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Geophysical Research Letters

RESEARCH LETTER

10.1029/2021GL093097

Key Points:

- The ambient sound level in the East Siberian Sea, showing a negative correlation with the sea ice concentration (SIC), is highest in September
- The ambient sound level increased by 16 dB because of geophony and anthrophony with the reduction in the SIC
- The ambient sound level may increase with accelerated sea ice melting in the future

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Han, D.-G., Joo, J., Son, W., Cho, K. H., Choi, J. W., Yang, E. J., et al. (2021). Effects of geophony and anthrophony on the underwater acoustic environment in the East Siberian Sea, Arctic Ocean. *Geophysical Research Letters*, *48*, e2021GL093097. https://doi.org/10.1029/2021GL093097

Received 28 FEB 2021
Accepted 27 APR 2021

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Effects of Geophony and Anthrophony on the Underwater Acoustic Environment in the East Siberian Sea, Arctic Ocean

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Abstract As Arctic warming accelerates, the underwater acoustic environment in the Arctic Ocean is rapidly changing. We present the first results of passive acoustic monitoring in the marginal ice zone of the East Siberian Sea (ESS). A high sea ice concentration (SIC) and seasonal variations in ice cover make the ESS an ideal region to verify how ambient sound levels respond to natural physical processes and anthropogenic activities during summer. Our observations show that the sound level in the ESS exhibits a strong negative correlation with SIC, and the sound level in September, which was higher than that in other months, was 16 dB higher than the annual average. This increase resulted from geophony and anthrophony with the reduction in the SIC, and sound level increased by 13 dB without anthrophony. Our results indicate that ambient sound level in the Arctic Ocean may increase as climate change accelerates sea ice melting.

Plain Language Summary Arctic ambient noise is expected to increase by the dramatic retreat of sea ice coverage in recent years. We present the first study to validate the effects of both geophony and anthrophony on the ambient noise associated with the great reduction of sea ice in the East Siberian Sea (ESS), Arctic Ocean, one of the acoustically primitive places on Earth. ESS is the relatively quiet sea in the presence of solid sea ice compared to other places in the Arctic Ocean, whereas ambient noise level shows a clear seasonal variability, largely determined by sea ice conditions. During open water season, ambient noise level is highly increased showing 16 dB higher than the annual average. This increase results from geophony and anthrophony and the ambient sound level increased by 13 dB without Anthrophony. Our results indicate that Arctic ambient noise will be highly increased by the effect of geophonic and anthrophonic noise in the future as climate change accelerates sea ice melting. These observations are of sufficiently broad interest for the public as well as the scientific community since they provide vital scientific evidence to develop a mitigation strategy for marine ecology and marine pollution in the Arctic Ocean.

1. Introduction

As global climate change and human activities in the ocean have intensified, the underwater acoustic environment has changed drastically (Duarte et al., 2021; Frisk, 2012; Mahanty et al., 2020). Polar regions are not an exception because interest in the development of natural resources in these areas is steadily increasing and geophysical exploration technology has been developed (Caldwell & Dragoset, 2000; Dragoset, 2000; Haver et al., 2018; Klinck, Mellinger, et al., 2012; Stroeve et al., 2007). Moreover, the decreasing sea ice extent in summer can increase ambient sound level coupled with sea-state and anthropogenic activities (Klinck, Nieukirk, et al., 2012; Roth et al., 2012). Noise from anthropogenic activities may affect the communication, foraging, and navigation of aquatic life and can cause severe damage, such as temporary or permanent threshold shifts (Ellison et al., 2011; Hawkins & Popper, 2017; Slabbekoorn et al., 2010). Therefore, it is necessary to regulate, mitigate and monitor underwater noise, and such activities are currently being performed by numerous international and regional commissions and organizations using passive

10.1029/2021GL093097

Writing – review & editing: Jee Woong Choi, Eun Jin Yang, Jeong-Hoon Kim, Sung-Ho Kang

acoustic monitoring (PAM) (Mellinger et al., 2007; Merchant et al., 2015; PAME, 2019). PAM is carried out in the fields of meteorology, geophysics and ecology, using the acoustic characteristics of rainfall, wind, T-waves, and marine mammal vocalizations (Dziak et al., 2010; Ma et al., 2005; Van Parijs et al., 2009; Yang et al., 2015).

The East Siberian Sea (ESS) is one of the least studied regions in the Arctic Ocean and there are many knowledge gaps regarding ambient noise around the East Siberian Shelf. Previous studies on underwater acoustic monitoring were conducted in the Bering Sea, Chukchi Sea, Beaufort Sea, Greenland Sea, and central Arctic Ocean (black circles in Figure 1a) (Chen et al., 2019; Geyer et al., 2016; Halliday et al., 2020; Heard et al., 2013; PAME, 2019; Southall et al., 2020; Wen et al., 2020). According to previous studies, the underwater acoustic environment in the Arctic Ocean is dependent on seasonal and geophysical conditions and is correlated with sea ice (PAME, 2019). The Arctic Ocean has a unique sound propagation environment because its sea ice cover and ice-containing water have different boundary conditions and sound speed profiles than those in open water. Sea ice dynamics induced by environmental forcing could also be a source of sound from an infrasound frequency range from below 20 Hz to several kHz (Geyer et al., 2016; Glowacki et al., 2018; Kinda et al., 2015; Pettit et al., 2015). Marine species, including Arctic endemic marine mammals produce different types of vocalizations over a wide frequency range, which also contribute to the underwater acoustic signature of the Arctic Ocean (Chou et al., 2020; Halliday et al., 2017; Simard et al., 2014; Stafford et al., 2017). In this study, we provide the first assessment of the seasonal variability of ambient noise in the East Siberian Arctic Shelf, an acoustically pristine region on the planet. The present results could provide implications for the seasonal variability of underwater ambient noise as the soundscape from one of the most largely unidentified places in the Arctic Ocean.

1.1. Measurements

Acoustic measurements were made from August 21, 2017 to August 13, 2018 on the East Siberian Shelf (74° 37.332′N, 174° 56.382′E) in the ESS (Figure 1b). The ESS is a marginal sea of the Arctic Ocean with relatively shallow water reaching an average depth of ~54 m (Gorbatenko & Kiyashko, 2019). An autonomous passive acoustic recorder (AURAL-M2, Multi-Electronique Inc.) was moored at a depth of 52 m, corresponding to 10 m above the seafloor. The AURAL was programmed to record acoustic data for 10 min every hour with 16-bit resolution and a 32,768 Hz sampling rate. An HTI-96-MIN hydrophone (High Tech

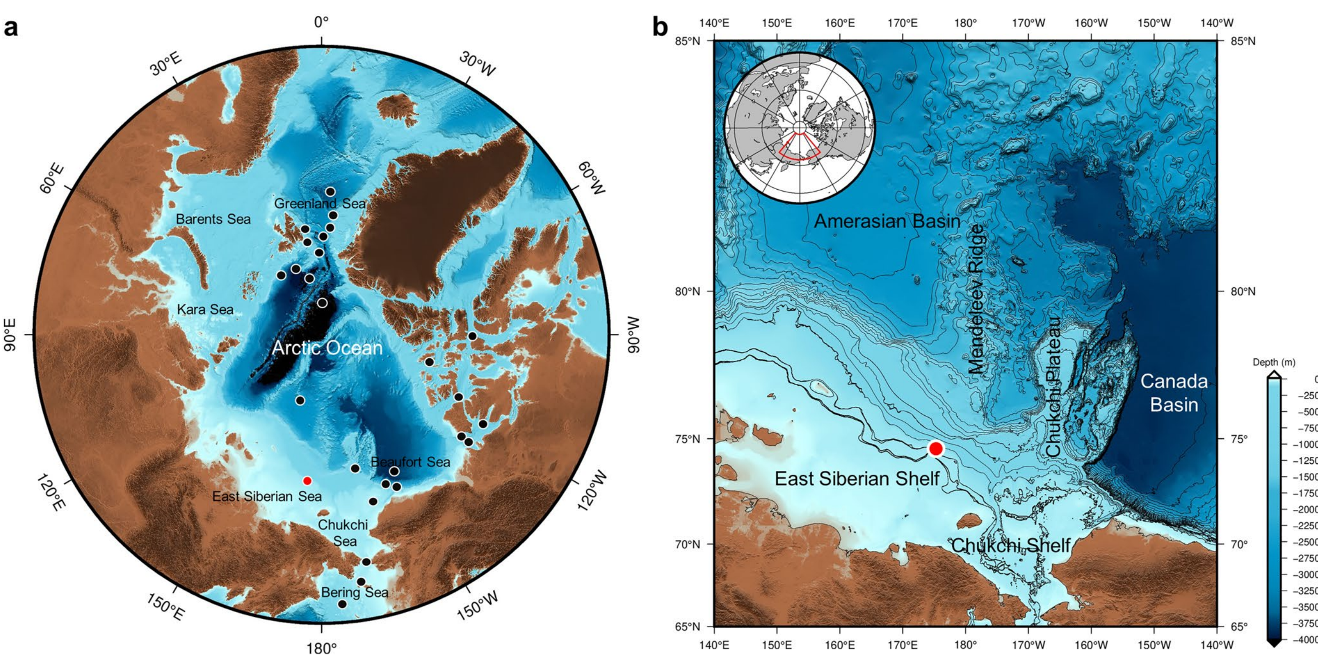

Figure 1. (a) Previous study sites (black circles) in the Arctic Ocean and (b) the location of the measurement site (red circle).

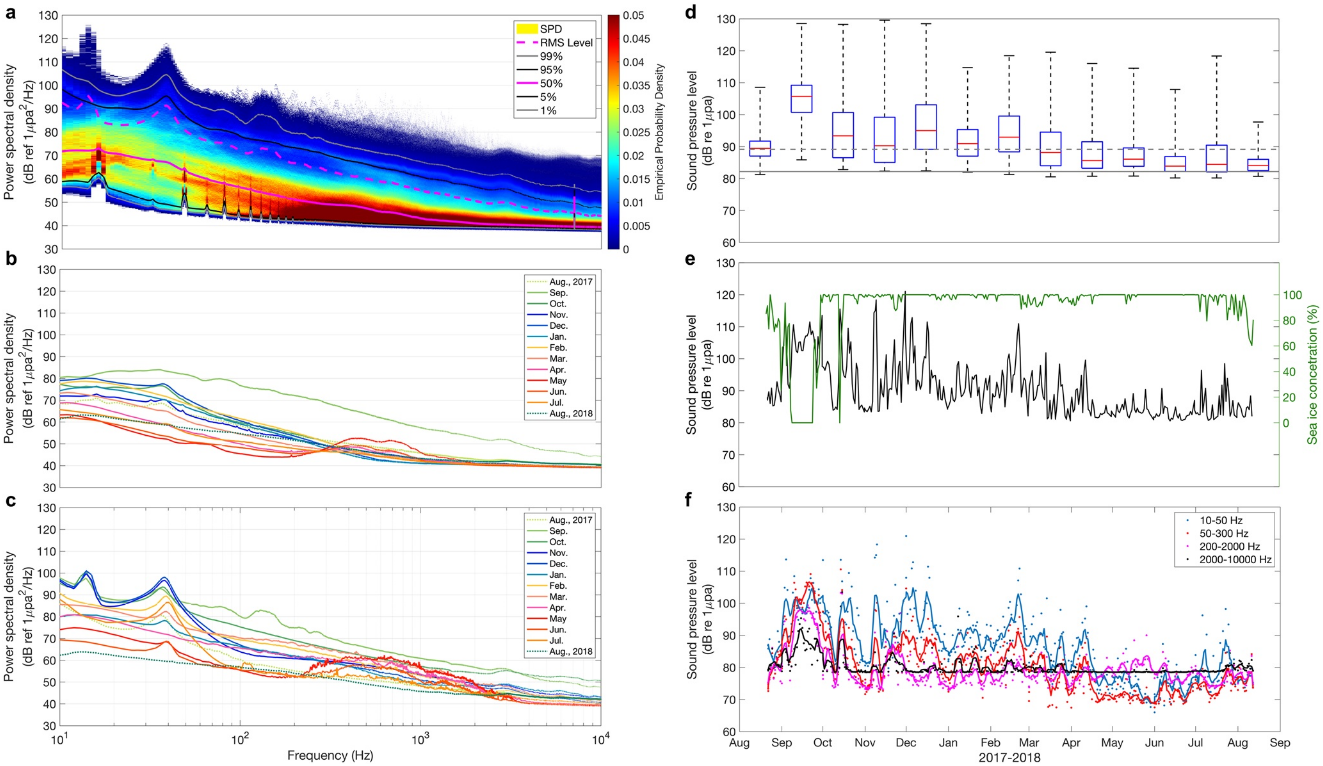

Figure 2. (a) The spectral probability density of the acoustic data measured for one year. Thick magenta lines represent the average values of the mean intensity spectrum level (dashed) and the median spectrum level corresponding to the 50th percentile (solid). Thin lines represent the percentiles of the power spectral density levels (gray: 1st and 99th, black: 5th and 95th). Monthly average power spectral density for (b) the median spectrum level and (c) the mean intensity spectrum. (d) Box and whisker plot of the monthly sound pressure levels in a frequency band between 10 Hz and 10 kHz. Red lines within the boxes are the median values, the tops and bottoms of the blue box represent the 25th and 75th percentiles, respectively, and the whiskers represent the minimum and maximum sound pressure levels. Dashed and solid gray lines show the annual median sound pressure level and the noise floor, respectively. (e) Daily sound pressure level (black line) in a frequency range of 10 Hz to 10 kHz with daily sea ice concentrations (SIC) (green line). (f) Daily sound pressure levels in frequency bands from 10 to 50 Hz (cyan), 50 to 300 Hz (red), 200 to 2,000 Hz (magenta) and 2,000 to 10,000 Hz (black), respectively. Dots and bold lines indicate the daily average sound pressure levels and the corresponding 5-day moving average.

Inc.) with a gain of 22 dB and receiving voltage sensitivity of −165 dB re 1 V/μPa was used. The frequency range was analyzed from 10 Hz to 10 kHz since the receiving voltage sensitivity was almost flat with a ±2 dB error in this range (De Robertis & Wilson, 2011). The spectrum level was produced using the power spectral density with units of dB re 1 μPa^2/Hz (Carey, 2006) that was computed from 60 s of continuous data with a 1 s Hanning window, 50% overlap and a fast Fourier transform (FFT) length of 32,768 points, yielding a 1 Hz band. Data contaminated by the saturated waveform of ~1.1% of the data corresponding to 958 min were excluded. The average spectrum level of the power spectral densities is represented by the mean squared sound pressure (mean intensity hereafter), a commonly used average metric. However, it is likely to be influenced by the transient high-pressure. Therefore, it was estimated by the spectral probability density with the median spectrum level meaning that level lasted for a long time (Menze et al., 2017; Merchant et al., 2013). The sharp spectral peak at 7 kHz and the harmonic peaks corresponding to odd multiples of the fundamental frequency of 16 Hz near the noise floor were identified as system self-noise and removed (Figure 2a). In addition, the sound pressure level in units of dB re 1 μPa was estimated at the band level in the frequency range of 10 Hz and 10 kHz (Kinsler et al., 2000) since the average spectra above 10 kHz reach the noise floor, and their correlation with environmental data was analyzed with Pearson correlation test. Sea ice concentration (SIC), ice drift speed, ice draft depth, wind speed and ocean current data were collected (Text S1) and are shown in Figure S1. The SIC at the measurement site remained high throughout the year except for a few days from August to October 2017, and open water was presented from September 9 to 24 and on October 14 (Figure S1a and Movie S1). According to automatic identification system data during the measurement period, there was one vessel (IBRV *Araon*) between August 12 and 13, 2018 within a radius of 16 km (10 miles) from the measurement location (MarineTraffic, 2018). The recorded data during the period of mooring deployment and recovery were excluded from the analysis.

2. Results

2.1. Temporal Variation in the Ambient Sound Level in One Year

The spectral probability densities and the average spectrum levels for one year are shown in Figure 2a, and the monthly spectrum levels are presented in Figures 2b and 2c. The median spectrum levels below 300 Hz were higher from August to February than from March to July. In particular, the average spectrum levels of September were strongest in terms of both metrics, except for the mean intensity spectra below 50 Hz from October to December. In September, the fluctuations in the spectrum peaks between ∼50 and 300 Hz were shown in both metrics which indicates that strong sounds were often produced. The spectrum levels between ∼200 and 2,000 Hz increased gradually from February to May and then decreased until July. Below 50 Hz in the mean intensity spectrum, the relatively strong noise, which was recorded almost throughout the year, showed two frequency peaks of 14 and 39 Hz from September to December when the ocean current speed was relatively high. Then, it gradually decreased and showed a single peak of 39 Hz in other months. The monthly sound pressure levels in a frequency range of 10 Hz and 10 kHz are represented in Figure 2d, and they show the highest value of 106 dB re 1 μPa in September and the lowest value of 84 dB re 1 μPa in June, respectively. Sound pressure levels divided into four bands of 10–50 Hz (band-1), 50–300 Hz (band-2), 200–2,000 Hz (band-3) and 2,000–10,000 Hz (band-4) based on the mentioned frequency characteristics are presented as the daily median values (Figure 2f). The daily sound pressure levels and their relationship with environmental data are shown in Table S1 and Table S2 by the Pearson correlation coefficient. Band-1 was best correlated with the ocean current speed (r = 0.42, $p < 0.001$), and band-2 (r = –0.56, $p < 0.001$), band-3 (r =–0.62, $p < 0.001$) and band-4 (r =–0.54, $p < 0.001$) exhibited strong negative correlations with the SIC.

2.2. Acoustic Events and Their Impact on Ambient Sound Levels in September and October

The acoustic data in September and October were intensively investigated since the SIC varied greatly during these periods, and the average spectrum levels were higher than those in the other months (Figure 3). In September, the SIC was less than 50% for 22 days, and the open water period lasted for 16 days. The airgun sounds, including intervals between airgun pulses, were at ∼68% and 26% of the acoustic data in September and October, respectively, and were recorded most often from September 9 to 13 and 17 to 28 (Figure 3b, Figure S2). Airgun sounds were recorded in August, September, October and November 2017 (Figure S3), and the monthly rate of acoustic data containing airgun sound was high when the SIC was low (r = –0.89, $p < 0.001$). The duration and interval of airgun pulses measured in our recordings were over a range of 1–5 s and 10–15 s, respectively, and the sweep frequency range varied between ∼20 and 1,000 Hz. Among several types of airgun pulses, the spectrum levels of 30 airgun pulses, their intensity average and ambient noise, and spectrogram of the prior two pulses measured on September 19 are shown in Figures 4a and 4b. The effective frequency range of airgun sounds was from ∼15 Hz up to 1 kHz, and the airgun sounds increased the ambient sound levels by 19 dB re 1 μPa. Figure 4c shows the comparison of the median spectrum levels in September for acoustic data with and without seismic airgun sounds which were detected by using matched filtering a representative single pulse to every 10 min recordings (Text S2, Kim et al., 2019); consequently, airgun sounds were effective from ∼15 to 800 Hz and increased the ambient sound level by 3 dB re 1 μPa compared to that without airguns. The days when the airgun sound was recorded show significantly strong energy below 800 Hz, and the higher spectral frequency seems to be positively correlated with the SIC inverted in the y-axis (Figure 3b). Interestingly, the SIC abruptly decreased on October 14, sea ice cover disappeared, and the spectra showed much higher levels. The large scale of sea ice extent in the Arctic Ocean increased from the end of September and passed through the measurement site in mid-October (Movie S1). The negative correlation between the sound pressure level and SIC in one year was obviously confirmed by these features.

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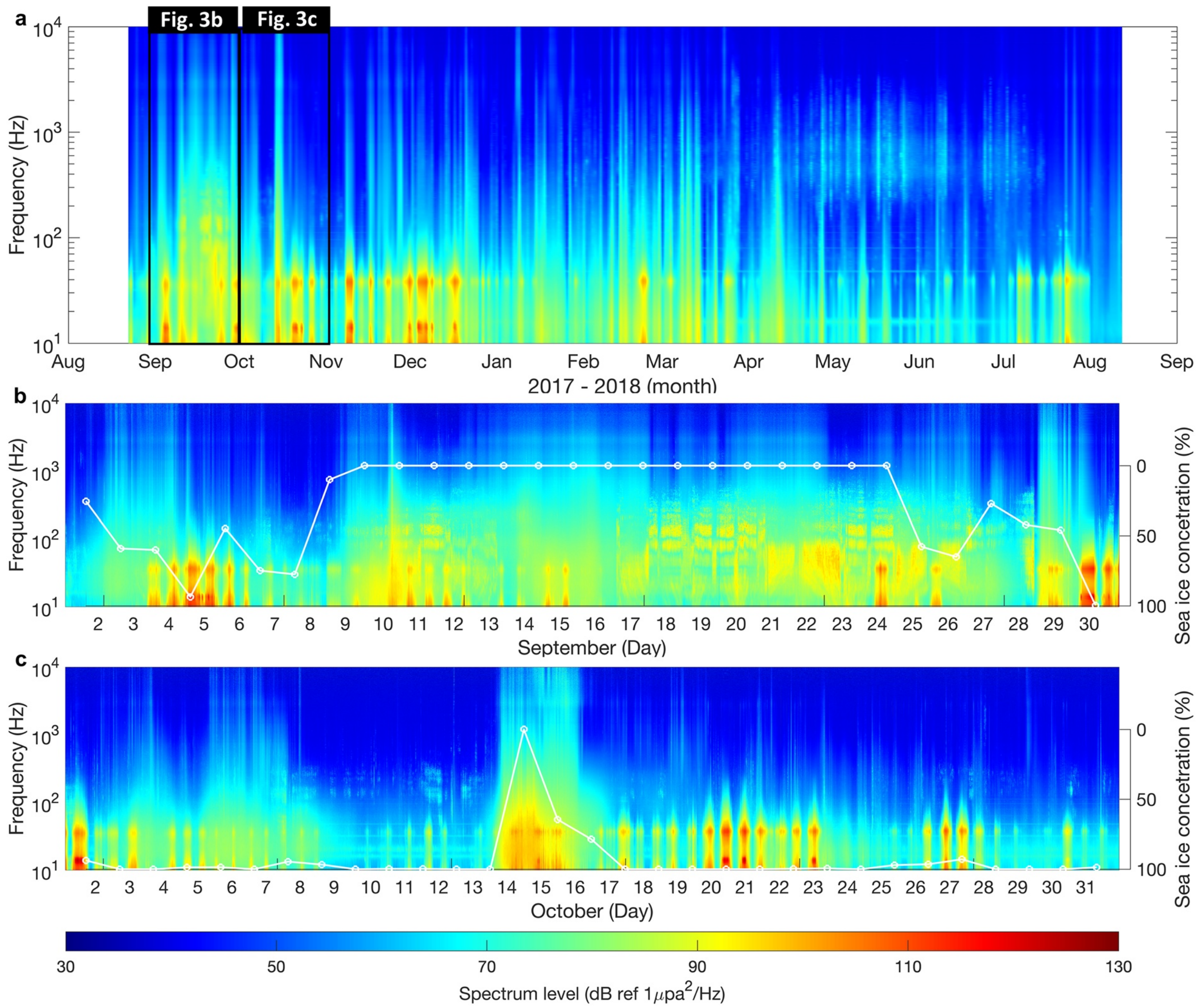

Figure 3. (a) The long-term spectrogram of ambient sound measured in the East Siberian Sea (ESS) from August 21, 2017 to August 13, 2018. Spectrograms of the ambient sound with the variation in the sea ice concentrations (SIC) (white lines with circles) for (b) September and (c) October.

3. Discussion

The increase below 800 Hz was affected by the airgun sounds, but the median spectrum level acquired from the period without airgun sounds was also significantly high in the measured frequency range. It can be affected by broadband wind-driven noise, as the decrease in the sea ice extent and concentration could increase the probability of being affected by sound sources through the sea surface. During an open-water period in September, the underwater acoustic environment at the measurement site was similar to the ambient noise of the open ocean directly affected by wind, cavitation bubbles and rainfall. In this regard, the measured spectrum level was compared to the Wenz curve corresponding to the prediction model of the open ocean sound level, which was dependent on ship density and sea state (Wenz, 1962). The gray dashed line in Figure 4c shows the prediction when an average wind speed of 6.6 m/s during the open-water period is applied to the model for the sea-state variable. The spectrum level of the Wenz curve is strongly dependent on the ship density below 500 Hz and the sea state above 500 Hz. The prediction above either 500 or 800 Hz was the best fit with measurements when the wind speed was 6 m/s, similar to the monthly average of 6.3 m/s. The other factor could be sea-ice-induced noise. Different types of sounds, presumed to be sound emitted from sea ice including broadband and frequency-modulated transient noise (Kinda et al., 2015), were measured in our recordings (Figure S4), and it has been reported that the ambient sound level in a frequency band from 10 to 500 Hz measured in the eastern Beaufort Sea has a high correlation with sea

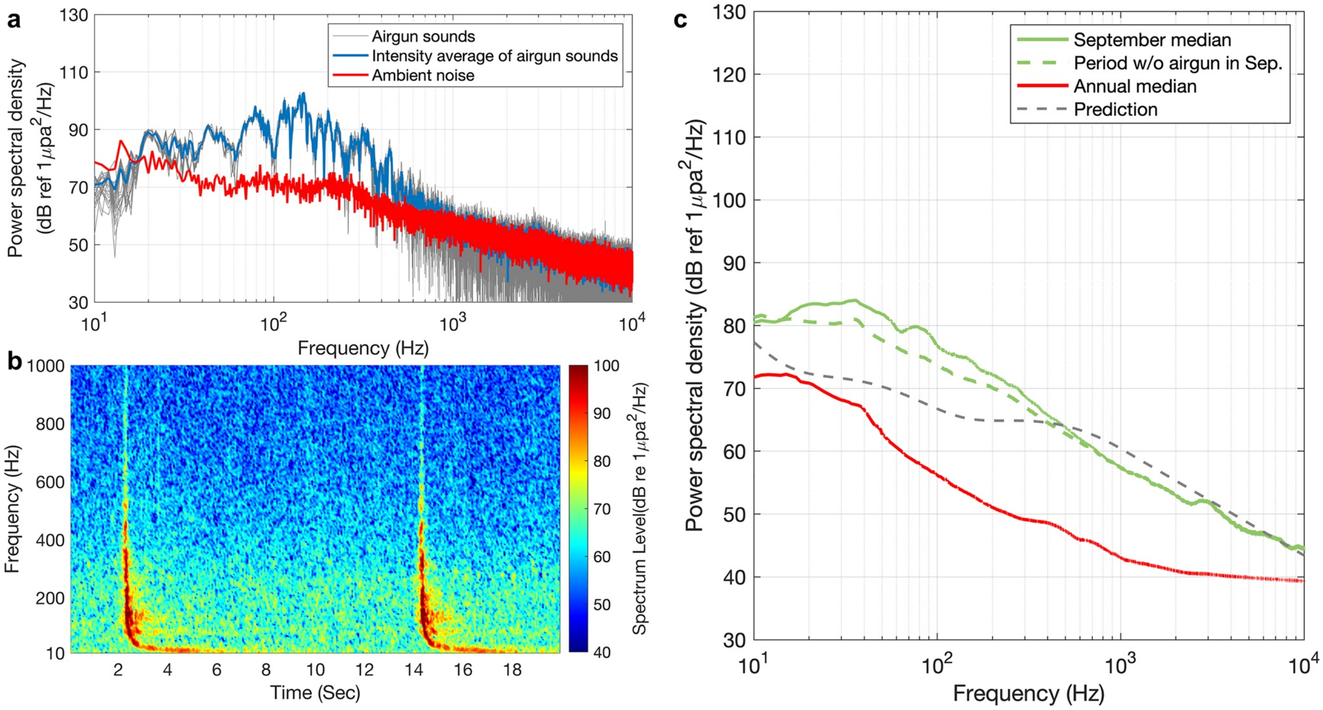

Figure 4. (a) Power spectral densities of 30 airgun pulses (thin gray lines) measured on September 19, their intensity average (thick cyan line) and the ambient noise (thick red line). (b) Spectrogram of the prior two airgun pulses among the 30 airgun pulses (8,192 fast Fourier transform (FFT) points, 50% overlap, Hanning window). Ambient noise data were used between airgun pulses where reverberation completely disappeared. (c) Median spectrum levels in September (solid yellow-green line) and those acquired from the periods without airguns (dashed yellow-green line). Annual meidan spectrum level is expressed by the red solid line. Wenz model prediction is shown as gray dashed line corresponding to a ship density of 0 and a wind speed of 6.6 m/s.

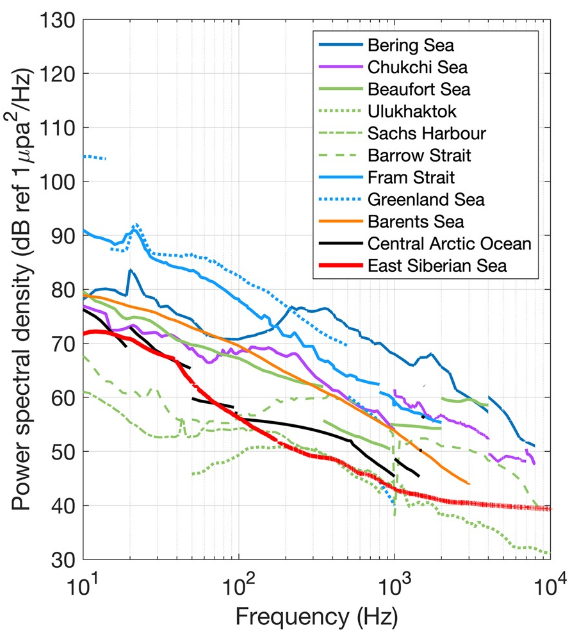

Figure 5. Median power spectral density measured in the East Siberian Sea (ESS) (red solid line) compared to that for other regions in the Arctic Ocean.

ice drift ~300 km from the recording location and large-scale circulation (Kinda et al., 2013). However, further study on the quantitative contribution of noise generated from sea ice distinguished from wind-driven noise to the ambient sound level is needed. Since the SIC was kept high throughout the year except for September and the difference in annual sound pressure level with or without acoustic data of September was less than 1 dB re 1 μPa, the median spectrum level in September was compared with the annual median spectrum level. The sound pressure levels with and without airgun sounds in September were 16 and 13 dB re 1 μPa higher than the annual average, respectively, in the frequency bands from 10 Hz to 10 kHz. The ambient sound level increased by both geophony and anthrophony, and the airgun was a conspicuous anthropogenic sound source that increased ambient sound levels. This finding also implies that ambient sound can be increased significantly by geophony even without anthrophony.

PAME (2019) reported the results of regional median spectra of underwater noise in the Arctic Ocean based on previous studies from 1965 to 2018. Figure 5 shows the median spectrum level in the ESS and a comparison to the median values of the spectra for other regions in the Arctic Ocean. The date and duration of each measurement were spatially different, so those spectra are depicted as shaded areas in Figure S5. The Bering Sea, Greenland Sea and Fram Strait, which are passages to the Arctic Ocean, show much higher levels than the other regions. The Beaufort Sea, Chukchi Sea and Barents Sea are the next, and Ulukhaktok and Sachs Harbor in the eastern Beaufort Sea are the quietest regions. The ESS is a relatively quiet region, although it shows a large seasonal variation in the sound pressure levels with the SIC. The median spectrum in June is similar to that in Ulukhaktok and Sachs Habour, and the annual average is similar to that in the central Arctic Ocean. Measurements represented by the black discrete lines were conducted in the central Arctic Ocean over a relatively short time of less than 1 day. Therefore, the values are insufficient to represent the temporal variability.

The source of the sound discriminated in the frequency range of ∼200 to 2,000 Hz from April to July was bearded seal vocalizations (Figure S6). The bearded seals of the Beringia distinct population segment occur in the ESS, and they migrate seasonally with changes in the sea ice extent and climate (Cameron et al., 2018; Chou et al., 2020). According to recent PAM results, bearded seal calls were detected nearly year-round in the Beaufort Sea and Chukchi Sea (MacIntyre et al., 2015) and were more likely to be present when the SIC was high (Halliday et al., 2017). The seasonal migration of bearded seals and their vocalizations influence the ambient sound level in the Canadian Arctic (Heimrich et al., 2021). In addition, the sound of sea ice melting has been reported to be between 1 and 3 kHz and the 3-kHz peak in the measurements in September seems to have originated from sea ice melting (Mahanty et al., 2020). The frequency peaks at 3 kHz appeared evidently in September (Figure 2b) when the SIC was low, when the variation was large, or in open water. According to the trends in the mean intensity spectrum peaks of 3 kHz, relatively quiet ice melting sounds were produced sporadically throughout the year. Finally, conspicuous frequency peaks near 14 and 39 Hz were identified as cable strum noise. Typically, cable strum noise is found to be on the order of 10 Hz when cables are pulled taut by ocean currents (Robinson et al., 2014). The annual trend in the pseudonoise was in close agreement with the fluctuation in the current speed from strong in September to December to weak in April to July. The spectrogram and daily current speed are shown in Figure S7.

4. Conclusions and Implications

Underwater sound was measured in the ESS from August 2017 to August 2018 using an autonomous passive acoustic recorder. This is the first study to conduct underwater acoustic observations in the ESS and to verify the effects of geophony and anthrophony on the underwater acoustic environment. Our results imply that the ambient sound level can increase with accelerated sea ice melting in the Arctic Ocean as well as the ESS, and the increased ambient noise produced by human activities can have negative effects on the Arctic marine ecosystem. However, the impact of anthropogenic noise on marine species should be carefully discussed based on ambient sound level with the help of multidisciplinary assessments. Our results can be used to develop a mitigation strategy for anthropogenic noise and may be applied to ecological marine mammal monitoring for the conservation of biological diversity. In addition, our results may be applied to studies on performance prediction and optimal operation of the sonar system in the ESS. Sonar performance can be predicted quite precisely using a performance model based on the sonar equation. The ambient sound level and their temporal and spatial variability are important factors determining the signal-to-noise ratio in the sonar equation. When in situ ambient noise data are used, sonar system performance can be more accurately predicted in the ESS.

Conflict of Interest

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

Data Availability Statement

Acoustic data used in this study (Annual, monthly and daily average sound pressure level in the East Siberian Sea from 2017 to 2018) are available at the Korea Polar Data Center (https://dx.doi.org/doi:10.22663/KOPRI-KPDC-00001617.2).

Acknowledgments

This research was a part of the projects titled 'Korea-Arctic Ocean Warming and Response of Ecosystem (K-AWARE, 1525011760)' and the 'Ecosystem Structure and Function of Marine Protected Area (MPA) in Antarctica (20170336)', funded by the Ministry of Oceans and Fisheries (1525011760 : 20170336), Korea.

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