

Statistics of underwater ambient noise at high sea states arisen from typhoon out zones in the Philippine Sea and South China Sea

Qiulong Yang^{1, 2, 3*}, Kunde Yang^{1, 2*}, Shunli Duan^{1, 2}, Yuanliang Ma^{1, 2}

¹ School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an 710072, China

² Key Laboratory of Ocean Acoustics and Sensing, Ministry of Industry and Information Technology, Xi'an 710072, China

³ Key Laboratory of Marine Environmental Information Technology, Ministry of Natural Resources, Tianjin 300171, China

Received 31 December 2020; accepted 10 November 2021

© Chinese Society for Oceanography and Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract

Oceanic noise is the background interference in sonar performance prediction and evaluation at high sea states. Statistics of underwater ambient noise during Typhoons Soulik and Nida were analyzed on the basis of experimental measurements conducted in a deep area of the Philippine Sea and the South China Sea. Generated linear regression, frequency correlation matrix (FCM), Burr distribution and Gumbel distribution were described for the analysis of correlation with environmental parameters including wind speed (WS), significant wave height (SWH), and the inter-frequency relationship and probability density function of noise levels (NLs). When the typhoons were quite close to the receivers, the increment of NLs exceeded 10 dB. Whilst ambient noise was completely dominated by wind agitation, NLs were proportional to the cubic and quintic functions of WS and SWH, respectively. The fitted results between NLs and oceanic parameters were different for “before typhoon” and “after typhoon”. The fitted slopes of linear regression showed a linear relationship with the logarithm of frequency. The average observed typhoon-generated NLs were 5 dB lower than the Wenz curve at the same wind force due to the insufficiently developed sea state or the delay between NLs and WS. The cross-correlation coefficient of FCM, which can be utilized in the identification of noise sources in different bands, exceeded 0.8 at frequencies higher than 250 Hz. Furthermore, standard deviation increased with frequency. The kurtosis was equal to 3 at >400 Hz approximately. The characteristics of NLs showed good agreement with the results of FCM.

Key words: statistics, underwater acoustics, cruise-measured ambient noise, typhoon, Philippine Sea, South China Sea, deep ocean

Citation: Yang Qiulong, Yang Kunde, Duan Shunli, Ma Yuanliang. 2022. Statistics of underwater ambient noise at high sea states arisen from typhoon out zones in the Philippine Sea and South China Sea. *Acta Oceanologica Sinica*, 41(7): 153–165, doi: 10.1007/s13131-022-1991-7

1 Introduction

Successfully forecasting typhoon intensity is of paramount importance in ensuring minimal damage to lives and properties. The knowledge on ambient noise at high sea states is useful in optimizing sonar performance and acquiring the Green function and sound speed profile (SSP) in an ocean waveguide (Brooks and Gerstoft, 2009). The highly complex physical processes associated with typhoon ocean interactions were investigated in the impact of typhoons on the ocean in the Pacific systematically (Pun et al., 2011; D'Asaro et al., 2014). Cyclonic eddies tend to promote upwelling, mixing and sea surface temperature (SST) cooling. SST cooling or wind wave agitation accumulates over time within the tropical cyclone inner-core (Jullien et al., 2014). Sound of short and long period double frequencies lower than 0.5 Hz are induced by the wave interaction generated by

typhoons. Gravity wave interacts with the seafloor and couples into wind-generated seismic surface and body waves (Lin et al., 2017; Gerstoft and Bromirski, 2016).

The relationship between noise and environmental parameters has been extensively measured and researched over the past decades. Noise levels (NLs) during extreme wind conditions were measured in the northern Gulf of Mexico during the summers of 2001 and 2002 with three environmental acoustic recording systems deployed by the Littoral Acoustic Demonstration Center (Newcomb et al., 2004). Underwater noise data on typhoon intensities were collected by passive aquatic listeners on possible typhoon paths (Ma and Yang, 2009). NLs show a better correlation with wind speed (WS) than wave height during cyclone crossing (Sanjana et al., 2014). The correlation coefficient between ocean ambient NLs and WS during a typhoon event is

Foundation item: The Project of Global Change and Air-Sea Interaction under contract No. D5120210106; the Open Fund Project of Key Laboratory of Marine Environmental Information Technology, Ministry of Natural Resources of the People's Republic of China under contract No. D5110200611; the Fundamental Research Funds for the Central Universities under contract No. 3102019HHZY030011; the China Postdoctoral Science Foundation under contract No. 2019M663822; the National Natural Science Foundation of China under contract Nos 11574251 and 11704313.

*Corresponding author, E-mail: yangqiulong@nwpu.edu.cn; ykdzym@nwpu.edu.cn

much better than that during non-typhoon periods under the same Beaufort scale (Wen et al., 2016). Underwater ambient NLs beneath tropical cyclones often indicate a complex dependence on WS. The intensity of underwater sound in 10–50 Hz band with a hydrophone deployed at 800 m from a 4 700 m deep sea floor below a hurricane is approximately proportional to the cube of local WS through linear regression (Wilson and Makris, 2008; Širović et al., 2013), which is often employed for analyzing the relationship between long-term low-frequency NLs and local WS (Farrokhrooz et al., 2017). On the basis of the relationship, the destructive power of a cyclone can be quantified and classified with oceanic noise (Chan and Chen, 2012; Wilson and Makris, 2006; Cauchy et al., 2018). However, a noise spectrum higher than 10 kHz decreases with increasing WS above 15 m/s due to breaking waves and quiescent bubbles (Zhao et al., 2014; Farmer and Lemon, 1984). The power spectrum and time series of the chopped portions of ambient noise, pertaining to heavy and light rainfall drops, were analyzed and showed prominently different characteristics during a cyclonic storm in the coast of India (Ashokan et al., 2018).

Numerical modelling, correlation matrices (CMs), statistical distribution and clustering analysis have been used in oceanic noise analysis during a cyclone. The power of local WS with respect to NLs in simulations based on a modified normal model agrees well with the experimental data in a range-independent environment (Wang and Li, 2015). Li et al. (2018) proposed a modified wind-generated numerical noise model based on bubble oscillations within arbitrarily-shaped bubble clouds entrained in the water of a few meters. The model could explain the observed data during the period of a tropical cyclone. Yang et al. (2018a, b) obtained different wind-driven noise source levels based on real data during the typhoon period in two regions. They described that the noise field were the weighted results of wind-driven and distant shipping noise fields. CMs, manual selection of noise spectra and principal component analysis, were utilized to determine the primary contributors to the ambient noise for frequency lower than 100 Hz (Nichols and Bradley,

2019). Asolkar et al. (2016, 2017) presented an ambient noise probability density function (PDF) model based on the SST statistical distribution. α stable distribution with a quantile-based method and the characteristic function was applied to the statistical modeling of the three typical underwater noise time series (Song et al., 2019). The term of exceedance levels and k-medoid clustering were utilized to determine the effect of noise sources on the background NLs (Farrell et al., 2017).

In the present study, the statistics of ambient noise arising from typhoon out zones at high sea states in the Philippine Sea and the South China Sea are analyzed. The rest of the paper is organized as follows. Section 2 describes the cruise experimental measurement and data processing. Section 3 presents the statistics including the relationship between NL and WS or significant wave height (SWH), comparison with the Wenz curve, frequency correlation matrix (FCM) and PDF during a typhoon period. Section 4 discusses the probable reason for different statistical phenomena in two experiments. Section 5 draws out the conclusions.

2 Cruise observation and data processing

Two experiments were conducted to measure the ambient noise generated by a typhoon in deep ocean. One experiment was conducted on July 1–15, 2013 in the Philippine Sea of the western Pacific (WP2013). Two omnidirectional hydrophones were moored near the bottom at a depth of 5 050 m with a pressure sensor. The hydrophone sensitivity and sample rate were -170 dB re $1\text{v}/\mu\text{Pa}$ (with preamp) and 8 kHz, respectively. The sea depth was approximately 5 300 m. Another experiment was conducted from July 29 to August 11, 2016 in the north of South China Sea (SCS2016). Omnidirectional receiver hydrophones with a sample rate of 20 kHz, sensitivity of -168 dB re $1\text{v}/\mu\text{Pa}$ (also with preamp), and a receiver depth of 300 m, were deployed. The frequency characteristics of the receiver hydrophone are flat from 10 Hz to 10 000 Hz. The sea depth was approximately 2 300 m. The receivers continuously recorded ambient noise in both experiments. Figure 1a shows the schematic of

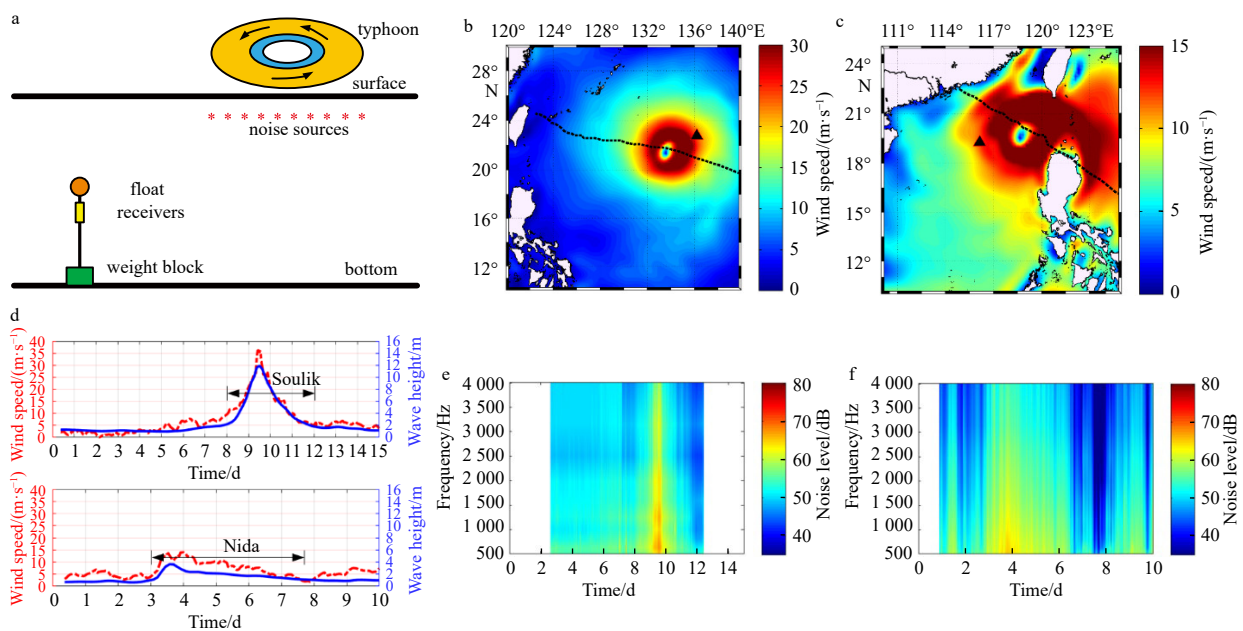


Fig. 1. Experimental measurement and received noise level (NL). a. Schematic of experiment; b. wind field and trace of Typhoon Soulik; c. wind field and trace of Typhoon Nida; d. ocean meteorological parameters; e. NL, in WP2013; f. NL, in SCS2016. The black triangle denotes receiver position.

the experiments.

During ambient noise measurement, Typhoons Soulik and Nida passed by the receivers in WP2013 and SCS2016, respectively. Figures 1b and c show the moving trace of the typhoons in the experiments. The typhoon trace data were obtained from the China Meteorological Administration tropical cyclone database (Yang et al., 2014). The black triangle denotes the positions of deployed receivers, which were (22.8°N, 136.2°E) and (19.2°N, 116.1°E) in WP2013 and SCS2016, respectively. In accordance with the intensity criterion, Soulik belonged to a super typhoon, and Nida was classified as a typhoon. Figure 1d shows the corresponding ocean meteorological parameters, including WS and SWH. These parameters were obtained from the reanalysis database of the National Centers for Environmental Prediction (NCEP) and the output of WAVEWATCHIII. The WS and wave height data were interpolated in accordance with the time interval of noise data processing, and were also 2D interpolated to the experiment site in space. The time duration was indicated by black arrows. The shortest distances between the typhoon centers and receivers were approximately 370 km and 470 km. The circle radiuses at wind force 7 were 380 km and 250 km for Soulik and Nida, respectively. WS and SWH reached their maximum values at the shortest distance between the typhoons and receivers. The maximum WS and SWH above the receivers in WP2013 were 20 m/s and 10 m greater than those in SCS2016, respectively. The correlation coefficients between WS and SWH in the both experiments were greater than 0.9 during the typhoons periods.

The received NLs are shown in Figs 1e and f in the time-frequency domain. The NLs were calculated for consecutive 20 s interval from each 2-min raw datum. The Hamming window was used to obtain segments of 20 s time series. Fast Fourier transform was applied to the noise samples, and the number of Fourier points was the data length. Then, the noise data were computed as spectrum levels with units of dB re 1 $\mu\text{Pa}^2/\text{Hz}$ and the mean results in 1/3 octave frequency band. When the typhoons were quite close to the receivers, the NLs increased and the increment exceeded 10 dB. After the typhoons stopped affecting

the ambient noise, because of low WS and low distant shipping density, the received NLs reached their minimum values, which were 5 dB lower than those when the typhoons started to affect the ambient noise. This result was attributed to the contamination of received NLs by distant shipping noise before the typhoons. Then, the NLs started to increase because the distant ship density increased. The global trend of NLs was proportional to corresponding WS and SWH. The numbers of total samples of WP2013 and SCS2016 in this paper were 5 518 and 8 080, respectively.

3 Statistical results of typhoon-generated noise

3.1 Wind speed dependence

In this paper, the highest SWH or WS was selected as the breakpoint, and the measured ambient noise data during the typhoon periods was divided into two parts, namely, that measured before typhoon and after typhoon. The relationship between NLs and local WS was analyzed with linear regression with least mean square (LMS). The power was defined as the exponent of WS or SWH in the analyses. Local WS of 20 m/s, which is an evident turning point, was selected as the critical point. Then piecewise linear fitting was used in WP2013. For SCS2016, the maximum WS was lower than 15 m/s. Thus, piecewise linear fitting was unnecessary. Figures 2a, b, d and e show the relationship between the noise spectrum levels and WS before and after typhoons at 500 Hz and 1 000 Hz in WP2013 and SCS2016. A linear relationship was observed clearly between NLs and the logarithm of WS. The slope between NLs and the logarithm of WS before typhoons was lower than that after typhoons from 400 Hz to 10 kHz. This result indicates that the increment rate of NLs before typhoons is lower than the decrement rate after typhoon. In addition, the NLs after typhoons at a low WS were less than those before typhoon. The condition was attributed to the fact that the NLs before typhoon were contaminated by distant shipping noise at a low WS probably at the beginning. By contrast, the NLs after typhoons were dominated by wind-driven noise sources due to the decline in distant shipping density.

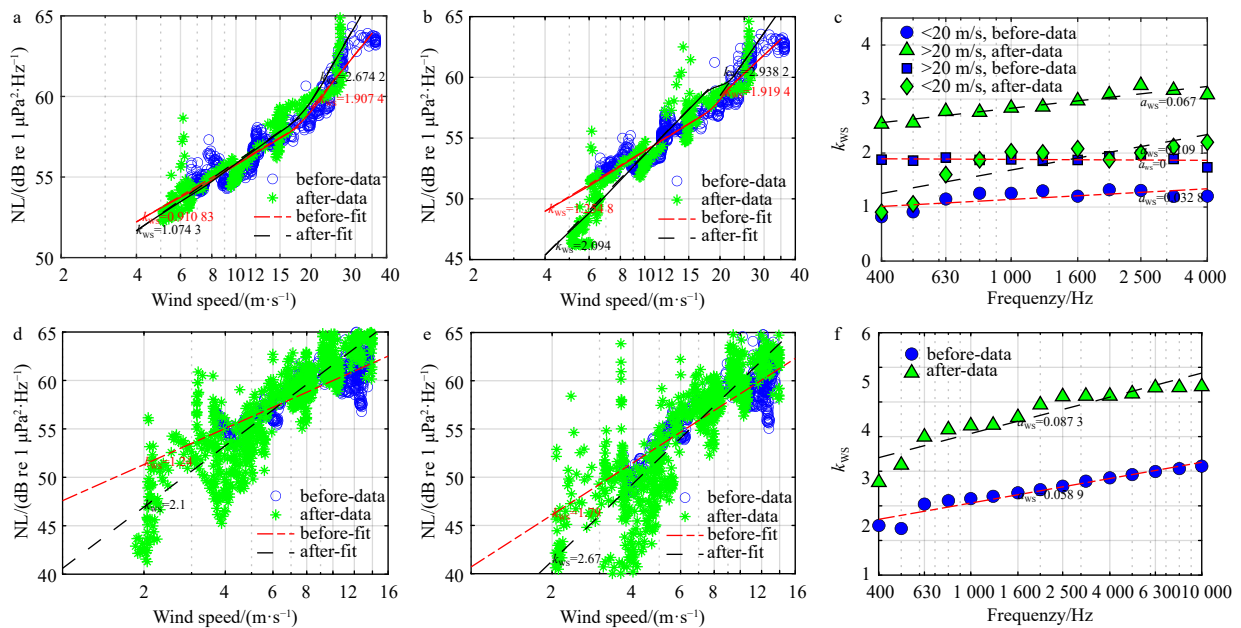


Fig. 2. Relationship between noise levels (NLs) and local wind speed (WS). a. 500 Hz in WP2013; b. 1 000 Hz in WP2013; c. frequency dependence in WP2013; d. 500 Hz in SCS2016; e. 1 000 Hz in SCS2016; f. frequency dependence in SCS2016.

Figures 2c and f show the frequency dependence of the slopes between NLs and local WS. For WS greater than 20 m/s, the power of local WS approached 3 at frequencies higher than 1 600 Hz after typhoon in WP2013. A power law relationship with a consistent high correlation was observed. However, before typhoon, the maximum power was approximately about 2 for WS higher than 20 m/s because NLs first increased and then persisted or decreased with WS due to the effect of quiescent bubbles and breaking waves. The results after typhoon in SCS2016 were qualitatively consistent with those after typhoon in WP2013 when WS was higher than 20 m/s. Moreover, the results were similar to those in WP2013 when WS was lower than 20 m/s before typhoon. At frequencies higher than 1 600 Hz after typhoon in both experiments, NLs were completely dominated by wind-driven noise sources. The measured noise intensity was approximately proportional to the cubic function of local WS. The distant noise sources might contaminate the NLs before typhoon through deep sea channel. The power of the local WS was lower than 3 and has a close relationship with the content affected by distant noise sources.

For before typhoon and after typhoon, the fitted slopes between NLs and WS showed an approximately linear relationship with the logarithm of frequency and increased with frequency. Overall, NLs can be formulated with local WS as follows:

$$\begin{cases} NL(f) = S_{WS}(f) + k_{WS}(f) \times 10 \log_{10} WS \\ k_{WS}(f) = a_{WS} \times 10 \log_{10} f + b_{WS} \end{cases}, \quad (1)$$

where NL and WS represent the received noise level and wind speed, respectively; f is the frequency in Hz; $k_{WS}(f)$ is the power of WS; and $S_{WS}(f)$, a_{WS} and b_{WS} are constants. Table 1 shows the power-fitting results between NLs and WS during the typhoon periods.

3.2 SWH dependence

Analogously, the relationship between NLs and the local SWH was analyzed with linear regression with LMS. A clear turning

Table 1. Power-fitting results between noise levels and wind speed

Frequency/Hz	WP2013				SCS2016	
	<20 m/s		>20 m/s		<20 m/s	
	before	after	before	after	before	after
400	0.82	0.91	1.88	2.54	1.31	2.84
500	0.91	1.07	1.91	2.67	1.24	2.10
630	1.15	1.60	1.92	2.77	1.53	2.50
800	1.26	1.88	1.87	2.76	1.58	2.60
1 000	1.25	2.02	1.88	2.83	1.60	2.66
1 250	1.30	2.00	1.86	2.85	1.64	2.67
1 600	1.20	2.08	1.87	2.97	1.69	2.78
2 000	1.32	1.88	1.94	3.08	1.73	2.96
2 500	1.31	2.00	1.97	3.25	1.78	3.08
3 150	1.19	2.12	1.89	3.16	1.87	3.09
4 000	1.20	2.20	1.74	3.08	1.90	3.09
5 000	–	–	–	–	1.95	3.12
6 300	–	–	–	–	2.01	3.21
8 000	–	–	–	–	2.04	3.22

Note: – denotes null on account of a limited sample rate.

point was visible at the SWH of 8.5 m in WP2013. The value corresponded to a WS of 20 m/s. The SWH of 8.5 m was selected as the breakpoint, and piecewise linear fitting was used in WP2013. A linear relationship was observed between NLs and the logarithm of SWH before and after typhoon for frequencies of 500 Hz and 1 000 Hz as shown in Figs 3a, b, d and e. The linear slope was dependent on frequency. The slopes before typhoon were less than those after typhoon for given frequencies higher than 400 Hz. The slopes between NLs and the logarithm of SWH before typhoon was lower than that after typhoon above 400 Hz.

Figures 3c and f show the frequency dependence of the slope between the NLs and the logarithm of SWH before typhoon and after typhoon. The fitted slopes between NLs and SWH showed an approximately linear relationship with the logarithm of frequency and increased with frequencies. For SWH greater than 8.5 m,

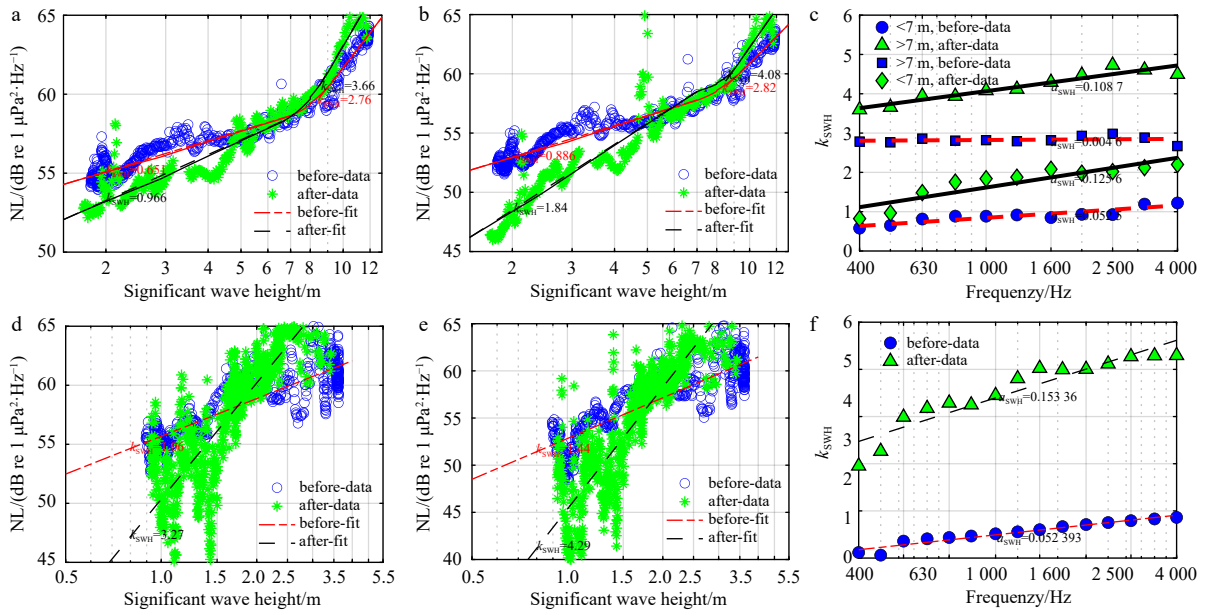


Fig. 3. Relationship between noise levels (NLs) and local significant wave height (SWH). a. 500 Hz in WP2013; b. 1 000 Hz in WP2013; c. frequency dependence in WP2013; d. 500 Hz in SCS2016; e. 1 000 Hz in SCS2016; f. frequency dependence in SCS2016.

the power of local SWH approached 5 for frequencies higher than 1 600 Hz after typhoon in WP2013. Before typhoon, the maximum power was approximately 2.2 for SWH higher than 8.5 m due to bubbles. The results after typhoon in SCS2016 were qualitatively consistent with those after typhoon in WP2013 for SWH higher than 8.5 m. The outcomes before typhoons in WP2013 and SCS2016 were similar for SWH lower than 8.5 m. NLs were completely dominated by wind-driven breaking wave noise sources for frequencies higher than 1 600 Hz in both experiments after typhoon. The measured noise intensity was proportional to the quintic function of the local SWH. However, when the distant noise sources contaminated the NLs, the power of local SWH with respect to NLs was less than 5 and was related to the constant affected by other noise sources.

In sum, the relationship between NLs and SWH can be expressed as follows:

$$\begin{cases} \text{NL}(f) = S_{\text{SWH}}(f) + k_{\text{SWH}}(f) \times 10 \log_{10} \text{SWH} \\ k_{\text{SWH}}(f) = a_{\text{SWH}} \times 10 \log_{10} f + b_{\text{SWH}} \end{cases}, \quad (2)$$

where NL and SWH represent the received noise level and significant wave height, respectively; f is the frequency in Hz; $k_{\text{SWH}}(f)$ is the power of SWH; and $S_{\text{SWH}}(f)$, a and b are constants. Table 2 shows the power-fitting results between NLs and SWH during the typhoon periods.

3.3 Comparison with the Wenz curve

Figure 4 shows the experimental NLs at different wind force scales during typhoon periods. When the wind force increases a scale, NLs increase approximately 2 dB above 500 Hz. However, in SCS2016, NLs at wind force 3 (WF-3) were 6 dB lower than those at wind force 4. The reason is that WF-3 occurred just when the typhoon finished affecting oceanic noise intensity, which differed from common WF-3. At this moment, distant shipping noise source density did not start to increase. Aside from wind-driven sources, noise at common WF-3 may contain other noise sources, such as shipping and biological noise. The median NLs

Table 2. Power-fitting results between noise levels and local significant wave height

Frequency/Hz	WP2013				SCS2016	
	<8.5 m		>8.5 m		<8.5 m	
	before	after	before	after	before	after
400	0.58	2.78	0.82	3.59	1.12	2.95
500	0.65	2.76	0.97	3.66	1.06	3.27
630	0.81	2.86	1.49	3.94	1.36	3.98
800	0.89	2.81	1.75	3.94	1.41	4.17
1 000	0.89	2.82	1.84	4.08	1.44	4.29
1 250	0.92	2.79	1.88	4.12	1.47	4.25
1 600	0.85	2.82	2.08	4.29	1.51	4.45
2 000	0.93	2.93	1.98	4.47	1.56	4.80
2 500	0.93	2.98	2.02	4.73	1.60	5.02
3 150	1.19	2.89	2.12	4.61	1.67	4.99
4 000	1.22	2.67	2.20	4.49	1.71	5.00
5 000	–	–	–	–	1.75	5.12
6 300	–	–	–	–	1.79	5.27
8 000	–	–	–	–	1.83	5.29

Note: – denotes null on account of a limited sample rate.

during the typhoon period were 5 dB less than the Wenz curves at the same wind force, because the duration at a specific WS and agitation might be insufficient due to the typhoon movement. Noise intensity may be related not only to WS but also to wind duration. The experiment results implied that there is a delay in the wind effect of on NLs (Marrett and Chapman, 1990). Percentile method (10%, 30%, 50%, 70%, and 90%) was used in the analysis of NLs. The variation range of NLs of different percentiles was lower than 5 dB except at WF-3 in SCS2016. The result at WF-3 in Fig. 4e was determined by the special oceanic environment conditions and were in good agreement with those in Fig. 4d. The NL peaks at 1 600 Hz and 3 150 Hz were induced by other noise sources and can be observed in Fig. 1d all the time before typhoon, but vanished at the 12th day in WP2013. Figure 5 shows the precipitation rate in both experiments. The precipitation data

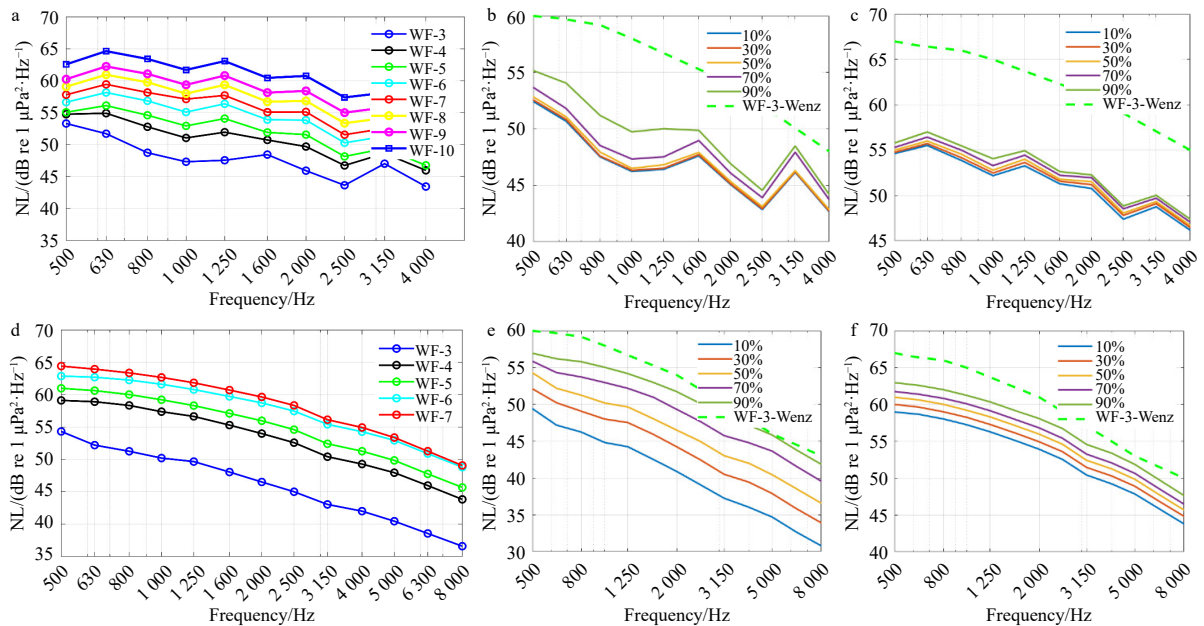


Fig. 4. Experimental noise levels (NLs) at different wind force scales and comparison with Wenz curve. a. NL in WP2013; b. NL at WF-3 in WP2013; c. WF-5, WP2013; d. NL in SCS2016; e. WF-3, in SCS2016; f. WF-5, in SCS2016.

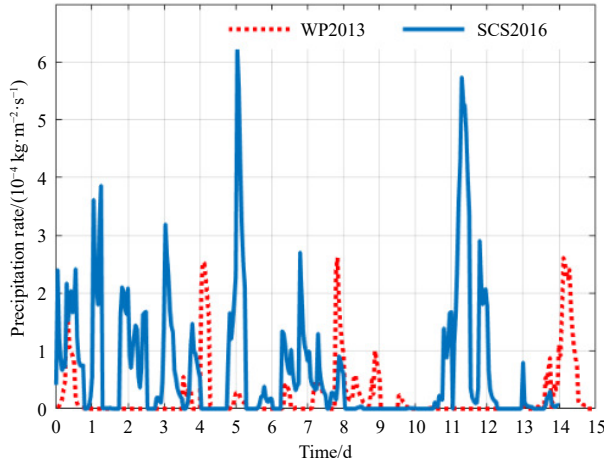


Fig. 5. Precipitation rate in experiments.

were also obtained from the NCEP database. Heavy rainfall existed in SCS2016 from the 3rd to the 8th day during typhoon “Nida” period. The noise sources of wind-driven and breaking waves affected the ambient noise. They lead to a wide variation range of NL at a wind force. By contrast, only light rainfall was present in WP2013 from the 8th to the 12th day for the Typhoon Soulik period. The sample rate in WP2013 and SCS2016 were 8 kHz and 20 kHz. According to reference (Ma et al., 2005), the ocean ambient sound generated from wind and rain can be categorized into

five sections with different sound producing and reduction mechanisms in the frequency band from 1 kHz to 50 kHz: wind-only, large raindrops, light rain (drizzle), both small and large raindrops and the masking effect due to layer of bubbles near the surface. The rainfall reduce noise at frequencies higher than 7 kHz (Zone III and Zone IV) for light rain in WP2013. According to Nyquist sample raw, the sample rate in WP2013 is not enough for analyzing the rainfall underwater noise. And heavy rainfall could induce noise at 1 kHz in SCS2016. It results in a wide variation range of NL at a wind force. Then the rainfall noise of typhoon is not considered in this paper. What’s more, wind agitation was the dominant noise source, and distant shipping could also arrive at receivers through deep sound channel (DSC), as will be described in Section 4. The factors led to a narrow variation range of NL at a wind force in WP2013.

3.4 Empirical expression with spectrum at 1 kHz

Reeder et al. (2011) proposed an empirical formula that describes the relationship between wind-driven NLs and those at a reference frequency on the basis of measurement data in a deep ocean basin. The formula can be expressed as follows:

$$NL(f) = a_0 NL_{f_0} + a_1, \quad (3)$$

where a_0 and a_1 represent the fitted parameters, which will change in different ocean regions and have not been researched for typhoon-generated underwater noise. The reference fre-

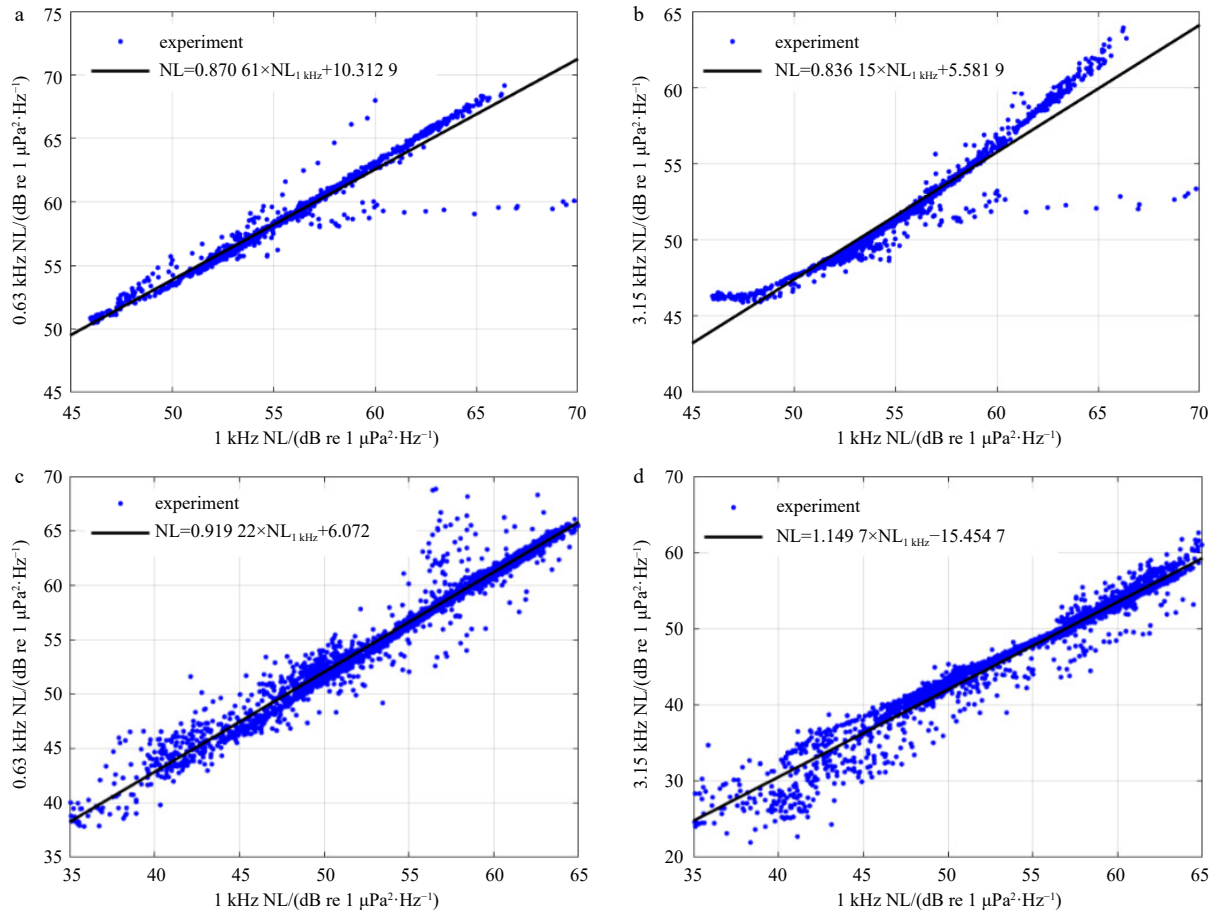


Fig. 6. Fitting results between noise levels (NLs) and NL at 1 kHz during typhoon periods in experiments. a. NL at 630 Hz in WP2013; b. 3 150 Hz, WP2013; c. 630 Hz, SCS2016; d. 3 150 Hz, SCS2016.

Table 3. Fitting results between noise levels and noise level at 1 kHz during typhoon periods

Frequency/Hz	WP2013		SCS2016	
	Slope	Intercept	Slope	Intercept
400	0.62	21.15	0.66	21.13
500	0.68	19.48	0.75	16.63
630	0.87	10.31	0.92	6.07
800	0.95	4.15	0.97	2.39
1 000	1.00	0.00	1.00	0.00
1 250	0.99	1.15	1.00	−1.10
1 600	0.86	6.86	1.04	−4.52
2 000	0.99	−0.58	1.11	−9.56
2 500	0.95	−1.87	1.15	−13.20
3 150	0.84	5.58	1.15	−15.45
4 000	0.86	1.72	1.16	−17.29
5 000	–	–	1.19	−20.16
6 300	–	–	1.21	−23.63
8 000	–	–	1.22	−25.90

Note: – denotes null for frequencies higher than 4 kHz on account of sample rate in WP2013.

quency was selected as 1 kHz due to the limit of sample rate. Figure 6 and Table 3 show the fitted results between NLs and those at the reference frequency. A linear relationship can be observed apparently between the NLs above 400 Hz and NL_{1 kHz}. Most of the measurement samples converged near the fitted line, but few of them deviated from the fitted results. Owing to the influences of other noise sources, as shown in Fig. 1d, the NLs in frequency bands 500–630 Hz, 1 250–2 000 Hz and 3 000–4 000 Hz were relatively greater than those in 800–1 250 Hz before typhoon. This condition induced the phenomenon that when the NL at 1 kHz increased with WS, NLs did not increase in those frequency bands. The characteristics of bands, in which the noise energy was great, were not determined by the self-noise of circuit, because NLs in all bands were less than those before typhoon at the 12th day. By contrast, almost no samples deviated from the fitted line in SCS2016. The convergence among the sample points was sparser than that in WP2013 due to the effect of rainfall as shown in Fig. 5. Furthermore, the slopes increased with frequency and exceeded 1 above 1 000 Hz. The intercepts decreased with frequency, and changed from positive to negative values.

3.5 Frequency cross-correlation matrix of noise levels

To form an FCM, the correlation coefficient between the time

series of spectral densities (in dB) at pair of frequencies is computed as follows:

$$r_f(f_1, f_2) = \frac{\sum_{n=1}^N [x(f_1, t_n) - \overline{x(f_1)}] [x(f_2, t_n) - \overline{x(f_2)}]}{\sqrt{\sum_{n=1}^N [x(f_1, t_n) - \overline{x(f_1)}]^2 \sum_{n=1}^N [x(f_2, t_n) - \overline{x(f_2)}]^2}}, \quad (4)$$

where $x(f_1, t_n)$ represents the spectral density, in dB, in the 1st frequency band at time t_n ; the overbar represents the mean for some time duration. The results indicated a normalized correlation coefficient between demeaned spectral densities at frequencies f_1 and f_2 . The correlation coefficients are then displayed in the form of a matrix. The resulting FCM was useful in identifying frequency bands in which spectral levels tend to change together. The results suggested that NLs within these correlated bands were driven by the same or similar source mechanisms. The FCMs of the measured NLs, shown in Fig. 7, are characterized by two dominant features. First, from 100 Hz to 200 Hz, a region of slightly evaluated correlations indicates that the noise source may be dominated by distant shipping traffic noise and wind-driven break waves simultaneously. The ambient noise of low frequency was the weighted results of shipping and wind-driven noise during the typhoon periods (Yang et al., 2018b). The light stripe at 125 Hz in FCM of Fig. 7a was the effect of system self-noise or other harmonic sound. The different correlation coefficient distributions in the band were caused by the shipping density at the experiment site. Second, from 250 Hz to 4 000 Hz, a block of strong correlation identified underwater noise induced by wind agitation and breaking waves completely. The correlation coefficient of noise levels exceeds 0.8 in the frequency band.

3.6 PDF and statistics of the noise levels

This section discusses the PDF of typhoon-generated oceanic noise measured in experiments. Several types of distributions, such as Gaussian, stable (Song et al., 2019), extreme value (Gumbel type (Galindo-Romero et al., 2017)), Weibull (Xu and Wang, 2011) and Burr, were used to fit the PDF of NLs. Besides, standard deviation (std), skewness and kurtosis of noise levels were also analyzed.

(1) Stable distribution

An Alpha stable distribution is also called non-Gaussian stable distribution or heavy-tailed distribution. No closed analyt-

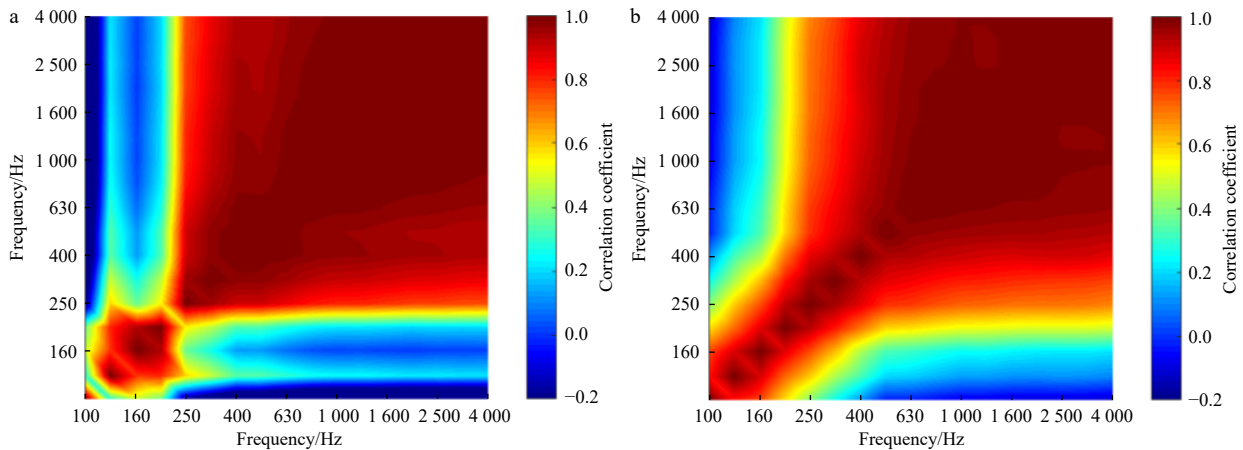


Fig. 7. Correlation coefficient of noise levels during typhoon period in experiments. a. WP2013; b. SCS2016.

ical expression is available to express its PDF. The characteristic exponent is generally used to describe the distribution. Random variables satisfy the alpha stable distribution, if and only if the characteristic exponent satisfies the following expression

$$\varphi(t) = \begin{cases} \exp \left\{ j\delta t - |\gamma t|^\alpha \left[1 + j\beta \operatorname{sgn}(t) \tan\left(\frac{\pi\alpha}{2}\right) \right] \right\}, & \alpha \neq 1 \\ \exp \left\{ j\delta t - |\gamma t|^\alpha \left[1 + j\beta \operatorname{sgn}(t) \frac{2}{\pi} \log_{10}|t| \right] \right\}, & \alpha = 1 \end{cases}, \quad (5)$$

where j and t denote imaginary number and random variable NL, respectively; $0 < \alpha \leq 2$ is the characteristic exponent determining the trailing thickness of PDF; $-1 \leq \beta \leq 1$ is the skewness parameter; $\gamma > 0$ is the scale parameter; $-\infty < \delta < \infty$ is the location parameter, and $\operatorname{sgn}(t)$ represents the signum function.

(2) Extreme value distribution

The PDF of extreme value distribution (Gumbel type) could be expressed as follows:

$$f(x; \mu, \sigma) = \exp \left[-\frac{x - \mu}{\sigma} - \exp \left(-\frac{x - \mu}{\sigma} \right) \right], \quad (6)$$

where μ and σ denote the location and scale parameters, respectively. The closed analytical expression for a stable distribution is not uniform, and the characteristic function is effective mean in expressing the alpha stable distribution.

(3) Weibull distribution

Weibull distribution (Xu and Wang, 2011) is widely used in the statistics of oceanic random variables including surface WS and wave height. The PDF of Weibull distribution could be written as

$$f(x; k, \lambda, a) = \begin{cases} \frac{k}{\lambda} \left(\frac{x - a}{\lambda} \right)^{k-1} \exp \left[-\left(\frac{x - a}{\lambda} \right)^k \right], & x \gg a \\ 0, & x < a \end{cases}, \quad (7)$$

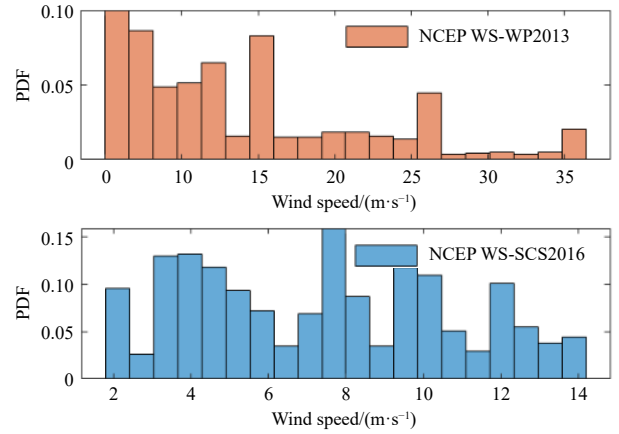


Fig. 8. Histogram of National Centers for Environmental Prediction (NCEP) wind speed (WS) during typhoon period in experiments of WP2013 and SCS2016. PDF: probability density function.

where k , λ , and a are the undetermined parameters. $k > 0$ represents the shape parameter, and $\lambda > 0$ denotes the scale parameter.

(4) Burr distribution

The Burr distribution can fit a large number of empirical measurement data, and satisfy broad skewness and kurtosis by using different parameters. The PDF of Burr distribution with three parameters can be written as

$$f(x; c, p, \eta) = \frac{cp}{\eta} \left(\frac{x}{\eta} \right)^{c-1} \left[1 + \left(\frac{x}{\eta} \right)^c \right]^{-p-1}, \quad (8)$$

where c , p , and η represent the first shape parameter, the second shape parameter, and the scale parameter, respectively.

Figure 8 shows the NCEP WS histogram in the experiments. No regular distribution of WS was determined, but clusters de-

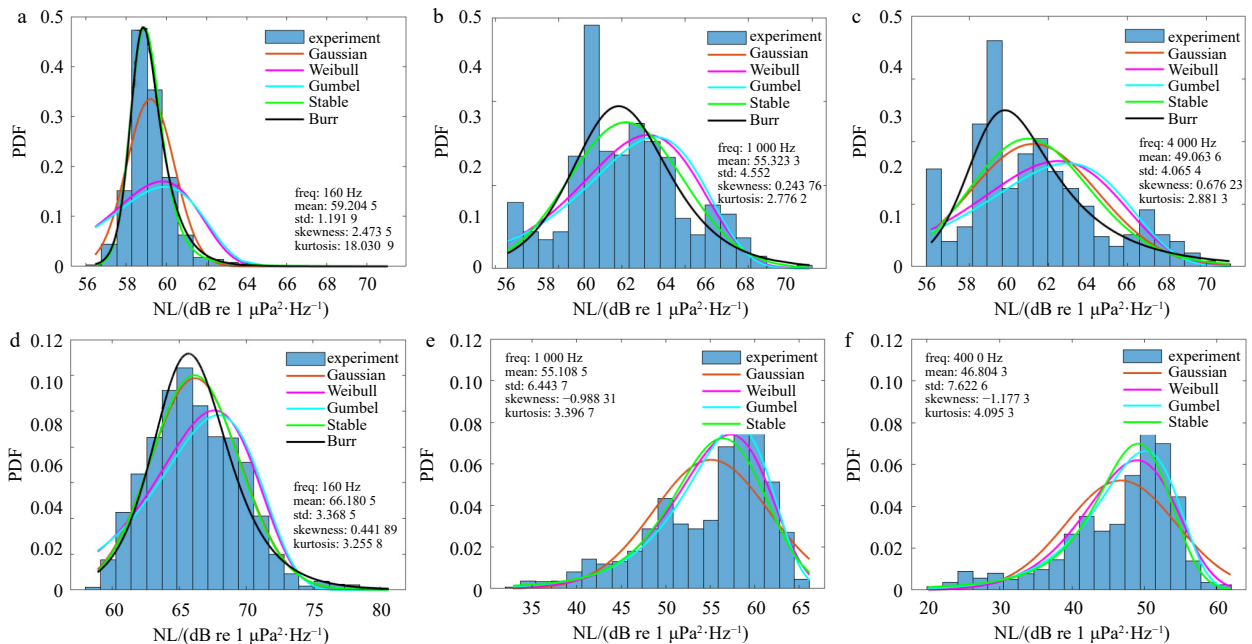


Fig. 9. Probability density function (PDF) of ambient noise levels (NLs) during typhoon period in experiments of WP2013 and SCS2016. a. 160 Hz, WP2013; b. 1 000 Hz, WP2013; c. 4 000 Hz, WP2013; d. 160 Hz, SCS2016; e. 1 000 Hz, SCS2016; f. 4 000 Hz, SCS2016.

terminated by typhoon path and intensity were identified at some values. Figure 9 indicates the PDF of noise spectrum levels observed in the experiments. The results revealed distributions that were considerable different from the distribution of WS. In WP2013, only the Burr distribution was in agreement with samples. Other distributions, including Gaussian, Stable, Gumbel and Weibull could not fit the measurements and deviated from the sampled data. In SCS2016, the Burr distribution showed good agreement with NLs at 160 Hz. Nevertheless, at 1 000 Hz and 4 000 Hz, the parameters of the Burr distribution could not be obtained. This phenomenon meant that the PDFs of NLs at 1 kHz and 4 kHz were not satisfied with the Burr distribution. The Gumbel distribution showed the best agreement with the samples in the four other distributions but still deviated minimally from the real data. This finding should be researched in the future work.

The statistics consisting of std, skewness and kurtosis of NLs are shown in Fig. 10. The std of NLs increased with frequency in both experiments. The low-frequency noise field was dominant by distant shipping density background, which was stable in general and merely changed near the typhoons. However, a high-frequency noise field was induced by wind-driven breaking waves, which was dominant by wind speed and wave height. The WS variation range near the experiment site, when typhoon passed by the receivers, was 30 m/s in WP2013 and 10 m/s in SCS2016, respectively. The skewness of NLs in WP2013 was almost positive (left-skewed distribution) and decreased with frequency. On the contrary, the skewness of NLs in SCS2016 changed from being positive to being negative as frequency increased. That is, PDF

changed from a left-skewed distribution to a right-skewed distribution. The kurtosis was about 3 at frequencies above 400 Hz in both experiments and showed a great difference at frequencies lower than 250 Hz. This results may have been effected by the shipping density distribution. It was in agreement with the frequency bands of wind-driven and shipping noise sources, and also showed good agreement with the findings in FCM, as shown in Fig. 7.

4 Discussion

The powers of local WS, SWH with respect to NLs, FCM, PDF and statistics were different in the two experiments. Figure 11 shows the measured SSPs and ship noise source distribution. The SSPs were measured with conductivity-temperature-depth sensors at the location of receivers in both experiments. The shipping density distribution was acquired from the Automatic Identification System (<http://www.shipxy.com/>). The BELLHOP model (Porter, 2011) based on a ray approach was utilized to calculate the sound propagation in the experimental regions. As shown in Figs 12 and 13, the simulation results of transmission losses (TLs) at azimuth angles of 0°, 90°, 180° and 270° were calculated for 500 Hz in WP2013 and SCS2016. The source depths were set to the 5 050 m and 300 m on the basis of sound field reciprocity. In general, the ship-radiated noise source depth was 20 m at most. The oceanic terrain at each bear was obtained from ETOPO1 database. The sound propagation was relatively complex due to the effect of bathymetry. Convergence zone channel could be observed in WP2013 clearly, whereas the channel did not exist and a bottom reflection channel was the dominant

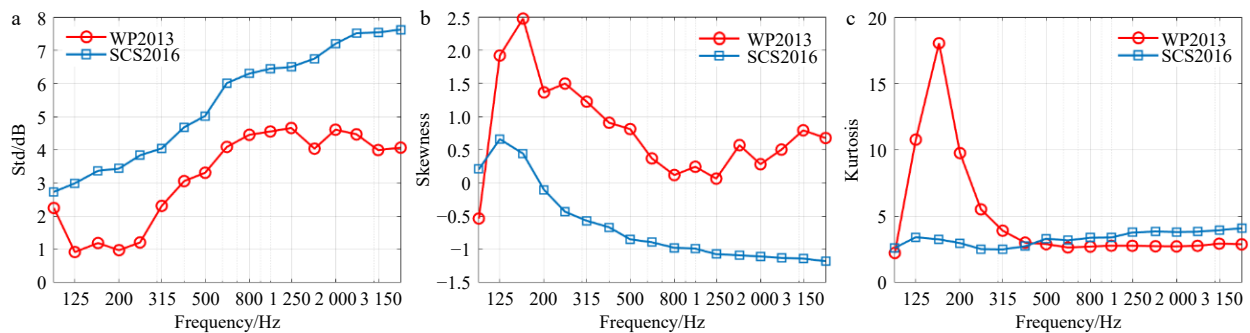


Fig. 10. Comparison of statistic results of ambient noise levels during typhoon period in experiments of WP2013 and SCS2016. a. Standard deviation (std); b. skewness; c. kurtosis.

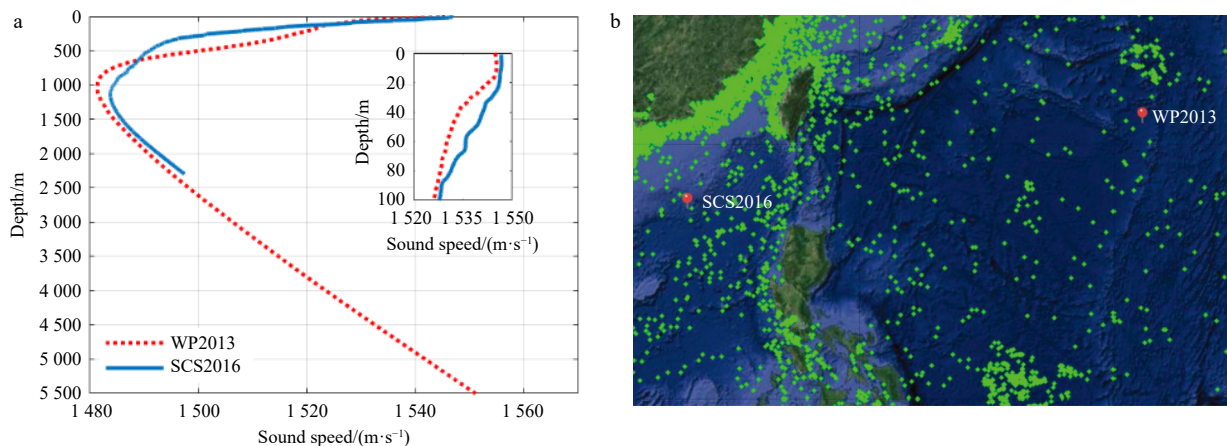


Fig. 11. Measured sound speed profiles (a) and shipping distribution (b).

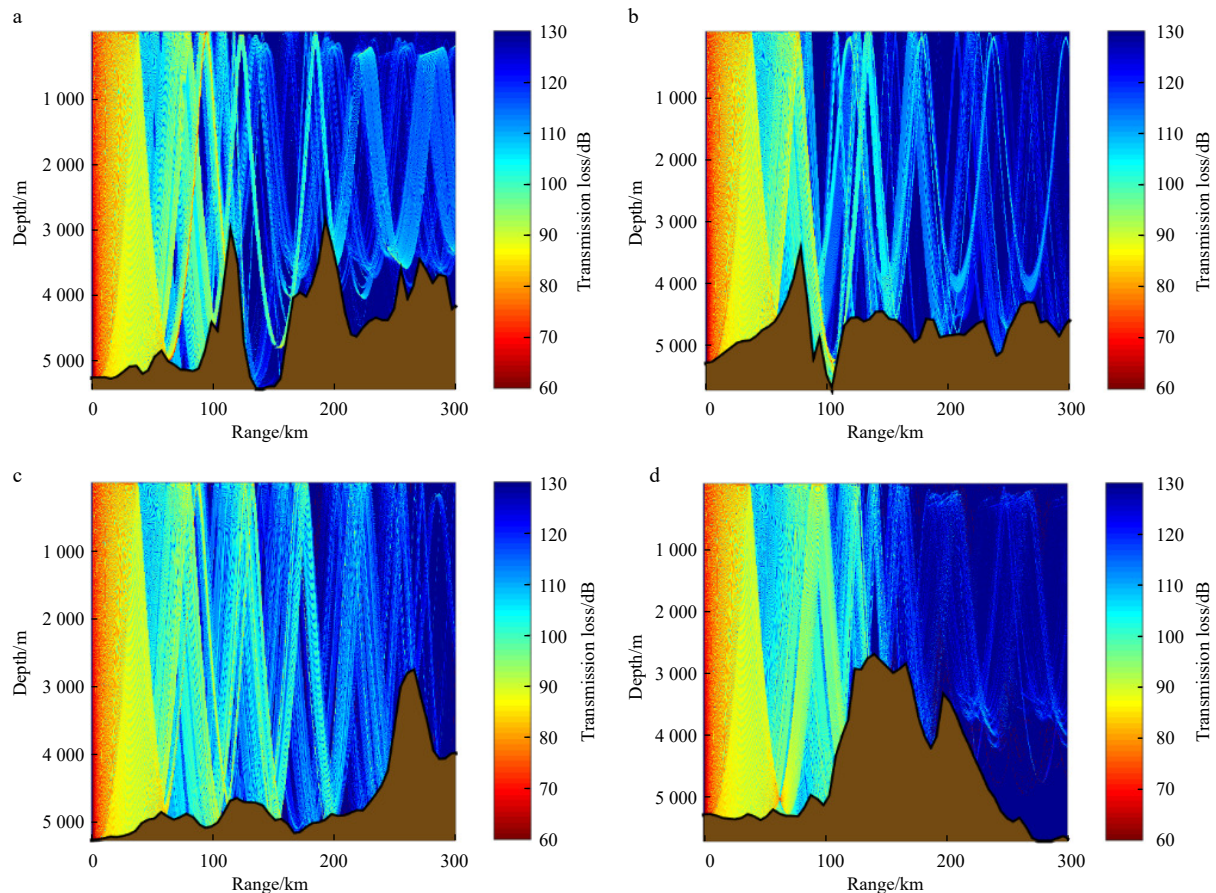


Fig. 12. Transmission loss simulation results at azimuth angles 0° (a), 90° (b), 180° (c) and 270° (d) at 500 Hz in WP2013.

acoustic ray path in SCS2016.

$N \times 2D$ TL numerical results with the BELLHOP model are shown in Fig. 14. The 0° denotes the north direction. As shown in Figs 12 and 13, 2D transmission losses could be calculated with bear interval of 3 degree clockwise. The quantity of noise sources is noncountable. In order to reduce calculated amount, sound reciprocity principle was utilized. In numerical calculation code, the sound source depth was set as real receiver depth and the receiver depth was set as real wind-driven noise source depth, which is quarter wavelength. The horizontal distance 300 km in noise propagation is considered. Then Cartesian coordinate system were transformed to polar coordinate system, and $N \times 2D$ TLs results could be acquired.

According to reference (Gaul et al., 2007), the noise spectrum levels are nearly constant at a high WS for a receiver depth from the sea surface to bottom in deep ocean. These differences may be attributed to several possible reasons. Firstly, the closest horizontal distances between the centers of typhoons and the receivers were different. The movement speeds, wind profiles, and wave height profiles of both typhoons also differed. Secondly, the long waves induced by the typhoon might have arrived at the receivers earlier than the typhoons themselves and be related to typhoon intensity. The long wave noise possibly contributed to measured NLs. Thirdly, the distant shipping distribution was different in the two experiments. The measured NLs in these experiments might have been contaminated by distant shipping noises before typhoon. This contamination might have induced a poor correlation and significant variance in estimates of the relation-

ship between WS and noise intensity, and that between SWH and noise intensity. Lastly, the propagation conditions, including water depth, bathymetry, and SSP, in the two experiments were different. Aside from the wind-driven noise sources near the sea surface, distant shipping or biological noise could propagate to the receivers through deep sound channel without significant bottom reflection loss, because a sea surface sound speed conjugate depth was present in WP2013 (Gaul et al., 2007). On the contrary, the water depth in SCS2016 was only 2 300 m; thus, the contribution of far field noise sources was attenuated by the typical sediment through bottom reflection loss.

The experiment results indicated that there are at least two regimes of behavior depending on the WS, with the transition occurring at the onset of wave breaking or the dominated absorption of bubbles (Chapman and Cornish, 1993). A number of mechanisms have been suggested for the generation of ambient noise during typhoon period in WP2013 and SCS2016. At low WSs, prior to wave breaking, the interaction between surface waves and sea surface turbulence was the dominated source. For WS that was sufficiently high to initiate breaking waves, the noise was due to collective oscillations of bubbles entrained by breakers. Bubbles clouds might oscillate collectively and radiate sound at frequencies lower than the resonant frequencies of individual bubbles. For WS higher than the critical value in WP2013, the received NLs first increased and then decreased with increasing WS. A WS produced a maximum sound level for each frequency. Bubble clouds that were generated and absorbed in a wind-dependent frequency band were mostly confined to the upper 1–2 m

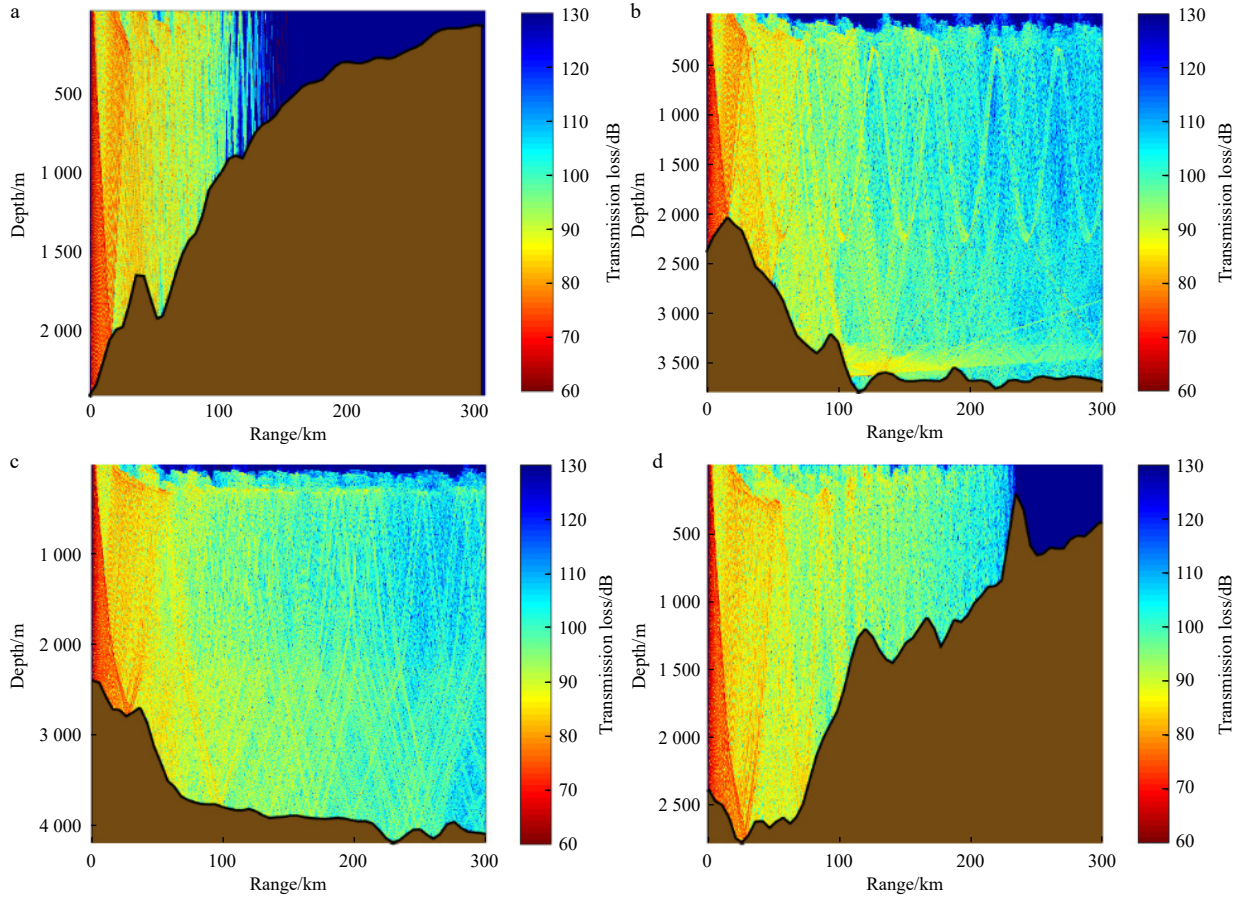


Fig. 13. Transmission loss simulation results at azimuth angles 0° (a), 90° (b), 180° (c) and 270° (d) at 500 Hz in SCS2016.

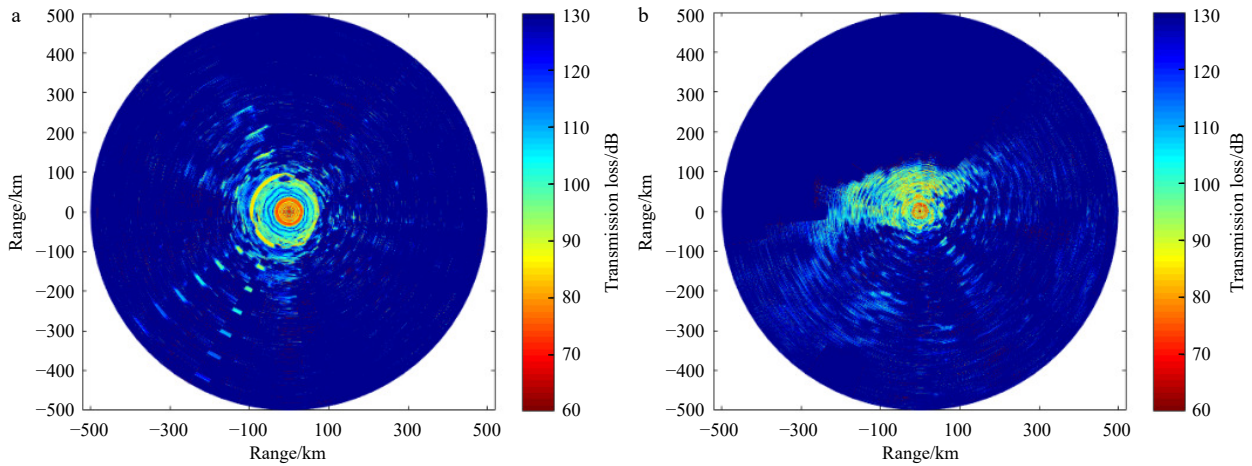


Fig. 14. Simulation results of $N \times 2D$ transmission loss (TL) with ray approach. a. $N \times 2D$ -TL, WP2013; b. $N \times 2D$ -TL, SCS2016.

at highest WS. In addition to resonant bubbles, there were bubbles advected deep than 2 m during tropical cyclones (Zhao et al., 2014).

5 Conclusions

The research of ambient noise at high sea states is valuable for typhoon intensity prediction, sonar performance optimization, the Green function and SSP acquisition in a deep ocean waveguide. In this work, experiments of WP2013 and SCS2016 were conducted in the deep areas of the Philippine Sea and the

South China Sea to measure the underwater ambient noise generated by Typhoons Soulik and Nida, respectively. The statistics of observed oceanic noise driven by the typhoon out zones were analyzed in both experiments. Characteristics including the correlation with environmental parameters, such as WS, SWH, and the inter-frequency relationship and PDF of NLs, were demonstrated by using methods, which consisted of generated linear regression, FCM, Burr and Gumbel distributions. The maximum local WS or SWH was selected as the turning point. Ambient noises, divided into those “before typhoon” and “after typhoon”,

were analyzed during the typhoon periods. The fitted results between NLs and oceanic parameters were different for before typhoon and after typhoon. When the typhoons were quite close to receivers, the increment of underwater noise spectrum levels exceeded 10 dB. By comparison, the average observed typhoon-generated NLs were 5 dB lower than the Wenz curve at the same wind force because the agitation and duration might be insufficient for sea state development. When ambient noise was completely dominated by wind-driven agitation, NLs were approximately proportional to the cubic and quintic functions of the local WS and SWH in WP2013 and SCS2016, respectively. The linear relationships between NLs and WS, SWH or NLs at 1 000 Hz were analyzed with LMS during the typhoon periods. The fitted slopes between the NLs and WS, or SWH also showed a linear relationship with the logarithm of frequency, and increased with frequency. Subsequently, NLs could be formulated via empirical expressions by using WS, SWH, or NLs at specific frequency. The cross-correlation coefficient of the FCM of NLs exceeded 0.8 at frequencies higher than 250 Hz in both experiments. This results meant that NLs were dominated by the same noise source mechanism in the band. The PDF of NLs generated by the typhoons could be fitted by using Burr and Gumbel distributions. Furthermore, std increased with frequency due to the impact of wind. The kurtosis was equal to 3 for frequencies >400 Hz approximately and changed drastically at low frequencies. The characteristics of NLs showed good agreement with the FCM results. In sum, acoustic sensors have potential as anemometers for estimating WS and SWH and for typhoon classification above receivers on the basis of statistical characteristics.

Acknowledgements

The authors would like to thank the anonymous reviewers for their efforts which led to considerable improvements of the paper. The authors are grateful to colleagues who made marvelous contribution to the experiment and data collection.

References

- Asishan M, Latha G, Raguraman G. 2018. Ocean ambient noise off Chennai due to very severe cyclonic storm Vardah. *Applied Acoustics*, 140: 256–262, doi: [10.1016/j.apacoust.2018.06.008](https://doi.org/10.1016/j.apacoust.2018.06.008)
- Asolkar P, Das A, Gajre S, et al. 2016. Tropical littoral ambient noise probability density function model based on sea surface temperature. *The Journal of the Acoustical Society of America*, 140(5): EL452–EL457, doi: [10.1121/1.4967524](https://doi.org/10.1121/1.4967524)
- Asolkar P, Das A, Gajre S, et al. 2017. Comprehensive correlation of ocean ambient noise with sea surface parameters. *Ocean Engineering*, 138: 170–178, doi: [10.1016/j.oceaneng.2017.04.033](https://doi.org/10.1016/j.oceaneng.2017.04.033)
- Brooks L A, Gerstoft P. 2009. Green's function approximation from cross-correlations of 20–100 Hz noise during a tropical storm. *The Journal of the Acoustical Society of America*, 125(2): 723–734, doi: [10.1121/1.3056563](https://doi.org/10.1121/1.3056563)
- Cauchy P, Heywood K J, Merchant N D, et al. 2018. Wind speed measured from underwater gliders using passive acoustics. *Journal of Atmospheric and Oceanic Technology*, 35(12): 2305–2321, doi: [10.1175/JTECH-D-17-0209.1](https://doi.org/10.1175/JTECH-D-17-0209.1)
- Chan H C, Chen Chifang. 2012. Underwater acoustic sensing applied to estimation of typhoon wind speed. *International Journal of Remote Sensing*, 33(23): 7398–7412, doi: [10.1080/01431161.2012.685984](https://doi.org/10.1080/01431161.2012.685984)
- Chapman N R, Cornish J W. 1993. Wind dependence of deep ocean ambient noise at low frequencies. *The Journal of the Acoustical Society of America*, 93(2): 782–789, doi: [10.1121/1.405440](https://doi.org/10.1121/1.405440)
- D'Asaro E A, Black P G, Centurioni L R, et al. 2014. Impact of typhoons on the ocean in the Pacific. *Bulletin of the American Meteorological Society*, 95(9): 1405–1418, doi: [10.1175/BAMS-D-12-00104.1](https://doi.org/10.1175/BAMS-D-12-00104.1)
- Farmer D M, Lemon D D. 1984. The influence of bubbles on ambient noise in the ocean at high wind speeds. *Journal of Physical Oceanography*, 14(11): 1762–1778, doi: [10.1175/1520-0485\(1984\)014<1762:TIOBOA>2.0.CO;2](https://doi.org/10.1175/1520-0485(1984)014<1762:TIOBOA>2.0.CO;2)
- Farrell D M, Dall'Osto D R, Dahl P H. 2017. The background noise environment during the 2013 target and REverbation eXperiment. *IEEE Journal of Oceanic Engineering*, 42(4): 1088–1093, doi: [10.1109/JOE.2017.2721158](https://doi.org/10.1109/JOE.2017.2721158)
- Farrokhrooz M, Wage K E, Dzieciuch M A, et al. 2017. Vertical line array measurements of ambient noise in the North Pacific. *The Journal of the Acoustical Society of America*, 141(3): 1571–1581, doi: [10.1121/1.4976706](https://doi.org/10.1121/1.4976706)
- Galindo-Romero M, Gavrilov A, Duncan A J. 2017. Fluctuations of the peak pressure level of man-made impulsive sound signals propagating in the ocean. *The Journal of the Acoustical Society of America*, 141(2): 661–668, doi: [10.1121/1.4974878](https://doi.org/10.1121/1.4974878)
- Gaul R D, Knobles D P, Shooter J A, et al. 2007. Ambient noise analysis of deep-ocean measurements in the Northeast Pacific. *IEEE Journal of Oceanic Engineering*, 32(2): 497–512, doi: [10.1109/JOE.2007.891885](https://doi.org/10.1109/JOE.2007.891885)
- Gerstoft P, Bromirski P D. 2016. “Weather bomb” induced seismic signals. *Science*, 353(6302): 869–870, doi: [10.1126/science.aag1616](https://doi.org/10.1126/science.aag1616)
- Jullien S, Marchesiello P, Menkes C E, et al. 2014. Ocean feedback to tropical cyclones: climatology and processes. *Climate Dynamics*, 43(9–10): 2831–2854, doi: [10.1007/s00382-014-2096-6](https://doi.org/10.1007/s00382-014-2096-6)
- Li Fenghua, Xu Dong, Wang Jingyan, et al. 2018. Observations of wind-generated noise by the tropical cyclone. *The Journal of the Acoustical Society of America*, 143(6): 3312–3324, doi: [10.1121/1.5039838](https://doi.org/10.1121/1.5039838)
- Lin Jianmin, Lin Jian, Xu Min. 2017. Microseisms generated by super typhoon megi in the western Pacific Ocean. *Journal of Geophysical Research*, 122(12): 9518–9529, doi: [10.1002/2017JC.013310](https://doi.org/10.1002/2017JC.013310)
- Ma B B, Nystuen J A, Lien R C. 2005. Prediction of underwater sound levels from rain and wind. *The Journal of the Acoustical Society of America*, 117(6): 3555–3565, doi: [10.1121/1.1910283](https://doi.org/10.1121/1.1910283)
- Ma B, Yang Y J. 2009. Detection and classification of typhoons using underwater acoustic sensors in the western Pacific Ocean. *The Journal of the Acoustical Society of America*, 125(4): 2619
- Marrett R, Chapman N R. 1990. Low-frequency ambient-noise measurements in the South Fiji Basin. *IEEE Journal of Oceanic Engineering*, 15(4): 311–315, doi: [10.1109/48.103526](https://doi.org/10.1109/48.103526)
- Newcomb J J, Wright A J, Kuczaj S, et al. 2004. Underwater ambient noise and sperm whale click detection during extreme wind speed conditions. *AIP Conference Proceedings*, 728(1): 296–303
- Nichols S M, Bradley D L. 2019. Use of noise correlation matrices to interpret ocean ambient noise. *The Journal of the Acoustical Society of America*, 145(4): 2337–2349, doi: [10.1121/1.5096846](https://doi.org/10.1121/1.5096846)
- Porter M B. 2011. The BELLHOP manual and user's guide: preliminary draft. La Jolla: Heat, Light, and Sound Research, Inc.
- Pun I F, Chang Y T, Lin I I, et al. 2011. Typhoon-ocean interaction in the western North Pacific: part 2. *Oceanography*, 24(4): 32–41, doi: [10.5670/oceanog.2011.92](https://doi.org/10.5670/oceanog.2011.92)
- Reeder D B, Sheffield E S, Mach S M. 2011. Wind-generated ambient noise in a topographically isolated basin: a pre-industrial era proxy. *The Journal of the Acoustical Society of America*, 129(1): 64–73, doi: [10.1121/1.3514379](https://doi.org/10.1121/1.3514379)
- Sanjana M C, Latha G, Thirunavukkarasu A. 2014. Ambient noise during rough weather and cyclones in the shallow Bay of Bengal. *Chinese Journal of Oceanology and Limnology*, 32(4): 921–932, doi: [10.1007/s00343-014-2238-2](https://doi.org/10.1007/s00343-014-2238-2)
- Širović A, Wiggins S M, Oleson E M. 2013. Ocean noise in the tropical and subtropical Pacific Ocean. *The Journal of the Acoustical Society of America*, 134(4): 2681–2689, doi: [10.1121/1.4820884](https://doi.org/10.1121/1.4820884)
- Song Guoli, Guo Xinyi, Ma Li. 2019. α stable distribution model in ocean ambient noise. *Acta Acustica*, 44(2): 177–188
- Wang Jingyan, Li Fenghua. 2015. Preliminary study on underwater ambient noise generated by typhoons. *Chinese Physics Letters*, 32(4): 044301, doi: [10.1088/0256-307X/32/4/044301](https://doi.org/10.1088/0256-307X/32/4/044301)
- Wen Hongtao, Yang Yanming, Wang Ning, et al. 2016. Effects of

- typhoon “KAI-TAK” on deep ocean ambient noise in the South China Sea. *Acta Acustica*, 41(6): 804–812
- Wilson J D, Makris N C. 2006. Ocean acoustic hurricane classification. *The Journal of the Acoustical Society of America*, 119(1): 168–181, doi: [10.1121/1.2130961](https://doi.org/10.1121/1.2130961)
- Wilson J D, Makris N C. 2008. Quantifying hurricane destructive power, wind speed, and air-sea material exchange with natural undersea sound. *Geophysical Research Letters*, 35(10): L10603
- Xu Delun, Wang Liping. 2011. *Analysis of Ocean Random Data: Principles, Methods and Applications* (in Chinese). Beijing: Higher Education Press
- Yang Qiulong, Yang Kunde, Cao Ran, et al. 2018a. Spatial vertical directionality and correlation of low-frequency ambient noise in deep ocean direct-arrival zones. *Sensors*, 18(2): 319, doi: [10.3390/s18020319](https://doi.org/10.3390/s18020319)
- Yang Qiulong, Yang Kunde, Duan Shunli. 2018b. A method for noise source levels inversion with underwater ambient noise generated by typhoon in Deep Ocean. *Journal of Theoretical and Computational Acoustics*, 26(2): 1850007, doi: [10.1142/S259172851850007X](https://doi.org/10.1142/S259172851850007X)
- Yang Ming, Zhang Wei, Yu Hui, et al. 2014. An overview of the China Meteorological Administration tropical cyclone database. *Journal of Atmospheric and Oceanic Technology*, 31(2): 287–301, doi: [10.1175/JTECH-D-12-00119.1](https://doi.org/10.1175/JTECH-D-12-00119.1)
- Zhao Zhongxiang, D'Asaro E A, Nystuen J A. 2014. The sound of tropical cyclones. *Journal of Physical Oceanography*, 44(10): 2763–2778, doi: [10.1175/JPO-D-14-0040.1](https://doi.org/10.1175/JPO-D-14-0040.1)