Article

Correlation between Underwater Noise and Sea Level at Ieodo Ocean Research Station

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Abstract: To investigate the correlation between underwater noise and sea level, data collected at Ieodo Ocean Research Station (from 15 May to 27 August 2013) were analyzed. Temporal variations in the overall level of underwater noise were similar to those in sea level. The average underwater noise levels at frequencies below 50 Hz were 99.0–106.6 dB during spring tides and 78.4–90.2 dB during neap tides, with a difference of 12.6–20.6 dB. When low-pass filtering at six hours was applied to the absolute value of sea level, a high correlation coefficient of 0.7 for its association with underwater noise was obtained. This strong correlation could indicate flow noise caused by currents. Underwater noise levels around the frequency of 16 Hz were relatively strongly correlated with sea level (correlation coefficient of 0.71). Wavelet analysis of the overall level of underwater noise showed strong periodicity at 0.25, 0.50, 1.0, 16.0, and 30.0 days, as well as characteristics of a tidal constituent. In wavelet coherence analysis, the overall level at a period of 0.25 days exhibited a phase difference of -90 degrees relative to sea level. This finding indicates that the noise level peaks at 1.5 h before the high tide or low tide, which was confirmed in the correlation analysis of noise level and sea height with various time lags. This study shows that the overall level of underwater noise from ebb currents is higher than that from flood currents due to differences in current velocity.

Keywords: underwater noise; flow noise; wavelet analysis; sea level; Ieodo Ocean Research Station (IORS)

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1. Introduction

The northern area of the East China Sea has complicated flow patterns due to the coexistence of a variety of currents (Kuroshio, Jeju Warm Current, and others) and tides [1]. There are also rotating tides that move in a clockwise direction near Jeju Island, South Korea. This area has a typical semidiurnal tidal cycle, in which the tide stage and direction change with time in the tidal cycle, and the strength of the tide changes between spring and neap tides [2]. Ieodo Ocean Research Station (IORS; $125^{\circ}10'56.81''$ E, $32^{\circ}07'22.63''$ N) was constructed around underwater rocks at 149 km southwest of Mara Island off Jeju Island (Figure 1) in 2003 [3]. Characteristics of the surrounding marine environment including water temperature, current, wave height, and underwater ambient noise are observed using a variety of sensors installed at IORS.

Underwater ambient noise in the ocean exhibits very different patterns in response to shipping, wind, marine life, breaking waves, rainfall, and water flow [4–18]. Generally, underwater ambient noise caused by water flow in the ocean is generated at frequencies below 100 Hz [6,9,10,12,14–16]. Such underwater noise is frequently called flow noise or pseudosound, a type of non-acoustic noise [6,7,11], as water flow can cause pressure fluctuations near the surface of the moored underwater hydrophone in the ocean. However, flow noise can be an important factor when investigating the characteristics of tides [16–18].

Previous studies on flow noise in the ocean caused by tides have mostly investigated the relationship between sea level and flow velocity [16–18]. These studies have shown that significant flow noise at 4.5 Hz can be observed due to semi-diurnal tides, and flow

noise can occur at frequencies of up to 500 Hz as tidal current velocity increases [16,17]. Willis et al. [18] reported that the underwater noise level related to tides can be higher during ebb tides than flood tides at Ramsey Island in the United Kingdom. However, previous studies did not specifically analyze the correlation strength and periodicity of the relationship between flow noise and tidal data. Therefore, in this study, we investigated the correlations and periodicity of underwater noise, sea level, and current velocity observed at IORS.

Figure 1. Location of the Ieodo Ocean Research Station (IORS). IORS is situated on Ieodo Rock, an underwater rock located approximately 149 km southwest of Mara Island.

2. Data and Methods

2.1. Underwater Noise

Figure 2 shows a schematic diagram of the experimental setup used for acoustic measurement of underwater noise. The water depth at IORS was 50 m. A self-recording hydrophone (SM2M, Wildlife Acoustics Inc., Maynard, MA, USA) consisting of a hydrophone sensor (HTI-96-MIN, High Tech Inc., USA), a 16-bit analog-to-digital converter, an amplification circuit, the main control unit, an SDXC (Secure Digital Extended Capacity) memory card, and a dry battery was deployed at a water depth of between 18 and 20 m. To minimize fluctuations in hydrophone position due to wave action and strong currents, the self-recording hydrophone was attached to a wire cable with a diameter of 5 mm, which was held vertical using a weight of 600 kg near the bottom to minimize the strumming noise. The hydrophone sensor has a nearly omni-directional receiving sensitivity of -165 dB re 1 V/ μ Pa within ± 3 dB in the frequency range of 2 Hz–30 kHz. Underwater noise was measured for 1 min at 30-min intervals over 24 h from 15 May to 27 August 2013. Data were recorded on an SDXC memory card at a sampling rate of 44,100 Hz.

Figure 2. Schematic diagram of the experimental setup used for acoustic measurement of underwater noise.

A 1/3-octave analysis was performed to obtain the mean noise spectra of underwater noise over the frequency range of 10 Hz–12.5 kHz [19]. The sampling rate is 44,100 Hz, but maximum useable frequency is generally 1/3 times of the sampling frequency. Therefore, the maximum frequency at 1/3-octave analysis was 12.5 kHz. The duration of each underwater noise used for analysis was 1 s. The overall intensity of 1/3-octave levels was used to analyze the correlation between underwater noise and sea level, and is given by:

$$IL = 10 \log \left(\sum_i 10^{\frac{IL_i}{10}} \right) \quad (1)$$

where IL_i is the intensity level of the i th 1/3-octave frequency.

2.2. Sea Level and Current Velocity

Sea level was measured every 10 min from 15 May to 27 August 2013 using a wave radar device (RangeFinder, Miros, Norway) that was installed on a steel frame at IORS and located at a height of 24 m above the sea surface. These data were rearranged in 30-min intervals for comparison with the overall underwater noise level measurements. The mean sea level (MSL), which has been measured since 2004 by the Korea Hydrographic and Oceanographic Administration, was 135 cm [20]. Therefore, sea levels in this study were determined by subtracting the MSL from our measured sea levels.

The current velocity must be measured for correlation analysis of the overall level of underwater noise and sea level. A recording Doppler current meter (RDCP 600, Aanderaa) was installed on the sea bottom a few tens of meters away from IORS. However, as this instrument was frequently lost due to fishing operations around IORS, no current velocity data were collected in 2013. Therefore, we used current velocity data obtained every 30 min from 17 October 2009 to 20 February 2010.

2.3. Correlation and Continuous Wavelet Transform Analyses

Sea level is a vector value that has a directional component. However, the underwater noise level is a scalar value that is not directional. Therefore, absolute values of sea level were taken for comparison with underwater noise data. Low-pass filtering at 6 h was

applied to overall levels of underwater noise for long-period analysis of the correlation between noise level and sea level. The continuous wavelet analysis was performed to analyze the coherence between the overall level of underwater noise and sea level. For wavelet calculation, MATLAB code was used, which was made by A. Grinsted. The type of wavelet was 'Morlet' [21]. This type provides a good balance between time and frequency localization.

3. Results

Figure 3 shows the sea levels and overall levels of underwater noise from 15 May to 27 August 2013. During the measurement period, seven spring tides and neap tides occurred, as shown in Figure 3a. The peak of each spring tide is marked with a yellow dot. The sea level curve repeated approximately every 15 days. The spring tide period was determined as the time of each yellow point ± 1 day. The neap tide period was set to ± 1 day from a point at -7.5 days relative to the peak of the spring tide. The spring tide (red lines) and neap tide (green lines) can be distinguished clearly, and they exhibit the semidiurnal tidal characteristic [1,2]. During this period, the sea level range during the spring tide, as shown in Figure 3a, was approximately 200 cm, whereas the range of the neap tide was approximately 60 cm, which differed sharply from that of the spring tide. Due to this difference, the tidal current velocity will change between the spring tide and neap tide. The overall level of underwater noise, shown in Figure 3b, exhibits a similar tendency to that of sea level. The noise level was high during the spring tide period (red lines), low during the neap tide period (green lines), and appeared to be closely correlated with sea level. The red dotted line in Figure 3b indicates the mean value (110.0 dB) of the overall noise levels during the spring tide period. The green dotted line indicates the mean value (97.9 dB) during the neap tide period. These two mean values have a large difference of 12.1 dB, which may be due to the change in tidal current velocity.

Figure 3. (a) Sea level and (b) overall level of underwater noise from 15 May to 27 August 2013. The red and green lines indicate spring tide and neap tide periods, respectively. Yellow points indicate the peaks of the spring tide. The number at the end of the red dotted line is the average for the spring tide, and the number at the end of the green dotted line is the average for the neap tide.

Figure 4 shows frequency spectra of underwater noise during the spring and neap tide periods. The thick solid lines in Figure 4 represent the average frequency spectra of underwater noise during the spring tide (red) and neap tide (green). The frequency spectra for the spring tide period exhibited large differences; in particular, at low frequency (below 50 Hz), noise levels varied from 67.2 to 119.1 dB, with an average range of 99.0–106.6 dB. Smaller differences were observed for the neap tide, with a low-frequency (below 50 Hz) range of 65.4–108.3 dB. The average range was 78.4–90.2 dB. The difference between the two average frequency spectra during both tide periods was approximately 12.6–20.7 dB below 50 Hz. The difference was less than 8.3 dB at frequencies of more than 60 Hz.

Figure 4. Frequency spectra of underwater noise during spring and neap tide periods. The thick solid lines represent the average frequency spectra of underwater noise during the spring tide (red) and neap tide (green). The magenta line indicates the differences between the two average frequency spectra.

Figure 5 shows the overall levels of underwater noise from 15 May to 27 August 2013. The x -axis in Figure 3b represents the total time of the measurement period, and the y -axis represents the time of day. The overall noise level was within the range of 90–125 dB, with a pattern of low and high levels every 6–8 days. When the overall level was high, it was more than 115 dB, and when it was low, it was less than 90 dB. These patterns of high and low noise occurred within a cycle of approximately 15 days. However, noise levels over 24 h, as indicated by the y -axis of Figure 5, were not consistently high or low due to variations in tidal current velocity, which affected the underwater noise level. The point of high or low water during the tidal cycle, when there is little or no change in the height of the tide, is known as the stand of the tide. The sea level is almost stationary at the stand of the tide, and the tidal current velocity falls to zero before reversing. Therefore, the overall level of underwater noise was lowest at the stand of the tide, which occurs four times per day.

Figure 5. Overall levels of underwater noise (contour label interval, 10 dB) from 15 May to 27 August 2013.

4. Discussion

4.1. The Correlation between Underwater Noise and Sea Level

Figure 6 shows the correlation between the absolute value of sea level and the overall level of underwater noise with and without low-pass filtering at six hours. As shown in Figure 6, the correlation coefficient between sea level and overall level of underwater noise had a low value of 0.33. However, the coefficient had a high value of 0.70 when a low-pass filter at six hours was applied to the noise level data, as low-pass filtering removed short periodic components caused by nearby shipping vessels or sea surface agitation [4,5,8–12].

Figure 6. Correlation between the absolute value of sea level and overall underwater noise level (a) without and (b) with low-pass filtering at 6 h.

Figure 7 shows the correlation coefficients between sea level and underwater noise level at different 1/3-octave frequencies. The red dotted line indicates a correlation coefficient of 0.70 for the overall level of underwater noise. The correlation coefficient for underwater noise was generally high at frequencies below approximately 50 Hz and had a maximum value of 0.71 around the frequency of 16 Hz, which was similar to the overall level. Underwater noise at frequencies below 50 Hz can be caused by tidal currents and, therefore, is related to sea level [16,18].

Figure 7. Spectral cross correlation coefficients between sea level and underwater noise level at various 1/3-octave frequencies.

4.2. Continuous Wavelet Analysis of Sea Level and Overall Underwater Noise Level

Figure 8 shows the results of continuous wavelet analysis of sea level and overall underwater noise level. As shown in Figure 8a, wavelet analysis of sea level revealed strong periodicity at 0.25 (6 h), 0.5 (12 h), 1 (24 h), 13.6, and 27.6 days. Wavelet analysis of underwater noise revealed a similar pattern of periodicity, as tidal currents significantly affected the underwater noise level. For the semidiurnal tides, which are the main tidal constituent, the period of the principal lunar component (M_2) was 12.42 h and the period of principal solar component (S_2) was 12.00 h. Among diurnal factors, the lunisolar period (K_1) was 23.93 h and the principal lunar period (O_1) was 25.82 h. Among tidal constituents acting over longer periods, the period of the lunar fortnightly constituent (M_f) was 327.9 h (13.66 days) and the period of the lunar monthly constituent (M_m) was 661.30 h (27.55 days; Table 1) [22]. In the underwater noise data, these tidal constituents could be readily identified and their periods were consistent. These results validate the possibility of measuring tidal constituents based on underwater noise.

Figure 8. The continuous wavelet power spectrum of (a) sea level and (b) the overall level of underwater noise. The tick black contour designates the 5% significance level against red noise and the cone of influence (COI) where edge effects might distort the picture is shown as a lighter shade.

Table 1. Characteristics of principal tidal constituents.

Type and Name	Symbol	Period (Solar Hours [Days])	Relative Size (%)
Semi-diurnal			
Principal lunar	M_2	12.42 (0.52)	100.0
Principal solar	S_2	12.00 (0.50)	46.6
Diurnal			
Lunisolar	K_1	23.93 (1.00)	58.4
Principal lunar	O_1	25.82 (1.08)	41.5
Long period			
Lunar fortnightly	M_f	327.67 (13.65)	17.2
Lunar monthly	M_m	661.30 (27.55)	9.1

4.3. Dependence of Sea Level and Overall Underwater Noise Level on Current Velocity

Figure 9 shows the wavelet coherence between sea level and overall underwater noise level. As shown in Figure 9, coherence was very high at periods of 0.25, 0.5, and 1 day. This finding indicates that underwater noise strongly influenced sea level variations. Coherence was also very high at periods of 8–32 days. The arrows in Figure 9 indicate the phase between sea level and noise level [21]. The relative phase relationships are indicated with arrows (with those pointing right, left, and straight down indicating an in-phase relationship, an anti-phase relationship, and that sea level was leading underwater noise by 90° , respectively). The arrows situated at a period of 0.25 day (six hours) in Figure 9 indicate phase differences of approximately -90° , which means that the noise level peak occurred at 1.5 h earlier than the sea level peak. The time lag between the noise peak and the sea level peak indicates that the tidal current velocity did not reach its maximum during the peak of sea level. Current velocity is generally slowest at low tide and high tide but may vary depending on the geographic characteristics of shallow waters.

Figure 9. Wavelet coherence analysis of underwater noise (overall level) and sea level. The relative phase relationship is indicated with arrows as follows: pointing right, in-phase; pointing left, anti-phase; pointing straight down, sea level leading underwater noise by 90° . The 5% significance level against red noise is shown as a thick contour. The cone of influence (COI) where edge effects might distort the picture is shown as a lighter shade.

Figure 10 shows the correlation coefficients between the overall level of underwater noise without low-pass filtering and sea level calculated using various time lags at 0.5-h intervals. The correlation coefficient was 0.33 with a time lag of 0 h, then increased to 0.44 with a lag of 0.50 h and had its highest value of 0.57 with a lag of 1.5 h. The coefficient decreased from 0.56 to 0.07 with 2.0–5.0 h time lags, and then increased again from 0.12 to 0.49 with 5.5–8.0 h time lags. Consequently, the maximum velocity of the tidal current occurred at approximately 1.5 h from the high tide and low tide in terms of sea level.

Figure 10. Correlation coefficients between the overall level of underwater noise (no low-pass filtering) and sea level calculated with various time lags at 0.5-h intervals.

Figure 11 shows the sea level and noise level averaged at each time point over 24 h based on the timing of the high tide on each day. As shown in Figure 11, the sea level (red line) falls from high tide to low tide over a period of approximately 6.5 h. Underwater noise exhibits a periodicity similar to that of sea level. However, the noise level is high at 1.5 h before the times of the low and high tides. Thus, the peak level of underwater noise occurred at 1.5 h earlier than the peak of sea height. This result is similar to that reported by Willis et al. [18]. As underwater noise at frequencies below 100 Hz is related to tidal currents [16,18], the maximum level of underwater noise observed at 1.5 h before the low and high tides, as shown in Figure 11, may be significantly driven by ebb and flood currents. Noise levels during the ebb and flood currents were 109.1 and 105.8 dB, respectively. This difference in noise level between currents might have been caused by a difference in current velocity.

Figure 12 shows the current velocity and sea level measured from 17 October 2009 to 20 February 2010. The current velocity was not measured during the experimental period because the RDCP was lost due to a fishing vessel, as noted in Section 2.2. Generally, monthly volatility of the current velocity is not expected to be high, but daily changes can be expected. In the daily pattern of current velocity, the ebb current was fastest at 1.5–2.0 h before the low tide, reaching velocities of 86.8 and 87.6 cm/s. The maximum flood current velocities were 82.3 and 80.2 cm/s before the high tide, which were somewhat lower than the ebb current velocities. Therefore, the periodicity of underwater noise in this study appears to be strongly related to tidal currents.

Figure 11. Sea level (red line) and overall level of underwater noise (bars) averaged at each time point over 24 h based on the timing of high tides each day from 15 May to 27 August 2013.

Figure 12. Current velocity (bars) and sea level (red line) from 17 October 2019 to 20 February 2010.

5. Conclusions

The correlation between underwater noise and sea level as measured at IORS was analyzed. Underwater noise was converted to overall levels. The overall level of underwater noise during the spring tide was 99.0–106.6 dB. It was 78.4–90.2 dB at neap tide, with a large difference of 20.6 dB observed between tidal periods. The average underwater noise levels at frequencies below 50 Hz were 99.0–106.6 dB during spring tides and 78.4–90.2 dB during neap tides, with a difference of 12.6–20.6 dB. The correlation coefficient between the overall level of underwater noise and sea level was high (0.7), which may be related to flow noise at low frequencies caused by tidal currents. Thus, underwater noise around the frequency of 16 Hz exhibited a strong correlation (0.71) with sea level. On the other hand, the correlation coefficients at frequencies above 60 Hz were less than 0.5 and the correlation was low.

Wavelet analysis of underwater noise and sea level revealed strong periodicity at 0.25 (6 h), 0.5, 1, 13.6, and 27.6 days, similar to the tidal constituents. Wavelet coherence analysis revealed very high coherence at 0.25, 0.5, and 1 day. In particular, the arrows representing the 0.25 day period indicated a phase difference of approximately -90° , indicating that the overall level of underwater noise peaks at 1.5 h earlier than sea level. Correlations were calculated with time lags between the noise level and sea level at 0.5 h intervals, and the highest correlation coefficient of 0.57 was obtained with a time lag of 1.5 h. The overall level of underwater noise was high at 1.5 h before the low and high tides. Therefore, the peak noise level occurred at 1.5 h earlier than the peak sea level. The maximum noise levels during ebb and flood currents were 109.1 and 105.8 dB, respectively. The difference between ebb and flood currents might have been caused by a difference in current velocity. In the daily current velocity measurements, the fastest ebb current was 86.8 cm/s, which occurred at 1.5–2.0 h before the low tide. We confirmed that the current velocity is strongest before the low tide and high tide. This finding indicates that underwater noise at IORS may be significantly related to tidal currents. Future research on the correlation between underwater noise and tidal currents (current velocity) should focus on the prediction of tidal currents using underwater noise levels.

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