TEMPORAL AND ENVIRONMENTAL DRIVERS OF SOUNDSCAPE COMPOSITION IN GALWAY BAY: AN ECOACOUSTIC ANALYSIS OF PASSIVE ACOUSTIC MONITORING DATA

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Abstract

The underwater soundscape off the west coast of Ireland is a dynamic acoustic environment shaped by a complex interplay of natural sounds and anthropogenic noises. This region, exposed directly to the north Atlantic, experiences pronounced seasonal and inter-annual fluctuations driven by meteorological forces, oceanographic processes, and biological rhythms. This study investigated the impact of environmental conditions on the underwater soundscape of Galway Bay using passive acoustic monitoring data collected from SmartBay, an integrated marine observatory located off the coast of Spiddal, Co. Galway. The platform collects simultaneous hydrophone and environmental data, facilitating direct comparison between acoustic and environmental records. Data were gathered at one-minute intervals over a week for each season from February 2023 to December 2024, with supplementary recordings obtained for notable weather events. Acoustic indices (acoustic complexity index, normalized difference soundscape index, acoustic diversity index, and acoustic evenness index) were used to characterise the underwater soundscape, and were compared against environmental factors including tidal state, current speed, and calendar season.

The soundscape was dominated by geophony year-round, with this dominance being noticeably more intense during the winter months. Sea temperature and wave height emerged as the proximal (environmental) drivers across seasons, with tidal phase having a statistically significant influence on key indices (Kruskal-Wallis, $p < 0.001$). Ebb tide was consistently associated with elevated acoustic complexity, while diel patterns in biological activity indices were most pronounced during calmer seasonal periods.

Keywords: *passive acoustic monitoring, underwater acoustics, soundscape characterisation, eco-acoustic analysis*

1. Introduction

Galway Bay, situated on Ireland's west coast, is a dynamically complex coastal system that is subject to strong tidal forcing, fluctuating Atlantic weather, and distinct seasonal cycles. The effective acoustic monitoring of coastal marine habitats requires an understanding of the factors that influence the underwater soundscape [1], making Galway Bay well suited to studying how various environmental factors shape the underwater soundscape.

Ireland's west coast is the subject of sustained offshore renewable energy development interest [2]. Both the construction and operation of offshore wind installations introduce noise into the marine environment at frequencies overlapping those used by resident fauna [3]. Regulatory assessment of that noise depends on a characterised pre-development baseline. Where the natural background is itself strongly non-stationary, a single static reference level is insufficient, and the magnitude and structure of that natural variability must be quantified before anthropogenic contributions can be attributed.

This study addresses that need using a passive acoustic monitoring campaign conducted at the SmartBay observatory in Galway Bay between February 2023 and December 2024, supplemented by targeted recordings during Atlantic storm episodes. A suite of acoustic indices is used to characterise the soundscape and

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to identify the dominant environmental drivers of its variability in the area (sea state, tidal cycle, seasonal variation, and water temperature) alongside the acoustic signatures of episodic storm events. In doing so, the work provides a baseline characterisation of the Galway Bay soundscape with implications for long-term biodiversity monitoring and marine spatial planning along the Irish Atlantic coast.

2. Materials and Methods

2.1. Study Site

Galway Bay is a large marine embayment located on the west coast of Ireland, separating Co. Galway to the north and Co. Clare to the south. The bay is approximately 50 km in length and 10 km in width with depths ranging from less than 30 m within the sheltered inner portion of the bay up to 70 m near the mouth [4]. At the mouth of the bay, the Aran Islands - Inis Mór, Inis Meáin, and Inis Oírr - act as natural barriers shielding the inner bay from the open Atlantic. The tidal regime is semi-diurnal, with a tidal range of approximately 5 m at springs decreasing to approximately 2 m. This strong tidal forcing, combined with the bay's broad, semi-enclosed bathymetry, drives energetic local current and wave conditions. This can be seen particularly during the Atlantic storm season (October - March), when the bay is directly exposed to North Atlantic swell entering through the North and South Sounds on either side of the Aran Islands [4].

2.2. Data Collection

Passive acoustic data were collected using an icListen HF Smart hydrophone (Ocean Sonics Ltd., Canada), a broadband digital hydrophone with a manufacturer-specified frequency range of 10 Hz to 200 kHz. The hydrophone forms part of the permanent instrument suite of the SmartBay observatory, a cabled subsea platform operated by the Marine Institute (Foras na Mara) [5] and connected to shore via fibre optic cable. It is mounted on a separate lander approximately 30 m from the observatory's cable end equipment node, at a water depth of approximately 25 m, 1.5 km off the coast of Spiddal, Co. Galway. (53°13.640'N, 9°15.979'W)

Table 1: Summary of the five deployment periods.

Deployment	Period	n
Spring	24–30 Mar 2023	5,560
Summer	15–22 Jul 2024	9,502
Autumn	24 Sep–1 Oct 2024	10,075
Winter	14–22 Dec 2024	10,078
Storms	4 events (2020–2025)	5,204

Acoustic data were recorded continuously as raw `.wav` audio files at one minute resolution and processed offline (see section Section 2.4). Recordings were made with a sampling rate of 64 kHz, identical across all five deployments, and were calibrated using the manufacturer-supplied end to end sensitivity (approximately $-171\,\mathrm{dB\ re\ 1\,V\,\mu Pa^{-1}}$; icListen HF S/N 1622). Recordings were obtained for one week in each of the four calendar seasons between February 2023 and December 2024, supplemented by additional recordings during periods of notable storm activity (Table 1). Concurrent environmental data including tidal phase, wave height, current speed, water temperature, and water level - were obtained from co-located sensors on the SmartBay observatory, and the data portals from both the Marine Institute and Met Éireann.

2.3. The Marine Institute - SmartBay

The acoustic and environmental data used in this study were collected at the SmartBay observatory, a cabled subsea sensor platform operated by the Marine Institute. Installed in 2015, the observatory hosts a permanently deployed instrument suite including a conductivity-temperature-depth (CTD) sensor, a dissolved oxygen sensor, a turbidity/fluorometer, an acoustic Doppler current profiler (ADCP), a HD video camera, and the icListen hydrophone used here [6]. As part of the European Multidisciplinary Seafloor and water column Observatory (EMSO) network [7], the site contributes to a wider system of regional observatories across Europe. This co-location of synchronised acoustic and environmental sensors at a single site underpins the direct comparison between soundscape composition and environmental drivers undertaken in this study.

2.4. Acoustic Signal Analysis Metrics

Acoustic Indices provide a means of characterising the acoustic environment without requiring manual identification of individual sound sources, making them well suited to large volume, continuous PAM datasets such as those collected at the SmartBay observatory [8], [9]. Four ecoacoustic indices were calculated for each one minute recording: The Acoustic Complexity Index (ACI) [10], the Normalised Difference Soundscape Index (NDSI) [11], the Acoustic Diversity Index (ADI), and the Acoustic Evenness Index (AEI) [12]. Each of the indices were computed directly from each one minute `.wav` recording in MATLAB (R2025b). A single short time Fourier transform (Hamming window of 2048 samples, 1024-sample overlap, 2048-point FFT) was computed per recording, and the resulting time-frequency power matrix was used as the common basis for all four indices.

The ACI quantifies the variability of sound intensity over time, exploiting the observation that biologically produced sounds tend to show greater intrinsic intensity variability than many sources of continuous anthropogenic or physical noise. It was computed as the sum of absolute frame to frame difference in spectrogram intensity across the full time-frequency matrix, normalised by the total spectrogram energy.

The NDSI estimates the relative contribution of biological (biophony) and human-generated (anthrophony) sound, computed as:

$$NDSI = \frac{\beta - \alpha}{\beta + \alpha} \quad (1)$$

where β and α are the summed, band-normalised spectrogram energy within defined biophony and anthrophony frequency bands, respectively. NDSI ranges from -1 (soundscape dominated by anthrophony or geophony) to $+1$ (soundscape dominated by biophony). The default terrestrial, frequency bands proposed by Kasten et al.[11] (1 kHz to 2 kHz: anthrophony; 2 kHz to 11 kHz: biophony) were adapted to < 50 Hz (geophony), 50 Hz to 1000 Hz (anthrophony), and 1 kHz to 20 kHz (biophony) to better reflect the dominant frequency ranges of the underwater anthropogenic and biological sound sources at the study site. Because the low-frequency band captures wind and wave generated geophony as well as vessel noise, a negative NDSI at this site should be read as physical plus anthropogenic dominance rather than evidence of vessel activity specifically.

The ADI and AEI both characterise the distribution of acoustic energy across frequency. The spectrogram frequency axis was divided into ten equal width bands spanning from 0 Hz to the Nyquist frequency, and the proportion of total band energy falling in each band was calculated directly from the spectrogram, rather than the proportion of samples exceeding a fixed amplitude threshold as in some published ADI/AEI implementations [12]. The ADI applies the Shannon diversity index to these proportions, analogous to a measure of species diversity across frequency bands. The AEI is derived here as $1 - ADI/\ln(10)$, clamped at zero, and is therefore a normalised measure of spectral energy concentration, ranging from 0 (energy distributed evenly across all bands) to 1 (energy concentrated within a single band); note that this is the inverse sense of the Gini-based AEI used in threshold implementation, and values are not directly comparable to those.

Because of the ADI and AEI band edges, and the upper limit of the NDSI biophony band, are both defined relative to the Nyquist frequency, all recordings were processed at a common analysis bandwidth with an upper limit of 32 kHz (the Nyquist frequency for the 64 kHz sample rate) so that index values remain comparable across deployments. Because the sample rate was identical across all deployments, the ADI and AEI band edges and the NDSI biophony ceiling were the same in every deployment, and the seasonal differences reported in Section 3.2 are therefore not attributable to differences in analysis bandwidth.

2.5. Sound Source Classification

Each one minute recording was assigned to a dominant source class between three energy fractions computed from normalised power spectral density: a geophony fraction (below 50 Hz), an anthrophony fraction (50 Hz to 1000 Hz), and a biophony fraction (1 kHz to the 20 kHz biophony ceiling). The three fractions were normalised to sum to unity, and each recording was labelled biophony, anthrophony, or geophony dominant according to whichever fraction exceeded a threshold of 0.35 and recordings in which multiple fractions reached the designated threshold were labelled mixed. The same rule was applied to all deployments.

2.6. Environmental Parameters

Environmental conditions concurrent with each acoustic recording were obtained from a combination of co-located sensors on the SmartBay observatory and from the Marine Institute's data portal. Water temperature was obtained from the observatory's CTD sensor, and current speed and direction from its ADCP. Water level and significant wave height were obtained from the Galway Bay wave buoy, located 1.59 km from the SmartBay site. Tide gauge records from the Irish National Tide Gauge Network were interpolated from their native resolution to one-minute resolution using a cubic spline, and sentinel artefact values were removed prior to analysis. Table 2 summarises the environmental parameters considered, their source, and native temporal resolution.

Table 2: Environmental parameters and data sources.

Parameter	Unit	Source	Resolution (min)
Wave Height	m	Wave Buoy	30
Current Speed	m/s	Wave Buoy	30
Current Direction	°	Wave Buoy	30
Water Temp	°C	Wave Buoy	30
Water Level	m	Tide Gauge	5
Tidal Range	m	Tide Gauge	5

Tidal phase was classified into four discrete phases (high water, ebb, low water, flood) based on the measured water level, with each one minute recording assigned to the tidal phase prevailing at the time of collection. Calendar season was assigned to the meteorological definition (Winter: Dec - Feb; Spring: Mar - May; Summer: Jun - Aug; Autumn: Sept - Nov), consistent with the four week long deployment periods analysed in this study.

2.7. Data Analysis

All statistical analyses were performed in R [version 4.5.1]. Acoustic index values (ACI, NDSI, ADI, AEI) and continuous environmental variables were tested for normality using the Shapiro-Wilk test; in all cases the assumption of normality was violated, and non-parametric tests were used throughout.

The effect of categorical environmental factors (tidal phase, diel phase, deployment period) on each acoustic index was assessed using the Kruskal-Wallis rank sum test, with pairwise post-hoc comparisons performed using Dunn's test implemented in base R with Bonferroni correction and cross validated against an independent implementation. Epsilon squared (ϵ^2) was used as a non parametric effect size measure, and the diel analysis was additionally stratified by deployment period. A significance threshold of $\alpha = 0.05$ was applied throughout unless otherwise stated.

The four storm deployments were retained as a separate level of deployment factor rather than being folded into their corresponding calendar seasons. This preserves the contrast of interest - storm conditions against routine seasonal conditions - and avoids inflating within season variance in the seasons from which the storm records were drawn. To test whether storm periods carry an acoustic signature beyond that attributable to elevated wave height and depressed sea temperature, a baseline linear model of the form (acoustic index $\sim$ wave height + sea temperature) was fitted to the four non-storm deployments and used to generate expected index values for the storm deployment. Residuals (observed − predicted) were compared between storm and baseline periods using the Wilcoxon rank sum test.

Relationships between each acoustic index and continuous environmental variables were assessed using Spearman's rank correlation coefficient (ρ). The relative contribution of each environmental variable was assessed by ranking the magnitude of its Spearman correlation against each acoustic index; wave height and sea temperature consistently returned the largest coefficients across acoustic indices and were identified as the dominant proximal environmental drivers, with current speed a secondary driver of ADI and AEI specifically.

3. Results & Discussion

3.1. Soundscape Classification and Composition

The compiled dataset comprised 40,446 one minute acoustic recordings across five deployment periods, of which 27 recordings were excluded due to file corruption, leaving 40,419 recordings for classification. Classification indicated that the recordings were overwhelmingly geophony-dominated (99.98%, n=40,410), with anthrophony-dominant classifications rare (0.02%, n=9).This near uniform classification suggests that physical noise sources - wind and wave generated - rather than vessel or anthropogenic activity dominate the SmartBay soundscape at this site, consistent with the strong environmental coupling reported in Section 3.3. It is also a partial consequence of the band definitions adopted in Section 2.4: the low-frequency band that anchors the classification contains both geophony and vessel noise, so the method is conservative with respect to detecting anthropogenic contributions.

The Spring deployment was the exception. Two distinct quantities are relevant here and should not be conflated: the dominant source classification reported above is a per-minute, dominant energy proportion label, whereas anthropogenic contribution can also be expressed as a mean energy proportion - the average share of band limited acoustic energy falling in the anthrophony band (Section 2.4) across all recordings in a deployment. By the first measure, only nine minutes across the entire dataset were anthrophony dominant. By the second, the Spring deployment carried a mean anthropogenic energy proportion of 27%, markedly higher than any other deployment. The elevated Spring values are considered further in Section 3.5.

3.2. Seasonal, Diel, and Tidal Variation in Acoustic Indices

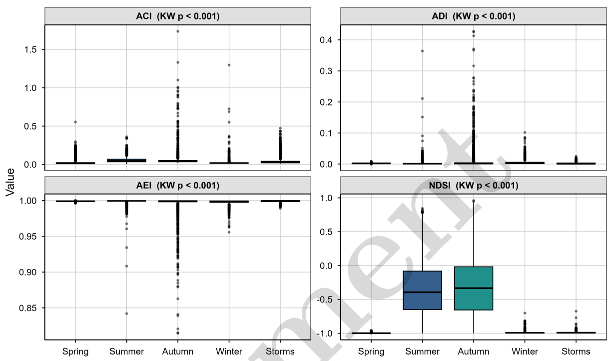

Figure 1: Distribution of each acoustic index by deployment period. Boxes show the interquartile range, the central line the median, and whiskers; outliers omitted for clarity.

Acoustic indices differed significantly across all three temporal groupings tested (Kruskal-Wallis, $p < 0.001$ in nearly all cases). The effect of deployment period was by far the largest: mean NDSI was markedly less negative in Summer (-0.34) and Autumn (-0.30) than spring, winter, and storms (all ≈ -0.99; $\chi^2 = 29665.7$, $df = 4$, $p < 0.001$), indicating a substantially greater relative contribution of biological sound during the warmer months. The distributions are shown in Fig. 1, and the corresponding pairwise comparisons in Fig. 2: post hoc Dunn's tests confirmed Summer and Autumn differed significantly from all other seasons for NDSI and ACI ($p < 0.001$, Bonferroni corrected).

Diel phase showed a smaller but still significant effect, with median NDSI during the day (-0.79) notably less negative than at dawn, dusk, or night (≈ -0.98), suggesting elevated daytime biological activity superimposed on the dominant seasonal signal. To test whether this diel effect varies by season, Kruskal-Wallis tests were re-run for each acoustic index within each seasonal deployment. The diel effect was strongest during the calmer Summer and Autumn deployments (mean $\epsilon^2 = 0.039$ and 0.031, respectively , averaged across all four acoustic indices) and weakest during Winter and Storm deployments ($\epsilon^2 = 0.005$ and 0.007, respectively), consistent with energetic sea states masking the biological component of the soundscape.

Tidal phase effects were smaller still: ebb tide was associated with the least negative NDSI and highest ACI among the four phases, while tidal range itself had no significant effect on the NDSI ($\chi^2 = 5.9$, $p = 0.117$), indicating that the timing of the tidal cycle matters more than its amplitude for this soundscape.

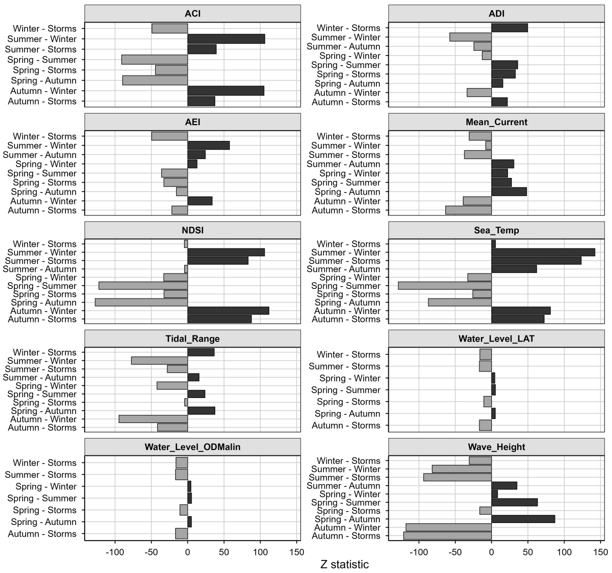

Figure 2: Dunn's post-hoc pairwise comparisons between deployment periods for each acoustic index, with bonferroni-corrected p-values

3.3. Environmental Drivers of Acoustic Variability

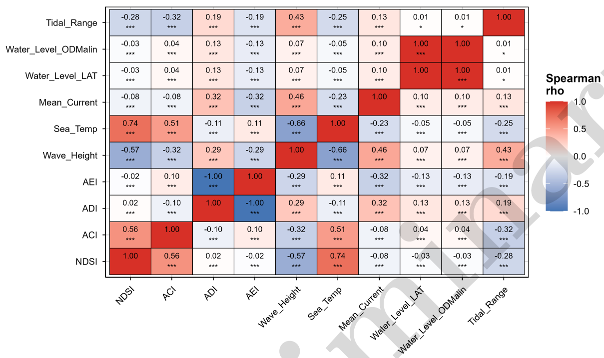

Figure 3: Spearman rank correlation coefficients between acoustic indices and environmental variables.

Spearman correlations (Fig. 3) identified sea temperature and wave height as the dominant environmental correlates of the acoustic indices, exceeding the influence of tide or time of day reported above. NDSI was positively correlated with sea temperature ($\rho = 0.74, p < 0.001$) and negatively correlated with wave height ($\rho = -0.57, p < 0.001$), indicating that calmer, warmer conditions shift the soundscape towards biophony dominance, while energetic sea states mask biological contributions beneath wind and wave generated geophony. Because wave height and sea temperature are themselves strongly correlated ($\rho = -0.66$), reflecting shared seasonal covariation, this environmental relationship, rather than tide or diel cycle, most likely underpins much of the seasonal pattern described in Section 3.2. Current speed showed weaker, though still significant, correlations with the acoustic indices ($\rho = 0.315$ with ADI, -0.315 with AEI, -0.084 with NDSI, and -0.083 with ACI; all $p < 0.001$), placing it behind sea temperature and wave height as a driver of NDSI and ACI, though comparable in magnitude to wave height for ADI and AEI specifically.

3.4. Storm Signature Relative to Baseline Weather Conditions

The baseline regression model was fitted using only the four non-storm periods ($n = 32,068$) and used to generate expected index values for the storm period ($n = 4,081$). Residuals differed significantly between storm and baseline periods for all four indices (Wilcoxon rank-sum, $p < 0.001$ in all cases: Fig. 4): storm NDSI was substantially more negative than the baseline model predicted (median residual -0.101 versus -0.044 at baseline), storm ACI was elevated beyond prediction (median residual $+0.005$ versus -0.005), and ADI and AEI showed corresponding shifts (ADI: -0.004 versus -0.002: AEI $+0.002$ versus $+0.001$). Storm events therefore carry an acoustic signature beyond that captured by wave height and sea temperature alone, indicating that the storm driven soundscape shift are not fully explained by the same weather variables that account for routine seasonal variability. The residual magnitudes for ACI, ADI, and AEI are small in absolute terms, and their practical significance should be interpreted alongside the large sample size.

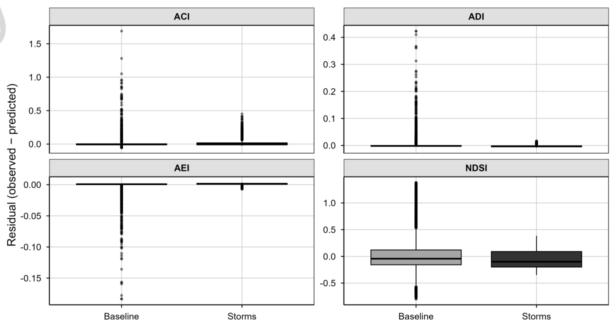

Figure 4: Distribution of baseline model residuals (observed − predicted) for storm and non-storm periods, for each acoustic index.

3.5. Limitations

This analysis is based on single hydrophone recordings and cannot resolve spatial variation in the soundscape across the bay. The Storms dataset comprised four discrete $\approx 24h$ deployments rather than a continuous record, limiting direct comparison of within storm temporal dynamics to the other seasonal datasets. Correlational relationships between acoustic indices and environmental variables, while statistically robust given the sample size, do not establish causal mechanisms. Salinity and wind speed were recorded but excluded from the formal statistical analysis, as both were unavailable for a substantial portion of the acquisition periods.

The elevated anthropogenic contribution recorded during the spring deployment was not reproduced in any other period. Whether this reflects genuine vessel activity local to that window or an artefact of the classification thresholds applied to that deployment could not be resolved with the present dataset, and warrants targeted verification against vessel traffic records before the Spring values are interpreted ecologically.

4. Conclusions

This study establishes a pre-development ecoacoustic baseline for Galway Bay, characterising the underwater soundscape prior to offshore wind installation. Acoustic indices were shown to vary primarily with season and its underlying environmental drivers - sea temperature and wave height - rather than with tidal or diel cycles, and the soundscape was found to be overwhelmingly geophony dominated across all deployments. This non-stationary natural background has direct implications for future turbine noise monitoring; rather than assuming a fixed acoustic baseline against which anthropogenic contributions can be simply detected, monitoring frameworks at this site will need to account for substantial weather and season driven variability. Future work will extend this baseline through controlled tank based exposure trials (SHELLWISE), examining how representative levels of turbine associated noise affect particle motion sensitive shellfish species identified as ecologically and commercially important to Galway Bay.

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