Seismic exploration noise reduction in the Marginal Ice Zone

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Abstract: A sonobuoy field was deployed in the Marginal Ice Zone of the Fram Strait in June 2011 to study the spatial variability of ambient noise. High noise levels observed at 10–200 Hz are attributed to distant (1400 km range) seismic exploration. The noise levels decreased with range into the ice cover; the reduction is fitted by a spreading loss model with a frequency-dependent attenuation factor less than for under-ice interior Arctic propagation. Numerical modeling predicts transmission loss of the same order as the observed noise level reduction and indicates a significant loss contribution from under-ice interaction.
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1. Introduction

The distribution of noise due to distant seismic exploration is of interest to the assessment of effects of anthropogenic noise on the Arctic habitat. Long-term noise recordings in Arctic waters have reported seasonal occurrence of low-frequency noise from seismic exploration activity (Moore *et al.*, 2012; Roth *et al.*, 2012; Klinck *et al.*, 2012). Such noise can propagate thousands of kilometers in open water (Nieukirk *et al.*, 2012) as well as in ice-free Arctic waters (Thode *et al.*, 2010). Focus in this letter is the propagation and attenuation of seismic exploration noise through the Marginal Ice Zone (MIZ). The MIZ comprises highly variable ice conditions ranging from open water to ice-covered regions composed by a mixture of new frozen, first year ice, and multi year ice. Below ice-covered regions, an oceanographic layer with cold and less saline water causes channeling of acoustic energy; this layer diminishes in thickness across the MIZ and disappears in the open ocean. A relevant question is how seismic exploration noise is affected by these unique propagation conditions (Mellberg *et al.*, 1987).

We present data from short-term synoptic measurements of noise in the Fram Strait (between Greenland and Spitsbergen) in June 2011. The recordings contain low-frequency (10–200 Hz) noise attributed to distant seismic exploration. A reduction of these noise levels with range into the ice cover is observed and fitted by a spreading loss model with a frequency-dependent attenuation factor. Numerical modeling of transmission loss predicts the observed noise level reductions.

2. Methods

Twenty-five sonobuoys were deployed by P-3 C aircraft on June 9, 2011, over an area of the Fram Strait bounded by 78° to 79° 30′ N and 3° W to 3° E. The experiment area (Fig. 1) covered the MIZ from open water to compact ice and was close to an area of similar measurements in April of 1987 (Johannessen *et al.*, 2003). Hydrophone data (sensor depth, 400 ft) were recorded over a 3 h time period starting at 10:40Z.
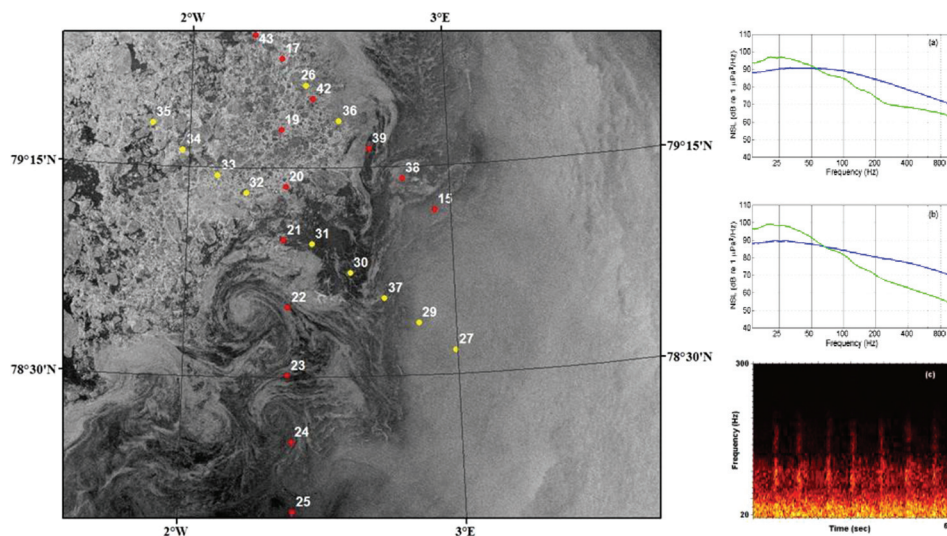
Fig. 1. Left panel, map of the Fram Strait experiment area. Numbered symbols indicate sonobuoy locations. The background is a RadarSat image date 2011/6/9 10:14 Z. Right panel, median noise spectral density levels (dB re 1 μPa^2/Hz) at 12.5–1000 Hz estimated from 2011 data (green line), and from 1987 data (blue line) from sonobuoys in (a) open sea, and (b) compact ice, and (c) spectrogram of recorded seismic exploration signals at buoy 27 in open water.

Sonobuoy calibration data sheets were supplied by the manufacturer (Ultra Electronics). To calibrate the onboard multichannel radio receiver and recording system, a reference radio signal was transmitted after the flight mission, the recorded signals thereafter processed to obtain a system calibration factor for each channel. Similar procedures were used for the 1987 data set (Johannessen *et al.*, 2003).

Reported here is median noise spectral density level (NSL) in dB re 1 μPa^2/Hz. For comparison with 1987 data, NSL was computed in 1/10-octave frequency bands from 12.5 to 1000 Hz for each sonobuoy. Signal processing applied Welch spectrum estimation (1 s samples, Hamming window with no overlap, 1 Hz frequency resolution, 10 s time segments). Estimates of median noise power levels were formed over the duration of the recordings for three to five buoys within the open ocean and within compact ice, before conversion to NSL. For the study of seismic exploration noise, a 1 h time period where seismic exploration signals prevailed was analyzed. Data from four sonobuoys (27, 31, 33, and 35 in Fig. 1) were then processed for NSL in 1/3-octave frequency bands from 10 to 200 Hz with noise distributions derived from 120 spectral estimates (30 s time segments) for each buoy.

Supporting data from the experiment included a RadarSat(c) satellite image, wind, ice, and sea observations, and information on ongoing seismic exploration surveys (NPD, 2012). A spreading loss model used to describe noise reduction is described in Sec. 3.2. Numerical modeling of transmission loss used environmental data and methods described in the appendix.

3. Results

3.1 Noise levels

Figure 1 shows median NSL from averages over data from buoys in open water [Fig. 1(a)] and in compact ice [Fig. 1(b)] in 1987 and 2011 (blue and green curves, respectively). In 2011, there is a broad peak in NSL at low frequencies with levels exceeding those measured in 1987 by up to 12 dB. Between 60 and 1000 Hz, the NSL decreases with frequency more rapidly in 2011 than in 1987. At 1000 Hz, the NSL in compact ice is 17 dB lower in 2011 than in 1987. The high noise levels in 1987 (sea

state 5) were due to sound generated by sea ice dynamics due to a significant swell (Johannessen *et al.* 2003); in 2011 (sea state 1), no swell was observed within the ice cover. Inspection of spectrograms in 2011 data [Fig. 1(c)] revealed distinct time arrivals of low-frequency energy (interval, 8 s), typical of seismic exploration signals. Ongoing seismic surveys on the day of the experiment were at ranges in excess of 1400 km southeast of the experiment area (NPD, 2012).

Table 1 shows the NSL at four 1/3-octave frequency bands and four buoys together with ice composition and range to the ice edge as interpreted from the RadarSat(c) image. At 25 Hz, the NSL varies less than 1 dB between the buoys. [At 10-25 Hz, the NSL (median) increases between the open-water and innermost compact-ice buoy; noise distributions are, however, wide and with considerable overlap.] At 31 to 200 Hz, the NSL decreases by 1–9 dB from buoy 27 in open water to buoy 35 in compact ice. For example, the decrease is 2 dB at 50 Hz, 7 dB at 100 Hz, and 9 dB at 200 Hz.

3.2 Noise attenuation

The premise applied in the following is that the observed reductions in noise levels are due to transmission loss of seismic exploration signals. Transmission loss in the Arctic can be described by a cylindrical spreading loss model (Thode *et al.*, 2010),

$$TL = 10 \log_{10} R + \alpha R, \tag{1}$$

where R is the source-receiver range and α is a linear attenuation factor (dB/km). With range ΔR_{12} between two buoys and range R_1 to the source (approximately) known, an estimate of the attenuation factor is obtained by

$$\alpha = \left[\Delta NSL_{12} - 10 \log_{10} \left(1 + \frac{\Delta R_{12}}{R_1} \right) \right] \Big/ \Delta R_{12}, \tag{2}$$

with ΔNSL_{12} the measured noise reduction. (For $R_1 \gg \Delta R_{12}$, the second term in the bracket, which accounts for difference in spreading loss, approaches zero.) Figure 2 shows estimates of α obtained via Eq. (2) from the open-water and innermost compact-ice buoys at relative range 118 km. (A spreading loss difference of 0.4 dB for source range 1400 km has been accounted for.) For comparison is shown α previously estimated from under-ice interior Arctic deep-water propagation loss data (Di Napoli and Mellen, 1986) and from Arctic open-ocean airgun data (Thode *et al.*, 2010) as well as attenuation in seawater with Arctic ocean properties. A curve fit to the attenuation factors derived from the Fram Strait data yields $\alpha(\text{dB/km}) = 0.4217 \times 10^{-4} f^{3/2}$, where the exponent of frequency f has been fixed in accordance with Di Napoli and Mellen (1986).

3.3 Numerical modeling

Figure 3 compares results from numerical modeling of transmission loss to measured NSL at four sonobuoys (Table 1) at frequencies of 31, 50, 100, and 200 Hz.

Table 1. Noise spectral density levels (in dB re 1 $\mu\text{Pa}^2/\text{Hz}$) in selected 1/3-octave frequency bands measured in the Marginal Ice Zone of the Fram Strait on June 9, 2011. Buoy number identifies the location in Fig. 1. Ice conditions at each buoy and range to the ice edge is estimated from the RadarSat image.

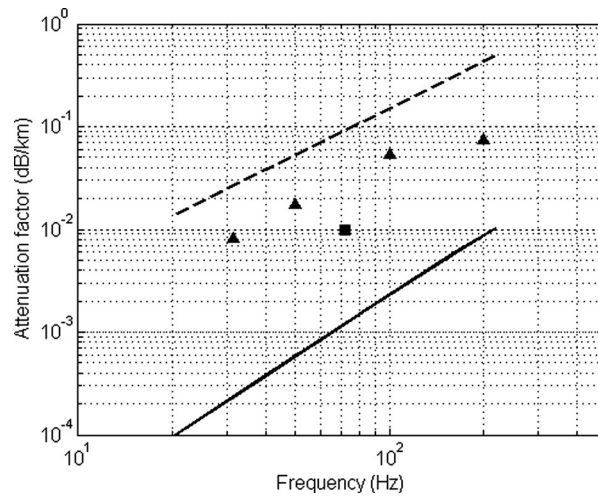| Buoy No.	Ice conditions	Range to ice edge (km)	NSL 25 Hz	NSL 50 Hz	NSL 100 Hz	NSL 200 Hz
27	Open water	−25	98	93	86	74
31	Diffuse ice	77	98	92	83	72
33	Compact ice	120	98	90	80	68
35	Compact ice	150	99	91	79	65

Fig. 2. Frequency-dependent attenuation factor (dB/km) estimated from acoustic data under various sea/ice conditions. Filled triangles: Fram Strait Marginal Ice Zone in June 2011; square: Ice-free Arctic conditions (Thode *et al.*, 2010); broken line: Deep-water under-ice interior Arctic propagation (Di Napoli and Mellen, 1986). Solid line is attenuation in seawater with Arctic ocean properties.

Transmission loss (TL) is relative to the levels modeled at the open-water buoy; the horizontal axis indicates the range from each buoy to the ice edge. The environmental model (described in the appendix) applied a 2.2 m thick homogeneous ice cover from the ice edge. The modeled increase in TL is within 3 dB of the measured NSL reduction (exceptions are 31 Hz/77 km and 100 Hz/150 km). For comparison is also shown modeling results with no ice cover, the environmental model otherwise equal. Modeled TL is then up to 9 dB less than for the model with ice cover (the difference increasing with range and frequency); this suggests a significant loss contribution due to under-ice interaction.
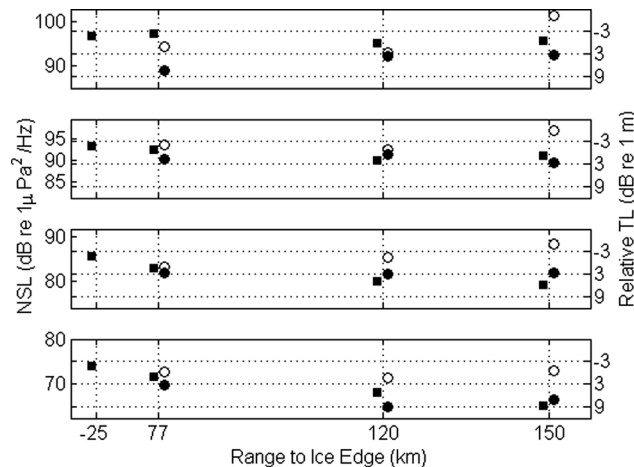

Fig. 3. Measured noise levels and modeled transmission loss in the Fram Strait Marginal Ice Zone at frequencies 31 Hz (upper), 50 Hz, 100 Hz, and 200 Hz (lower panel). Measurements (squares) are median noise spectral density levels in dB re 1 μPa^2/Hz (left axis) from sonobuoys in open water (left), diffuse ice, and compact ice (right), range to the ice edge on horizontal axis. Transmission loss in dB re 1 m (right axis) is relative to the open water buoy, for environmental models with a 2.2-m thick ice cover from the ice edge (closed circles) and no ice cover (open circles).

4. Discussion

High noise levels were observed at low frequencies in the Fram Strait in June 2011 and attributed to distant (1400 km range) seismic exploration. Noise levels at 10–60 Hz exceeded by up to 12 dB the levels measured under heavy swell conditions in April 1987, both in the open ocean and in compact ice, despite calm conditions in June 2011. A reduction of noise levels with range into the ice cover was observed and used to estimate an attenuation factor for seismic exploration noise in the MIZ. The estimated attenuation factor is less than one-third of that derived by Di Napoli and Mellen (1986) from historic under-ice interior Arctic propagation data. Numerical modeling predicted transmission loss of the same order as the observed noise level reduction and indicated a significant loss contribution from under-ice interaction. We suggest that further noise measurements can be used to infer the reduction of seismic exploration noise in the MIZ under other sea and ice conditions than those reported here.

Acknowledgments

Appendix: Numerical modeling of transmission loss

Transmission loss was modeled by use of the range-dependent raytrace model BELLHOP (Acoustic Toolbox, 2013) with range-dependent surface reflection loss added to the model. Environmental input was taken from the TOPAZ4 coupled ocean–sea ice model (Sakov et al., 2012) with temperature and salinity versus depth forecast profiles for June 9, 2011, extracted along transects from the seismic source position to each buoy. The profiles were converted to sound speed versus depth using the McKenzie formula (Ainslie, 2010) and interpolated in range using the quadrilateral interpolation scheme in BELLHOP. An approximation to Leroy's equation (Ainslie, 2010) was used for attenuation of sound in seawater. Range-dependent bathymetry profiles were taken from TOPAZ4. For the seabed, geoacoustic parameter values were set to compressional wave speed $c = 1520$ m/s, density $\rho = 1.5$ g/cm^3, attenuation $\alpha = 0.1$ dB/λ (wavelength, λ). For the ice cover, we used a mean thickness of 2.2 m from recent measurements in the Fram Strait (Renner et al., 2013), ice edge location interpreted from the RadarSat image, and acoustic properties of sea ice from (Dosso et al., 2002): $c = 2900$ m/s and $\alpha = 2.6$ dB/λ, $\rho = 0.91$ g/cm^3, shear speed 1670 m/s, and attenuation 1.6 dB/λ. Interface roughness was modeled using root mean-square values of 1.32 m at the water-ice boundary and 0.33 m at the ice-air boundary (Gavrilov and Mikhalevsky, 2006). The reflection coefficient versus grazing angle for a layered air-ice-water model was computed with the Bounce model (Acoustic Toolbox, 2013). The position of the seismic source was determined using information from directional sensors on sonobuoys, supported with numerical modeling of propagation from candidate survey sites; this established a location in shallow water at range approximately 1400 km southeast of the open-water buoy. A point source at depth 12 m was used in the modeling.

References and links

Acoustic Toolbox (**2013**). http://oalib.hlsresearch.com/ (Last viewed 2 January 2014).

Ainslie, M. A. (**2010**). *Principles of Sonar Performance Modeling* (Springer, Heidelberg).

DiNapoli, F. R., and Mellen, R. M. (**1986**). "Low frequency attenuation in the Arctic Ocean," in *Ocean Seismo-Acoustics*, edited by T. Akal and J. Berkson (Plenum, New York).

Dosso, S. E., Heard, G. J., and Vinnis, M. (**2002**). "Source bearing estimation in the Arctic Ocean using ice-mounted geophones," J. Acoust. Soc. Am. **112**, 2721–2734.

Gavrilov, A. N., and Mikhalevsky, P. N. (**2006**). "Low-frequency acoustic propagation loss in the Arctic Ocean: Results of the Arctic climate observations using underwater sound experiment," J. Acoust. Soc. Am. **119**, 3694–3706.

Johannessen, O. M., Sagen, H., Sandven, S., and Stark, K. V. (**2003**). "Hotspots in ambient noise caused by ice-edge eddies in the Greenland and Barents seas," IEEE J. Ocean. Eng. **28**, 212–228.

Klinck, H., Nieukirk, S. L., Mellinger, D. K., Klinck, K., Matsumoto, H., and Dziak, R. P. (**2012**). "Seasonal presence of cetaceans and ambient noise levels in polar waters of the North Atlantic," J. Acoust. Soc. Am. **132**, EL176–EL181.

Mellberg, L. E., Johannessen, O. M., Connors, D. N., Botseas, G., and Browning, D. (**1987**). "Modeled acoustic propagation through an ice edge eddy in the East Greenland Sea Marginal Ice Zone," J. Geophys. Res. **92**, 6857–6868, doi:10.1029/JC092iC07p06857.

Moore, S. M., Stafford, K. M., Melling, H., Berchok, C., Wiig, Ø., Kovacs, K. M., Lydersen, C., and Richter-Menge, J. (**2012**). "Comparing marine mammal acoustic habitats in Atlantic and Pacific sectors of the High Arctic: Year-long records from Fram Strait and the Chukchi Plateau," Polar Biol. **35**, 475–480.

Nieukirk, S. L., Mellinger, D. K., Moore, S. E., Klinck, K., Dziak, R. P., and Goslin, J. (**2012**). "Sounds from airguns and fin whales recorded in the mid-Atlantic Ocean, 1999-2009," J. Acoust. Soc. Am. **131**, 1102–1112.

Norwegian Petroleum Directorate. (**2012**). "Fact Pages," http://factpages.npd.no/factpages/ (Last viewed 2 January 2014).

Renner, A. H. H., Dumont, D., Beckers, J., Gerland, S., and Haas, C. (**2013**). "Improved characterization of sea ice using simultaneous aerial photography and sea ice thickness measurements," Cold Region Sci. **92**, 37–47.

Roth, E. R., Hildebrand, J. A., Wiggins, S. M., and Ross, D. (**2012**). "Underwater ambient noise on the Chukchi Sea continental slope from 2006-2009," J. Acoust. Soc. Am. **131**, 104–110.

Sakov, P., Counillon, F., Bertino, L., Lisæter, K. A., Oke, P. R., and Korablev, A. (**2012**). "TOPAZ4: An ocean-sea ice data assimilation system for the North Atlantic and Arctic," Ocean Sci. **8**, 633–656.

Thode, A., Kim, K. H., Greene, C. R., and Roth, E. (**2010**). "Long range transmission loss of broadband seismic pulses in the Arctic under ice-free conditions," J. Acoust. Soc. Am. **128**, EL181–EL187.