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ACOUSTIC INDICATORS OF ECOSYSTEMS' AND ENERGY DYNAMICS IN MARINE ENVIRONMENTS

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ABSTRACT

The marine environment is a complex system constituted by physical, chemical, and biological variables. Human activities impact on ocean ecosystem services and environmental status, involving diverse interconnected agents in a coupled human-natural system. Observations of the acoustic field can provide clues for the understanding the processes acting within marine ecosystems. This study explores underwater soundscapes to monitor the status and dynamics of marine environments. Experiments in the Adriatic Sea revealed a day-night cycle in the underwater soundscape, linked to marine biodiversity's circadian rhythms. An indicator of ecosystem status based on this property is proposed, reflecting an ancestral emergent property of the pristine environment. Underwater ambient noise highlights also the signatures of physical processes on acoustic measurements and their potential as indicators of energy transfer within the ecosystem, such as air-sea interactions and gas exchange mechanisms. The activities focus on the underwater acoustic signals as an effective information for understanding energy transport and communication in marine environments. By analyzing underwater soundscapes across different seasons and instruments, the study aims to identify emerging properties that can serve as indicators of ecosystem status.

Keywords: *underwater soundscape, acoustic indicators, marine ecosystem status, energy dynamics.*

1. INTRODUCTION

Marine ecosystems are intricate and dynamic systems that encompass a vast array of physical, chemical, and biological components. Physical, chemical and biological components are entangled in a highly interconnected ecosystem, with changes in one component affecting others [1, 2, 3].
In addition human activities affect ocean ecosystem services with an impact on the environmental status.
Understanding the complexity of marine ecosystems is crucial for effective monitoring and management. Acoustic measurements are one valuable tool for assessing and monitoring marine ecosystems. By capturing and analyzing underwater sounds, it is possible to get valuable insights into the energy states and transfers, biological activity, and physical processes within these systems [4, 5, 6]. This information is essential for understanding ecosystem dynamics, tracking changes, and guiding conservation efforts.
The multifaceted nature of marine ecosystems underscores the importance of comprehensive approaches to study and interpret such systems.
Sound propagation in water is characterized by an efficient transmission, making it an effective medium for studying large portions of the ocean. The study of different frequencies can provide information about various aspects of the marine environment, physical and biological, from low-frequency sounds indicating large-scale processes to high-frequency sounds revealing additional details.
Underwater acoustic measurements offer a high level of detail that is invaluable for assessing the status of marine

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ecosystems. By analyzing different frequency ranges, it is possible to gain insights into various aspects of the underwater environment. High-frequency sounds are particularly useful for studying biological activities and responses, such as the presence and behavior of marine organisms, including fish, crustaceans, and marine mammals. These frequencies can reveal patterns in communication, feeding, and movement, providing indicators of biodiversity and population dynamics. On the other hand, low-frequency sounds are more informative for investigating physical processes, such as ocean currents, wind and wave dynamics, and geological activities. These frequencies can help monitor physical processes, helping in understanding how energy is transferred within the ocean and across the ocean surface, with the atmosphere, through air-sea interactions.
The ambient noise level in the ocean represents the background, including sounds from marine life, meteo and oceanographic processes coupled with human activities, or the overall energy state of the ecosystem [7].
The study seeks to identify emerging properties that can act as indicators of ecosystem dynamics by examining underwater soundscapes throughout various seasons and using different instruments, serving as a baseline for assessing changes, patterns and impacts.

2. MATERIALS AND METHODS

The study has been developed under the framework of the SEAmPhonia project, with the aim to design and test an innovative experimental approach to study the underwater acoustic field, in particular to enable the analysis of the signals that would identify indicators for the changes of the processes acting in the marine environment.
Different hydrophones have been installed across distinct experimental campaigns carried out at the Acqua Alta Oceanographic Tower (AAOT), a fixed research infrastructure managed by the National Research Council of Italy in the northern Adriatic Sea. Installed approximately 8 miles off the coast of Venice, in a basin with a depth of approximately 17 m (Global Positioning System (GPS) coordinates 45.3142467 N, 12.5082483 E), it consists of a laboratory module and accommodation, as well as sophisticated distribution systems for real-time data transmission from a large number sensors permanently installed for monitoring purposes. It also allows dedicated experimental campaigns operating as a laboratory at sea.

The Acqua Alta Oceanographic Tower also constitutes an important fixed point for the periodic acquisition of samples of the water column and the analysis of biological and chemical parameters.
Six observing campaigns were implemented during different seasons. For each campaign a set of different hydrophones was deployed in a known configuration, as showed in Figure 1.

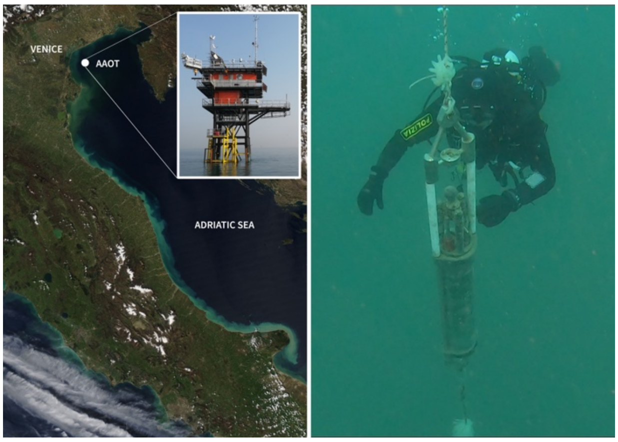

Figure 1. Identification of the position of the Acqua Alta Oceanographic Tower in the northern Adriatic Sea and details of the experimental configuration set-up. Elaborated after NASA image courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC.

The present study refers in particular to three experimental campaigns, carried out in different seasons, hereinafter referred to as EXP-01, EXP-04 and EXP-06.
Details of the experimental set-up for each campaign is provided in Table 1-3, respectively.

Table 1. Experimental set-up relative to campaign EXP-01 - period 27/12/2023 – 09/01/2024

Hydrophone	Gain (dB)	# bits	Sampling rate (kHz)
H0	7[1]	16	96
H1	7[2]	16	96
H2	7[2]	16	96

[1] Ceramic -199.0dB + Preamp 48.1dB + VGA 16.9dB + ADC -5.6dB = -139.6dB

[2] 42dB

For EXP-01, H0 denotes the Multi-Purpose Digital Hydrophone (MupHydro) from Colmar S.r.l., utilizing a National Instruments NI sbRIO-9651 circuit, installed at 15m depth at the AAOT location. H1 and H2 are both Sono Vault Acoustic Recorders manufactured by Develogic GmbH, each equipped with a standard Reson TC4037-3 hydrophone; they are installed as autonomous instruments 50 m from the AAOT, following a known geometrical configuration.

Table 2. Experimental set-up relative to campaign EXP-04 - period 16/04/2024 – 07/05/2024

Hydrophone	Gain (dB)	# bits	Sampling rate (kHz)
H0	7[1]	16	96
H1	15dB[3]	16	128

For EXP-04, H0 denotes the same instrument described in Table 1, installed at 15m depth at the tower location, while H1 is an RtSys Sylence LP-440-H-P-S underwater recorder equipped with a Colmar GP1516 hydrophone installed at 5 m depth at the tower location.

Table 3. Experimental set-up relative to campaign EXP-06 - period 05/11/2024 – 15/11/2024

Hydrophone	Gain (dB)	# bits	Sampling rate (kHz)
H0	7[1]	16	96
H1	15dB[3]	16	128
H1-Hyd01	15dB	16	156.250
H1-Hyd02	15dB	16	156.250

For EXP-06, H0 denotes the same instrument described in Table 1, installed at 15m depth at the tower location; H1 is the same instrument described in Table 2, but installed as an autonomous instrument 50 m from the AAOT at 15 m depth, alongwith the instrument H1-hyd01, installed at 13 m depth along the same mooring line. Finally a second H2-hyd02 is installed as an autonomous instrument 50 m from the AAOT at 15 m depth, following the geometrical configuration described in Figure 1. The two Hydromic384K hydrophones are integrated analog-to-digital converters able to achieve a 384 kHz data sampling rate.

[3] SH: -168, amplification factor 15dB, correction factor 1

Hourly recordings have been taken in a continuous way for the periods described in Table1-3, respectively. The recordings duration and the selected sample rates allow to explore the full spectrum of acoustic properties of the marine soundscape up to the Nyquist frequencies, while the campaigns length and distribution along different seasons enable the identification of different processes and system variability.
The signals from the each hydrophone have been analysed to estimate the relative sensitivities, the detection of the synchronization signals in terms of signal to noise, frequency profiles, and accuracy of the time lag between the signals.

3. RESULTS

The study main objective consist in the identification of possible indicators of ecosystems' and energy dynamics from acoustic measurements.
Variations in underwater soundscapes between day and night have been observed, which can be linked to biodiversity, recalling to the circadian rhythms of marine organisms, providing a natural indicator of ecosystem status and dynamics [8].

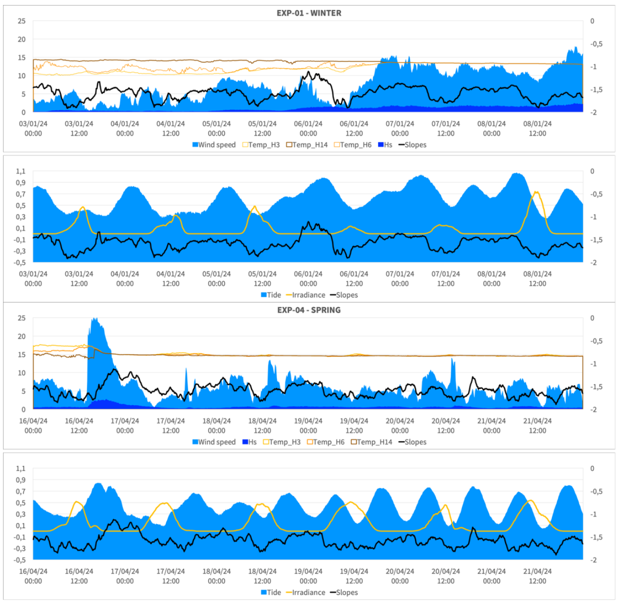

Figure 2. Identification of the day-night cycle in underwater soundscapes and definition of a possibile indicator for the status of marine

biodiversity (see text). Bold black line represents the time-series of the slopes of high-frequency acoustic spectra in combination with different ancillary measurements.

Figure 2 shows the comparison between the timeseries of acoustic power spectra slopes, calculated between 13 and 37 kHz, with a relevant set of ancillary variables describing the physical processes under play across different seasons and sea state conditions. This spectral characteristic proves the possibility to define an ecosystem status indicator based on the observed soundscape properties helping to track the ecosystem's response to environmental changes.

No correlation is observed between the acoustic spectra slopes and variables like wind speed, significant wave height and water sub-surface temperature changes, while a clear day-night cycle is recognizable, herwith represented through irradiance. The same behaviour can be recognized both in winter and in spring.

At lower frequencies, the analysis of underwater ambient noise reveales signatures of physical processes, such as air-sea interactions and gas exchange mechanisms at a different scale, offering high-resolution observations of the evolution of these interaction processes, addressing their physical interpretation.

4. DISCUSSION

The general characteristics of the marine soundscape in the frequency domain has been illustrated by [7], showing the superimposition of the power of various acoustic sources, ranging from human activities (such as drilling, transport, fishing, and wind farming) to natural events and physical conditions (like earthquakes, wind, and sea states), as well as sounds produced by living organisms. Human-activities predominantly affect the low-frequency bands (below 5kHz), which corresponds also to the area mostly covered by current observations [9, 10, 11]. Observations focusing on higher frequencies are rare and are primarily aimed at species identification [12].

This key findings reveal that underwater soundscapes exhibit distinct 24-hour oscillations in the slopes of high-frequency spectra, with consistent differences between day and night values. These oscillations are not synchronized with physical processes such as irradiance, water temperature, wind, wave height, or tides, suggesting that biological sources primarily drive them. This indicates that marine organisms significantly influence the underwater acoustic environment. The detection of this contribution through acoustic measurements, which is representative of the circadian rithms of marine biodiversity, provides a novel approach to monitoring marine ecosystems. By understanding the acoustic signatures of biological activity, it is possible to gain insights into the temporal dynamics of marine life and their interactions with the environment. Nonetheless, the proposed method offers a non-invasive and efficient way to assess ecosystem health and track changes over time, contributing to more effective conservation and management strategies, also in view of the increasing interest for underwater noise in monitoring activities also supported by the European Marine Strategy Framework Directive (EU MSFD, https://research-and-innovation.ec.europa.eu/research-area/environment/oceans-and-seas/eu-marine-strategy-framework-directive_en).

The study proposes that the amplitude of the 24-hour oscillations in the slopes of high-frequency spectra reflects an ancestral emergent property of the pristine marine environment. These properties are rooted in the evolutionary history of marine organisms, which have developed endogenous rhythms to anticipate and adapt to environmental extremes. The presence of these rhythms in modern marine ecosystems highlights the continuity of biological processes over geological timescales. Understanding these emergent properties is significant as they provide a baseline for assessing the impact of human activities and environmental changes on marine ecosystems, accounting for its complexity. By identifying the system's inherent properties effective conservation strategies can be assessed and the integrity and resilience of marine environments can be preserved, ensuring the sustainability of ecosystem services and biodiversity.

Underwater acoustic signals serve as efficient information carriers for long-range energy transport and communication within marine ecosystems. Marine mammals, such as whales and dolphins, use sound for communication and navigation over vast distances, reflecting their interaction with the environment. Similarly, fish and invertebrates produce sounds during spawning and feeding, which can be monitored to understand their life cycles and population dynamics. Acoustic measurements capture these signals, providing valuable data on the spatial and temporal distribution of marine organisms.

Additionally, sounds generated by physical processes, such as waves and currents, indicate energy transfers within the ocean. By analyzing these acoustic signals, it is possible to gain insights into the functioning of marine ecosystems, including the movement of energy and matter. This approach offers a powerful tool for studying ecosystem dynamics, enhancing our ability to model, hence predict, as well as to monitor marine environments effectively.

Figure 3 shows how the exploration of the acoustic properties of the marine soundscape can help definiting an indicator of energy dynamics within the marine ecosystem.

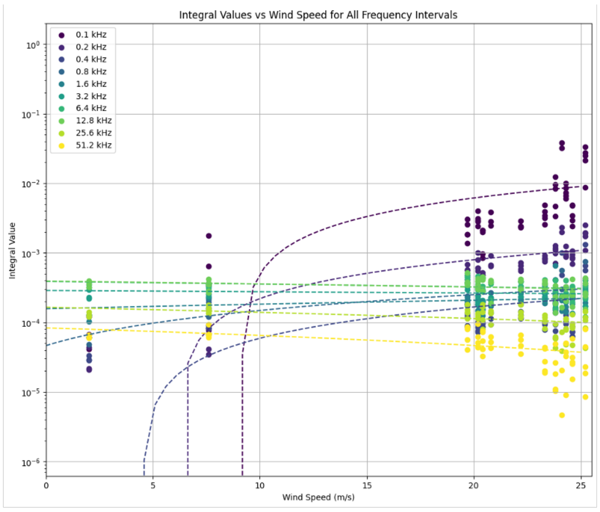

Figure 3. Definition of a possibile indicator of energy dynamics based on acoustic properties, namely the integral values over different frequency ranges of acoustic measurements. Dashed lines represent the linear fit of the scatter plot data versus different wind speed values wuth the y-axis in log10 scale.

5. CONCLUSION

The study revealed that underwater soundscapes exhibit clear 24-hour oscillations in the slopes of high-frequency spectra, with consistent differences between day and night values. These oscillations are not synchronized with physical processes such as irradiance, water temperature, wind, wave height, or tides, suggesting that biological sources primarily drive them. The study explores the potential acoustic observations through the analysis of high-frequency spectra and proposes the amplitude of the oscillations of the slopes of those spectra as a novel indicator of marine ecosystem status. These findings confirm that the circadian rhythms of marine organisms significantly influence the underwater acoustic environment [8, 13]. At the same time, the study shows the potential for information retrieval, at lower frequencies to explore and understand oceanographic processes occurring at different scales.
Future research should focus on expanding observations to different marine sites to characterize ecosystems based on emergent acoustic properties. Additionally, employing various instrumental setups for underwater acoustic observations will enhance the robustness of the findings. Long-term continuous datasets are essential to delve deeper into the acoustic signals contributing to provide a more comprehensive understanding of marine ecosystem functioning. This approach could open new avenues for marine chronobiology and ecosystem monitoring, as well as an expansion towards the comprehension of the three-dimensional acoustic field of the ocean.

6. ACKNOWLEDGMENTS

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