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Assessing the influence of offshore wind turbine noise on seasonal fish chorusing

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Abstract

Offshore wind farms have recently emerged as a renewable energy solution. However, the long-term impacts of wind turbine noise on fish chorusing phenology are largely unknown. We deployed a hydrophone 10 m from a foremost turbine in Taiwan situated at the Miaoli offshore wind farm (Taiwan Strait) for two years to investigate sound levels and assess the potential influence of turbine noise on seasonal fish chorusing patterns during 2017 and 2018. Wind turbine noise (measured in the 20–250 Hz frequency band) was significantly higher in autumn and winter (mean SPL: 138–143 dB re 1 μPa) and was highly correlated with wind speed ($r = 0.76$, $P < 0.001$). During both years, fish chorusing exhibited a consistent trend, that is, beginning in spring, peaking in summer, decreasing in autumn, and absent in winter. Our results show the noise from a single turbine during the two-year monitoring period did not influence the seasonal fish chorusing ($r = -0.17$, $P \approx 1$). Since the offshore wind farm installations are growing in magnitude and capacity across the Taiwan Strait, this study for the first time provides baseline operational sound levels and an understanding of the fish seasonal vocalization behavior at the foremost turbine of the first wind farm in Taiwan. The results presented here provide useful insights for policymakers and constitute a reference starting point for advancing knowledge on the possible effects of wind turbines on fish chorusing in the studied area.

Keywords: marine environment monitoring; marine soundscape; behavioral assessment; offshore windfarm

Introduction

Offshore wind farms have recently emerged as reliable renewable energy sources, which can significantly contribute to decreasing greenhouse gas emissions and consequently mitigate the influence of climate change (Prior and McMath 2008, Doney et al. 2012). In 2016, the Taiwan government presented an ambitious energy transition plan aimed at increasing renewable energy national use from 5% in 2016 to 20% in 2025 (Gao et al. 2021, Lau and Tsai 2022) and generate 5.7 GW by 2025 (Kung and McCarl 2020, Liao et al. 2021, Yang et al. 2022). Currently, wind farms off the Miaoli coast can produce 500 MW with 69 wind turbines in operation, and to achieve the power target set by the government, the offshore wind farm infrastructures are expected to substantially increase within the Taiwan Strait (Yang et al. 2022).

The installation of wind farm structures at sea produces varying levels of underwater sound according to its different lifetime phases: (1) the prospecting phase and site surveys; (2) the construction phase; (3) the operational and maintenance phase during power production; and (4) the decommissioning or dismantling phase (Mooney et al. 2020). The noise generated during all four phases can potentially influence marine life (Hawkins and Popper 2017, Jager et al. 2021, Popper et al. 2022).

During the operational phase of the offshore wind farm, the rotation of the turbine blades, gearbox, and other moving accessories produces vibrations and mechanical noise, which are transmitted to the water through the foundation and support structures (Betke et al. 2004, Cheesman 2016). The operational sound is continuously emitted, usually characterized by broadband and tonal frequency components with harmonics mostly falling below 1 kHz (Uffe 2002, Pangerc et al. 2016, Mooney et al. 2020). Depending on the wind speed, the tonal harmonics of the sound shift in frequency with intensities reaching 125 dB re 1 μPa^2/Hz (Sigray and Andersson 2011, Tougaard et al. 2020). Studies have shown that the sound from an offshore wind farm can be detected over a few kilometers, especially the tonal component. For example, noise from a 6 MW wind turbine can be detectable up to a distance of 20 km (Marmo 2013). There is a positive correlation between the generated underwater noise and the size of the turbine (Norro and Degraer 2016), which is a cause of concern because the size of turbines has increased tenfold in the past 30 years and is anticipated to further increase in the future (van der Molen et al. 2014). An increased background noise for an extended duration of time might influence marine organisms, especially those that heavily depend on sound for their survival (Bergström et al. 2014).

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Fish extensively utilize sound to orientate in their environment and for communication purposes (Weilgart 2018). In particular, soniferous fish species vocalize in large numbers to produce chorusing (Farina and Gage 2017), which is essential for maintaining social cohesion, foraging, territorial defense, and spawning (Mann and Lobel 1997, Buscaino et al. 2015, Van Oosterom et al. 2016, Farina and Gage 2017). Fish chorusing can exhibit seasonal phenology governed by several factors such as temperature, lunar cycle, timing, and length of the dawn and dusk periods (Pieretti et al. 2015, Ruppé et al. 2015, Buscaino et al. 2016). Understanding the normal variation of a species' chorusing pattern at a specific location has been recently suggested as a new way to determine species' well-being (Pieretti and Danovaro 2020, Siddagangaiah et al. 2021). Deviation from the usual chorusing pattern might be the result of an introduced stressor for the species, such as intense noise from pile driving and severe anomalous weather conditions such as storms and flooding (Siddagangaiah et al. 2021).

Noise produced during operational phases of wind turbines has been found to not be hazardous to marine species because its intensity is not high enough to cause physical injury (Koschinski et al. 2003, Mooney et al. 2020). Fish chorusing behavior analyzed during the summer of 2017 and 2018 did not reveal that any disturbances were caused by operational noise (Siddagangaiah et al. 2022a). Similarly, tagged cods did not exhibit any behavioral change due to increased operational noise levels during higher wind speeds (Bergström et al. 2014). However, the operational noise over an extended duration may cause behavioral influences on the species that live in close range of the turbines (Thomsen et al. 2006), such as altering their vocalization behavior by increasing or decreasing the intensity of vocalization (Siddagangaiah et al. 2022a). Further, fish utilize vocalizations for communication to maintain social cohesion and vital functioning, such as attracting mates and territorial defense (Van Oosterom et al. 2016). Noise has the potential to influence acoustic communication by masking vocalizations (Clark et al. 2009, Radford et al. 2014, De Jong et al. 2018, Putland et al. 2018).

The possible influence of the operational noise on the fish vocalization remains largely unclear, mainly for two reasons: (1) distribution and vocal behavioral patterns of the species have not been documented before the wind farm installation, and (2) long-term monitoring programs required to compare the seasonal variations of the operational noise and the behavioral patterns of fish are lacking (Thomsen et al. 2006, Siddagangaiah et al. 2022a). Because of these shortcomings, there are few published studies on the effects of operational noise on fish vocalization behavior (Mooney et al. 2020, Svendsen et al. 2022).

In this study, we passively monitored and analyzed fish sounds and the operational noise of a wind farm recorded during different seasons in 2017 and 2018. The wind farm site off the Taiwan Strait fish predominantly produce two types of choruses, which start at dusk in early spring, extend till dawn in summer, diminish to dusk in late autumn, and stop during winter (Siddagangaiah et al. 2021). The knowledge of the chorusing species and their usual phenology at the site provides the opportunity to assess the eventual influence of the operational noise of wind farm turbines on their seasonal chorusing patterns. In particular, we monitored wind turbine operational noise levels from one of the foremost demonstrational wind turbines (4 MW of capacity) and compared them with the wind speed along the various seasons. Furthermore, we studied seasonal fish chorusing patterns during the monitoring periods and verified whether the operational noise influenced the vocalizing behavior of fish.

Materials and methods

Study site

Acoustic samples were collected at the Formosa 1 wind farm situated 6 km off the west coast of Miaoli (Taiwan Strait), spanning an area of 10.27 km^2 (Fig. 1). The water depth at the site is 15–30 m, where the substrate is mostly composed of coarse sand. At the Taiwan Strait, winds are abundant, mostly due to the annual monsoons, which are characterized by the strong northeasterly wind in winter and the weaker southwesterly wind in summer (Cheng and Chang 2018). The Formosa 1 offshore wind farm is one of the three projects approved by the Taiwan Ministry of Economic Affairs Bureau of Energy, and it was planned to develop in two phases: a demonstration and a commercial phase. During the demonstration phase, two wind turbines (#21 and #28, each with a capacity of 4 MW) were installed in November 2016 and started operation in April 2017. The second phase involved the installation of 20 additional wind turbines with a cumulative capacity of 120 MW, and the construction was completed in October 2019 (Supplementary Fig. S1).

Data collection

To monitor operational noise during 2017 and 2018, we deployed a hydrophone 10 m from one of the two demonstrational wind turbines, #28 (24°41′35.75″N, 120°49′1.54″E) (Supplementary Fig. S1). Turbine #28 was installed on a monopile foundation with a diameter of 5.5 m and a length of 75 m, and the rotor diameter and blade length were 120 and 58.5 m, respectively (Supplementary Fig. S2).

We used an SM4M from Wildlife Acoustics fastened to a bottom-mounted metal frame placed ∼1–2 m from the seabed at a depth of ∼15–20 m (Supplementary Fig. S3). The SM4M hydrophone was programmed to record continual hourly acoustic data in.wav format, in the frequency range of 2–48 000 Hz, with a sensitivity of −164.2 dB re:1v/μPa, gain 2 dB, and sampling frequency of 96 kHz. We recorded 104 days in 2017 and 117 days in 2018. The timeline of the monitoring intervals and the number of recording days is detailed in Table 1. Hourly wind speed (in m/s) was measured using a buoy ∼3.8 km away from turbine #28, deployed by the Central Weather Bureau (24°45′27.6″N, 120°50′20.4″E).

Chorusing species and their vocalization phenology

The underwater soundscape in the frequency range of 500–2500 Hz is dominated by two types (Types 1 and 2) of chorusing, produced by a Sciaenidae family of the soniferous fish (Siddagangaiah et al. 2021, Siddagangaiah et al. 2022a). Both types of choruses exhibit seasonal patterns, commencing in spring (March), peaking in summer (June–August), beginning to diminish from late autumn (late October), and going silent in winter (December–February) (Supplementary Fig. S4) (Siddagangaiah et al. 2021, Siddagangaiah et al. 2022b). Whereas the species responsible for Type 1 chorusing remains unclarified, the Type 2 chorusing has been identified as the *Johnius Taiwanensis*, from the Sciaenidae family (Siddagangaiah et al. 2022a).

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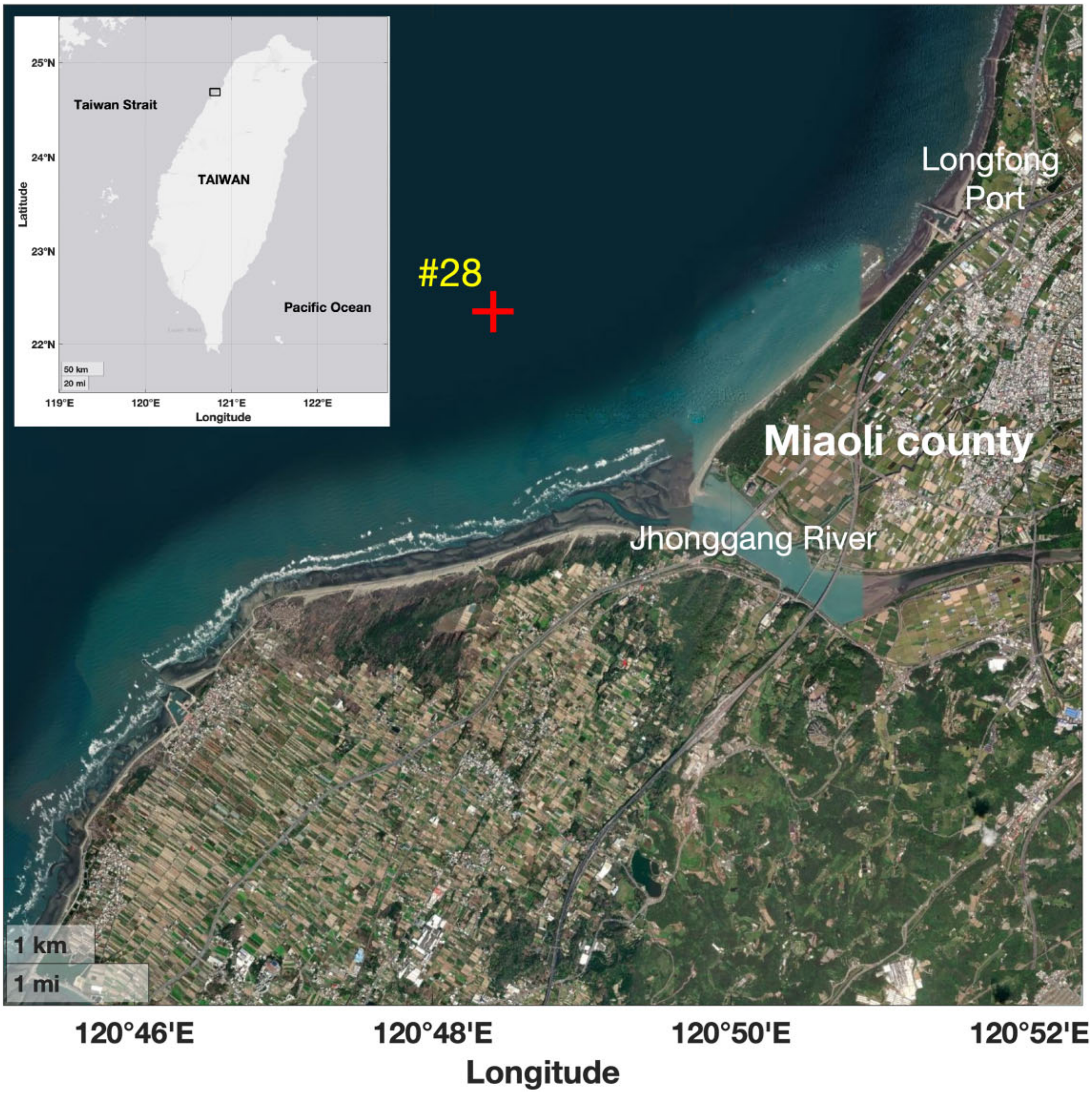

Figure 1. Map of the Miaoli coast (Taiwan Strait, Taiwan) depicting the passive acoustic monitoring recorder deployed at turbine #28, located in the Miaoli offshore wind farm area.

Table 1. Timeline of deployment of PAM at turbine #28 located in the offshore wind farm area.

Year	Monitoring period (DD MMM)	Total days monitored
2017	27 April–25 May	28
	05 July–27 July	22
	29 July–17 Aug.	19
	06 Nov.–11 Dec.	35
2018	25 Jan.–09 March	43
	03 April–10 May	37
	27 Aug.–05 Sep.	9
	07 Sep.–05 Oct.	28

Supplementary Fig. S5 shows the 24-hour spectrogram depicting the two types of chorusing, the waveform, and the power spectrum of the individual calls composing the choruses (Siddagangaiah et al. 2021, Siddagangaiah et al. 2022a). The acoustic features of the two call types, such as duration of the call, number and duration of pulses, time interval between pulses, and peak frequency, are tabulated in Supplementary Table S1 (Siddagangaiah et al. 2022a).

Acoustic analysis

The acoustic data was stored in.wav format and processed using the PAM Guide toolbox in MATLAB (Merchant et al. 2015). We computed long-term spectrograms based on the power spectral density (PSD) and sound pressure levels (SPLs). PSD was calculated in the frequency range 10–10 000 Hz by setting a 1 s Hanning window, 50% overlap, and 60 s time-averaged. The SPLs were computed in the frequency range 20–250 Hz with a 1 s Hanning window, 50% overlap, and time-averaged every hour. Similarly, the 1/3rd octave band SPL was evaluated for the various frequency bands ranging from 20 to 1600 Hz.

Permutation entropy-based automatic detection of fish chorusing

We used the permutation entropy (H) to measure the degree of randomness or periodicity using the concept of symbolic dynamics or permutation patterns (Bandt and Pompe 2002, Zanin and Olivares 2021). The H method translates the relative amplitudes of an acoustic time series in the selected win-

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dow of a certain length M into their symbolic representation to recover the patterns (Siddagangaiah et al. 2020), thus enabling the evaluation of temporal causality in the acoustic data. This enables the assessment of the dynamical characteristics, such as periodicity and randomness, induced by the fish chorusing and noise in the acoustic data (Siddagangaiah et al. 2019). The H technique is data-driven, simple, and robust for evaluating several noises occurring in the PAM acoustic recordings (Siddagangaiah et al. 2019, Siddagangaiah et al. 2020).

For a given time series $\{x(t)\}_{t=1}^{N}$, we assume a pattern length of M and divide the time series into $T = N - [M - 1]$ overlapping windows. The elements of each M-window $x_s = (x_s, x_{s+1}, \ldots, x_{s+(M-1)})$ of $x(t)$ are arranged by increasing amplitude to capture their indexes $i_0, i_1, \ldots, i_{(M-1)}$, such that $x_{s+i_0} \leq x_{s+i_1} \leq \ldots \leq x_{s+i_{(M-1)}}$. Hence, words $\pi = (i_0, i_1, \ldots, i_{(M-1)})$ are symbols representing all possible $M!$ permutations of $\{0, 1, 2, \ldots, M - 1\}$, and this procedure of encoding the relative amplitude is done for each M-segment. The associated probability density function $P(\pi)$ relates the occurrence frequency of permutation patterns π in the data, satisfying $\sum_{\pi} P(\pi) = 1$.

The H measures the abrupt changes and dynamical regime transition from the data and is defined as follows:

$$\mathrm{H}[P] = \frac{-1}{S_{max}} \sum\nolimits_{\pi=1}^{N} P(\pi) \log(P(\pi))$$

Here, H measures the level of the disorder of the system and is given by the ratio of the entropy of $P(\pi)$ to the maximum entropy of the system modeled by a uniform probability $(P_e|S_{max}) = \log(M!)$. Therefore, $0 \leq \mathrm{H}[P] \leq 1$ for a periodic $(\mathrm{H} = 0)$ or uncorrelated random system $(\mathrm{H} = 1)$, respectively. The H is shown to detect fish chorusing with an accuracy of $\sim$95%, and it is robust to anthropophony and geophony, such as sound originating from shipping activity or natural sources, such as wind and tides (Siddagangaiah et al. 2019). Further, the H was applied to the five-year passive acoustic monitored data to derive the fish vocalization phenology (Siddagangaiah et al. 2021). H works on the principle of detecting the periodic dynamical structures induced by the fish chorusing in the ocean ambient noise. Because of the periodicity caused by the fish chorusing amidst the ambient noise results in a lower H (0–0.5), and in the absence of fish chorusing, just the ambient noise and other noise sources will enhance the randomness, the resulting H will be higher and fall between 0.7 and 1. In this study, H is evaluated hourly for each acoustic file, for the pattern length $M = 6$ in R v4.1.1 , using the command *global-complexity* from the *statcomp* package (Sippel et al. 2016).

Statistics

All statistical analyses were computed in R using the *agricolae* package (de Mendiburu and de Mendiburu 2019). The non-parametric Kruskal–Wallis test, followed by *posthoc* Bonferroni's multiple comparisons, was used to assess statistical differences of SPL, wind speed, and H in spring (March, April), summer (May–August), autumn (September–November), and winter (December–February). For the comparison of seasonal fish chorusing and operational noise levels, the 24-hour H and SPL in the frequency range of 20–250 Hz were time-averaged to produce a single value of H and SPL for each day, thus resulting in 41, 81, 34, and 89 days in spring, summer, autumn, and winter, respectively, in 2017 and 2018. To evaluate the influence of the wind farm operational noise on the fish chorusing, and the influence of the wind speed on the operational noise, the Pearson correlation coefficient was evaluated between each hourly H and wind speed with corresponding hourly SPL in the frequency range 20–250 Hz. The correlation coefficient and significance were computed using the *corrcoef* function in MATLAB. The logarithmic mean and standard deviation of the SPL were calculated using the *meandB* and *sddB* commands included in the *seewave* package in R (Sueur et al. 2008), and the standard error was evaluated by dividing the standard deviation by the square root of the sample size.

Results

Long-term spectrogram and annual variation of wind speed during 2017 and 2018

Stronger wind speeds (10−20 m/s) occurred from autumn until early spring, while 2−8 m/s were recorded for the rest of the year. However, during typhoons and storms, the wind speed reached up to 10−12 m/s even in summer (Fig. 2a and b). As expected, when higher wind speeds occurred higher sound levels were observed at low frequencies due to an increased activity of the wind turbine (Fig. 2c–f, Label W). In particular, PSD reached 120−140 dB re 1 μPa^2 Hz^{-1}, and SPL in the frequency range 20–250 Hz was 130–150 dB re 1 μPa (Fig. 2c–f, Label ON, Label W). The vertical striations appearing in light yellow on the spectrogram in the frequency band 500–2500 Hz show the diurnal fish chorusing with PSD reaching 100–120 dB (Fig. 2c and d, Label F).

Operational sound levels of the wind farm

Higher wind speeds caused the wind turbines to produce higher sound pressure levels in the frequency range of 20–250 Hz, occurring as continual tonal sounds with harmonic components (as shown in the spectrogram in Fig. 2a and b, Label ON). The 1/3rd octave band SPL from 25 to 1600 Hz revealed that the higher sound levels were witnessed at three frequency bands, namely 32 Hz (mean ± SE = 135.7 ± 0.61 dB re 1 μPa), 40 Hz (133.3 ± 1.4 dB re 1 μPa), and 160 Hz (137 ± 1.1 dB re 1 μPa) (Fig. 3a).

Annual variation of fish vocalization during 2017 and 2018

The evaluation of the seasonal fish chorusing at the wind farm site showed that fish chorusing was not observed from December to March, with H falling over than 0.6 (Fig. 2h). During later spring and summer (May–August) till early autumn (October), the fish chorusing was consistently observed between 06:00 p.m. and 03:00 a.m. (Fig. 2g and h; labeled FC). The blue contours (H < 0.5) represent the fish chorusing hours (Fig. 2g and h; labeled FC). This is consistent with the elevated sound levels from May till early October with SPL (500–2500 Hz) varying between 125 and 145 dB re 1 μPa (Supplementary Fig. S6a and b, Label FC). During later autumn until early winter (December), fish chorusing continually diminished in duration (Fig. 2g; trapezoid marked FC). Similarly, from November until early December, a consistent reducing of the SPL (500–2500 Hz) from $\sim$130 dB re 1 μPa to $\sim$125 dB re 1 μPa was recorded (Supplementary Fig. S6a, trapezoid marked FC).

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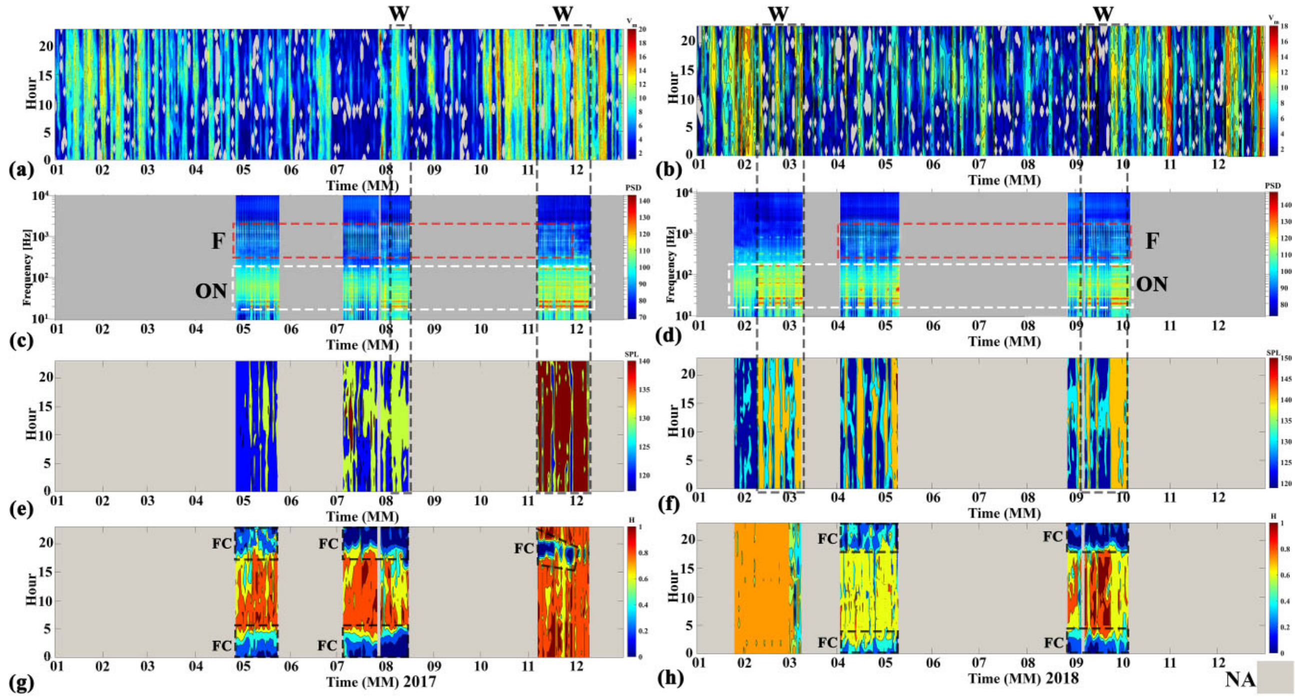

Figure 2. (a, b) Annual variation of the wind speed during 2017 and 2018; the color label represents the mean wind velocity (V_m) in units of m/s. (c, d) Annual spectrogram at the turbine #28 site during 2017. The color label represents the power spectral density (PSD) in units of dB re 1 μPa^2 Hz^{-1}; the label F represents the Types 1 and 2 chorusing activity occurring in the frequency band 500–2500 Hz; the label ON shows the sustained noise originating from the turbine in the frequency band 20–250 Hz. (e, f) Annual variation of the sound pressure level (SPL) in the frequency band 20-250 Hz during 2017 and 2018. The color label represents the SPL in dB re l μPa. The label W represents the periods of the increased SPL corresponding to the elevated wind speed (a, b) and PSD (c, d) caused due to the operational noise from the turbine. (g, h) Annual distribution of the hourly permutation entropy (H) during 2017 and 2018. The color label represents the H and the label **FC** highlights the blue contours (H < 0.5) representing the periods of the fish chorusing.

Influence of seasonal wind speed on operational sound levels

The SPL (20–250 Hz) during winter (mean $\pm$ SE $= 137.5 \pm 0.82$ dB re 1 μPa) was significantly higher and during summer (130.4 ± 0.65 dB re 1 μPa) was significantly lower compared to other seasons ($P < 0.001$) (Fig. 3b, Table 2). Similarly, the wind speed was significantly higher in winter (10.4 ± 0.2 m/s) than in other seasons ($P < 0.001$) (Fig. 3c, Table 2), and there was a significantly positive correlation between the hourly wind speed and SPL (20–250 Hz) ($r = 0.76$, $P < 0.001$) (Fig. 3d).

Wind turbine operational noise and seasonal fish chorusing

Because of the absence of fish chorusing in the winter, the H (mean $\pm$ SE $= 0.51 \pm 0.01$) was significantly higher than that in other seasons ($P < 0.001$), and the consistent fish chorusing in summer resulted in significantly lower H (0.26 ± 0.01) compared to the other seasons ($P < 0.001$) (Fig. 3e, Table 2). No correlation was found between the hourly SPL (20–250 Hz) and H ($r = -0.17$, $P \approx 1$) (Fig. 3f) or between frequency bands of fish chorusing (500–2500 Hz) and wind turbine noise (20–250 Hz) when evaluated in different seasons (Supplementary Fig. S7a–d).

Discussion

In this study, we investigated the influence of offshore wind farm operational noise on seasonal fish chorusing. Results revealed operational noise measured in 2017 and 2018 seemed to not significantly influence the seasonal fish vocalization pattern, which still followed the well-established phenology of the two chorusing types previously studied in the Taiwan Strait, thus maintaining silence in winters and significantly increasing in summer (Siddagangaiah et al. 2021, Siddagangaiah et al. 2022b). Furthermore, we showed that wind speed and sound pressure levels were highly correlated over the monitoring duration, with higher wind speeds in winter causing faster rotation of the turbines and thus producing higher sound levels.

The Taiwan Strait is severely influenced by the Northeasterly monsoon in winter and storms in summer, with mean wind speeds reaching 18–20 m/s. The hourly annual wind speeds were positively correlated with the SPL ($r = 0.71$, $P < 0.001$) in the frequency range of 20–250 Hz (Fig. 3d), induced by the operation of the turbine with 4 MW capacity, installed on the monopile foundation. Similar results were observed on the steel monopile foundation in Belgium, where the SPL and wind speeds were highly correlated (Norro and Degraer 2016). Underwater noise levels from the operational wind farm are mostly limited to frequencies below 1 kHz (Madsen et al. 2006, Pangerc et al. 2016, Tougaard et al. 2020), usually originating at the nacelle of the wind turbine by the rotating parts, resulting in strong tonal and harmonic components. Our findings are consistent with previous literature, with the operational noise resulted in strong tonal and harmonics in the 1/3rd octave frequency bands at 32, 40, and 160 Hz (Fig. 3a). Other studies suggested that higher wind speeds produce louder sound levels, resulting in newer harmonics and tones (Kastelein et al. 2008, Kikuchi 2010, Tougaard et al. 2020), and a strong correlation was found between the underwater noise generated and the tower's me-

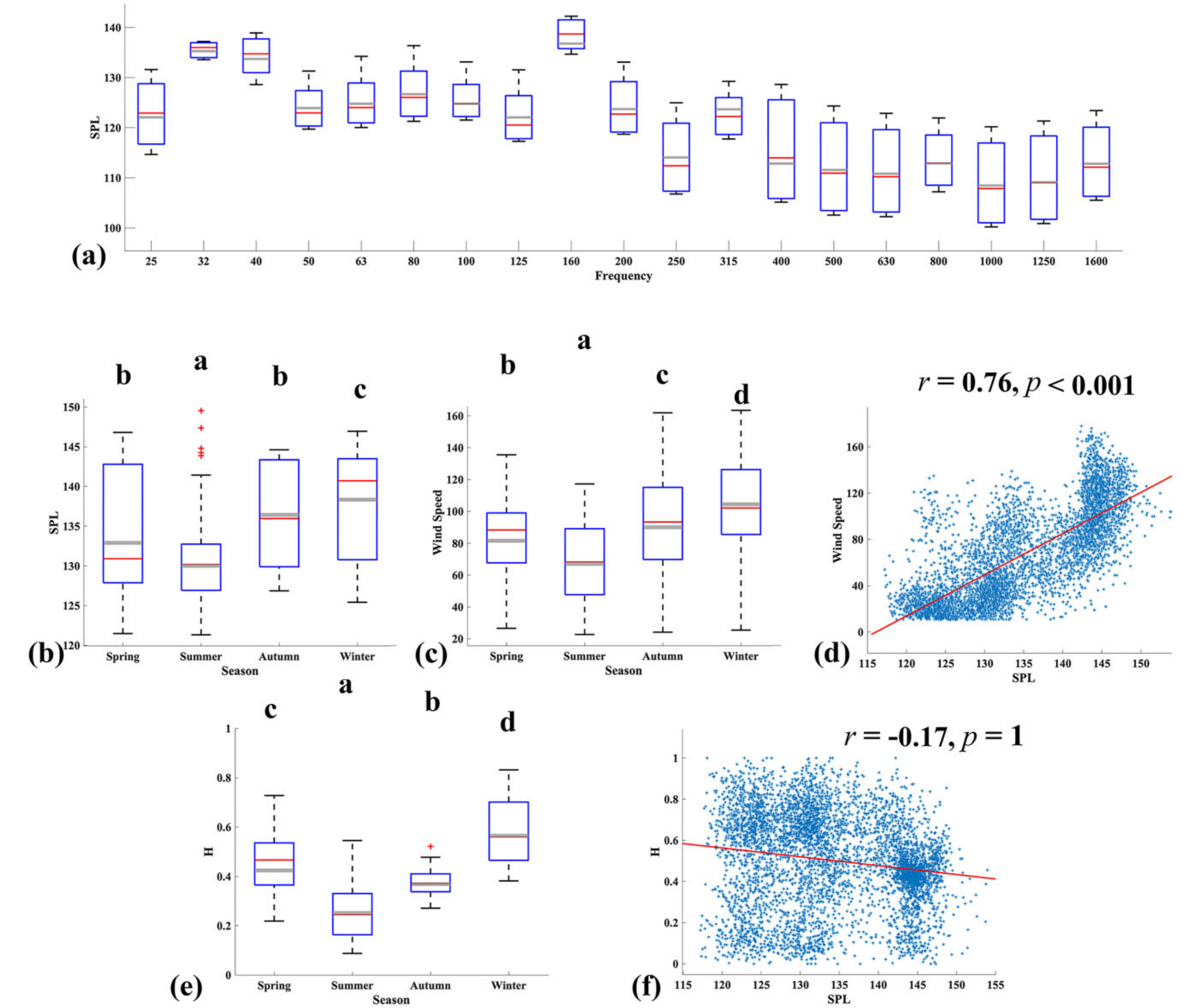

Figure 3. (a) Variation of 24-hour SPL (20–250 Hz) (in units of dB re 1 μPa) during the turbine operation ($n = 24$) at different 1/3-octave band frequencies. (b) Comparison of SPL (20–250 Hz) during spring ($n = 41$ days), summer ($n = 81$ days), autumn ($n = 34$ days), and winter ($n = 69$ days) of 2017 and 2018. (c) Comparison of wind speed (in units of m/s) during spring ($n = 97$ days), summer ($n = 188$ days), autumn ($n = 101$), and winter ($n = 165$ days) of 2017 and 2018. (d) Scatter plot representing the Pearson correlation between hourly SPL and wind speed during 2017 and 2018; $n = 5075$ pair of hourly SPL(20-250 Hz) and wind speed. The fitting line (in red) and r and p represent the values of the correlation and statistical significance. (e) Comparison of fish chorusing index H (H < 0.5 represent the presence of the fish chorusing) during spring ($n = 41$ days), summer ($n = 81$ days), autumn ($n = 34$ days), and winter ($n = 69$ days) of 2017 and 2018. (f) Scatter plot representing the Pearson correlation between hourly SPL (20–250 Hz) and H during 2017 and 2018; $n = 5400$ pair of hourly SPL and H. The fitting line and r and p represent the values of the correlation and statistical significance. In each box, the center red and gray lines depict the median and mean, and the top and bottom edges of the box represent the 25th and 75th percentiles. The maximum and minimum values are marked in black at the extreme ends. The + symbol represents outliers. Each box with a superscript letter represents the results from post-hoc multiple comparison tests. Different superscript letters indicate significant differences ($P < 0.05$), with the letter "a" at the top and subsequent statistical differences represented at a lower level.

chanical vibration (Yang et al. 2018). Thus, the underwater noise levels and the tonal frequencies that originate during the normal operation of the wind farm determine an increase in the sound levels and newer harmonics introduced because of the excessive vibrations, which are induced by the wear and tear of the rotating mechanical parts inside the nacelle (Gu et al. 2021).

The underwater sound originating from an operational wind farm can spread out a few kilometers; however, the low-frequency tonal components can be detected at distances beyond tens of kilometers (Bergström et al. 2014) lasting over the 20–30 years of their operational phase, which makes the wind farms a unique and highly localized acoustic noise source (Mooney et al. 2020) at which the marine species in the region will inevitable be exposed in the long-term period. The elevated underwater noise levels caused by the wind farm operation can potentially influence psychological and behavioral changes in fish (Svendsen et al. 2022).

The results of this study regarding the seasonal vocalization pattern of two chorusing types (Types 1 and 2) are consistent with the long-term vocalization pattern previously observed at the Taiwan Strait (Siddagangaiah et al. 2021). The elevated

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Table 2. Results of Kruskal–Wallis test and the post hoc Bonferroni's multiple comparison tests showing the significance of differences in the seasonal SPL, wind speed, and fish chorusing index permutation entropy (H) during the spring, summer, autumn, and winter seasons.

Category	Kruskal–Wallis test			Bonferroni's multiple comparison test					
	Chi-square	P	df	Spring vs. summer	Spring vs. autumn	Spring vs. winter	Summer vs. autumn	Summer vs. Winter	Autumn vs. Winter
Seasonal SPL	34.44	0	3	***	ns	***	***	***	**
Seasonal wind speed	94.98	0		***	***	***	***	***	***
Seasonal fish chorusing (H)	136.13	0		***	***	***	***	***	***

ns: non-significant; df: degrees of freedom. P: significance level; $^{**}P \leq 0.01$, $^{***}P \leq 0.001$

SPLs in the frequency range of 20–250 Hz caused by the operational noise from offshore wind turbines did not exhibit to be influenced on the seasonal vocalization pattern ($r = -0.17$) (Fig. 3f). Few studies have examined the influence of offshore wind farm operational noise, indicating a varied response in different fish species (Svendsen-Erquiaga et al. 2022), mainly observed over a short period (10 to 40 days). Bluefin tuna in semi-free conditions exhibited altered movement patterns when exposed to recordings of wind farm operational noise measured ~50 m from the turbine (Puig-Pons et al. 2021). The wind farm harmonics at 125 Hz, with sound levels reaching 96 dB re 1μPa, can potentially interfere with the hearing thresholds of the Marbled rockfish (Zhang et al. 2021). Similarly, when the black sea bass in the lab was exposed to tones of varying frequencies from 80 to 1000 Hz, the acoustics were within the detection window of the species and could cause acoustic masking with subsequent influence on their behavior and physiology (Stanley et al. 2020). When exposed to continual operational noise in the laboratory for three days to a week, the milkfish showed elevated mRNA levels of hydroxysteroid dehydrogenase (Wei et al. 2018).

However, studies have emphasized that species' behaviors and physiological changes associated with operational noise are usually difficult under semi-free and laboratory conditions (Puig-Pons et al. 2021) and cannot be extrapolated to the species' behaviors in their natural habitats (Wei et al. 2018, Svendsen et al. 2022). Thus, it is necessary to understand the specific behavior of the species during the several phases of the offshore wind farm project, which may help identify the specific stressors and the corresponding phases that affect the species' behaviors. For example, understanding the long-term vocalization pattern of the two chorusing types (Types 1 and 2) enabled us to evaluate the influence of pile driving on these Sciaenidae species (Siddagangaiah et al. 2022a).

The results in this study show that during the season when the highest operating sound levels are in winter, spring, and later autumn, the fish chorusing is not as sustained as in the summer. Thus, it seems to limit the scope of evaluating the influence of noise from the operating turbines on the peak chorusing activity. Nevertheless, no in-situ studies of the long-term effects of wind farm noise on fish vocalization behavior exist to date, and the information presented herein is, therefore, noteworthy.

This study was conducted when the two foremost wind turbines were operating, and at this wind farm site, the turbines are expected to grow to 67 in total, spanning ~80 km^2. Due to the addition of these turbines in the wind farm area, the study site may experience rapid changes in the habitat and the soundscape (Dannheim et al. 2020), by causing an elevation in the low-frequency sound levels. Additionally, turbines with a different capacity may introduce new harmonic components compared to the harmonics observed in the 1/3rd octave frequency bands (32, 40, and 160 Hz).

Anthropogenic interference during construction, coupled with the installment of new foundation structures, may alter the local ecosystem and produce habitat changes. Increased turbidity has been observed at the wind farm sites, potentially affecting fish behavior (Wollschläger et al. 2021). However, the abundance of fish may increase at the wind farm due to the enhanced microfauna accumulation on the foundation structures and decreased fishing (Coates et al. 2014). These positive and negative premises regarding the expansion of the

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wind farm further emphasize the need for hypothesis-driven research to understand the influences and changes in the fish vocalization behavior. The results derived in this study can function as a first baseline for the operational noise levels and the fish vocalization behavior.

Taiwan's government is expected to rapidly develop offshore wind farms in the Taiwan Strait (Zhou and Guo 2023). The accelerated offshore wind farm developmental projects, which are scheduled to achieve the expected power output at a swift phase, provide a limited time window for the study of the species living in the area and their physiological, physical, and behavioral characteristics, including seasonal occurrences, migration, movement patterns, feeding, and reproduction (Hawkins and Popper 2017, Popper et al. 2022). This knowledge may clarify the influence of the noise from different phases of the offshore wind farm operation. In particular, it would be essential to study the diverse influence of short high-intensity noises originating from pile driving during construction and longer durations of sustained operational noise. Numerous studies have shown the impact of pile-driving noise on fish, while fewer have studied the operational phase (Svendsen et al. 2022). Although fish exposed to a continuous noise source, such as different frequency tones and playbacks of the operational noise, have shown physiological and behavioral changes under laboratory conditions and in short-term investigations (Kastelein et al. 2008, Winter, Aarts et al. 2010), there is a lack of studies performed at real-world wind farms or investigating long-term operational noise.

Conclusion

This study aimed to assess the influence of wind farm noise on the fish vocalization phenology during the operational stage, which is the longest phase of the offshore wind farm spanning most of its lifecycle. Our investigation revealed that two-year operational noise from a single turbine did not influence the seasonal phenology of the fish chorusing. This study began at the onset of the operational stage, when only two wind turbines were operating at the wind farm; however, more turbines were added in 2019. Studies have emphasized that the evaluation of the impact of noise from the offshore wind farm cannot be considered completed when based on the sound levels originating from a single individual turbine (Degraer et al. 2016, Tougaard et al. 2020). More comprehensive investigations observing the cumulative effect obtained when all the turbines are in place are therefore needed. Still, the findings of this study provide the first baseline knowledge on wind turbine operational sound levels compared to wind speed and vocalization phenology of two chorusing types at the Taiwan Strait. The acoustic assessment presented herein constitutes a starting point from which changes can be monitored along the successive advancements of the wind farm project.

Author contributions

Shashidhar Siddagangaiah: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - Original Draft, Writing - Review & Editing, Visualization. Chi-Fang Chen: Funding acquisition, Data Curation, Resources . Wei-Chun Hu: Data Curation, Resources. Tom Akamatsu: review & editing; Nadia Pieretti: Writing - review & editing, Conceptualization.

Supplementary data

Supplementary material is available at *ICES Journal of Marine Science* online.

Conflict of interest : The authors declare no competing interests.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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