

Effects of islands and downslope seafloors on underwater noise in the northern South China Sea during a typhoon

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Abstract

The correlation of ambient noise with wind speed, and the depth dependence of ambient noise are both investigated, where the ocean noise data were recorded by a vertical line array in the northern South China Sea. It is shown that the correlation coefficients increase with increasing hydrophone depth during typhoon periods when the frequency ≥ 250 Hz, which opposes the generally accepted knowledge that the correlation coefficients of noise level and wind speed decrease with increasing depth during non-typhoon periods. Particularly at frequencies of 250 Hz, 315 Hz and 400 Hz, the correlation coefficients increase by more than 0.05 at depths ranging from 155 m to 875 m. At the three frequencies, the average noise levels also increase with increasing depth during typhoon periods. It is suggested that these differences are attributed to the wind-generated noise in shallow waters and the effect of “downslope enhancement” to sound propagation. During typhoon periods, the surf breaking and surf beat upon the shores and reefs are strengthened, and the source levels are increased. The wind-generated noise in shallow waters interacts with the downslope sea floor, with the noise-depth distribution changed by a “downslope enhancement” effect promoting noise propagation.

Key words: underwater noise, typhoon, downslope enhancement, the northern South China Sea

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1 Introduction

Due to the rapid increases in sea surface wind during a typhoon, the impact of typhoons on underwater noise has attracted more attention. In the frequency range of 25 Hz to 50 kHz, the influence of typhoon on underwater noise characteristics at different frequencies had been studied (Newcomb et al., 2007; Snyder, 2009; Zhao et al., 2014), and the noise levels (Newcomb et al., 2007) were compared to the “Wenz curves”. All the above results indicated that strong winds from typhoons will cause a significant increase in the underwater noise level. In addition, the underwater noise data had been used to accurately evaluate the local wind speed of a typhoon if its eye wall passed directly over the receiving hydrophone (Wilson, 2006; Wilson and Makris, 2006, 2008; Chan and Chen, 2012). In addition to causing local wind-generated noise, microseisms are produced during typhoon periods due to the non-linear interaction of ocean waves (Longuet-Higgins, 1950), which propagate in half of the ocean wave period and affect the distant infrasonic frequency noise field (Gerstoft et al., 2006; Gerstoft and Tanimoto, 2007; Hetzer et al., 2008; Traer et al., 2008).

Explosion sound signals were recorded on SOFAR depth hydrophones when they occurred at the continental slope (Northrop et al., 1968). These signals indicated that the sound reflection by the downslope seafloor was conducive to the propagation of un-

derwater sound, and the significant factors influencing this relationship were changes in bottom slope, bottom material, and water depth in the source area. Islands, reefs and seamounts in the ocean can provide the conditions for downslope sound propagation, so that the radiation noise of nearby ships can enter a deep sound channel after repeated reflection from the seafloor, and affect the depth distribution of the deep-sea ambient noise (Wagstaff, 1981; Zhang et al., 2019). An experiment to perform the coupling of surface-ship noise to a deep ocean sound channel had been carried out (Carey, 1986). The measurements of downslope sound propagation from the 135 Hz shallow source were obtained at a deep ocean receiver, it was shown that the “downslope enhancement” is responsible for deep ocean ambient noise. The experiment of downslope acoustic propagation of shallow explosive sources over the continental slope also had been performed (Dosso and Chapman, 1987), and a downslope enhancement was observed at a receiver in a deep sound channel. As a result, the downslope enhancement of noise generated on the continental slope has been suggested as a mechanism to explain the observed vertical directionality of low-frequency ambient noise in the deep oceans (Anderson, 1979; Wales and Diachok, 1981; Dashen and Munk, 1984).

Wilson et al. (1985) measured the acoustic ambient noise in shallow waters from breaking surf. The noise of surf breaking and

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surf beat upon the shores were the main noise sources of underwater noise in the frequency range 20–700 Hz. The contributions of these noise sources to underwater noise depend on the surf intensity, on the range from the beach and on the frequency range. Under a high sea state, the underwater noise of 300 Hz toward shoreward will increase by 10 dB compared to that toward seaward at a site 9 km off the beach. So the noise of surf breaking and surf beat upon the shores and reefs are all the important sources of shallow sea ambient noise, especially in high sea states. For example, the intensity of these noise sources will increase significantly during a typhoon. Therefore, shallow sea noise sources during a typhoon period can affect the ocean background noise at different depths and distances when the effects of downslope seafloor acoustic reflection and deep sound channels are considered. Inspired by these works, the effects of islands and downslope seafloors on depth-dependence of underwater noise in the northern South China Sea during a typhoon are discussed in this paper.

2 Experimental background

The underwater noise data were recorded by the acoustic mooring in the north of Zhongsha Islands in the South China Sea from 9:00 UTC on August 6th to 16:00 on August 23rd, 2012. The acoustic mooring system is mainly consisted of communication and positioning systems, a data recording system, a power supply system, a vertical line array, and TD (temperature and depth recorder) chain and floating bodies. The data recording system was programmed to record acoustic data for 10 min per hour with 24-bit resolution and 6 002 Hz sampling rate of the low-pass antialiasing filtered signal. The vertical line array of the mooring has 32 hydrophones (HTI-97-DA Exportable), with a space between two hydrophones of 30 m, producing an array with total length of 938 m. The -3 dB frequency response bandwidth of each hydrophone is 10 Hz to 5 kHz and the hydrophone sensitivity is -180 dB re 1 V/ μ Pa. The maximum working depth of the hy-

drophones is $950\text{ m}\pm 50\text{ m}$, so data from some hydrophones are lost when their depths exceeded the maximum. After examination, only the shallowest 25 hydrophones appeared to work. The depth of the first hydrophone is nearly 155 m, and the depth of the 25th hydrophone is nearly 875 m.

Typhoon KAI-TAK passed through the north area of the South China Sea from 6:00 UTC on August 15th to 13:00 on August 18rd, and its path is displayed in Fig. 1a, the temporal variety of horizontal distance between typhoon center and acoustic mooring is shown in Fig. 1b. The wind field in the northern South China Sea during the Typhoon KAI-TAK is shown in Fig. 2, and the temporal variety of wind speed at the sea area of the receiving acoustic mooring is shown in Fig. 3. The wind speed data are collected from the National Centers for Environmental Prediction (NCEP), and the spatial resolution of the data is $0.205^\circ\times 0.204^\circ$. During Typhoon KAI-TAK, the wind speed was affected and varied rapidly. The sound speed profile is shown in Fig. 4. It was calculated by the Del Grosso (1974) empirical formula of sound speed by using the seawater temperature, salinity and depth profile data that were measured by the SBE-911 plus CTD (conductance, temperature and depth) near the location of the acoustic mooring. The water depth is approximately 3 400 m at the acoustic mooring sea area, the maximum measuring depth of the CTD is only 2 080 m. Therefore, the sound speed profile of the seawater with depth greater than 2 080 m is obtained by expanding the curve using a slope coefficient of 0.017 5.

3 Results and discussion

3.1 Spectrogram of underwater noise

Underwater noise was measured over a 415 h period during the experiment. For every hour, 120 s stationary noise data were selected and processed, and the results were used to represent the underwater noise level of that hour. The noise levels were processed using the 120 s data with a Hanning window and 6 002

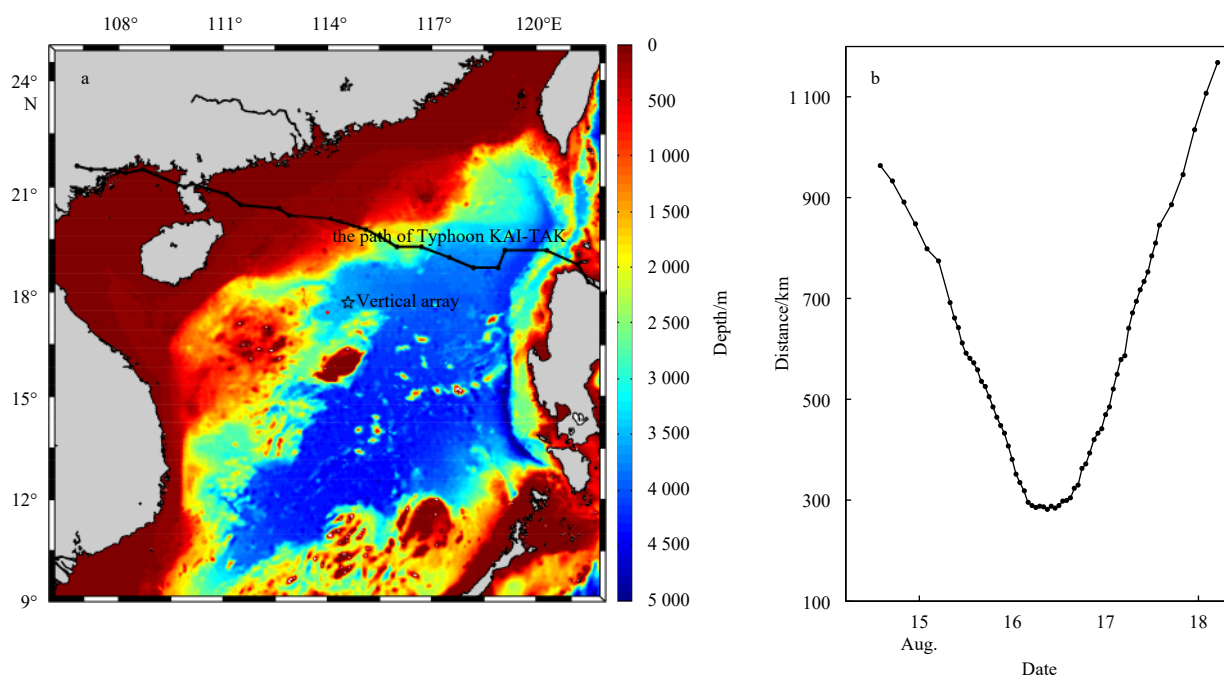


Fig. 1. The relative position and distance between the Typhoon KAI-TAK and the vertical line array. a. The path of Typhoon KAI-TAK, the location of vertical line array and the topography of the northern South China Sea; and b. the temporal variety of horizontal distance between typhoon center and receiving acoustic mooring.

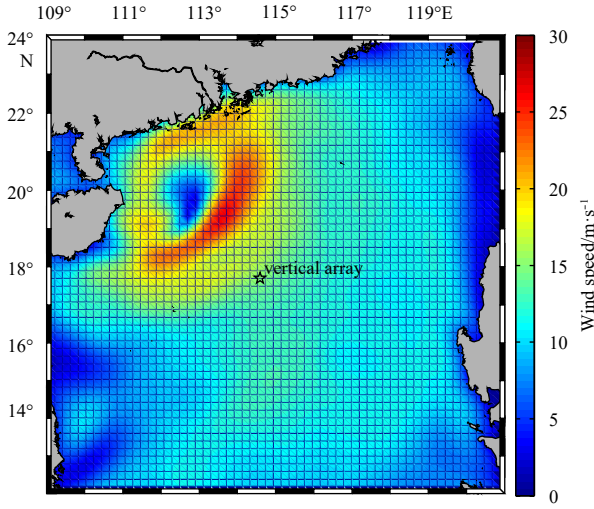


Fig. 2. Wind field in the northern South China Sea during the passage of Typhoon KAI-TAK.

point FFT length, yielding 1 Hz frequency bins with 50% overlap.

The strong wind caused by a typhoon will increase underwater noise levels significantly. The noise spectrogram that was measured by the middle (13th) hydrophone of the vertical line array is shown in Fig. 5. The receiving depth of the 13th hydrophone is 515 m. Affected by Typhoon KAI-TAK, the underwater noise level has firstly increased and then decreased from 6:00 UTC on August 15th to 13:00 on August 18th, which is also consistent with the changes of wind speed shown in Fig. 3. For this reason, the data recorded from 6:00 UTC on August 15 to 13:00 on August 18th are defined as the data during the typhoon period, and the others are defined as the data during the non-typhoon period.

3.2 Effect of typhoon on correlation coefficients between the noise level and the wind speed

The correlation coefficients between the noise level and the wind speed have been calculated and are shown in Figs 6-9. The equation for calculating the correlation coefficient is

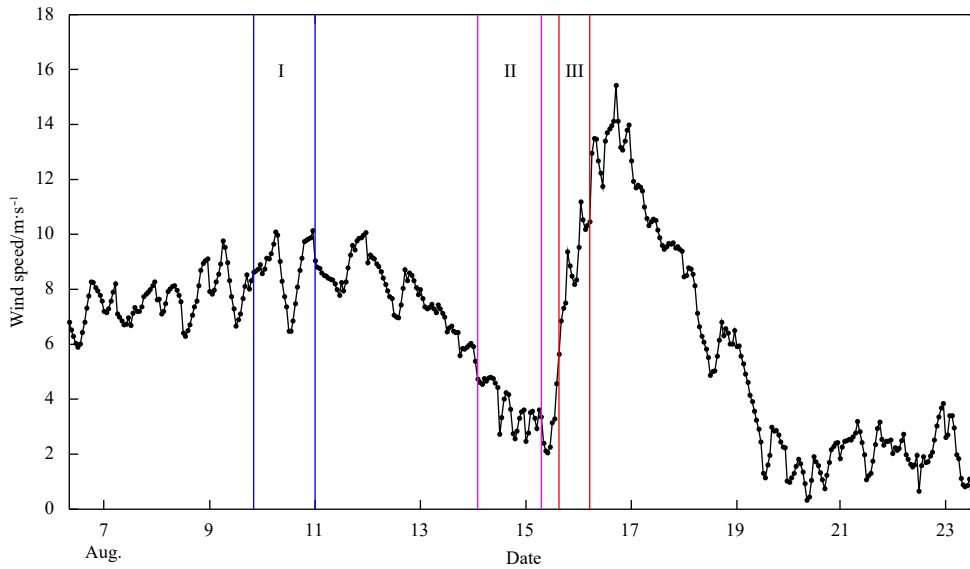


Fig. 3. Variability of wind speed at the sea area of the receiving acoustic mooring from 9:00 UTC on August 6 to 16:00 on August 23, 2012.

$$r_{xy} = \frac{E[(x - \bar{x})(y - \bar{y})]}{\sigma_x \sigma_y} = \frac{1}{N - 1} \sum_{k=1}^N \left(\frac{x_k - \bar{x}}{\sigma_x} \right) \left(\frac{y_k - \bar{y}}{\sigma_y} \right), \quad (1)$$

where x is the time series of underwater noise level at a certain frequency, y is the time series of wind speed, \bar{x} is the mean value of x , \bar{y} is the mean value of y , σ_x is the standard deviation of x , σ_y is the standard deviation of y , and N is the length of the time series.

Figure 6 shows the correlation coefficients between the noise level and the wind speed for various frequencies and receiving depths in the non-typhoon period, where the frequency bandwidth is 10 Hz to 2.5 kHz and the receiving depth is from 155 m to 875 m. The correlation coefficients increase rapidly from 200 Hz to 630 Hz. When the frequency is greater than 630 Hz, the correlation coefficients increase slowly with increasing frequency, and they reach a peak value and come to stabilize at last. When the frequency is less than 200 Hz, there are no obvious laws of the

correlation coefficients. Figure 7 shows the depth profiles of correlation coefficients between the noise level and the wind speed in the non-typhoon period which the frequency is greater than 200 Hz. The correlation coefficients decrease with increasing receiving depth and by approximately 0.1 at a depth ranging from 155 m to 875 m.

Figure 8 shows the correlation coefficients between the noise level and the wind speed for various frequencies and receiving depths during typhoon period, where the frequency bandwidth is 10 Hz to 2.5 kHz and the receiving depth is from 155 m to 875 m. When the frequency is greater than 200 Hz, the correlation coefficients increase rapidly with increasing frequency, before reaching a peak value at approximately 630 Hz. After that, the correlation coefficients gradually decrease with increasing frequency. Correlation coefficients of all receiver hydrophones are greater than 0.8 when the frequency is greater than 500 Hz. Figure 9 shows the depth profiles of correlation coefficients between the noise level and the wind speed during the typhoon period which

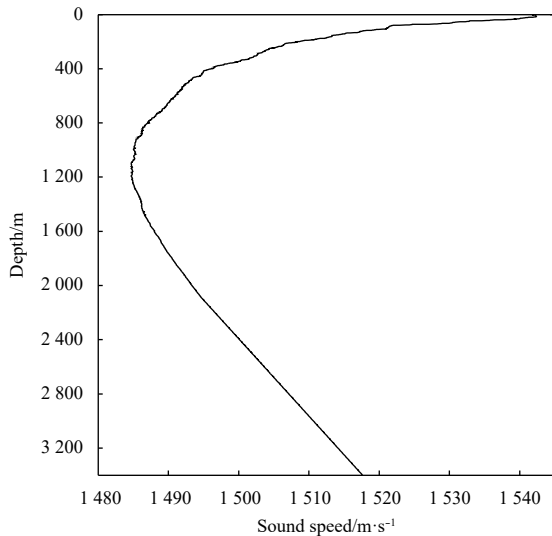


Fig. 4. Sound speed profile.

the frequency is greater than 200 Hz. The correlation coefficients generally increase with increasing receiving depth. The correlation coefficients increase by more than 0.05 in the 250–400 Hz frequency range at depths ranging from 155 m to 875 m, with a maximum increase exceeding 0.1.

Comparing Fig. 7 with Fig. 9, the correlation between the underwater noise and the wind speed during the typhoon period is significantly better than during the non-typhoon period in the frequency range of 250 Hz to 1.6 kHz. The correlation coefficient between the noise level and the wind speed at 250 Hz is less than 0.2 during the non-typhoon period, which is taken to be uncorrelated. However, this correlation coefficient is greater than 0.55 during the typhoon period, indicating a moderate correlation. When the frequency is greater than 250 Hz, the correlation coefficients generally decrease with increasing receiving depth during the non-typhoon period. However, during the typhoon period,

the correlation coefficients increase with increasing receiving depth dramatically, especially in the 250–400 Hz frequency range.

Shipping channels are busy in the South China Sea, however the noise from distant shipping generally dominates the spectra at frequencies less than 200 Hz (Wenz, 1962; Urick, 1984; Shooter et al., 1990). Generally, underwater noise is mainly caused by wind in the frequency range of several hundred Hz to tens of kHz (Wenz, 1962; Urick, 1984). When the frequency is greater than 250 Hz, the wind-generated noise gradually dominates, although many noise sources contribute to noise in this frequency range.

3.3 Effect of the typhoon on the depth dependence of the noise level

The depth dependence of the underwater noise level is analyzed at three selected typical frequencies and three typical periods. For the dramatic change of the correlation coefficients with receiving depth in the 250–400 Hz frequency range, the selected three typical frequencies are 250 Hz, 315 Hz, and 400 Hz. The three typical periods are shown in Fig. 3, and include the high wind speed period during the non-typhoon period that is marked I (the data length is 29 h), the low wind speed period during the non-typhoon period that is marked II (the data length is 30 h), and the high wind speed period during the typhoon period that is marked III (the data length is 15 h). The average wind speed during these three time periods are 8.71 m/s, 3.77 m/s and 8.70 m/s respectively. The average wind speed of period II is significantly slower, and the average wind speeds of period I and period III are nearly equal. The change in wind speed across these three periods also reflects the trend of wind speed during these three periods in the northern part of the South China Sea.

The depth profiles of average noise level for the three typical frequencies and three typical periods are shown in Figs 10–12. The straight lines in the three figures are the trend lines from the fitting. From the three figures, it is determined that the average underwater noise levels of period I and period II all generally decreased with increasing receiving depth at the three typical frequencies. These trends are consistent with the variation trends of

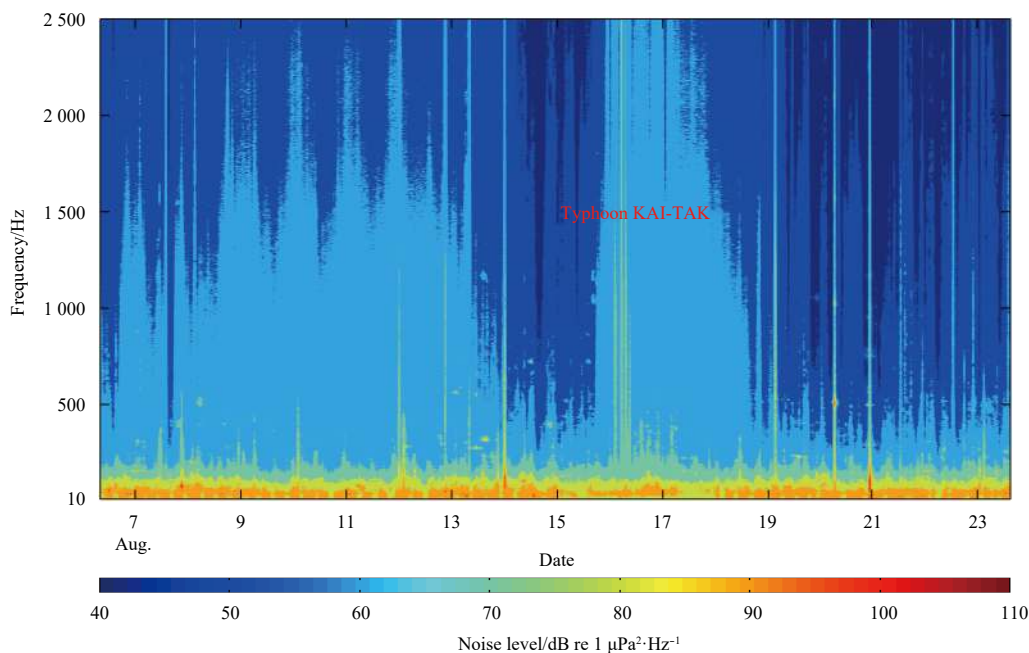


Fig. 5. Spectrogram of underwater noise from 9:00 UTC on August 6 to 16:00 on August 23, 2012.

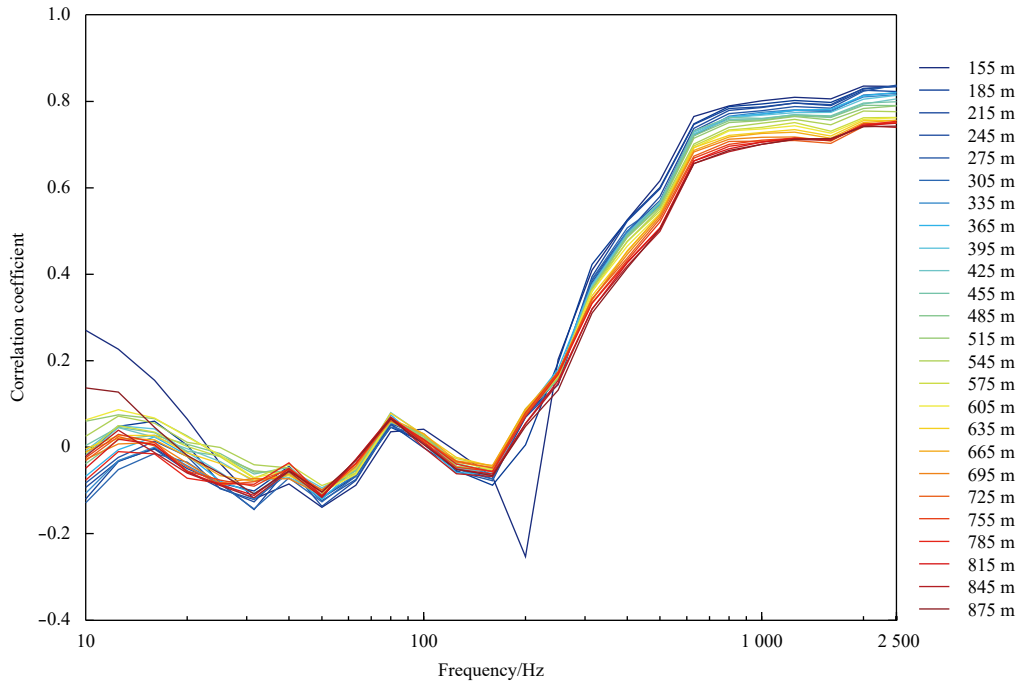


Fig. 6. The correlation coefficients between the noise level and the wind speed for various frequencies and receiving depths during the non-typhoon period.

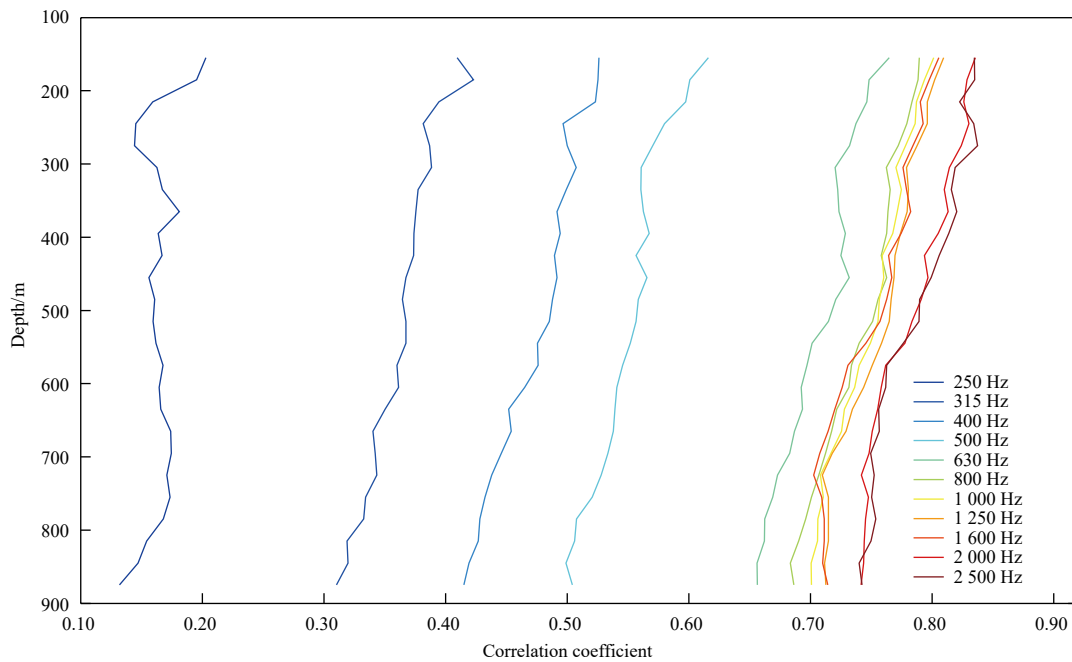


Fig. 7. Depth profiles of correlation coefficients between the noise level and the wind speed for various frequencies during the non-typhoon period.

the correlation coefficients in Fig. 7. The average underwater noise levels of period III all generally increased with increasing receiving depth at the three typical frequencies. These trends are consistent with the variation trends of the correlation coefficients in Fig. 9.

The existing studies show that the depth dependence of underwater noise level is affected by the water depth, acoustic frequency, sea surface wind speed, sound velocity of seawater, and

presence or absence of distant ship noise (Perrone, 1970; Morris, 1978; Shooter et al., 1990). At depths between 120 m and 762 m, a prior study showed that underwater noise spectrum levels ranged from 11 Hz to 1 414 Hz (Perrone, 1970). It was concluded that local wind-generated noise mainly affected underwater noise above 177 Hz and that in this frequency range, the ambient noise spectrum levels decreased with increasing water depth and that this decrease in level as a function of depth became larger

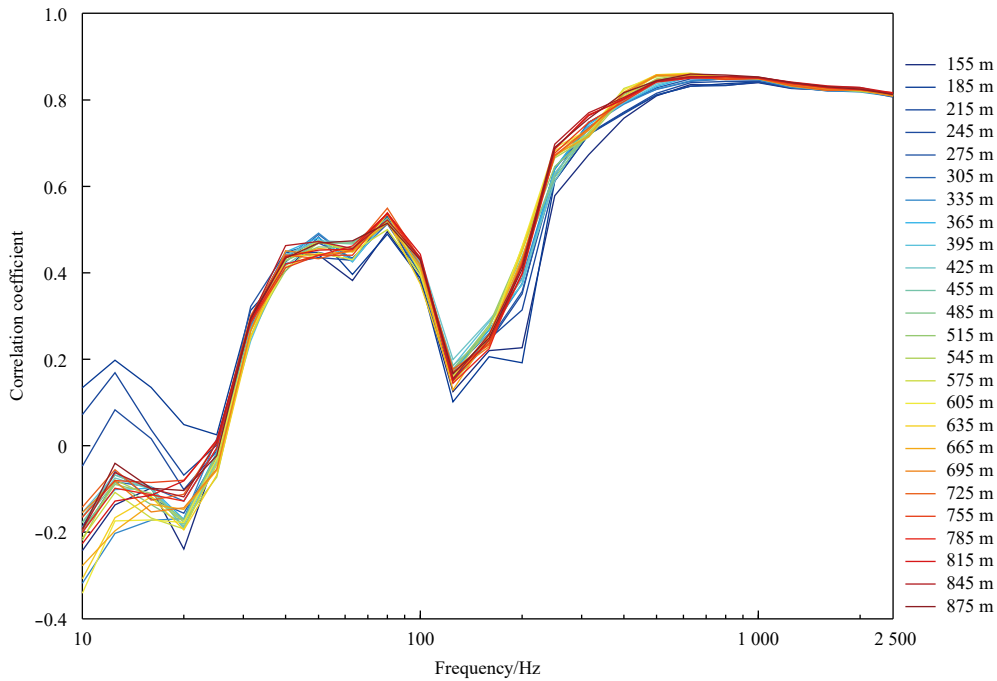


Fig. 8. The correlation coefficients between the noise level and the wind speed for various frequencies and receiving depths during the typhoon period.

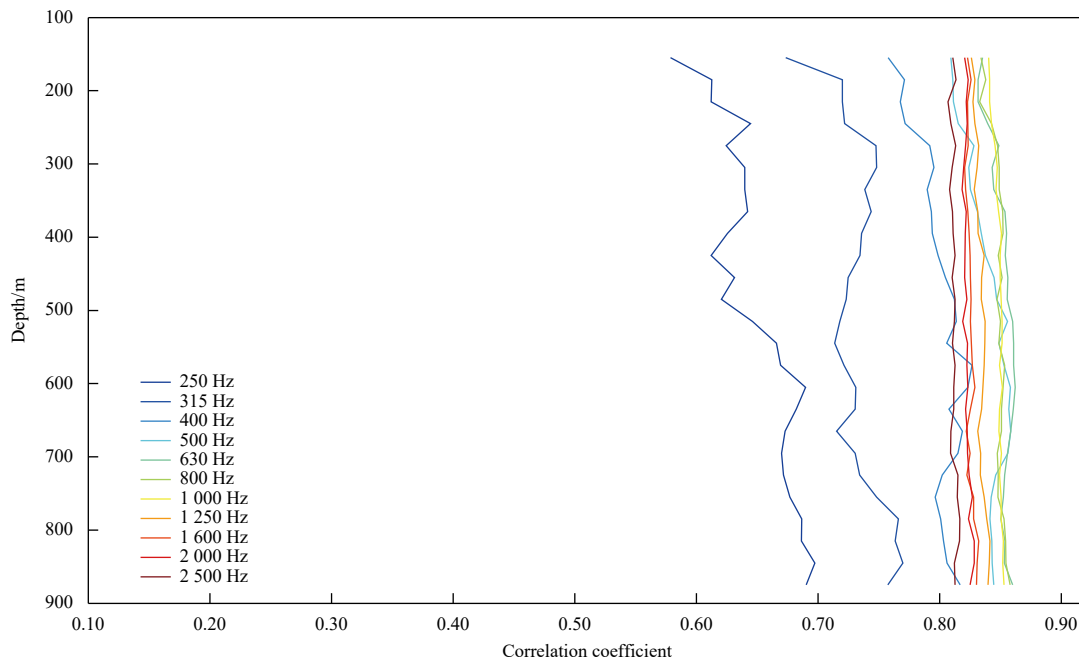


Fig. 9. Depth profiles of correlation coefficient between the noise level and the wind speed for various frequencies during the typhoon period.

with increasing frequency. In the depth of approximately 200 m to 5180 m, a prior study had shown that the underwater noise levels from 15 Hz to 800 Hz (Morris, 1978). It was concluded that at low frequencies, the noise levels decreased with increasing depth and were independent of the wind speed. In the depth of seawater from 3460 m to 4853 m, a prior study showed that the effect of ship traffic and sea surface wind on the depth dependence of the underwater noise from 10 Hz to 500 Hz, and indicated that the critical depth was 4060 m (Shooter et al., 1990). It

was concluded that the noise field of large depth excess is strongly depth dependent under distant source conditions and that the noise levels decrease with increasing depth. It was also concluded that the noise level generated from local sources such as wind and nearby shipping is almost independent of receiver depth. At higher frequencies, the noise levels and their depth dependence were controlled by wind-generated noise. When the hydrophone depth was less than 844 m or below the critical depth, the noise levels decreased with increasing depth. At other

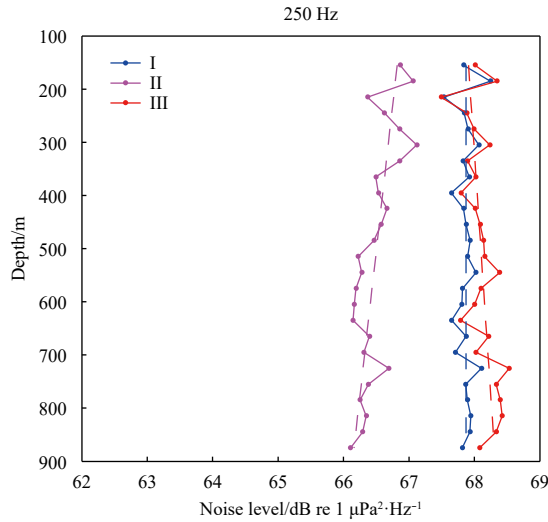


Fig. 10. Depth profiles of average underwater noise level at 250 Hz in three periods.

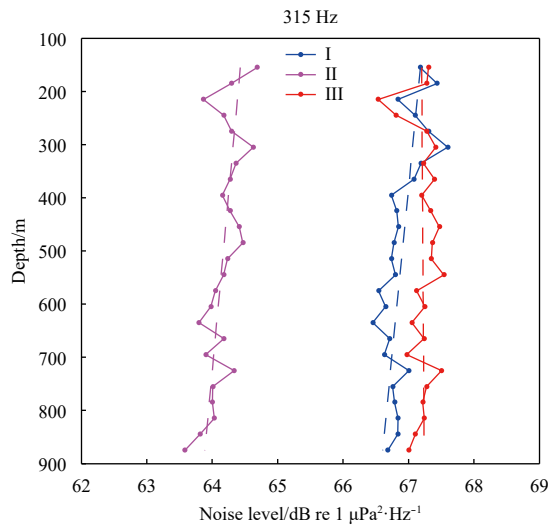


Fig. 11. Depth profiles of average underwater noise level at 315 Hz in three periods.

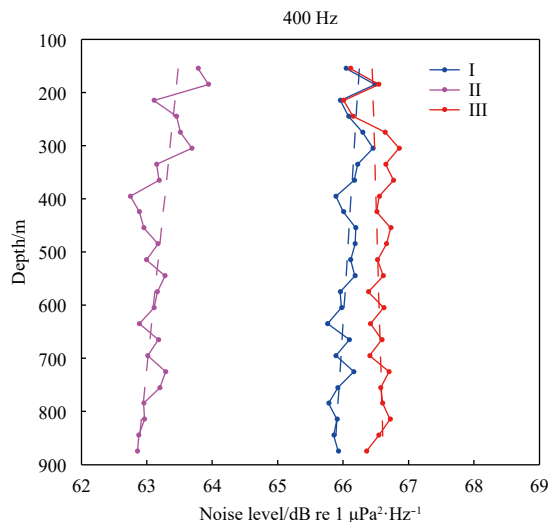


Fig. 12. Depth profiles of average underwater noise level at 400 Hz in three periods.

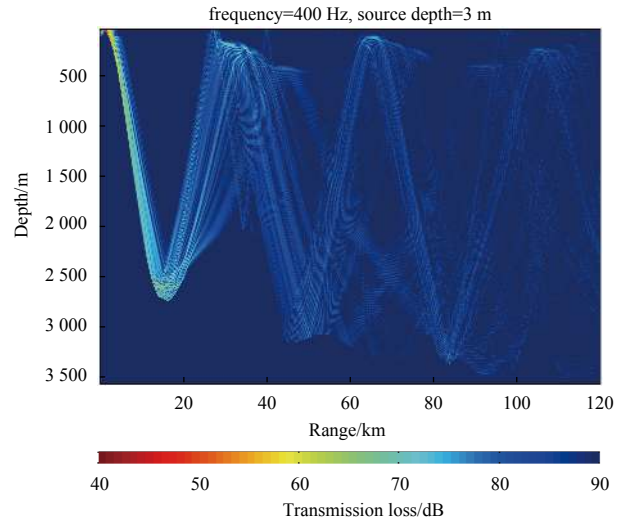


Fig. 13. A simulation example of sound propagation from shallow water at Zhongsha Islands to the noise measuring acoustic mooring in the northern South China Sea.

hydrophone depths, both increases and decreases in noise levels with depth were noted.

In this paper, the hydrophone receiving depth was from 155 m to 875 m. Variability of the average noise level with the receiving depth observed during period I and period II were consistent with prior results in the literature (Perrone, 1970; Morris, 1978) when the hydrophone depth is less than 844 m, which the average noise levels decrease with increasing receiving depth. However, during the typhoon period III, the average noise levels dramatically increase with increasing receiving depth. In Fig. 9, the correlation coefficients between the noise level and the wind speed increase with increasing receiving depth. This indicates that trend of increasing average noise levels with receiving depth during period III should be mainly attributed to wind-generated noise. The existing studies show that the locally generated wind noise presumably reaches the hydrophone via direct paths only if local wind-generated noise sources are from high wind speed (Perrone, 1970; Morris, 1978; Shooter et al., 1990). The noise levels will not increase with increasing depth. Consequently, the increase in noise levels of period III with increasing receiving depth should be attributed to distant wind-generated noise.

A prior study (Wagstaff, 1981) points out that there are two mechanisms for the distant noise will trap into the deep sound channel. The first is the axis of the deep sound channel approaching the surface with increasing latitude, this happens in the North Pacific and the North Atlantic. The second is the “downslope enhancement”. This refers to the conversion of bottom reflected/surface reflected ray paths into continuously refracted ray paths, when a sloping bottom is encountered at depths within a deep sound channel. Our experimental area is in the South China Sea, so the first mechanism can be excluded, it should be attributed to the effect of “downslope enhancement” on distant wind-generated noise.

Due to the non-linear interaction of ocean waves (Longuet-Higgins, 1950), the microseisms are produced during typhoons, and the microseisms are mainly responsible for the distant infrasonic frequency noise field (Gerstoft et al., 2006; Gerstoft and Tanimoto, 2007; Hetzer et al., 2008; Traer et al., 2008). However, the frequency of microseisms is much less than 250 Hz, so micro-

seisms can be excluded.

The results of Wilson et al. (1985) and Deane (1999, 2000) showed that surf breaking and surf beat upon the shores produced wind-generated underwater noise that increased significantly under a high sea state. In particular, the results of Wilson et al. (1985) indicate that the underwater noise at frequencies of 200 Hz to 500 Hz will increase significantly from surf breaking and surf beat upon the shores during heavy surf conditions. Prior studies (Northrop et al., 1968; Wagstaff et al., 1981; Carey, 1986; Dosso and Chapman, 1987) show that a downsloping seafloor will cause a “downslope enhancement” effect on sound propagation. As a result, the wind-generated noise in shallow waters can affect the deep-sea noise distribution due to the effect of “downslope enhancement.” As shown in Fig. 1, the acoustic mooring is located on the edge of the deep-sea basin. The noise of surf beat upon the shores and reefs and the noise of surf breaking in shallow waters around the deep-sea basin are interacted with the downsloping seafloor, and they will impact the ambient noise distribution at the sea area of the receiving acoustic mooring due to the “downslope enhancement” effect on noise propagation. To the west and south of the acoustic mooring are Xisha Islands and Zhongsha Islands. A simulation example of sound propagation from shallow water (at one island of the Zhongsha Islands) to the noise measuring acoustic mooring has been shown in Fig. 13. Most of the time, the wave height at the acoustic mooring, Xisha Islands and Zhongsha Islands is roughly 2–4 m during the typhoon, so we choose 3 m as the source depth, and the simulation source frequency is 400 Hz. It is shown that wind-generated noise in shallow waters can alter the deep-sea ambient noise distribution. The sound energy is converged or enhanced at depths ranging from several hundred meters to thousands of meters. There are many islands and reefs in Xisha Islands and Zhongsha Islands, the islands and reefs have different horizontal distances and topography with the acoustic mooring, but they all have the downsloping seafloor and lead to the effect of “downslope enhancement”. The variation of noise level at acoustic mooring with receiving depth is the result of the interaction of many wind-generated noise in shallow waters at the Xisha Islands and Zhongsha Islands.

The average underwater noise levels during period I all generally decreased with increasing receiving depth at the three typical frequencies, but in period III, they generally increased with increasing receiving depth. Consequently, there is also a question to be answered: why are the trends in average noise level with receiving depth in period I and period III completely different? In general, the average wind speed of period I and period III are nearly equal. In my opinion, there are two reasons for this phenomenon in this paper. First, the long wave swells that are generated during the typhoon period (Munk et al., 2013) will superpose with the local wind-driven waves and the wave height will be increased. Second, the typhoon will cause storm surge (Harris, 1963). Powerful wind whips up large, strong waves in the direction of its movement, and when waves are breaking on a line more or less parallel to the beach, they carry considerable water shoreward. Therefore, surf breaking and surf beat in shallow waters will be strengthened. The source level of wind-generated noise in shallow waters will be increased significantly during period III and will be greater than that during period I. This will alter the noise-depth distribution at the measuring sea area due to the effect of “downslope enhancement” on the sound propagation, and generate depth distributions of average noise levels that are completely different in period III compared to period I.

4 Conclusions

It has been shown that the noise field was affected by the Typhoon KAI-TAK in the north of Zhongsha Islands in the South China Sea. The correlation of ambient noise with wind speed is increased during the typhoon period in the frequency range of 250 Hz to 1.6 kHz. The correlation coefficients and average noise levels generally decreased with increasing depth during non-typhoon period, however, they increased dramatically with increasing depth during the typhoon period at frequencies of 250 Hz, 315 Hz, and 400 Hz.

The noise in the measured sea area is affected not only by local wind-generated noise sources but also by distant wind-generated noise sources during a typhoon period, especially in frequency ranges of 250 Hz to 400 Hz. A prior study (Wilson et al., 1985) showed that underwater noise at frequencies of 200 Hz to 500 Hz increased significantly due to surf breaking and surf beat during heavy surf conditions in shallow waters. Furthermore, the acoustic mooring is located on the edge of the deep-sea basin in the northern South China Sea. There are many islands, reefs and shallow waters around it, and there is downslope topography along the way from islands and shallow waters to the location of acoustic mooring. During the typhoon period, the source level of wind-generated noise of the surf breaking and surf beat in shallow waters will increase significantly. As a result of interactions between the wind-generated noise in shallow waters and the downsloping seafloor, the effect of “downslope enhancement” on noise propagation occurs. The noise-depth distribution is changed during the typhoon.

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