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Wind-driven ambient noise characteristics in the Western Canadian arctic

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Abstract: An analysis of ambient noise data collected from seven locations in the western Canadian Arctic at varying depths (30–350 m) during ice-free seasons over a period of five years (2018–2022) has been conducted. The measured noise level correlates well with wind speed after the removal of contaminated (sources other than wind) noise data. The characteristics of wind noise are predicted by fitting a multi-parameter empirical model to data. Results from the model are compared with existing empirical wind noise models and validated using data collected from one of the measurement locations. *© 2025 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).*

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1. Introduction

Wind-induced ambient noise is generally considered as the resultant noise field due to the superposition of sound sources distributed randomly at the ocean surface.[1] Most of the background noise in the ocean is generated by surface agitation at frequencies between 20 Hz and 50 kHz.[2] Individual and collective bubble oscillations created by breaking waves mainly contributes to sound generation. Noise is produced by collective bubble oscillations at lower frequencies (<500 Hz), while individual bubble oscillations produce noise at higher frequencies (>500 Hz).[3] Early studies of ocean ambient noise showed a direct relationship between wind speed and measured spectrum amplitude.[4,5] However, the wind speed dependence of ambient noise exhibits clear frequency dependence and significant variation among different studies were observed, perhaps due to measurement location characteristics.[3] Spectral features of wind noise can also be affected by propagation conditions and sensor depth, especially in shallow waters.[6] In addition to measurements, analytical and numerical models were also developed to study the spectral and spatial features of surface generated ambient noise.[7–9] In recent years, long-term passive acoustic recordings have been used to develop empirical wind noise models.[10–12] Due to the omnipresence of wind generated noise, it is essential to understand its spectral and spatial features in applications such as sonar performance modelling, ocean environment inversions, and marine mammal monitoring.

The western Canadian Arctic is experiencing longer ice-free periods due to climate change in coastal and offshore areas.[13] Consequently, during the summer and fall months, wind-generated noise dominates the Arctic ambient sound field and may be increasing as climate change progresses. Thus, understanding the frequency and wind speed dependence of ambient noise during ice-free periods is critical. Studies mainly focusing on wind-generated noise in the western Canadian Arctic are rather limited.[14–17] With data collected from seven different locations, this work aims to characterize wind-generated ambient noise in this region. A logarithmic model based on frequency and wind speed dependence has been developed using the measured data between 50 Hz and 10 kHz. Due to sporadic ship noise events in the area, the data can also be used to compare against available empirical wind noise models.[10,11,18,19]

The Arctic has undergone rapid changes due to climate change and the loss of sea ice, which impact the habitats of marine mammals. A prolonged ice-free season in the Arctic could increase the contribution of wind-driven noise to the overall sound field. Therefore, characterizing the benchmark of wind generated noise is important for detecting, identifying, and localizing marine mammal vocalizations. Also, increased wind-generated ambient noise may reduce the active listening space of marine mammals and soniferous fishes.[20] Since ambient noise is location-specific, determining the wind

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noise of a specific region using measurements or models from another region might not be feasible. Technological advances have allowed for longer monitoring periods of passive acoustic data in the Arctic.[16,17] These large-scale (temporal and geographic) data provide an excellent opportunity to examine wind noise in the Arctic.

2. Ambient noise measurement and processing

The ambient noise data used in this study were collected from various locations in the western Canadian Arctic during ice-free periods between 2018 and 2022. Satellite-derived ice concentration data at the sensor location were used to identify totally ice-free periods.[21] A map of the measurement locations is shown in Fig. 1(a), and the metadata related to the recorders were also provided (Table S1). The duty cycle for most measurements was 5 min/h, except for 2021–2022 measurements where the duty cycle was 5 min/30 min, and sampling frequency was 48 kHz. The hydrophones were calibrated and showed flat sensitivity in the frequency range of interest. Sensors were positioned 2–5 m from the seabed, expanding the possible listening area for wind-generated noise. The depth of the water column for the locations varied from 30 to 350 m.

Figure 1(b) shows sound speed profiles (SSP) closer to ambient noise measurement locations during summer. Shallow locations (<160 m) showed a downward refracting SSP. Amundsen Gulf's typical summer SSP was observed at two of the deepest locations (Pearce Point and Cape Bathurst-300).[22] The sound speed in the surface mixed layer stays constant but rapidly decreases because of a strong cold halocline. There is a sound speed minimum between 50 and 150 m due to the presence of cold Pacific water followed by a warm halocline and warm Atlantic water, resulting in an increase in sound speed with depth. Seafloor composition in the region is poorly known. A recent study of sedimentary processes in the Canadian Arctic Archipelago determined that the sediment type of the region was fine silt.[23] Due to SSP and sediment type, distant sound sources may not have a significant contribution in shallow locations.[24]

Noise power spectral density was calculated every second with a bin width of 1 Hz using a fast Fourier transform and a Hanning window with 50% overlap. Additionally, we calculated one-third octave noise levels and converted back into noise spectral levels at the center frequencies of each one-third octave band for statistical analysis. By averaging these 1 s levels, hourly estimates of noise level were obtained. Using manual inspection and a method exploiting the spectral shape of wind generated noise, we removed acoustic data influenced by other noise sources (shipping and biological) based on frequency vs frequency plot of noise levels at different frequencies.[18] Even though this method was applied, ice generated noise from multiyear ice edges and other distant sources can still contribute to the ambient noise field, especially at low frequencies (<0.5 kHz). Wind speed data were obtained from the European Centre for Medium-Range Weather Forecasts Reanalysis 5 dataset close to the measurement locations (31-km grid) every hour at 10 m above the sea surface with some uncertainty (~1 m/s).[25] Since breaking waves do not contribute to noise below 1.6 m/s, data below that speed were removed from further analysis. The highest wind speed encountered was 15.1 m/s. Wind speed data 15 min prior to the acoustic recording provided the best correlation between windspeed and noise level at 1 kHz. Ambient noise depth dependence was not considered in this study. According to physics-based numerical models, surface generated noise

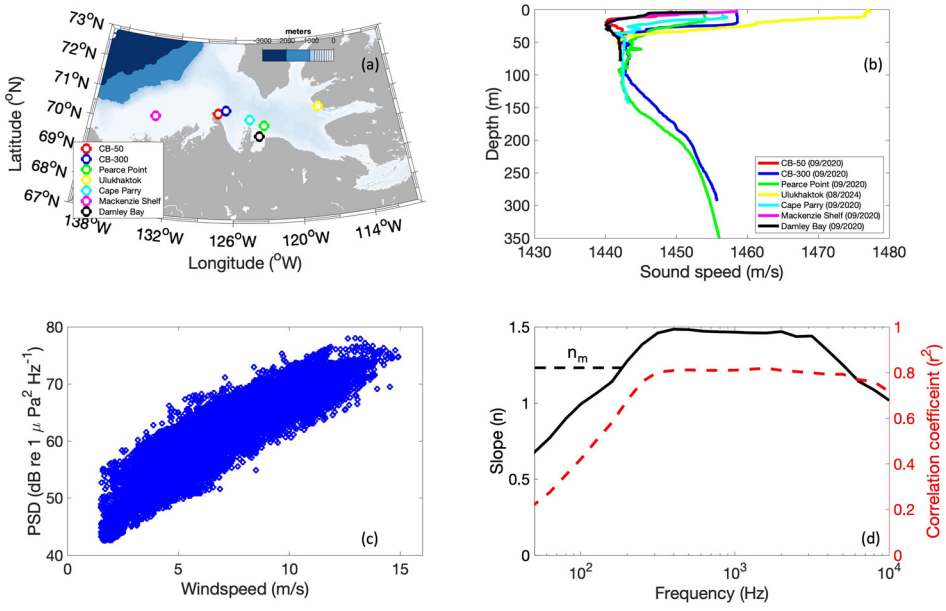

Fig. 1. (a) Locations of ambient noise measurement, (b) the measured sound speed profiles, (c) noise spectral level vs wind speed at 1 kHz, and (d) the slope (solid black line) and coefficient of determination (dashed red line) as a function of frequency.

intensity is depth independent in shallow waters (100–300 m) with constant and refracting sound speed profiles.[1,8,26] Wind generated noise measured by a glider in shallow waters (0–220 m) with a downward refracting sound speed profile also showed relatively weak depth dependence.[27] Moreover, the depth dependent noise correction based on absorption loss was negligible (<1 dB) for all measurement locations.[28,29]

3. Results and discussions

The wind speed dependence of measured ambient noise in the western Canadian Arctic was studied using data collected from all locations. Based on wind speed data, measured spectra were categorized into different Beaufort wind (BW) scales. A total of 15 084 measurements for BW scales 2 to 7 were available, comprising 719, 3367, 4897, 4501, 1556, and 44 datasets. The frequency range from 50 Hz to 10 kHz was analyzed since it is most relevant for marine mammals and shipping in the area. Moreover, above 10 kHz, the received noise level decreases with increase in wind speed due to absorption in the surface bubble layer.

The measured spectra and wind speed showed a linear relationship in our analysis. Figure 1(c) shows the correlation between wind speed and noise level at 1 kHz (Correlation between wind speed and noise level at other frequencies are shown in Fig. S1). Previous studies of wind-generated noise assumed a logarithmic relationship between wind speed and noise spectral level (NSL) given as

$$\mathrm{NSL} = S + 20 * n * \log_{10}(u), \tag{1}$$

where n is the slope, S is the y-intercept and u is wind speed in m/s. We conducted a linear regression as a function of frequency between the measured noise and wind speed $[\log10(u)]$. The coefficient of determination (r^2) and slope (n) as a function of frequency are shown in Fig. 1(d). It is observed that the r^2 is low at frequencies below 0.15 kHz and reaches 0.8 at frequencies above 0.3 kHz. The value of r^2 remains relatively constant between 0.3 kHz and 10 kHz, indicating a strong correlation between wind speed and noise spectral level.

A similar pattern is observed for the wind-dependent factor (n) as well. The value of n gradually increased up to 0.3 kHz, reaching a maximum of 1.5 at 0.4 kHz. In the frequency range of 0.4 kHz to 10 kHz, n varied between 1 and 1.5. Wind-generated noise's spectral amplitude mainly depends on the value of n. The ideal value of n is 1, suggesting a linear relationship between wind stress (u^2) and received noise spectral level.[3] Values of n varied within this study's frequency range from 0.7 to 1.5. The mean value of $n(n_m)$ was 1.21 in the frequency range of 0.05–10 kHz [Fig. 1(d)], slightly higher than the wind dependence slope (1.12) given by Applied Physics Laboratory-Under Water (APL-UW) noise model and Ainslie's composite wind noise model.[19,30] From other investigations of wind dependence, n was observed to range between 0.5 and 1.75.[2,11,12] The variation in wind dependence can be influenced by the propagation condition, measurement depth, wind speed, and frequency. Low n and r^2 values observed at low frequencies in the present study could be due to the low spatial (31-km grid) and temporal resolution (1-h) in ERA5 wind speed data, noise generated by currents at the hydrophones, distant shipping noise, and differences in propagation conditions (sound speed profile and sediment properties).

To study the frequency dependence of noise data, mean spectral levels at each BW scales were calculated. Figure 2 shows the average spectral level and the corresponding standard deviations for each BW scale. In the frequency range of 0.05–10 kHz, the standard deviation remains almost constant for BW scales 2 (∼4 dB) and 3 (∼3.6 dB). For BW scales 4–6, standard deviation decreases with increasing frequency. The lowest mean standard deviation was obtained for BW scale 7 (1.5 dB), possibly due to the limited number of measurements available (44) for this category. In terms of spectral slopes, three frequency ranges can be used to describe the mean spectral level for BW scales 2–4. At low frequencies (0.05–0.2 kHz), the mean spectra showed an almost constant spectral slope (∼−3 dB/oct). A significant decrease in spectral slope can be seen between 0.2 and 0.6 kHz, indicating almost flat noise levels in the middle frequency range. Above 0.6 kHz, BW scales 2, 3, and 4 had spectral slopes of −10, −12, and −14 dB/dec, respectively. BW scales 5–7, however, can be described by two frequency ranges in terms of their spectral slope. There is a broad peak between 0.2 and 0.6 kHz in the low frequency range that has a low slope. A gradual decrease in noise level was observed in the high frequency range (0.6–10 kHz). For BW scales 5, 6, and 7, the spectral slope was −14.5, −15, and −17.5 dB/dec, respectively.

Spectral slope increased gradually from BW scales 2–7 according to our data. However, the mean spectral slope for the moderate wind speed regime (<8 m/s) was −12 dB/dec; for the high wind speed regime (>8 m/s), the average value was −15.6 dB/dec. The spectral slope of wind-generated noise varied between −11.6 dB/dec and −20 dB/dec in previous studies.[4,5,10,11,18,31] The spectral slope estimates in our study were in close agreement with the APL-UW noise model estimate (−15.9 dB/dec) and with previous studies in high wind conditions.[30] The distinctive characteristics of spectral slope observed at low frequencies and winds in our data could be due to the difference in propagation conditions between the measurement locations, which require further investigation using a numerical ambient noise model and beyond the scope of the present analysis.

To represent the spectral features of noise data presented in this study, we used a multi-parameter logarithmic model. The equation for wind-generated noise spectral level can be expressed as

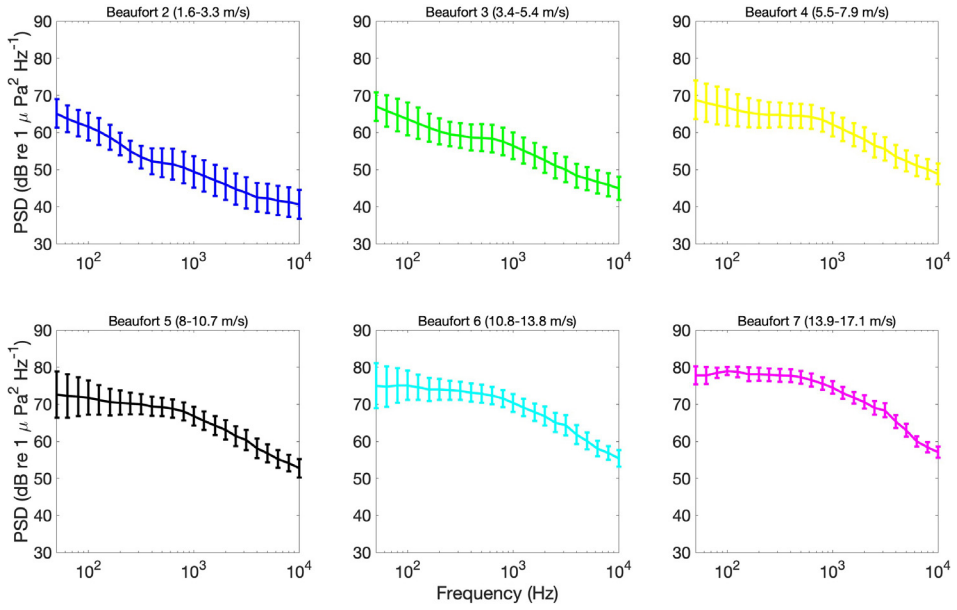

Fig. 2. The mean noise spectral level for the Beaufort wind scales 2–7 and the respective standard deviations.

$$\mathrm{NSL}(f,u) = S_0 + 20 * n_m * \log_{10}(u) + 10\log_{10}\left\{\frac{\left[1+\left(\frac{f_0}{f}\right)^{m_0}\right]}{\left[1+\left(\frac{f_1}{f}\right)^{m_1}\right]\left[1+\left(\frac{f}{f_2}\right)^{m_2}\right]}\right\}, \tag{2}$$

where $\mathrm{NSL}\left(\mathrm{dB\,re\,1\,}\mu\mathrm{Pa}^2/\mathrm{Hz}\right)$ is the noise spectral level at frequency $f(\mathrm{Hz})$ and wind speed u, S_0 is a constant spectrum level, n_m is the mean of wind dependence factor (slope), f_0, f_1, and f_2 are the critical frequencies, and m_0, m_1, and m_2 are the spectral slope factors. Details about the third term in Eq. (2) can be found in Ref. 32. We used this term to represent the mean spectral level of wind generated noise at different BW scales. To obtain the seven unknown parameters, Eq. (2) is fitted to the measured spectra at each BW scale. We fitted the curve based on the least square estimate to obtain the parameters for the best fit. Figure 3 shows the mean measured spectra for each BW scale and best fit. The fitted parameters for each BW scale are listed in Table 1. The modelled noise spectrum and measurements were very well matched. For all BW scales, the frequency averaged residual difference between measurement and the best fit was less than 0.5 dB.

The present model can be compared with other noise models. Four empirical wind noise models were considered for comparison (Hildebrand's, Reeder's, Ma's and Ainslie's).[10,11,18,19] Ma's model uses ambient noise data collected from shallow-water locations (<100 m) of the Pacific Ocean to predict wind noise features.[10] Hildebrand's model was developed based on extensive noise data collected from various locations in the Pacific and Atlantic covering a wide range of depths (40–1400 m) and latitudes.[11] Reeder's model was based on ambient noise data collected from Tongue of the Ocean (TOTO) in deep water (2200 m) that was free from any anthropogenic influence.[18] Ainslie proposed a composite wind noise model based on shallow water noise measurements accounting for waveguide effect and APL formula for wind speed dependenc.[19] To compare the present model to existing noise models, frequency averaged absolute residuals were calculated across BW scales 2–7. Between the present model and other models, BW scale 2 showed the highest difference (>4 dB). For BW scale 3, the average residual between the present model and Hildebrand's, Reeder's, Ma's, and Ainslie's models were 3, 4.5, 1.6, and 2.2 dB, respectively. Hildebrand's and Ma's noise models agreed well (<1.8 dB) with the present model for BW scales 4–7. The difference between the present model and Reeder's model stayed around 3 dB for Beaufort scales 4–7. For BW scales 4–6, Ainslie's model showed good agreement with the present model (<2.5 dB), but the difference was relatively large for BW scale 7 (3.8 dB). Figures 4(a), 4(b), and 4(c) compare the present model to other noise models for wind speeds of 6.7, 9.3, and 12.3 m/s. For all frequency ranges, Hildebrand's noise model showed the best agreement. Similarly, Ma's model matched our predictions for Beaufort scales 3–7 well. However, the model is only valid for frequencies above 1 kHz. Except for the highest BW scale, Ainslie's model also showed good agreement. It is evident that the present model differs from Reeder's model especially at low frequencies (<1 kHz). Even though contaminated noise data were removed in the present analysis, occasional distant shipping, surf breaking on nearby shallow shorelines and ice-generated sounds could have contributed to the rise in low-frequency noise levels.[33]

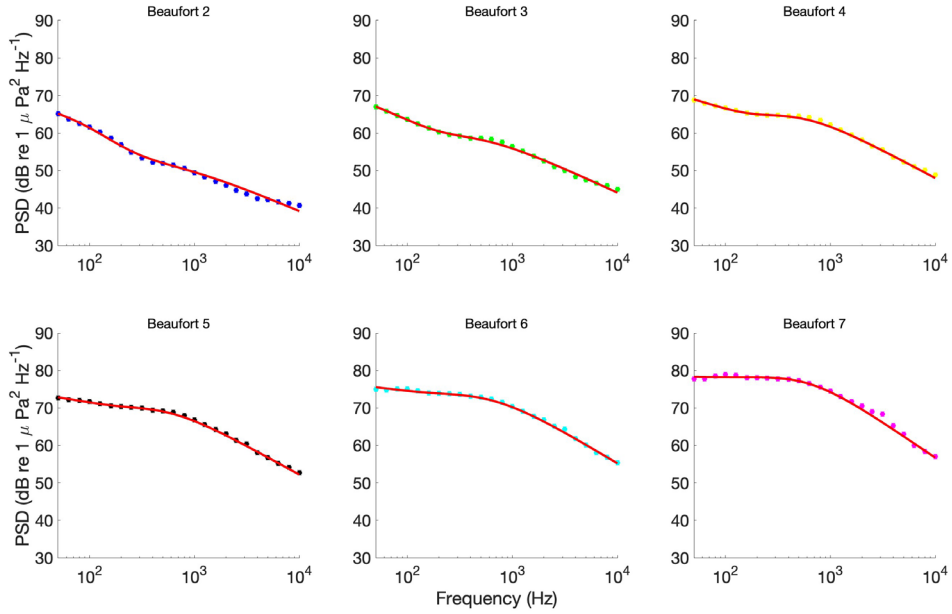

Fig. 3. The mean noise spectral level for the Beaufort wind scales 2–7 at the center frequencies of one-third octave bands (∗) and respective model curves (solid red line) fitted to the data.

A comparison between the present model and observation from one of the measurement sites was made to determine the applicability of the developed model. These data were not used to derive the parameters of Eq. (2). A time series of noise spectral levels measured at Mackenzie Shelf in 2021 over a month is shown in Fig. 4(d). To simulate the wind noise spectral level based on Eq. (2), wind speed data from the location and parameters given in Table 1 were used. Figure 4(e) shows the simulated wind noise spectrum. Time series of modelled noise spectra compare well with measurements, especially at higher frequencies (>0.4 kHz). The model underestimated the received level at lower frequencies. To examine the difference between observation and model, two frequency bands (0.1–0.5 kHz and 2–5 kHz) were chosen, and the absolute residuals were calculated. Figure 4(f) shows the time series of residuals along with windspeed. In the lower frequency band (0.1–0.5 kHz), residuals were relatively low (<4 dB) for most of the observation period. Time series showed that residuals increased (>5 dB) during low wind events and transient events. In the high-frequency band (2–5 kHz), the model reproduced measurements reasonably well. Wind speed and residuals have a clear negative correlation, indicating the suitability of the present model during high wind speeds (>8 m/s). The model's accuracy is uncertain, especially at low wind speeds. At low wind speeds, distant noise sources (shipping and transients from sea ice), current generated flow noise at the hydrophones and sound propagation characteristics of the environment may affect the noise field.[33,34] These factors, along with additional data obtained from other locations, must be considered in future studies to accurately represent wind-generated noise in the region.

4. Conclusion

This study presents wind-driven ambient noise data collected from multiple locations in the western Canadian Arctic, covering a range of depths. A good correlation was found between noise level and wind speed in our analysis. The value of the wind dependence factor obtained in the current study was consistent with those reported in previous studies. By grouping measured spectra according to BW scales, wind noise frequency dependence was examined. The data were fitted with a multi-parameter logarithmic noise model to represent wind speed and frequency dependence. We compared the

Table 1. The model curve parameters used in Eq. (2).

Beaufort	S_0	f_0	m_0	f_1	m_1	f_2	m_2
2	45	248	2.6	100	2	585	1.2
3	46.9	190	3	210	2	400	1.3
4	48.7	180	2.8	288	2	430	1.5
5	52.6	200	2.3	410	1.88	300	1.55
6	55	190	2	590	1.64	288	1.68
7	57.7	210	2	600	1.95	280	1.9

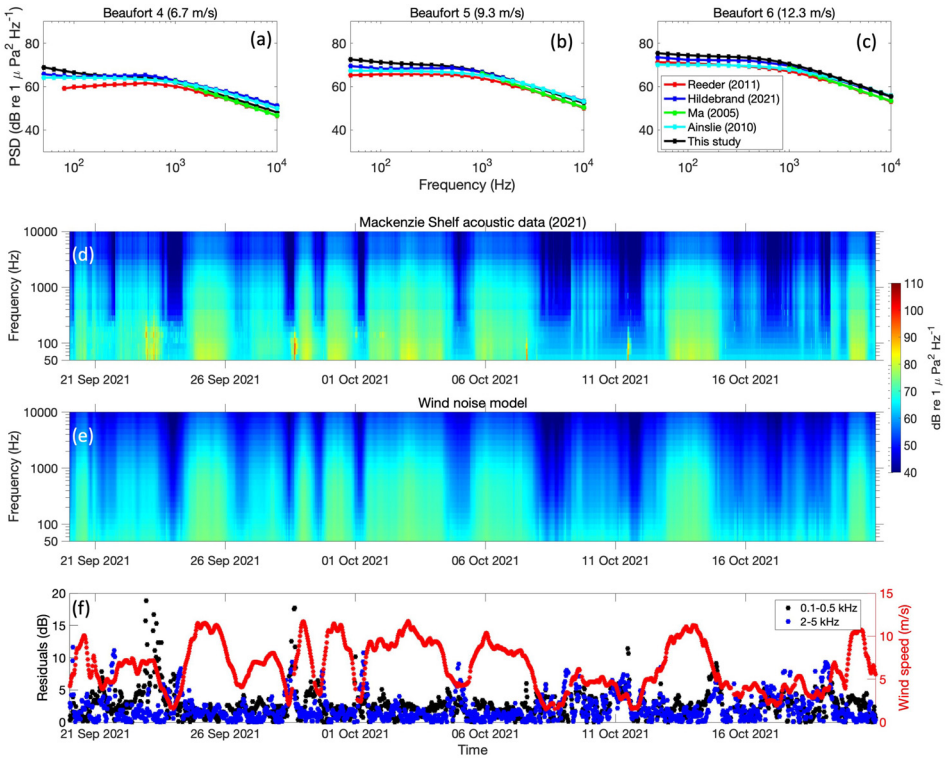

Fig. 4. Comparison between present model and existing empirical noise models for wind speeds of (a) 6.7 m/s, (b) 9.3 m/s, and (c) 12.3 m/s. The (d) measured and (e) modeled spectral level of ambient noise per hour at Mackenzie Shelf in 2021 over a period of one month (20th September to 20th October), and (f) the absolute residuals between observation and model at two frequency bands, and wind speed.

model predictions with existing empirical wind noise models. The model developed in this study was consistent with an empirical model based on an extensive dataset.[11] Finally, the empirical noise model was validated using data from one of the measurement locations, which agreed well with the measured values.

The present analysis provides a benchmark and insights into wind-generated noise for future marine-habitat monitoring studies in the region. Wind noise model proposed in this study can be used for noise impact assessment, noise mapping, and habitat study of marine mammals. Measurements in the future can be incorporated in the analysis for further validation and modification of the model. Future analysis can also examine the influence of other factors such as ice concentration, water column depth, wave height, direction, and fetch on received noise levels.[12,14,34,35]

Supplementary Material

See the supplementary material for additional figure and the deployment details of passive acoustic data used in this study.

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Author Declarations

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data Availability

Data will be made available upon reasonable request.

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