, and continuous choruses of biological origin.

### *Weather data*

To investigate weather conditions versus ambient noise, weather data for Fiskardo were acquired from the Ionian Network of Meteorological Stations (Kalimeris *et al*., 2015), specifically from station KEF-1 "Antipata" (38.455° N, 20.552° E). The parameters considered were hourly rainfall, wind speed, wind gusts, and mean wind direction, measured at 10 m above ground level, covering the entire study period from July 2022 to January 2023. Custom MATLAB scripts were used to tabulate the weather information across the respective acoustic descriptors. Overall, station downtime was minimal, with only 6.1% meteorological data gaps over our study period.

## Results

### *Soundscape overview*

The underwater coastal soundscape of northern Kefalonia displayed temporal patterns during this 7-month study, shaped by diurnal cycles and seasonal changes linked to biological sounds and anthropogenic noise. Both of these soundscape components resulted in a distinct alternation between day and night during the summer months (July to September 2022), as illustrated for July in the long-term averaged spectrograms of Figure 2A, B. Although intermittent to the shallow-water system studied here, offshore oil and gas seismic surveys in the eastern Ionian played a major role on the Fiskardo soundscape during winter, as illustrated for December in Figure 2C, D.

Specifically, biological activity was the main component of the summer soundscape at night. Fish sounds occurred either sporadically or as continuous choruses (Fig. 3A) and were prominent in the 0.5–1.5 kHz frequency band from dusk to dawn (Fig. 3B), especially if confounding noise from speedboats was absent. Snapping sounds from crustaceans were constantly present on a 24-hour basis at frequencies of 2–24 kHz (*i.e.*, the upper frequency limit of the LS1 recorder), although their sound production was more intense during the night. Regarding cetaceans, their acoustic presence during our study period was rather rare, and delphinid sounds (Fig. S1) were predominantly observed in December (Table 2). Our records also include several unidentified vocalisations (Fig. S2) that could be attributed to the Mediterranean monk seal (*M. monachus*), which inhabits these coastal waters. While similar to those reported recently by Charrier *et al*. (2023), the source of these biological sounds remains inconclusive and under investigation.

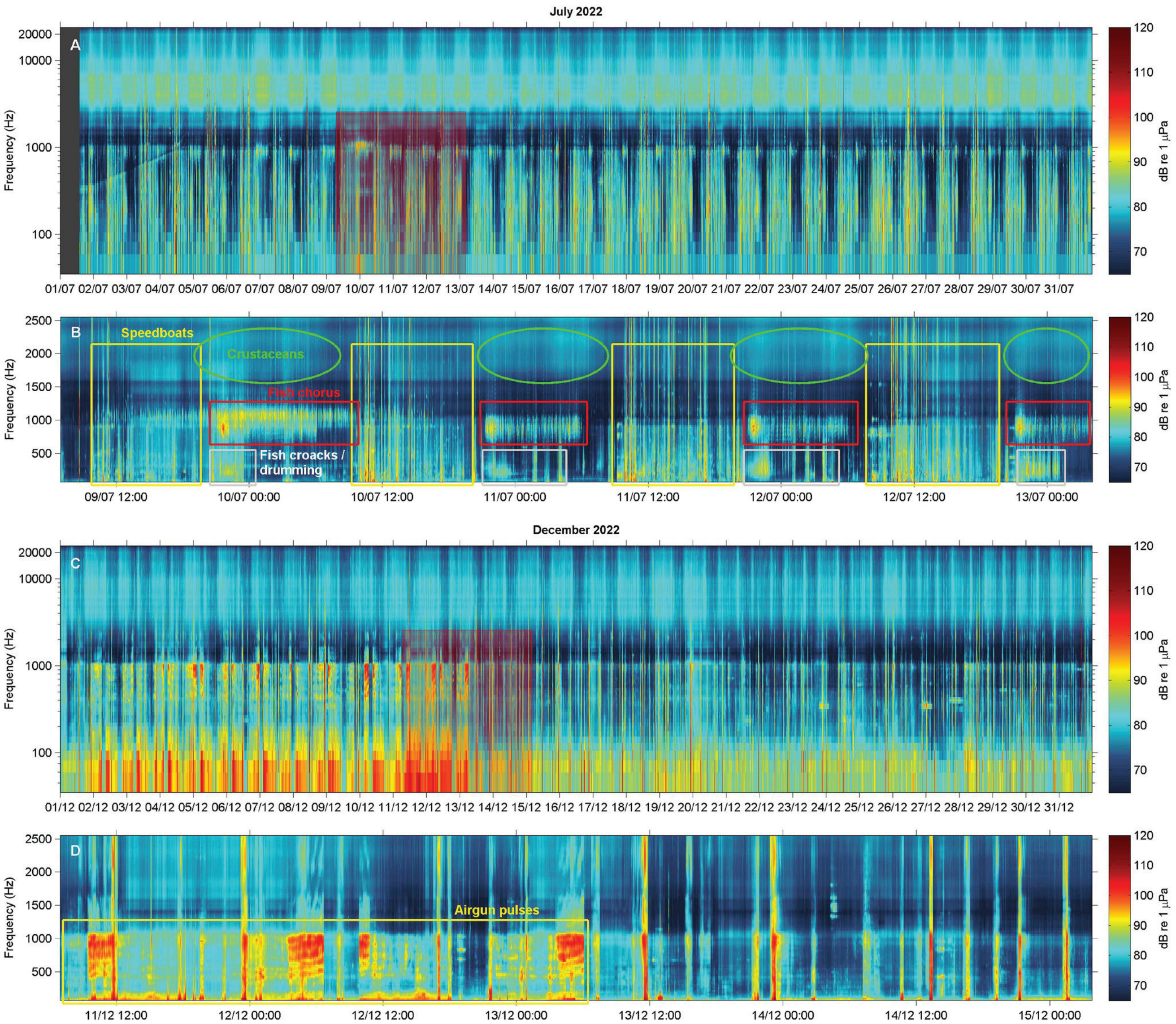


***Fig. 2:*** Long-Term Spectral Average plots (LTSA, 60 s averaging window) for two selected months. A) LTSA for the entire duration of July 2022. B) Zoomed-in LTSA of four successive July days, annotated with the main contributors to the underwater soundscape. C) LTSA for the entire duration of December 2022. D) Zoomed-in LTSA of four successive December days, illustrating the contribution of airgun pulses from seismic surveys conducted offshore. Time is labelled as day/month hour:minute. The red transparent rectangles in panels A and C (log-scale frequency axis) mark the days shown in B and D, respectively.

Geophony (i.e., sounds from geophysical and atmospheric processes) was less pronounced in the soundscape. The meteorological data showed that heavy rain events (≥5 mm/h) occurred mostly during the winter months, while the summer months experienced approximately a quarter of these rainfall events. The maximum rain intensity catalogued was 28.1 mm/h, with rain measurements of ≥ 0.1 mm/h comprising about 3.8% of the total recording period. Throughout our study, sustained rainfall and instances of abrupt rain showers resulted in elevated diffuse noise, especially at the mid- to high-frequency range of the spectrum (Fig. S3). Overall, hourly wind speed and precipitation intensity showed weak or no correlations with the respective 1/3-octave RMS underwater noise levels (Fig. 4). Specifically, rainfall had weak positive correlation (0.22–0.24) with noise level at frequencies above 2.5 kHz. At lower frequency bands (0.5, 1, 2 kHz), RMS noise was associated with average wind speed (Fig. 4B).

### *Anthropogenic noise*

While diffuse low-frequency noise from distant shipping was constantly present in the background (especially during the winter period), the summer daytime soundscape was dominated by local marine traffic from recreational speedboats, jet-skis, and various inboard

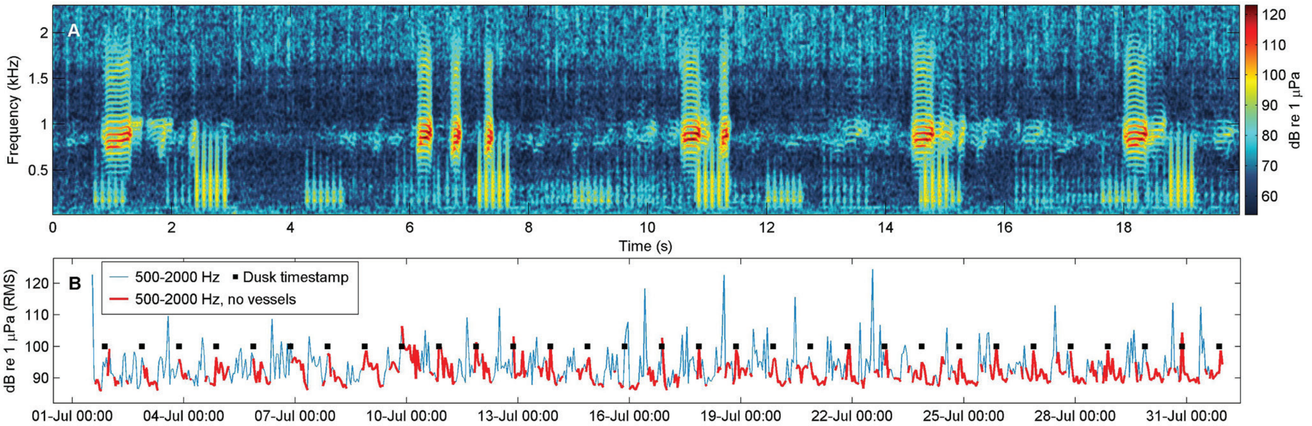


***Fig. 3:*** A) Segment of a typical fish chorus, recorded during the night of 04-07-2022, 22:22 local time ($N_{FFT}$ = 4096 samples, Hamming window, 90% overlap). B) Time series of ambient noise levels (RMS) at the 500–2000 Hz frequency band during July 2022. The black squares mark dusk time per day and were arbitrarily plotted at y = 100 dB.

**Table 2.** Summary of delphinid presence per month, expressed as the number of delphinid sounds manually marked on the spectrograms. Whistles were marked individually, while successive click trains and buzzes were pooled into a single selection.

| Jul 2022 | Aug 2022 | Sep 2022 | Oct 2022 | Nov 2022 | Dec 2022 | Jan 2023 |
|---|---|---|---|---|---|---|
| 3 | 65 | 28 | 591 | 182 | 1044 | 177 |

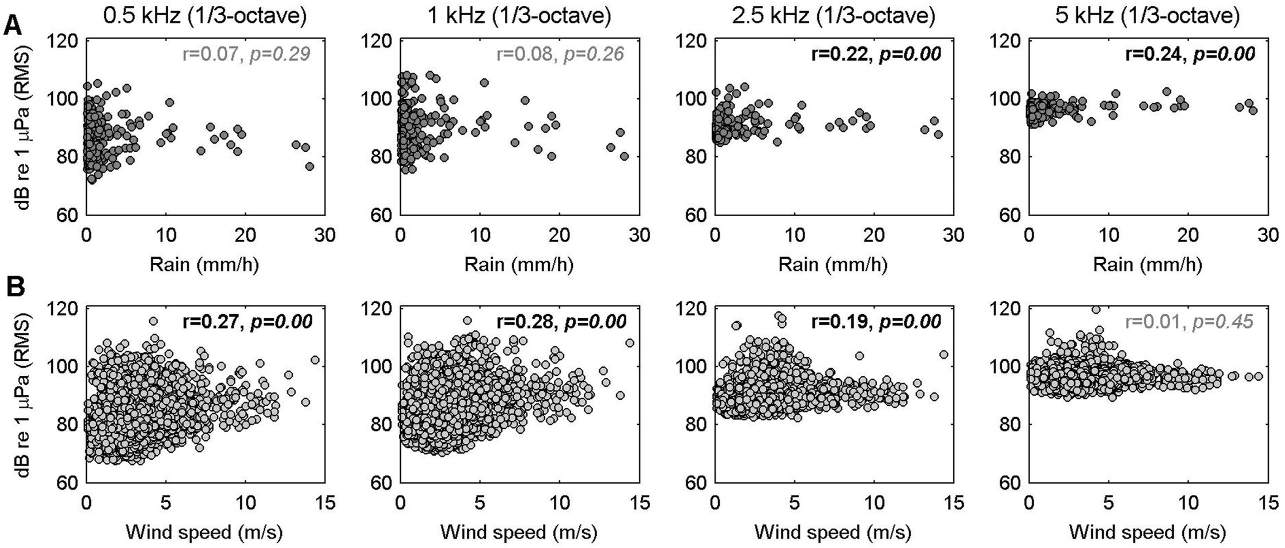


***Fig. 4:*** Scatter plots of hourly 1/3-octave levels (RMS) *vs.* A) rainfall and B) wind speed at Fiskardo station (all data pooled), for 4 centre frequencies. Statistically significant ($p < 0.05$) rank correlations are marked in bold.

vessels (Fig. 5). These noise-producing leisure activities were not uniformly distributed across summer days, but followed the recreational and tourism marine activities in the region. They systematically occurred from early morning to afternoon, peaking at noon, and often persisting through to late evening hours (Fig. 6A). When compared with sound samples with no prominent vessel presence, speedboat traffic resulted in a temporary 10 dB increase of noise levels (RMS) for all 1/3-octave bands below 1 kHz (Fig. 6C). Inboard fishing vessels were also undoubtedly part of this anthropogenic component (late evening through night included), with sounds originating from small-scale coastal fishery boats and purse seiners; bottom trawlers cease operations in Greek territorial waters from June to September.

In contrast, anthropogenic noise was markedly different during winter, both in terms of temporal pattern (Fig. 6B) and received levels (Fig. 6C, D). Commercial shipping was operating as normal, speedboat instances were fewer and more sporadic than summer, and bottom trawl fisheries were active between North Kefalonia and South Lefkada. Moreover, airgun pulses (Fig. 7) dominated with impulsive noise the low-frequency bands (≤1 kHz) from the 1st of November to the 13th of December (Fig. 8F), alongside low-frequency diffuse noise from vessels conducting the hydrocarbon surveys. Therefore, the very high zero-peak noise levels at 500 and 1000 Hz (the upper 50% of measurements were between 110 and 147 dB, Fig. 6D) cannot be attributed solely to marine traffic that is usual to this region. Similarly, the seismic survey vessels also contribute to the December counts of Figure 6B.

The prominent footprint of seismic surveys on the coastal soundscape of North Kefalonia is also highlighted by the hourly progression of RMS noise levels across the low- and mid-frequency 1/3-octave bands over the entire study period (Fig. 8). The variability of underwater noise levels at Fiskardo at the frequency bands centred at 63, 125, 630 and 1000 Hz is shown in Figure 9, tabulated by calendar week. Additionally, four summary noise metrics were computed per month and are reported in Table 3: the RMS, the SEL, the median, and the 90th percentile. Regarding the latter metric, its maximum value was measured in December 2022 at 1 kHz (129.5 dB re 1 μPa).

## Discussion

Anthropogenic underwater noise is of global concern for biodiversity conservation (Chou *et al*., 2021; Duarte *et al*., 2021), and is generated by a broad range of activities, including commercial shipping, seismic surveys, pile driving, active sonars, offshore installations, fisheries, and recreational boat traffic (Hildebrand, 2005, 2009). Given this variety of sound sources, monitoring underwater noise requires deployment periods that span across many years (Merchant *et al*., 2015) and ultimately involves noise mapping, *i.e.*, a combination of sound propagation modelling with *in situ* validation measurements (Putland *et al*., 2022), ship traffic density analysis (Frassà *et al*., 2023) and source level assessments (Basan *et al*., 2024). International cooperation is essential to this end (Lewandowski & Staaterman, 2020; IMO, 2023), as shipping and other important noise contributors are often cross-boundary in nature. In light of the MSFD, several joint programs have recently focused on monitoring and assessing impulsive noise in the Mediterranean (see pro-

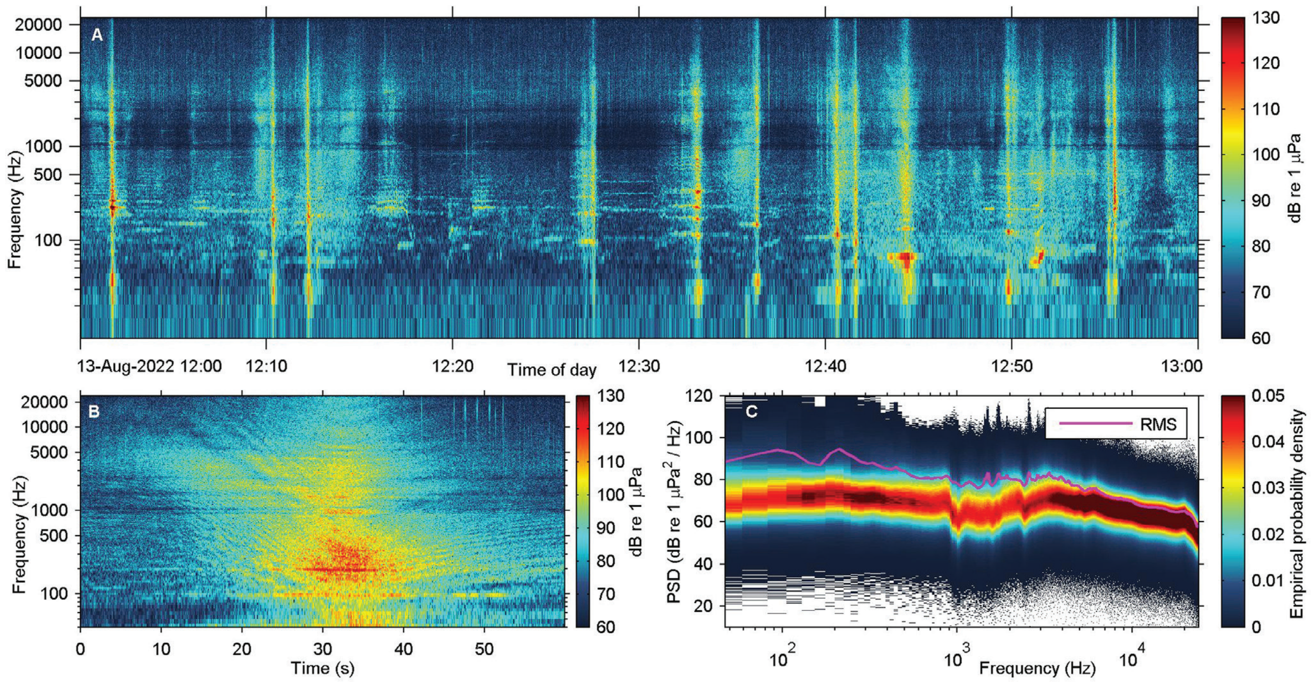


***Fig. 5:*** Spectral characteristics of recreational speedboat traffic in the vicinity of the fixed acoustic recorder. A) One hour-long example spectrogram of a typical busy summer day at noon (13-08-2022, 12:00–13:00 local time; $N_{FFT}$ = 8192 samples, Hamming window, 50% overlap, log-scale frequency axis). B) Instance of a single speedboat ($N_{FFT}$ = 8192, Hamming, 50%, log-scale frequency axis). C) Spectral probability density plot (broadband) and corresponding RMS level of the PSD for all speedboat occurrences manually marked on the spectrograms (13th to 19th of August 2022).

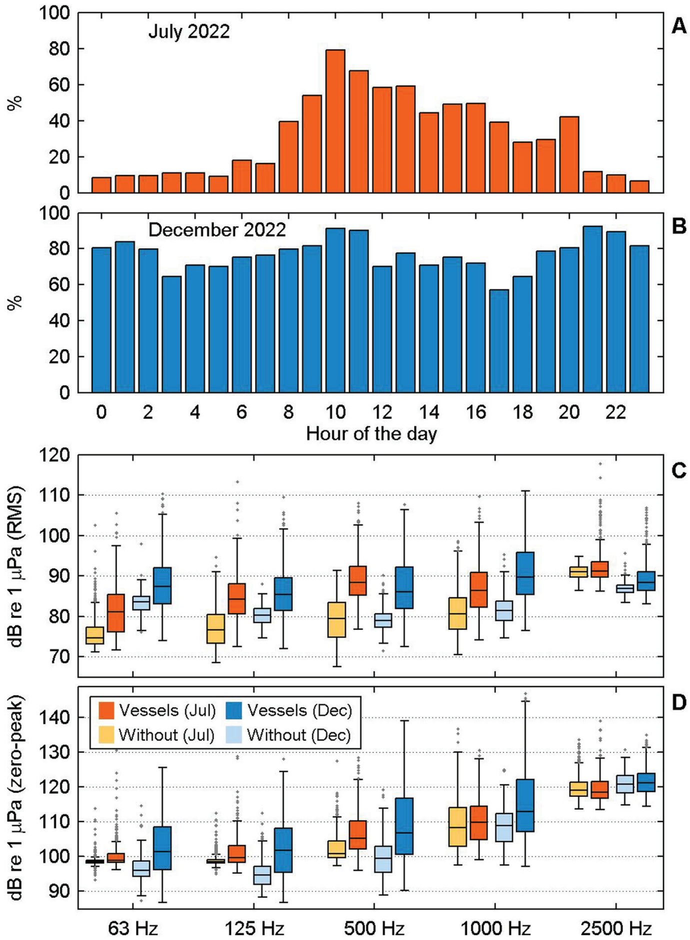


*Fig. 6:* Hourly vessel traffic density at Fiskardo during A) July and B) December 2022, expressed as the percentage of 1-min subsamples with vessel presence over the total number of subsamples per month. C) RMS and D) zero-peak 1/3-octave noise levels for July and December 1-min subsamples, tabulated by vessel presence. The centre line marks the median, boxes and whiskers denote the inter-quartile and non-outlier range, respectively.

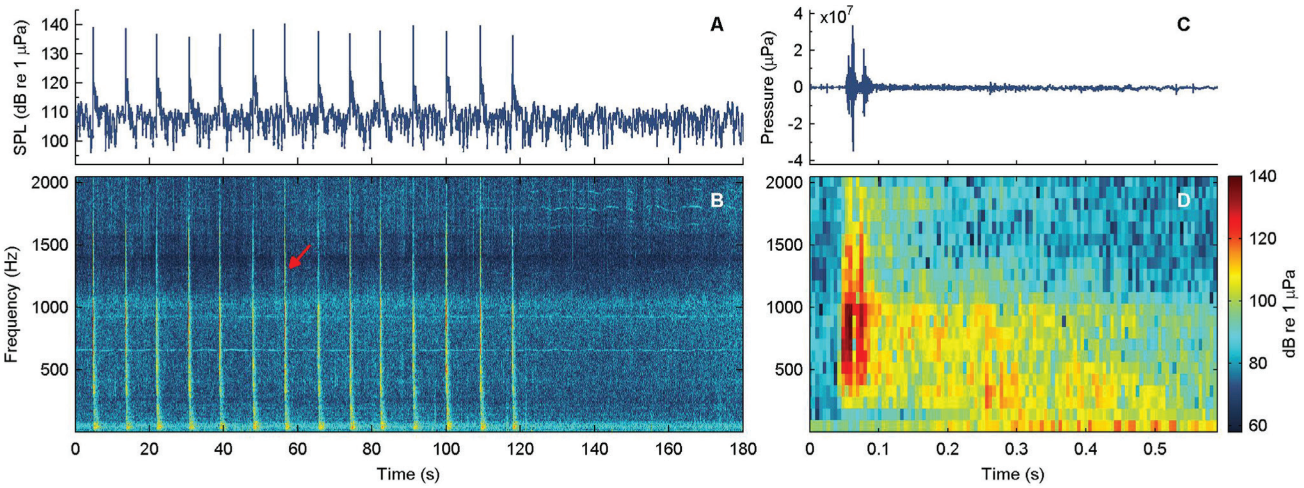


*Fig. 7:* Seismic airgun pulses recorded on 13-12-2022, 05:50 local time. A) Time series of received sound pressure level at the fixed acoustic recorder in the 10–2000 Hz frequency band. B) Spectrogram of the same pulses depicted in panel A ($N_{FFT}$ = 8192 samples, Hamming window, 50% overlap). The sound at the 120 s timestamp is the last airgun pulse of this type recorded for the day and apparently marks a pause in operations. C-D) Waveform and spectrogram of a single airgun pulse ($N_{FFT}$ = 512, Hamming, 50%); the depicted pulse is marked with a red arrow in panel B.

ject list in Merchant *et al.*, 2022), and our findings from Kefalonia substantiate that the near-shore waters of the eastern Ionian Sea are not immune to this pressure.

Most of the energy produced by airguns is generally below 200 Hz (Kyhn *et al.*, 2019); however, in agreement with other studies (Hermannsen *et al.*, 2015), our findings and Fig. 7D show that there is also substantial energy at higher frequencies that can reach a shallow-wa-

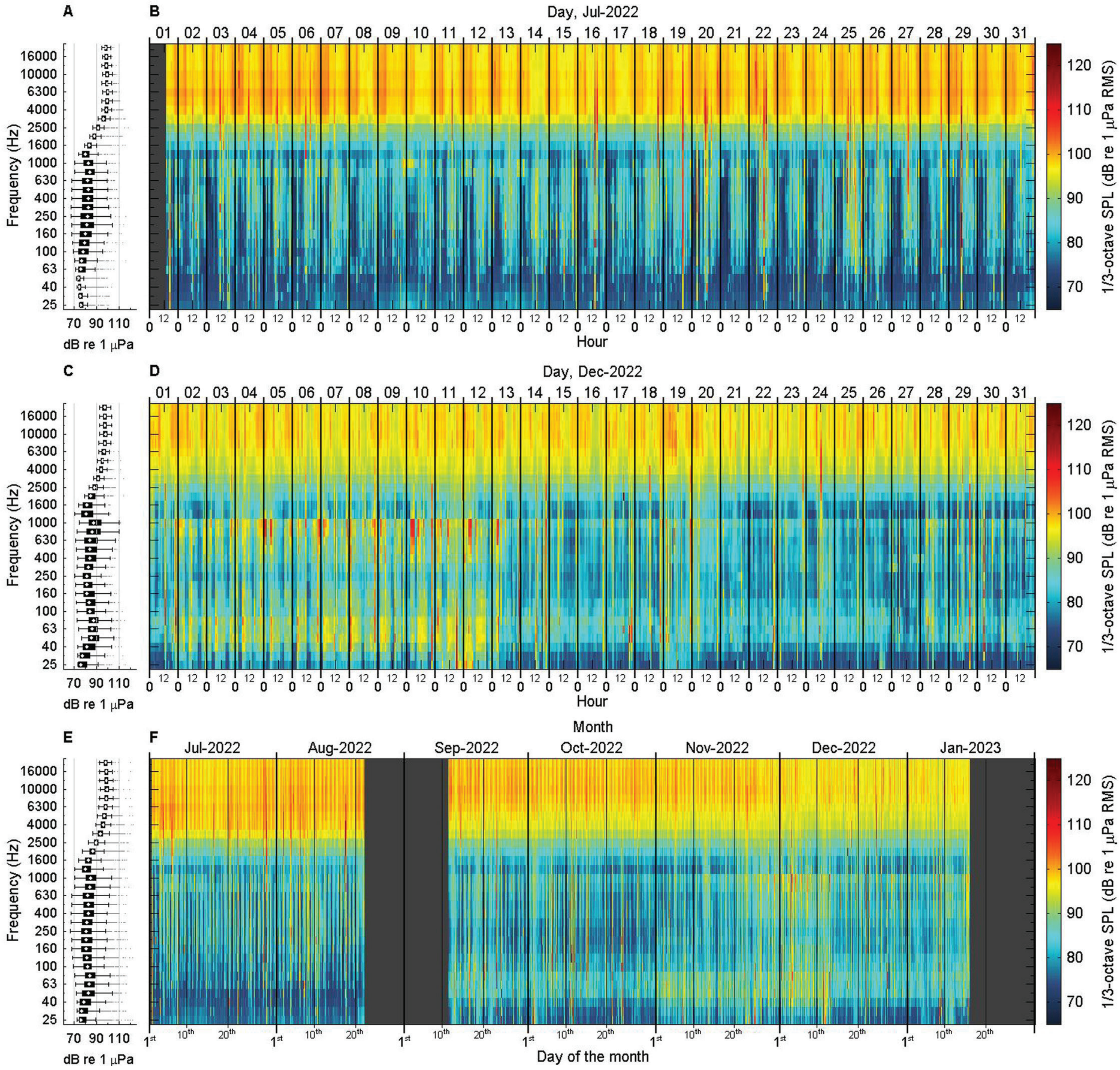


*Fig. 8:* Hourly timeline (based on 1-min subsamples) of underwater ambient noise levels across all 1/3-octave bands (0.025–20 kHz, RMS), for A-B) July 2022, C-D) December 2022, and E-F) the entire study period. For the boxplots in panels A, C and E, the median is denoted by the centre marker, while boxes and whiskers define the inter-quartile and non-outlier range, respectively.

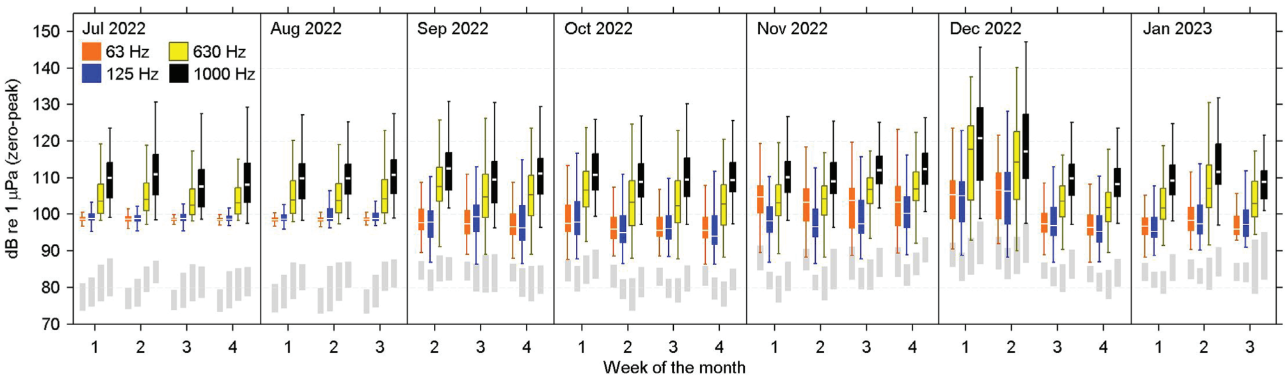


*Fig. 9:* Low- and mid-frequency weekly noise levels (zero-peak) at four 1/3-octave bands across the entire recording period (based on 1-min subsamples). The light grey boxes in the background show the inter-quartile range (25-75%) of the respective RMS levels. Note the abrupt rise of noise levels during the first two weeks of December 2022 when seismic survey operations approached West Lefkada Island (for geographical coordinates of the polygon delineated for these operations, see NAVTEX message ZCZC PA20 251700UTC NOE 22, STATHMOS KERKYRA AR.MIN 238/22).

**Table 3.** Noise level metrics at five 1/3-octave frequency bands, tabulated by month. The RMS and SEL means were calculated at the linear domain and then converted back to dB ($log_{10}$-transformed). SEL units are dB re 1 μPa$^2$/s; all other sound pressure level metrics are in units of dB re 1 μPa.

| 1/3 octave band | Month | Mean SEL | Mean RMS | Median (0-peak) | Percentile 90% (0-peak) |
|---|---|---|---|---|---|
| 63 Hz | 07/2022 | 102.7 | 84.9 | 98.6 | 100.7 |
| | 08/2022 | 110.6 | 92.8 | 98.6 | 101.0 |
| | 09/2022 | 111.8 | 94.0 | 97.2 | 106.0 |
| | 10/2022 | 109.9 | 92.1 | 96.2 | 106.8 |
| | 11/2022 | 109.9 | 92.2 | 103.8 | 111.0 |
| | 12/2022 | 111.5 | 93.8 | 99.1 | 112.8 |
| | 01/2023 | 108.6 | 90.8 | 97.4 | 106.4 |
| 125 Hz | 07/2022 | 106.5 | 88.7 | 98.7 | 103.3 |
| | 08/2022 | 115.3 | 97.6 | 98.8 | 105.8 |
| | 09/2022 | 108.4 | 90.6 | 97.6 | 106.5 |
| | 10/2022 | 109.2 | 91.5 | 95.8 | 107.7 |
| | 11/2022 | 107.5 | 89.7 | 98.2 | 108.5 |
| | 12/2022 | 108.0 | 90.2 | 98.9 | 111.7 |
| | 01/2023 | 105.7 | 87.9 | 96.5 | 106.6 |
| 630 Hz | 07/2022 | 107.2 | 89.4 | 103.4 | 112.3 |
| | 08/2022 | 112.0 | 94.2 | 103.9 | 114.4 |
| | 09/2022 | 107.8 | 90.0 | 105.4 | 115.6 |
| | 10/2022 | 105.2 | 87.4 | 104.0 | 114.1 |
| | 11/2022 | 105.9 | 88.2 | 105.1 | 114.3 |
| | 12/2022 | 110.3 | 92.5 | 105.4 | 125.0 |
| | 01/2023 | 107.7 | 90.0 | 103.7 | 116.5 |
| 1000 Hz | 07/2022 | 107.7 | 89.9 | 108.9 | 119.2 |
| | 08/2022 | 113.1 | 95.3 | 109.9 | 118.4 |
| | 09/2022 | 107.5 | 89.7 | 110.6 | 120.2 |
| | 10/2022 | 106.7 | 88.9 | 109.5 | 119.5 |
| | 11/2022 | 109.7 | 91.9 | 110.9 | 119.7 |
| | 12/2022 | 114.4 | 96.6 | 111.5 | 129.5 |
| | 01/2023 | 110.5 | 92.8 | 110.4 | 121.2 |
| 1995 Hz | 07/2022 | 112.0 | 94.2 | 116.4 | 127.2 |
| | 08/2022 | 116.1 | 98.3 | 116.4 | 128.2 |
| | 09/2022 | 106.1 | 88.3 | 118.3 | 126.8 |
| | 10/2022 | 105.2 | 87.4 | 117.9 | 126.9 |
| | 11/2022 | 107.0 | 89.2 | 117.8 | 127.4 |
| | 12/2022 | 108.8 | 91.1 | 116.4 | 126.2 |
| | 01/2023 | 106.4 | 88.6 | 116.1 | 125.1 |

ter receiver. Sounds produced by seismic surveys can propagate to long distances (Nieukirk *et al*., 2012) and, in the Ionian Sea, Affatati *et al*. (2025) recorded airgun-array pulses produced during the Upper LIthosphere Ship Subduction Exploration (ULYSSE) research survey 650 km away from the source. In our data, when compared to the 90$^{th}$ percentile of sound pressure levels during July and August at 63 Hz (100.7 and 101.0 dB, Table 3), the corresponding monthly metrics during survey operations in November and December were 10–12 dB higher (111.0 and 112.8 dB, respectively). Similar monthly differences were noted at other 1/3-octave frequency bands, especially those centred at 630 and 1000 Hz. If measured at a weekly temporal scale, zero-peak noise levels at 630–1000 Hz increased by 25 dB during the seismic surveys (Fig. 9). Notably, during the first two weeks of December 2022, received sound pressure levels at the 630 and 1000 Hz 1/3-octave bands exceeded 140 dB re 1 μPa (zero-peak). High SEL values were also computed during the months of seismic survey activity; mean SEL for November was 109.7 dB re 1 μPa$^2$/s at 1000 Hz, while mean SEL for December was 114.4 and 110.3 dB re 1 μPa$^2$/s at 1000 Hz and 630 Hz, respectively (Table 3). In December (at 1000 Hz), 30% of the month was exposed to SEL >110 dB re 1 μPa$^2$/s and 10% to SEL >117.6 dB re 1 μPa$^2$/s.

The high noise levels reported herein for North Kefalonia are in notable agreement with the only noise monitoring study previously available for this region (Fakiris *et al*., 2023). Specifically, Fakiris *et al*. (2023) conducted 13 spot measurements (3 to 6 hours each) at coastal stations of the eastern Ionian Sea, as part of marine seismic surveys conducted between 2016 and 2023. They reported that the highest noise levels were measured in the Inner Ionian, with a mean SPL (zero-peak) of 129.2 dB re 1 μPa and a maximum of 150 dB. Our mean SPL (zero-peak) metrics for December 2022 were 123.8, 129.4, and 129.7 dB re 1 μPa at 630, 794, and 1000 Hz, respectively, while our maximum corresponding measurements were 142.8, 146.3, and 147.0 dB.

These results show that offshore seismic surveys in the deep waters of the eastern Ionian Sea can dominate the soundscape of near-shore marine habitats at low and mid frequencies. The potential impacts of these increased noise levels are yet to be assessed, as our 7-month passive acoustic dataset was rather limited in temporal scope. Nonetheless, all findings suggest that it is crucial to further assess airgun sound propagation in different marine environments (e.g., deep- *vs.* shallow-water), even at long distances from the source.

Instead of seismic surveys during winter, the presence of recreational speedboats in North Kefalonia emerged as a persistent daytime anthropogenic noise source during summer. At short temporal scales, the high-amplitude speedboat signals temporarily increased all noise metrics (especially RMS values due to their sensitivity to outliers, Fig. 6C). This is also apparent at the 1995 Hz 1/3-octave band (Table 3), where the RMS noise during July and August 2022 was markedly elevated compared to all other months. In general, the near-shore summer soundscape of North Kefalonia was similar to that of other coastal Mediterranean localities (e.g., La Manna *et al*., 2016, 2021; Corrias *et al*., 2023). Recreational boat noise was more pronounced during summer and mirrored the daily leisure activities in the area, while fish choruses, the ‘kwa’ fish vocalization (Bolgan *et al*., 2019) and various pulsed fish sounds (Desiderà *et al*., 2019) constituted the main biological components of the low- to mid-frequency spectrum of the nightly soundscape. At higher frequencies (>2.5 kHz), biophony from invertebrates was more prominent during summer, decreasing in contribution towards winter (Fig. 8F). Regarding geophony, wind and rainfall events were not significant during our study period and their expected positive correlations with mid- to high-frequency TOLs (Knudsen *et al*., 1948; Ma *et al*., 2005) were weak or not statistically significant.

Overall, this 7-month passive acoustic study documented that a rich in biodiversity, but high-use near-shore area in the eastern Ionian Sea is subjected to high levels of anthropogenic noise, originating both from offshore and coastal activities. Underwater noise has been linked to numerous adverse effects on marine biota and more so on marine mammals, including stress, behavioural state changes, disorientation, masking of sounds, hearing loss or, in extreme cases, physical injury that leads to death (Hildebrand, 2005; Richardson *et al*., 1995; Southall *et al*., 2007; 2021; Harris *et al*., 2015; Duarte *et al*., 2021). Seismic surveys in particular have documented negative impacts on a variety of species, including zooplankton, invertebrates, fish, and reptiles (de Soto *et al*., 2013; Carroll *et al*., 2016; Nelms *et al*., 2016; McCauley *et al*., 2017; Paxton *et al*., 2017). High-amplitude impulsive noise sources are particularly detrimental to cetaceans (Gordon *et al*., 2004; Harris *et al*., 2015; Nowacek *et al*., 2015; Kavanagh *et al*., 2019; Southall *et al*., 2021), with some families (e.g., Ziphiidae) being apparently more susceptible than others (Ketten, 2014). While loud and/or persistent underwater noise can cause harm, defining unambiguous exposure threshold values above which marine animal populations are adversely affected has been, and still is, challenging (Merchant *et al*., 2022). Clearly, our study design and findings alone cannot identify Levels of Onset of adverse Biological Effects (LOBE), as described in MSFD guidelines (Borsani *et al*., 2023; Sigray *et al*., 2023). Nonetheless, if the alarming noise levels measured during the winter of 2022-2023 in North Kefalonia are indicative of neighbouring coastal regions, there is little confidence that Good Environmental Status is achieved in large parts of the eastern Ionian Sea.

Forecasts for moving forward with a ‘business as usual’ scenario suggest that sound energy introduced in the Mediterranean Sea by maritime shipping will continue to increase for the foreseeable decades (EMSA, 2024). Other industrial activities related to deep-sea hydrocarbon deposits and offshore renewable energy installations are also expected to increase in the eastern Ionian Sea, notwithstanding fishing, aquaculture and leisure marine activities that are historically active in these waters. Well-substantiated calls for national and international underwater noise monitoring, mitigation, and policy action have been advanced in recent years (e.g., Chou *et al*., 2021; Duarte *et al*., 2021), many of which are already supported by the EU. Particularly pertinent to this region are the establishment of long-term noise monitoring plans, the development of habitat and noise models to support environmental status assessments where underwater noise is the primary stressor, and the regulation of shipping routes and vessel speed measures that can also reduce collision risk with cetaceans (Frantzis *et al*., 2019). In addition, growing attention is being directed toward the cumulative impacts of industrial offshore activities, highlighting the need for precautionary management and robust environmental assessment in ecologically important marine regions.

A further implication of our findings concerns Marine Spatial Planning (MSP) and the operationalisation of conservation objectives in the eastern Ionian Sea. In Greece, the recently declared Ionian National Marine Park provides an immediate governance vehicle for translating ecological evidence into spatially explicit management measures (e.g., zoning, conditions of use, and monitoring priorities). In the Park’s Special Environmental Study (Katsanevakis *et al*., 2025), underwater noise is recognised as a key pressure exerted on cetaceans in particular, and a dedicated management measure is proposed for long-term monitoring of underwater noise through the installation of permanent fixed PAM stations, with the same recordings also supporting assessment of cetacean acoustic presence. In this context, the current study contributes an empirical baseline for a high-use coastal sector and identifies the dominant noise contributors (seasonal recreational traffic and episodic, high-intensity seismic airgun activity), which are directly actionable within MSP. Specifically, these results can support (i) the delineation of priority "quiet" or reduced-noise areas (or seasons) for marine mammals, (ii) targeted vessel speed and routing measures in near-shore corridors during peak recreational periods, and (iii) stricter spatiotemporal controls (and cumulative-impact screening) for impulsive industrial activities in and adjacent to sensitive habitats, in line with the monitoring and adaptive-management logic articulated for the Park and required under MSFD Descriptor 11.

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## Supplementary Data

The following supplementary information is available online for the article:
***Fig. S1:*** Spectrogram of delphinid clicks, buzzes, and whistles recorded on 16-10-2022 ($N_{FFT}$ = 1024 samples, Hamming window, 90% overlap).
***Fig. S2:*** Spectrograms of possible Mediterranean monk seal (*Monachus monachus*) vocalisations recorded on A-B) 13-08-2022 and C) 10-07-2022 ($N_{FFT}$ = 2048 samples, Hamming window, 90% overlap).
***Fig. S3:*** Beginning of heavy rain shower recorded on 22-11-2022, 23:15 local time. A) Spectrogram ($N_{FFT}$ = 2048 samples, Hamming window, 50% overlap) and B) spectral probability density plot (broadband) and corresponding RMS level.
***Fig. S4:*** A) Waveform and B) spectrogram of an earthquake (magnitude 4.0 on the Richter scale) recorded underwater on 14-08-2022, 13:47 local time. The earthquake's epicentre was the marine area 9.3 km north of Fiskardo and its focal depth was 9 ± 1 km, according to the Earthquake Catalogue maintained by the National and Kapodistrian University of Athens. Spectrogram parameters are $N_{FFT}$ = 8192 samples, Hann window, 50% overlap. Note the clipped waveform in panel A upon first reception of the signal (10 s timestamp).