

# Silent winters and rock-and-roll summers: The long-term effects of changing oceans on marine fish vocalization

Shashidhar Siddagangaiah<sup>a,\*</sup>, Chi-Fang Chen<sup>a,\*</sup>, Wei-Chun Hu<sup>a</sup>, Roberto Danovaro<sup>b,c</sup>, Nadia Pieretti<sup>b</sup>

<sup>a</sup> Underwater Acoustic Laboratory, Department of Engineering Sciences and Ocean Engineering, National Taiwan University, Taipei, Taiwan, ROC

<sup>b</sup> Department of Life and Environmental Sciences, Polytechnic University of Marche, Ancona, Italy

<sup>c</sup> Stazione Zoologica Anton Dohrn, Naples, Italy

## ARTICLE INFO

### Keywords:

Fish vocalization  
Marine soundscape  
Passive acoustic recordings  
Behavior  
Climate-driven episodic events  
Acoustic indices

## ABSTRACT

The analysis of temporal trends and spatial patterns of marine sounds can provide crucial insights to assess the abundance, distribution, and behavior of fishes and of many other species. However, data on species-specific temporal and seasonal changes are still extremely limited. We report here the result of the longest recording ever conducted (five years, from 2014 to 2018) on fish vocalization. Findings from the Eastern Taiwan Strait (ETS) revealed a periodic fish chorusing pattern, with peaks in summer and almost complete silence, for ~2 months, during winter. Chorusing pattern was influenced by abiotic parameters, including temperature, tides and moon phase. We also report, for the first time, that extreme weather events (e.g., typhoons, storms with sediment resuspension) caused the cessation of the chorusing. The chorusing pattern explored in this long-term study provides important baseline data to understand the impact of climate change and of climate-driven extreme/episodic events on the phenology of fishes; this work also provides evidence that changes in the ambient conditions might significantly alter the phenology of vocalizing marine species.

## 1. Introduction

Similar to other vertebrate and invertebrate terrestrial taxa, fishes are known to produce a variety of sounds. Many fish species vocalize in large numbers and produce sustained choruses that result in a unique sound signature of the marine soundscape (Buscaino, 2016). Fish choruses, which can raise ambient noise levels by ~10–40 dB re 1  $\mu$ Pa (Cato, 1969, 1978; Wyllie, 1971; D'spain, G. and H. Batchelor, 2006), have important behavioral functions, such as social cohesion (Van Oosterom, 2016), territorial defense (Buscaino, 2015), foraging (Versluis, 2000; Au and Banks, 1997), and spawning activity (Buscaino, 2015; Mann and Lobel, 1997). Previous studies have shown fish choruses to exhibit periodicity based on several abiotic factors, such as lunar patterns, time of dawn and sunset, season, temperature, and salinity (McCauley, 2012; Halliday, 2017; McWilliam, 2017; Helfman, 1986; Ruppé, 2015; Rice et al., 2017). However, these studies are frequently based on short-term datasets, which hampers the possibility of understanding the boundaries of the natural variability of the acoustic patterns (Buscaino, 2016; McWilliam, 2018) or assessing eventual shifts in

fish acoustic activity caused by specific events (Morissette, 2009). The occurrence of anomalous weather events, such as heatwaves, flooding, or storms, might generate a behavioral change in fishes, which is likely to be associated with a shift in their acoustic patterns. Assessing normal levels of variation in biological marine sounds according to their seasonal and daily patterns could provide essential information on the health status of marine ecosystems, requiring further investigation or the development of conservation actions if drifts from the usual trend occur (Ruppé, 2015; Pieretti, 2015). In this context, long-term investigations are urgently required to establish background information and identify the factors controlling the variability or cyclical rhythms of sound production by marine organisms (Sobel, 2016; Rahmstorf, 2017; Asch, 2015; Hastings and Širović, 2015).

Obtaining accurate analyses of biological activity from large datasets is still challenging (Fairbrass, 2017) due to the difficulty of distinguishing biological sounds from other noise sources in acoustic recordings. Passive acoustic monitoring (PAM) has recently emerged as a non-invasive and cost-effective tool for the investigation and monitoring of marine environments (Burivalova et al., 2019; Oliver, 2018; Lindseth

\* Corresponding authors.

E-mail addresses: [shashi.18j@gmail.com](mailto:shashi.18j@gmail.com) (S. Siddagangaiah), [chifang5762@gmail.com](mailto:chifang5762@gmail.com) (C.-F. Chen).

<https://doi.org/10.1016/j.ecolind.2021.107456>

Received 29 October 2020; Received in revised form 21 January 2021; Accepted 22 January 2021

Available online 23 February 2021

1470-160X/© 2021 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

and Lobel, 2018). It targets single sound sources (i.e., single species or noise) or all the sound sources in a given environment (i.e., the soundscape). The marine soundscape is shaped by three components: biophony (signals and vocalizations produced by marine mammals, fishes, invertebrates), geophony (i.e., sounds from waves and rain, undersea earthquakes) and anthropophony (human-produced noise from shipping, industrial activities, oil and gas explorations) (Pieretti, 2017; Putland et al., 2017; Gage and Axel, 2014; Mullet, 2016; Farina, 2013; Pijanowski, 2011; Krause, 1987). PAM technologies allow the collection of large acoustic datasets (including species' presence/absence and their behavioral alterations due to external factors (Burivalova et al., 2019), consequently enabling the investigation of ecological patterns at different spatial and temporal scales (Erbe, 2015; Haver, 2018; Merchant, 2016). However, obtaining accurate species-specific behavior estimates from large passive acoustic datasets is challenging (Pieretti, 2017) due to the difficulty of automatically detecting biological sounds and other sound sources occurring in the acoustic recordings.

Ecoacoustic indices enable to detect and quantify biophony from the entire animal community or single target species present in the acoustic recordings (Sueur and Farina, 2015; Towsey, 2014). Recently, several studies have applied acoustic indices, such as Acoustic Complexity Index (ACI) (Pieretti et al., 2011) and Acoustic Diversity Index (ADI) (Villanueva-Rivera, 2011), for studying temporal and nocturnal chorusing patterns in marine fauna (Buscaino, 2016; Pieretti, 2017). Here, in this study, we utilize complexity indices based on the Complexity-Entropy method (C-H) to detect fish choruses (Siddagangaiah, 2019). The C-H method has been recently proven to accurately track fish choruses even in the presence of noise due to shipping or sediment transportation (Siddagangaiah, 2019).

Long-term analyses are required to understand the temporal and seasonal vocalizing behavior of fishes living in a region, and to assess the factors controlling their vocalization. In this study, we provide the results of the longest temporal assessment (from 2014 to 2018) ever conducted on fish choruses in order to identify their circadian, seasonal, and interannual changes and to establish the background conditions. We compare the intensity and temporal distribution of fish chorusing to provide the benchmark of the soundscape of the area, identify the factors controlling fish vocalization, and assess the influence of different climate-driven events on fish chorusing, which are predicted to be exacerbated as a result of ongoing climate changes.

## 2. Methods

### 2.1. Study area

The study area was selected off the Eastern Taiwan Strait in the Changhua region because this region was influenced by seasonal temperature fluctuations, severe tropical storms, high wind speeds, sediment transportation, and abnormal turbidity due to flooding, all of which can be used to identify the abiotic factors interacting with fish vocalization. The Changhua coast lies in the Eastern Taiwan Strait that is ~180 km wide and ~350 km in length (Wenlan, 1983). ETS experiences robust climatic and oceanographic variations due to several factors, such as: 1) two monsoons in summer and winter, triggering volume and sediment transport (Zilang et al., 1991), 2) the extreme short-term events induced by typhoons, tropical storms, and wind/cold bursts occurring in winters (Wu et al., 2007; Zhang et al., 2013; Cheng et al., 2018).

### 2.2. Data measurement

Data were collected at Changhua (24° 4.283 N/120° 19.102 E) by deploying a PAM recorder at a depth of ~ 18 m, situated approximately 4–5 km off the ETS. Recordings were carried out from 2014 and ended in 2018 (Table 1). During 2014–2015, recordings were collected using a Wildlife Acoustic SM2M PAM recorder. During 2016–2018, we used a

**Table 1**

Timeline of deployment of PAM at Changhua monitoring station.

Year	Monitoring Period(MM-DD)	Total days monitored
2014	09-10 to 10-18	112
	10-20 to 12-31	
2015	01-01 to 02-26	282
	04-07 to 05-24	
	06-16 to 08-10	
	08-19 to 10-23	
	11-07 to 12-31	
2016	01-01 to 02-11	105
	03-14 to 05-16	
2017	04-01 to 05-11	157
	06-10 to 08-04	
	10-03 to 12-01	
2018	04-28 to 06-24	117
	07-19 to 09-15	

Wildlife Acoustic SM3M. Both hydrophones have a flat frequency response from 2 Hz to 48 kHz, with a sensitivity of  $-165$  dB re:1v/ $\mu$ Pa. The soundscape of the recording site is composed of biophony from fish chorusing and snapping shrimps, and anthropophony from transiting boats and pile driving. The deployed hydrophone was programmed to record continuously, storing a file every 60 min in .wav format with a sampling frequency of 48 kHz. Hourly temperature ( $^{\circ}$ C), wind speed (in m/s), and tide height (mm) data were recorded by a buoy deployed by the Central Weather Bureau of Taiwan (24° 15.411 N /120° 33.793 E), ~9 km away from the listening station.

The gaps in the monitoring period are due to several factors, such as weather conditions at the monitoring site that impeded recorder's retrieval and deployment (see Table 2 for typhoons occurrence at the deployment site), availability of a higher number of PAM recorders, and even instances of losing recorder during storms. About 42% of the days were monitored from 2014 to 2018.

### 2.3. Data processing

Firstly, the soundscape records were subjected to careful auditory examination and then visually inspected via detailed scrutiny of the spectrograms. Spectrograms and sound pressure levels (SPLs) were computed using PAMGuide (Merchant, 2015) and processed with an FFT size of 1,024 points and 1-s time segment averaged to 60-s resolution via the Welch method. The empirical probability distribution of SPL in the frequency band (300 Hz–2500) was evaluated by using the "ksdensity()" function in MATLAB. The peak power spectral density (PSD) and duration of the chorusing were annotated by direct measurement of the spectrograms. The 3D-contour plots were built in MATLAB by plotting the day in the x-axis versus the hourly values in the y-axis, with color scales representing the varying temperature, wind speed, and tidal height. The trend of the temperature and SPL was determined by

**Table 2**

List of typhoons with their period of occurrence at ETS.

Year	Typhoon Name	Period (MM-DD)
2015	Kujira	06-21 to 06-24
	Chan-hom	06-30 to 07-13
	Linfa	07-02 to 07-10
	Soudelor	07-30 to 08-09
	Dujuan	09-19 to 09-30
	Koppu	10-13 to 10-21
	In-Fa	11-17 to 11-26
2017	Mufia Philippine	04-26 to 04-27
	Merbok	06-10 to 06-13
	Nanmadol	07-02 to 07-05
	Nesat	07-26 to 07-30
	Haitang	07-29 to 07-31
2018	Khanun	10-12 to 10-16
	Ester	06-14 to 06-17

utilizing the “*detrend()*” command in MATLAB. A Pearson correlation (R) was computed between the seasonal trend of temperature and SPL, and between the tidal height and peak chorusing intensity (SPL) for every 36 h.

#### 2.4. Acoustic indices based on permutation entropy method

Acoustic Indices (AIs) have been recently proposed and tested so that both biophony and anthropophony from large datasets collected by PAM can be rapidly quantified (Sueur and Farina, 2015; Towsey, 2014a, 2014b; Siddagangaiah, 2020). AIs have already been applied for the study of temporal and nocturnal chorusing patterns in marine fauna (Buscaino, 2016; Rice et al., 2017; Pieretti, 2017). In our study, we used Complexity-Entropy (C-H) method because it has recently been demonstrated to accurately track fish choruses even in recordings, including noise due to shipping or sediment transportation (Siddagangaiah, 2019).

Permutation entropy (H) is based on symbolic dynamics, representing an ordinal probabilistic approach introduced by Bandt and Pompe (Bandt and Pompe, 2002). For a given acoustical time series  $\{x(t)\}_{t=1}^N$ , an embedding dimension  $d > 1$ , the ordinal pattern of order  $d$  generated by

$$s \mapsto (x_s, \dots, x_{s+d-1}) \quad (1)$$

There exists  $d!$  possible permutations of amplitude ordering within the ordinal pattern ( $d!$  different states). A time series of length  $N$  produces  $N - (d - 1)$  ordinal patterns. The probability distribution  $P$ , the normalized Shannon entropy is given by,  $H(P)$

$$S(P) = \sum_{i=0}^{N=d!} P_i \ln(1/P_i) \quad (2)$$

$$H(P) = \frac{S(P)}{\max(S)} = \frac{S(P)}{\ln(N)} \quad (3)$$

$\ln(n)$  is the maximum value of the  $S(P)$  which happens, when all permutations are equally likely to occur ( $P_i = 1/N$ ). The permutation entropy (H) quantifies the measure of randomness.  $H \approx 1$  represents a random order, and  $H \approx 0$  indicates perfect order. In our study, H was evaluated using the R package “*statcomp*” (Version 0.0.1.1000) (Sippel et al., 2016) using the function “*global-complexity()*”, for embedding dimension  $d = 6$ . Fish chorusing trends were computed by constructing 3D contour plots based on data gathered from the normalized H index, where the x-axis represented the day of the year and the y-axis the hourly values. Lower values of  $H < 0.5$  represented by light and dark blue are indicative of fish chorusing (Siddagangaiah, 2019).

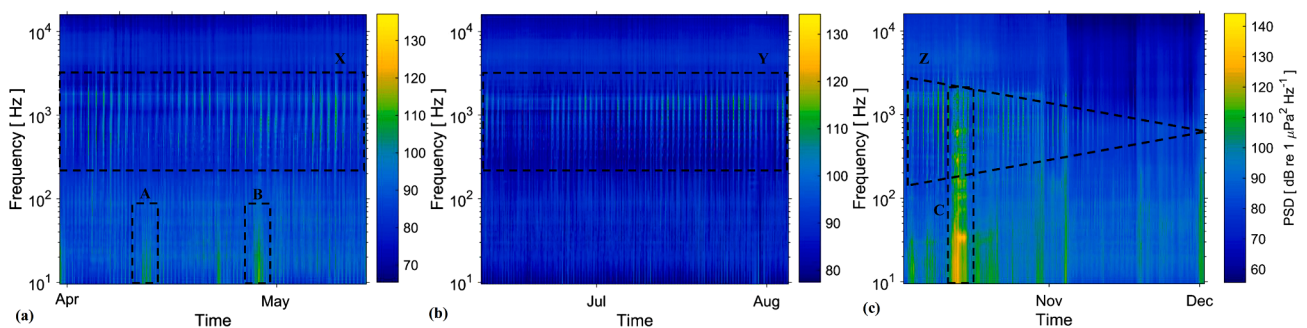
### 3. Results

#### 3.1. General soundscape features

Underwater noise levels in the area were not significantly affected by anthropogenic noise sources, registering sparse events of low-intensity noise at low frequencies (10–500 Hz) in correspondence with boat transits distant from our study site (Fig. 1, Label B); geophysical sound sources were more prominent. The presence of jet currents (strong currents determined by specific tidal conditions) determined the collision of sediment particles with the recorder (Fig. 1, Labels A and C) and the increase in acoustic intensity in the frequency range varying from 10 to 2000 Hz. This noise was episodic and occurred only for brief time-frames (from one to two days) in concomitance with extreme weather events. The soundscape was largely dominated by biophony, which was particularly intense at certain hours of the day due to the presence of fish chorusing. During spring and summer (from March to August), a consistent fish chorusing activity was observed throughout the entire recording period (Fig. 1a and b, Labels X and Y). In October and November, the intensity of the chorusing gradually decreased (Fig. 1c, Label Z) to nearly disappear for approximately 2 months in winter. This pattern is also evident from the empirical probability distribution function (EPDF) of the SPL (frequency band: 300–2500 Hz) (Fig. 2), where a secondary peak is noticeable at the right tail of the graphs when choruses occur (Fig. 2a, b, c). Fish choruses increased the SPLs from  $\sim 120$  dB to  $\sim 140$  dB during spring (Fig. 2a), reached up to  $\sim 150$  dB in summer (Fig. 2b), and persisted at high levels during autumn even if less frequently (Fig. 2c). In winter, when choruses were absent, the SPLs were typically around 100–110 dB for the selected frequency band (Fig. 2d).

#### 3.2. Fish chorusing types

The biological component of the soundscape primarily comprised two types of choruses, hereafter named Chorus 1 and Chorus 2. Both choruses fell in the frequency band from 500 to 2500 Hz (Fig. 3a). The Chorus 1 type of call is audible as a series of knocks. Each fish call is  $\sim 250$  ms long, covers frequencies between 300 and 2000 Hz, and consists of  $\sim 11$  pulses of approximately 8 ms of length each. The first and second pulses are separated by a gap of  $\sim 50$  ms, whereas the successive pulses occur at an interval of  $\sim 10$  ms (Fig. 3c). The call has two dominant spectral peaks,  $\sim 700$  Hz and  $\sim 1700$  Hz, with mean PSD levels of  $\sim 120$  dB that can reach up to  $\sim 140$  dB (Fig. 3e). The Chorus 1 calling features are similar to those reported for *Johnius macrorhynchus* as documented by Lin et al. (Lin et al., 2007). This species was recently renamed as *Johnius taiwanensis* by Chao et al. (Chao, et al., 2019), who documented its presence in the ETS. The genus *Johnius* is a group of small-to-medium-sized sciaenids with approximately 35 recognized species (Chao, et al., 2019). Chorus 1 typically occurred during dusk hours and



**Fig. 1.** Spectrogram for monitoring periods during the year 2017; color label represents PSD in units of  $\text{dB re } 1 \mu\text{Pa}^2 \text{Hz}^{-1}$  (a–c) During spring, summer, autumn–winter, respectively. Label X, Y: Continuous fish chorusing throughout the monitoring duration; Z: Depicts the diminishing fish chorus intensity during the autumn–winter season; A, C: Increase of acoustic intensity due to sediment noise; B: Boat transit noise.

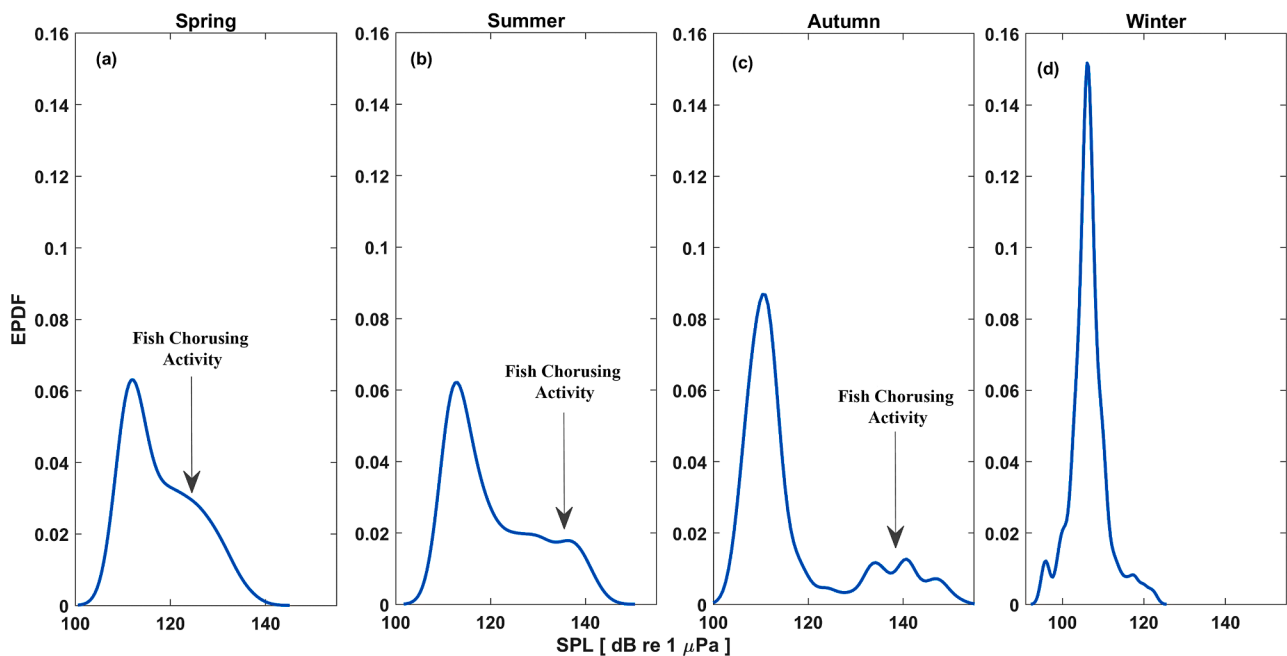


Fig. 2. Empirical probability distribution of SPL evaluated at 300–2500 Hz (a), (b), (c), and (d) During spring, summer, autumn, and winter, respectively.

varied according to the season and length of the day. Chorus 2 was composed of calls that exhibited a train of pulses of  $\sim 200$  ms of length. Each call consisted of about 14 pulses, each spanning  $\sim 6$  ms with an interval of  $\sim 10$  ms between successive pulses (Fig. 3b). The call can be heard as a tonal sound. Its energy spreads from 500 to 2500 Hz, with an average peak frequency from 1200 to 1800 Hz, and mean received peak power spectral density (PSD) levels of  $\sim 120$  dB (Fig. 3d). It generally extended from dusk till dawn, often presenting a rise in levels and number of calls in the hours that preceded dawn. Unfortunately, we were not able to associate a species to this call. The calling characteristics of Chorus 2 was not analogous to any of the recognized species in the region. We hypothesize that it may belong to the family Sciaenidae, as well as Chorus 1, because many Sciaenid species are known to produce sustained nightly choruses that begin around dusk and last for several hours (Mann and Locascio, 2006).

### 3.3. Long-term fish chorusing trend

The overall picture of the long-term chorusing was obtained by processing the entire acoustic dataset via the permutation entropy (H) index (Fig. 4). This index has recently been demonstrated to be anti-correlated with the fish chorusing (Siddagangaiah, 2019); hence, the blue contours represent the fish chorusing periods, whereas yellow indicates an absence of chorus. The permutation entropy index revealed fish choruses to be absent in January and February. The chorusing generally began at dusk in late February and steadily extended until dawn throughout the spring (Fig. 4b–4d; SR (spring rise)). During summer (May–August), fish chorusing was intense and consistent both at dawn and dusk. From September–early October (autumn), choruses showed a progressive decline, particularly at dawn. In November, fish chorusing occurred just at dusk and gradually diminished in intensity and duration (Fig. 4; Arrow: WD (winter decline)) until ending in December or early January. Every year, the cycle of the singing pattern restarts in early spring.

The two types of fish choruses were temporally shifted, and their occurrence during the day varied depending on the season. Chorus 1 was exclusively concentrated around dusk hours ( $\sim 18:00$ – $21:00$  hrs.) and displayed a duration of  $\sim 2$ – $3$  h. Chorus 2 varied according to the season and length of the day. It extended from dusk to dawn in spring

( $\sim 22:00$ – $6:00$  hrs.) (Supplementary Material, Figure S1) but lengthened during the summer months (June–August) and overlapped with Chorus 1 (Supplementary Material, Figure S2). In September, Chorus 2 began to gradually reduce in intensity and duration until ending in late autumn ( $\sim$ December) (Supplementary Material, Figure S3).

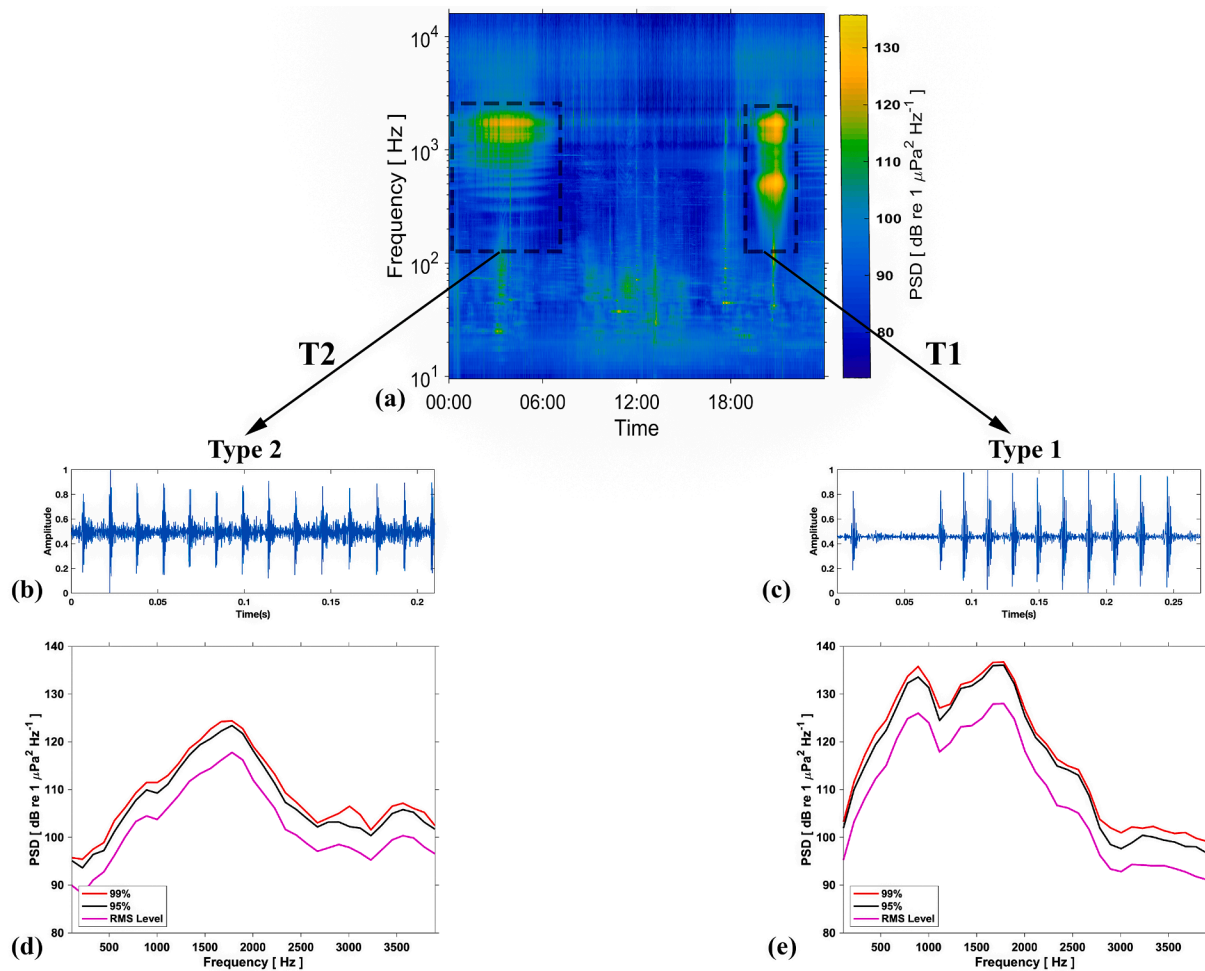
In some of the recording days, we found an increase in H throughout the day. This was particularly evident during August 7th 2015 (Supplementary Material, Figure S4; Label SN – sediment noise) and is related to the high-intensity noise produced by the collision of sediments with the hydrophone (Supplementary Material, Figure S4b).

### 3.4. Effects of temperature on fish chorusing

The fish chorusing was closely related to the sea surface temperature along the diverse seasons in 2017 (Fig. 5). The R evaluated between the seasonal trends of temperature (Fig. 5a) and SPL trend (Fig. 5b) showed the existing close correlation between varying temperature and SPL ( $R_{\text{Spring}} = 0.98$ ,  $R_{\text{Summer}} = 0.97$ ,  $R_{\text{Autumn-Winter}} = 0.96$ ). During spring, the temperature increased from  $\sim 21$  °C to 25 °C and, similarly, SPLs increased from  $\sim 115$  dB to  $\sim 117$  dB. In the summer months, both sea surface temperature and SPLs continued to rise (reaching  $\sim 29$ – $31$  °C and 120 dB, respectively). The transition from autumn to winter was associated with a decrease of the sea surface temperatures, from  $\sim 28$  °C to 21 °C, correspondingly to a parallel decrease of the SPL from  $\sim 117$  dB to  $\sim 110$  dB (Fig. 5).

### 3.5. Effect of moon cycle and tides on fish chorusing

The investigated area was characterized by semidiurnal tides, with two high and low tides per day (Supplementary Material, Figure S5b). The rise in tide height during the full and new moon was associated with an increase in the SPL due to higher chorusing intensity (Fig. 6). The change of temporal chorusing pattern was correlated with the tidal regimes ( $R > 0.6$ ). It is important to note that the dawn choruses appeared to begin just after the full moon lunar phase (e.g., 23rd March 2016 and 11th April 2017; see white circles in Fig. 4). Similarly, the ceasing of the chorusing activity in winter was associated with the full moon event that occurred on 5th January 2015, 2nd January 2016, and 4th November 2017 (Fig. 4, marked as white circles).



**Fig. 3.** (a) Spectrogram depicting chorus types occurring at dawn and dusk hours; color label represents PSD in units of  $\text{dB re } 1 \mu\text{Pa}^2 \text{Hz}^{-1}$ . (b, c) Waveform of individual fish calls of types 1 and 2, occurring at dawn and dusk hours, respectively. (d, e) PSD of individual fish calls of choruses types 1 and 2, respectively. Arrows T1, T2 represent the individual calls Type 1 and Type 2 responsible for the corresponding chorusing marked on the spectrogram. Red and black lines indicate the 99th and 95th percentiles of the PSD. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

### 3.6. Effect of tropical storms on fish chorusing

An increase in wind gust velocity exceeding  $\sim 10\text{--}12$  m/s (Supplementary Material, Figure S5a), observed during tropical storms in the Taiwan Strait, led a higher sea tidal level (Supplementary Material, Figure S5b). In particular, typhoon Merbok occurred on  $\sim 10\text{--}13$ th June 2017 and caused a rise in the wind velocity that reached  $\sim 12\text{--}18$  m/s; the H index did not detect the usual chorusing pattern (Fig. 4d; Labelled as T1). Similarly, during typhoons Nanmadol, Nesat, and Khanon, a disruption in the usual fish chorusing was observed (Fig. 4d; Labelled as T2, T3, T4, respectively).

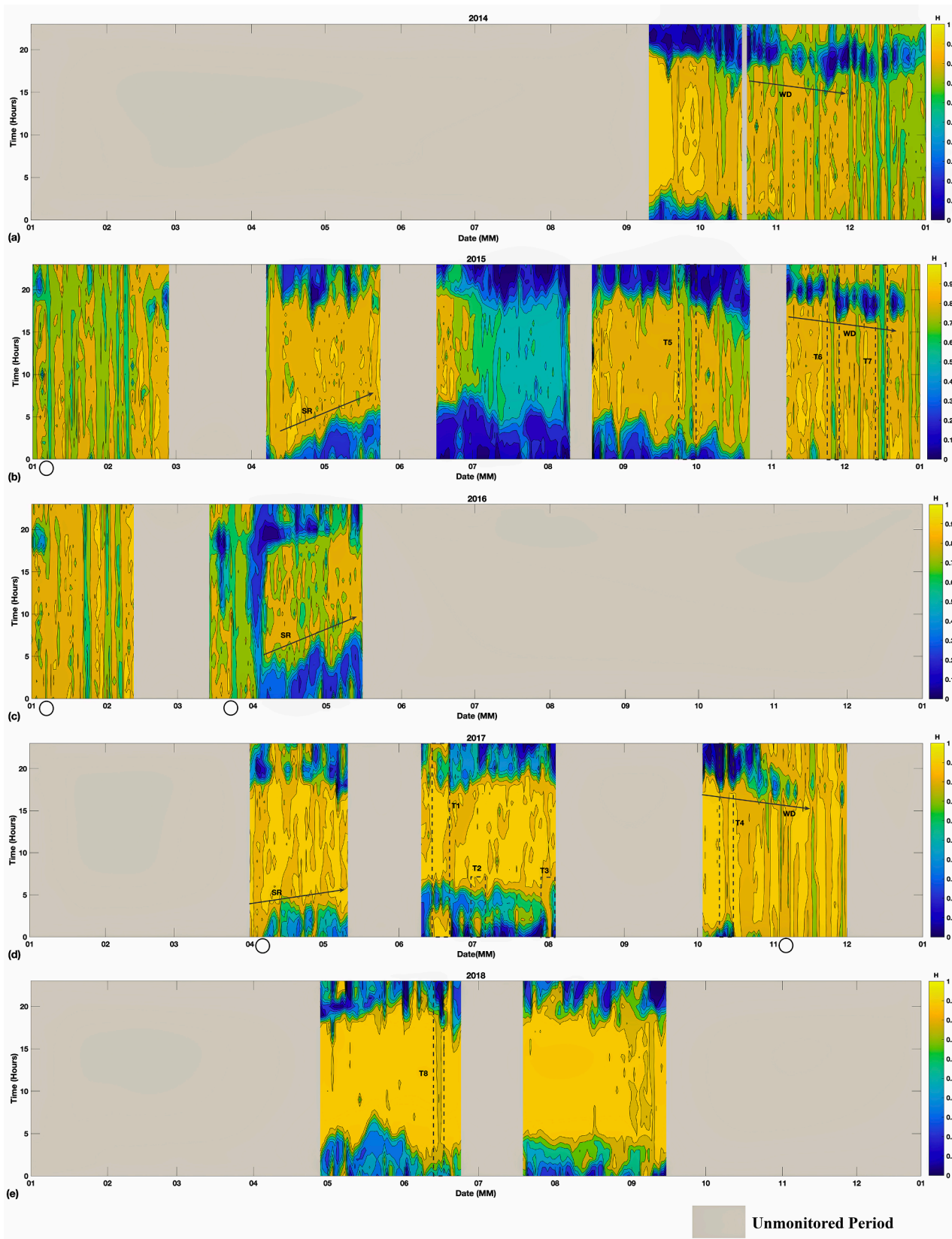
In 2015, typhoons In-fa and Melor coincided with a disruption of the fish chorusing (Fig. 4b; Labelled as T6, T7). This finding was also observed for typhoon Dujan (Fig. 4b; Labelled as T5), which registered a mild increase in levels of the H index ( $\sim 0.5\text{--}0.6$ ) for the entire monitoring duration ( $\sim 1\text{--}2$  days) that was due to sediment particles hitting the sensor. In particular, this increased fish chorusing was noted during super typhoon Dujan (category 4), which occurred from 19th to 30th September, making landfall on Taiwan on the 28th (Fig. 7a). From September 19th, the intensity of the fish chorusing of both Chorus 1 and 2 began to gradually decline ( $\sim 20\text{--}25$  dB), and Chorus 1 was not observed from September 22nd to 29th (Fig. 7c, d). Conversely, from 24th to 25th, we recorded a longer duration of Chorus 2 of approximately two hours (Fig. 7c, d).

When the typhoon crossed the Taiwan island during September

26–29, we observed sediment transportation that hit our microphone. In concomitance, the intensity of the Chorus 2 increased by  $\sim 15$  dB, whereas the duration shortened to approximately two hours (Fig. 7b–d). After the typhoon dissipated (September 30th), Chorus 1 restarted its singing activity, and both Chorus 1 and 2 resumed their typical patterns. Further evidence for the disturbance in the fish chorusing pattern and triggering of the sediment transport occurring during Typhoon Merbo (2017) and Ester (2018) are documented in Supplementary Material, Figures S6 and S7.

## 4. Discussions

Many studies have analyzed the link between the vocalization and phenology of several terrestrial species, but information on marine species is still extremely limited. Because acoustic impedance in seawater is approximately 3710 times higher than in the air, and its propagation in ca. 5 times higher, it is evident that hearing likely represents the main sense controlling the behavior of several vertebrate and invertebrate marine species (Popper, 2003). However, to provide background ambient noise levels, identify species-specific vocalization patterns, and understand the biological and abiotic factors controlling biological sound production, long-term assessments are necessary. Here, we report the results of a long-term (2014–2018) analysis of fish chorusing in the Changhua region, Eastern Taiwan Strait (ETS) through passive acoustic monitoring (PAM), which provides a cost-effective



**Fig. 4.** 3-D contour plots showing distribution of hourly H index on daily basis for the monitoring duration 2014–2018 (a–e); Color labels represent normalized H index at a given time period and hour of the day. Label: WD (Winter Diminish): Depicts diminishing of dusk chorusing as days in winter progress; SR (Spring Rise): Depicts increasing of dawn chorusing as days in spring progress. White circle on x-axis (Date) represents a full moon day. Label T1; T2; T3; T4: Depicts disruption of fish chorusing during typhoons that occurred in the year 2017. Label T5; T6; T7; T8: Depicts triggering of sediment transport during typhoons occurring in 2015 and 2018.

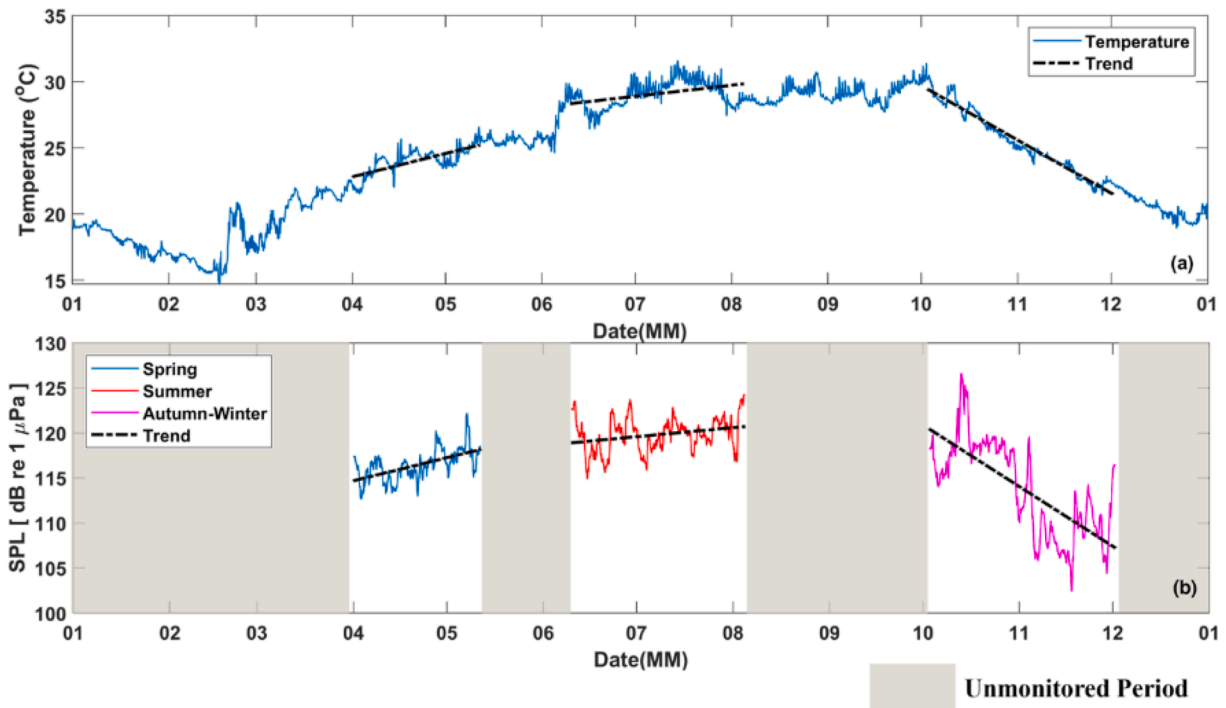


Fig. 5. (a) Annual sea surface temperature variation during the year 2017. (b) Seasonal variation of SPL during the year 2017. Black dotted line represents trend of corresponding temperature and SPL variations.

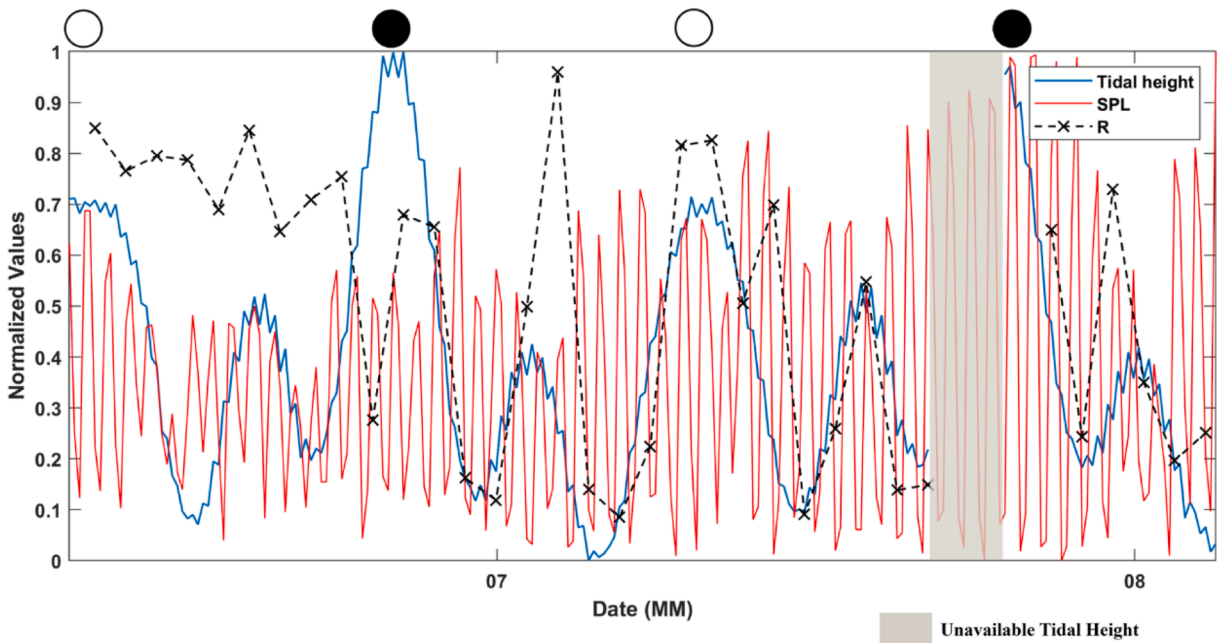
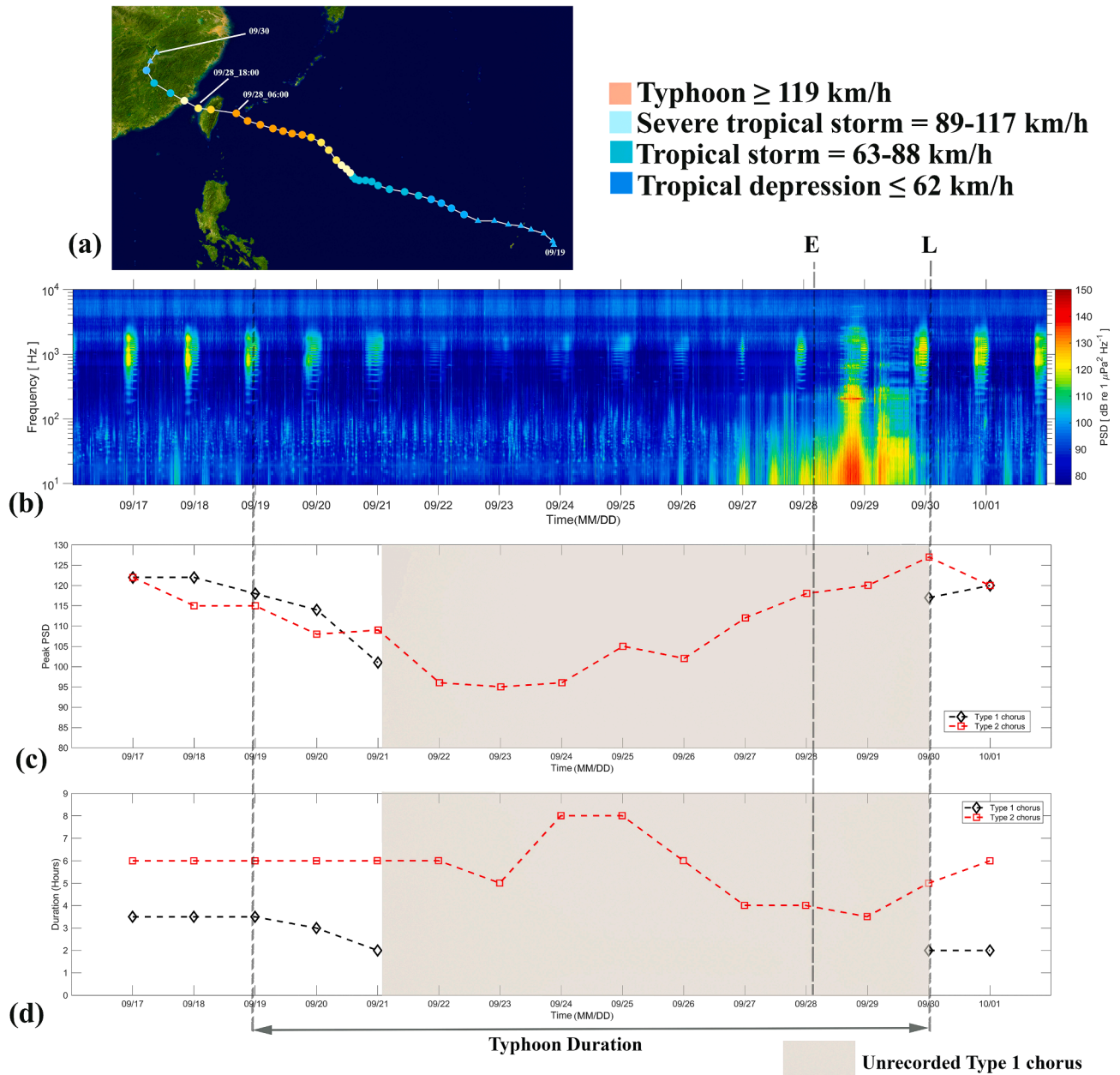


Fig. 6. Normalized tidal height and peak chorusing intensity (SPL) during summer of 2017. Corresponding Pearson correlation coefficient R (computed every 36 h) is represented in dashed black line; white circle depicts full moon, and black circle depicts new moon.

system to monitor a fish population’s response to climatic-driven episodic events.

At Changhua, we found two types of fish choruses, Chorus 1 and Chorus 2, produced respectively by *Johnius taiwanensis* and an unidentified species possibly attributable to the family Sciaenidae, genus *Johnius*, which is largely present in the study area (Chao, et al., 2019). Annually, we found a repetitive seasonal chorusing pattern observed over the five-year monitoring period. The occurrence, duration, and intensity of both choruses were dependent on the season, presenting a

higher peak in summer months. Chorus 2 always began after dusk and varied in length until dawn, whereas Chorus 1 occurred just around dusk. Both choruses peaked in intensity levels during the summer months, had lower intensity and shortened duration in spring and autumn, and were mostly absent in winter. Choruses were synchronized with the season (i.e., starting and stopping during the same period of the year (Fig. 4)). Studies have shown similar yearly patterns for terrestrial animals and proposed the assessment of eventual shifts in acoustic phenology as a cost-effective method for monitoring changes in songbird



**Fig. 7.** Effects of typhoon Dujan on fish chorusing intensity and duration of chorusing. (a) Map depicting typhoon Dujan's path with varying wind speeds; (Right-side) Different colors representing varying intensity of wind speed in km/h. Labels E and L represent when the typhoon enters and leave the monitoring area at Changhua. (b) Spectrogram showing fish chorusing activity before, during, and after the typhoon passed through Taiwan island; color labels represent PSD in units of  $\text{dB re } 1 \mu\text{Pa}^2 \text{Hz}^{-1}$ . (c),(d) Shows peak PSD and duration of chorus types 1 and 2 for corresponding days.

activity (Buxton, 2016). Birds' ability to sense the photoperiod and vary the daily and seasonal vocalization patterns accordingly are well known in the literature (Coppack and Pulido, 2004). Vocal activity in birds is influenced by several other environmental factors, such as temperature, rainfall, and food resources (Bruni et al., 2014). Some of the findings have also documented a lower vocalization rate in birds during times of low temperature (Liao et al., 2018).

Similarly to what happens for birds, the daily and seasonal rhythm of fish chorusing might be influenced by ordinary environmental factors, such as temperature, winds, and tides, or by extraordinary and episodic events, such as intense sediment transport by strong currents, caused due to flooding events or tropical storms (Bailey and Secor, 2016; Sueur et al., 2019).

On short time scales, fish chorusing was influenced by lunar phases and tidal regimes. In particular, we observed an increase in the SPLs of

fish chorusing during the full and new moon (Fig. 6). Similarly, the restart of both choruses in early spring and their ceasing in winter took place after a full moon (Fig. 4). These results confirm the importance of the lunar photoperiod already documented in other research on fish chorusing and other ecological processes (McWilliam, 2017; Numata and Helm, 2015).

The effect of tropical storms on the chorusing behavior of fishes has been debated for a long time (Bailey and D.H.J.S.r. Secor, 2016; Midway, 2012). In this study, we found that tropical storms alter or even cease the typical chorusing activity of fishes (Fig. 7). In particular, typhoons that were triggering significant sediment loads (for  $\sim 2-3$  days; Fig. 7, Supplementary Material, Figure S7) determined the ceasing of activity of Chorus 1, whereas Chorus 2 deviated in intensity and duration from the normal pattern. Tropical storms are becoming more frequent and intense as a result of climate change (Sobel, 2016; Asch,

2015; Stefan Rahmstorf et al., 2018; Gordon, 2018). On the basis of our findings, stronger storms might disrupt choruses, thus interrupting biological interactions such as fish species mating, with several potentially relevant ecological consequences, including spawning, feeding, and communicating. In addition, displacement of sediment particles during storms may result in abrasion of eggs and potential mortality of their offspring (Bailey and Secor, 2016; Birtwell, 1999). Further, sediment transport is associated with an increase of turbidity, which may affect the correct perception of the moonlight (Birtwell, 1999).

We know that water temperature might alter fish behavior, such as vocalization patterns, spawning, and physical and neurophysiological metabolism (Ladich and Fisheries, 2018). In the present study, however, we documented for the first time that the low sea surface temperature of the winter period silenced fish chorusing (Figs. 4 and 5), because when the temperature fell below 21–20 °C, fish choruses tended to reduce in duration and intensity, and a further decrease in temperatures resulted in a total ceasing of fish calls. In the investigated area, we recorded on average ~ 120 days of cold water temperatures during winter months, which are susceptible to cold events caused by strong winds and circulation changes that may have important ecological consequences (Cheng et al., 2018). In our study, we observed that fishes are silent during the cold period. Fish chorusing activity was observed until early January of 2015 and 2016 (Fig. 4b, c). However, in 2017, this activity ceased in early November (Fig. 4d). The shortening of the chorusing activity due to a reduction in water temperature may affect spawning activity and, thus, fish abundance (Asch, 2015; Sueur et al., 2019; Poloczanska, 2008).

This study, via long-term acoustic monitoring of the marine species, showed for the first time clear and periodic short-term and seasonal changes in fish vocalizations, which might overlap with episodic events (such as storms, flooding, and resuspension events). In particular, the close association between chorusing activity and sea surface temperatures or storm events indicates a strong dependence of these marine species to the effects of climate change (Sueur et al., 2019; Ladich and Fisheries, 2018; Harley, 2011), either in terms of the effects due to rising average temperatures and heat waves or in terms of increased frequency and amplitude of the episodic/extreme events, such as flooding and tropical storms, indicating that ongoing climate change could increasingly alter fish behavior and phenology in the coming decades.

The fish chorusing pattern deduced from recordings carried out at Changhua from 2014 to 2018 revealed a consistent seasonal chorusing trend, characterized by the absence of fish choruses in winter, softly starting in spring, peaking in summer, and diminishing in autumn. These long-term vocalization trends obtained with the use of ecoacoustical indicators such as permutation entropy (H) utilized in this study may facilitate understanding the influence of external factors such as rise in noise levels, temperature, and even the impact of extreme events such as increased storms and flooding caused by climatic changes. In 2018, the Taiwan government-approved the “Greater Changhua offshore wind farm project,” which is expected to produce 2.4GW of power by 2026 (Greater Changhua Offshore Wind Farms, 2019). The construction of these offshore wind farms is expected to begin in 2019 and will produce high-intensity noise caused by constructing and pile driving activities. The long-term chorusing trends derived in this study will enable us to understand, in the future, if the noise has triggered any deviation from the normal fish chorusing pattern.

In the future, real-time monitoring could be employed to check the chorusing behavior after high-intensity noise generated by construction activities. If any deviation in the chorusing behavior is observed, noise mitigation measures can be put forward to suppress the noise. Additionally, the temperature rise and increased flooding due to climate change may also cause the fishes’ migration from the monitoring site. A permanent passive monitoring network at the site could enormously boost our understanding of tracking fishes’ migration routes by providing real-time spatial and temporal details of the presence and intensity of the fish choruses (Gibb, 2019).

Determining vocalization trends for monitoring the species’ health has resulted in enormous datasets of acoustic files. Ecoacoustical indicators play a significant role in extracting the vocalizations amidst the various geophony and anthropophony (Pieretti and Danovaro, 1814), proving direct information of the target species. Anthropogenic activities such as construction, windfarm operation, seismic surveys, and mining activities resulted in higher noise levels that overlap with the frequencies in which fish vocalizations occur. Hence, there is an urgent need to develop efficient ecoacoustical indicators capable of extracting the vocalizations present amidst the complex noise source. The long-term chorusing trends obtained in this study via the combination of passive monitored acoustics and ecoacoustical indicators provide essential baseline data to compare future trends in fish chorusing. This data will serve as a starting point for analyzing the impact of noise and climate change on fishes in this region and framing management strategies for future conservation policies.

#### Author contributions

S.S. designed the research, performed the analysis, prepared the figures and drafted the manuscript. C.C.F supervised the manuscript and acquired the funds. W.C.H conducted the field work and data collection. N.P. helped in the interpretation and discussion of the data. N.P and R.D. helped write and edit the manuscript.

#### Experimental Techniques

Data were conducted in the sea by deploying an autonomous passive recorder. The authors claim that this deployment did not cause any hindrance to any species or the environment. The experiments were approved by the National Taiwan University.

#### Data availability

The authors declare that the data supporting the findings of this study are available within the article and its Supplementary Information Files, or are available from the corresponding authors upon request.

#### CRedit authorship contribution statement

**Shashidhar Siddagangaih:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization. **Chi-Fang Chen:** Funding acquisition, Supervision, Project administration. **Wei Chun Hu:** Data curation. **Roberto Danovaro:** Writing - review & editing, Conceptualization. **Nadia Pieretti:** Conceptualization, Methodology, Validation, Formal analysis, Writing - original draft, Writing - review & editing, Visualization, Supervision.

#### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

#### Acknowledgements

This work was supported by Ministry of Science and Technology (MOST) under national energy program phase II (NEPII) under the grant numbers MOST 103-3113-E-002-002-CC2, MOST 104-3113-E-002-002-CC2, MOST 105-3113-E-002-002-CC2 with funding to Chen Chi Fang. The fellowship from MOST to Shashidhar under the grant number MOST 106-2811-E-002-077.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolind.2021.107456>.

## References

- Asch, R.G., 2015. Climate change and decadal shifts in the phenology of larval fishes in the California Current ecosystem. *Proc. Natl. Acad. Sci.* 112 (30), E4065–E4074.
- Au, W.W., Banks, K., 1997. The acoustics of snapping shrimps. 1997, ASA.
- Bailey, H., Secor, D.H.J.S.R. 2016. Coastal evacuations by fish during extreme weather events. 6: p. 30280.
- Bandt, C., Pompe, B., 2002. Permutation entropy: A natural complexity measure for time series. *Phys. Rev. Lett.* 88 (17), 174102.
- Birtwell, I.K. 1999. The Effects of Sediment on Fish and Their Habitat. Fisheries and Oceans Canada.
- Bruni, A., Mennill, D.J., Foote, J.R., 2014. Dawn chorus start time variation in a temperate bird community: relationships with seasonality, weather, and ambient light. *J. Ornithol.* 155 (4), 877–890.
- Burivalova, Z., Game, E.T., Butler, R.A., 2019. The sound of a tropical forest. *Science* 363 (6422), 28–29.
- Buscaino, G., et al., 2015. Acoustic signals and behaviour of *Ovalipes trimaculatus* in the context of reproduction. *Aquat. Biol.* 24 (1), 61–73.
- Buscaino, G., et al., 2016. Temporal patterns in the soundscape of the shallow waters of a Mediterranean marine protected area. *Sci. Rep.* 6, 34230.
- Buxton, R.T., et al., 2016. Using bioacoustics to examine shifts in songbird phenology. *Ecol. Evol.* 6 (14), 4697–4710.
- Cato, D.H., 1978. Marine biological choruses observed in tropical waters near Australia. *J. Acoust. Soc. Am.* 64 (3), 736–743.
- Cato, D. 1969. Ambient sea noise in the eastern Timor Sea. Royal Australian Navy Research Laboratories. Technical note.
- Chao, N.L., et al. 2019. *Johnius taiwanensis*, a new species of Sciaenidae from the Taiwan Strait, with a key to *Johnius* species from Chinese waters. *Zootaxa* 4651(2): p. zootaxa. 4651.2. 3-zootaxa. 4651.2. 3.
- Cheng, Y.-H., Chang, M.-H.J.N.H., Sciences, E.S. 2018. Exceptionally cold water days in the southern Taiwan Strait: their predictability and relation to La Niña. 18(7): pp. 1999–2010.
- Coppack, T., Pulido, F., 2004. Photoperiodic response and the adaptability of avian life cycles to environmental change. *Adv. Ecol. Res.* 35, 131–150.
- D'spain, G., and, H., Batchelor., 2006. Observations of biological choruses in the Southern California Bight: A chorus at midfrequencies. *J. Acoust. Soc. Am.* 120 (4), 1942–1955.
- Erbe, C., et al., 2015. The marine soundscape of the Perth Canyon. *Prog. Oceanogr.* 137, 38–51.
- Fairbrass, A.J., et al., 2017. Biases of acoustic indices measuring biodiversity in urban areas. *Ecol. Ind.* 83, 169–177.
- Farina, A. 2013. *Soundscape ecology: principles, patterns, methods and applications*. Springer.
- Gage, S.H., Axel, A.C., 2014. Visualization of temporal change in soundscape power of a Michigan lake habitat over a 4-year period. *Ecol. Inf.* 21, 100–109.
- Gibb, R., et al., 2019. Emerging opportunities and challenges for passive acoustics in ecological assessment and monitoring. *Methods Ecol. Evol.* 10 (2), 169–185.
- Gordon, T.A., et al., 2018. Habitat degradation negatively affects auditory settlement behavior of coral reef fishes. *Proc. Natl. Acad. Sci.* 115 (20), 5193–5198.
- Greater Changhua Offshore Wind Farms. 2019 [cited 2019 26 November]; Available from: <https://www.power-technology.com/projects/greater-changhua-offshore-wind-farms/>.
- Halliday, W.D., et al., 2017. Seasonal patterns in acoustic detections of marine mammals near Sachs Harbour, Northwest Territories. *Arctic Sci.* 1–20.
- Harley, C.D.J.S. 2011. Climate change, keystone predation, and biodiversity loss, 334 (6059): pp. 1124–1127.
- Hastings, P.A., Sirović, A., 2015. Soundscapes offer unique opportunities for studies of fish communities. *Proc. Natl. Acad. Sci.* 112 (19), 5866–5867.
- Haver, S.M., et al., 2018. Monitoring long-term soundscape trends in US Waters: The NOAA/NPS ocean noise reference station network. *Marine Pol.* 90, 6–13.
- Helfman, G.S., 1986. Fish behaviour by day, night and twilight. In: *The Behaviour of Teleost Fishes*. Springer, pp. 366–387.
- Krause, B., 1987. Bioacoustics, habitat ambience in ecological balance. *Whole Earth Rev.* 57, 14–18.
- Ladich, F.J.F., Fisheries. 2018. Acoustic communication in fishes: Temperature plays a role, 19(4): pp. 598–612.
- Liao, C.-C., Shieh, B.-S., Chen, C.-C., 2018. Air temperature influenced the vocal activity of birds in a subtropical forest in southern Taiwan. *Taiwan J. For. Sci.* 33, 291–304.
- Lin, Y.C., Mok, H.K., Huang, B.Q., 2007. Sound characteristics of big-snout croaker, *Johnius macrorhynchus* (Sciaenidae). *J. Acoust. Soc. Am.* 121 (1), 586–593.
- Lindseth, A.V., Lobel, P.S., 2018. Underwater soundscape monitoring and fish bioacoustics: A review. *Fishes* 3 (3), 36.
- Mann, D.A., Lobel, P.S., 1997. Propagation of damselfish (*Pomacentridae*) courtship sounds. *J. Acoust. Soc. Am.* 101 (6), 3783–3791.
- Mann, D., Locascio, J., 2006. Chorusing in fishes. *J. Acoust. Soc. Am.* 119 (5).
- McCauley, R., 2012. Fish choruses from the Kimberley, seasonal and lunar links as determined by long term sea noise monitoring. *Proceedings of the Acoustical Society of Australia*.
- McWilliam, J.N., et al., 2017. Patterns of biophonic periodicity on coral reefs in the Great Barrier Reef. *Sci. Rep.* 7 (1), 17459.
- McWilliam, J.N., et al., 2018. Soundscape diversity in the Great Barrier Reef: Lizard Island, a case study. *Bioacoustics* 27 (3), 295–311.
- Merchant, N.D., et al., 2015. Measuring acoustic habitats. *Methods Ecol. Evol.* 6 (3), 257–265.
- Merchant, N.D., et al., 2016. Underwater noise levels in UK waters. *Sci. Rep.* 6, 36942.
- Midway, S. 2012. Hurricane Impacts on Fish. *Ecology: Organisms & Habitats, Threat to Fisheries* [cited 2020 30 May]; Available from: <https://thefisheriesblog.com/2012/11/hurricane-impacts-on-fish/>.
- Morisette, J.T., et al., 2009. Tracking the rhythm of the seasons in the face of global change: phenological research in the 21st century. *Front. Ecol. Environ.* 7 (5), 253–260.
- Mullet, T.C., et al., 2016. Temporal and spatial variation of a winter soundscape in south-central Alaska. *Landscape Ecol.* 31 (5), 1117–1137.
- Numata, H., Helm, B. 2015. *Annual, Lunar, and Tidal Clocks: Patterns and Mechanisms of Nature's Enigmatic Rhythms*. Springer.
- Oliver, R.Y., et al., 2018. Eavesdropping on the Arctic: Automated bioacoustics reveal dynamics in songbird breeding phenology. *Sci. Adv.* 4 (6).
- Pieretti, N., et al., 2015. Determining temporal sampling schemes for passive acoustic studies in different tropical ecosystems. *Trop. Conserv. Sci.* 8 (1), 215–234.
- Pieretti, N., et al., 2017. Marine soundscape as an additional biodiversity monitoring tool: a case study from the Adriatic Sea (Mediterranean Sea). *Ecol. Ind.* 83, 13–20.
- Pieretti, N., Danovaro, R., 2014. Acoustic indexes for marine biodiversity trends and ecosystem health. *Philos. Trans. R. Soc. B* 2020 (375), 20190447.
- Pieretti, N., Farina, A., Morri, D., 2011. A new methodology to infer the singing activity of an avian community: The Acoustic Complexity Index (ACI). *Ecol. Ind.* 11 (3), 868–873.
- Pijanowski, B.C., et al., 2011. What is soundscape ecology? An introduction and overview of an emerging new science. *Landscape Ecol.* 26 (9), 1213–1232.
- Poloczanska, E.S., et al. 2008. Modeling the response of populations of competing species to climate change, 89(11): pp. 3138–3149.
- Popper, A.N., et al., 2003. Anthropogenic sound: Effects on the behavior and physiology of fishes. *Mar. Technol. Soc. J.* 37 (4), 35–40.
- Putland, R., Constantine, R., Radford, C., 2017. Exploring spatial and temporal trends in the soundscape of an ecologically significant embayment. *Sci. Rep.* 7 (1), 5713.
- Rahmstorf, S., 2017. Rising hazard of storm-surge flooding. *Proc. Natl. Acad. Sci.* 114 (45), 11806–11808.
- Rice, A.N., Soldevilla, M.S., Quinlan, J.A., 2017. Nocturnal patterns in fish chorusing off the coasts of Georgia and eastern Florida. *Bull. Mar. Sci.* 93 (2), 455–474.
- Ruppé, L., et al., 2015. Environmental constraints drive the partitioning of the soundscape in fishes. In: *Proceedings of the National Academy of Sciences*, p. 201424667.
- Siddagangaiah, S., et al., 2019. A complexity-entropy based approach for the detection of fish choruses. *Entropy* 21 (10), 977.
- Siddagangaiah, S., et al., 2020. Automatic detection of dolphin whistles and clicks based on entropy approach. *Ecol. Ind.* 117, 106559.
- Sippel, S., Lange, H., Gans, F. 2016. *statcomp: Statistical Complexity and Information Measures for Time Series Analysis*. R package version.
- Sobel, A.H., et al., 2016. Human influence on tropical cyclone intensity. *Science* 353 (6296), 242–246.
- Stefan Rahmstorf, K.E., Mike Mann, Jim Kossin. 2018. Does Global Warming Make Tropical Cyclones Stronger? 30 May. Available from: <http://www.realclimate.org/index.php/archives/2018/05/does-global-warming-make-tropical-cyclones-stronger/>.
- Sueur, J., Farina, A., 2015. Ecoacoustics: the ecological investigation and interpretation of environmental sound. *Bioacoustics* 8 (3), 493–502.
- Sueur, J., Krause, B., Farina, A., 2019. Climate change is breaking earth's beat. *Trends Ecol. Evol.* 34 (11), 971–973.
- Towsey, M., et al., 2014. Visualization of long-duration acoustic recordings of the environment. *Procedia Comput. Sci.* 29, 703–712.
- Towsey, M., et al., 2014. The use of acoustic indices to determine avian species richness in audio-recordings of the environment. *Ecol. Inf.* 21, 110–119.
- Van Oosterom, L., et al., 2016. Evidence for contact calls in fish: conspecific vocalisations and ambient soundscape influence group cohesion in a nocturnal species. *Sci. Rep.* 6, 19098.
- Versluis, M., et al., 2000. How snapping shrimp snap: through cavitating bubbles. *Science* 289 (5487), 2114–2117.
- Villanueva-Rivera, L.J., et al., 2011. A primer of acoustic analysis for landscape ecologists. *Landscape Ecol.* 26 (9), 1233.
- Wenlan, D., 1983. The characteristics of the tides and tidal currents in the Taiwan Strait. *J. Oceanogr. Taiwan Strait* 2.
- Wu, C.-R., Chao, S.-Y., Hsu, C., 2007. Transient, seasonal and interannual variability of the Taiwan Strait current. *J. Oceanogr.* 63 (5), 821–833.
- Wyllie, D. 1971. Sea noise measurements in the Coral, Solomon, and Bismarck Seas-1970. Australian Defence Weapons Research Establishment, Technical memorandum, 1971: pp. 4–32.
- Zhang, W.-Z., Hong, H.-S., Yan, X.-H., 2013. Typhoons enhancing northward transport through the Taiwan Strait. *Cont. Shelf Res.* 56, 13–25.
- Zilang, F., Jianyu, H., Guoming, Y., 1991. Seawater flux through Taiwan Strait. *Chin. J. Oceanol. Limnol.* 9 (3), 232–239.