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Acoustic Signatures of Shipping, Weather and Marine Life: Comparison of NE Pacific and Arctic Soundscapes

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Acoustic signatures of shipping, weather and marine life are relatively well constrained, but there are strong variations with their oceanographic context and human activities. We investigate two contrasted settings, for timescales up to a year and frequencies up to 2 kHz. Arctic data from NOAA Noise Reference Station (NRS) NRS01, 500 m deep in the Arctic Chukchi Sea and away from major shipping areas is compared with measurements from Folger Deep, part of the Ocean Networks Canada network, 95 m deep and close to shipping lanes. PAMGuide is used to quantify broadband Sound Pressure Levels (SPLs), Third-Octave band Levels (TOLs), Power Spectral Densities (PSDs) and percentile contributions. The Acoustic Complexity Index (ACI) is an emerging metric to measure the apparent acoustic biodiversity, and we use its Seewave implementation. We compare the third-octave bands centred on 63 Hz and 125 Hz ("shipping" bands of the European Marine Strategy Framework Directive) in each environment and assess their use in the presence of heavy ice and little to no shipping. Metrics designed for open waters are not directly applicable to icy environments, or at least not on their own. They must be supplemented with multivariate analyses of context-specific third-octave bands.

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1. RATIONALE

The Arctic environments are fragile and undergoing rapid changes, associated with climate change and increased anthropogenic activities. Passive Acoustic Monitoring (PAM) allows measuring these changes from their acoustic signatures underwater, but it relies on sampling soundscapes at the right places (and the right times). Autonomous recorders and ocean observatories now enable the measurement of complex and extremely large time-series with the right metrics, encompassing time periods ranging from seconds to years and ultimately decades. The analysis of this data will in turn be used to inform management of the different Arctic regions, at local, national and international scales, hopefully working toward compliance with the United Nation's Sustainable Development Goal SDG-14 "Conserve and sustainably use the oceans, seas and marine resources" (https://www.un.org/sustainabledevelopment/oceans/). There are plans to implement the components of the future Arctic Ocean Observing System[1] and build on existing long-term observatories. But can metrics designed for other environments also work in the multi-faceted Arctic soundscapes?

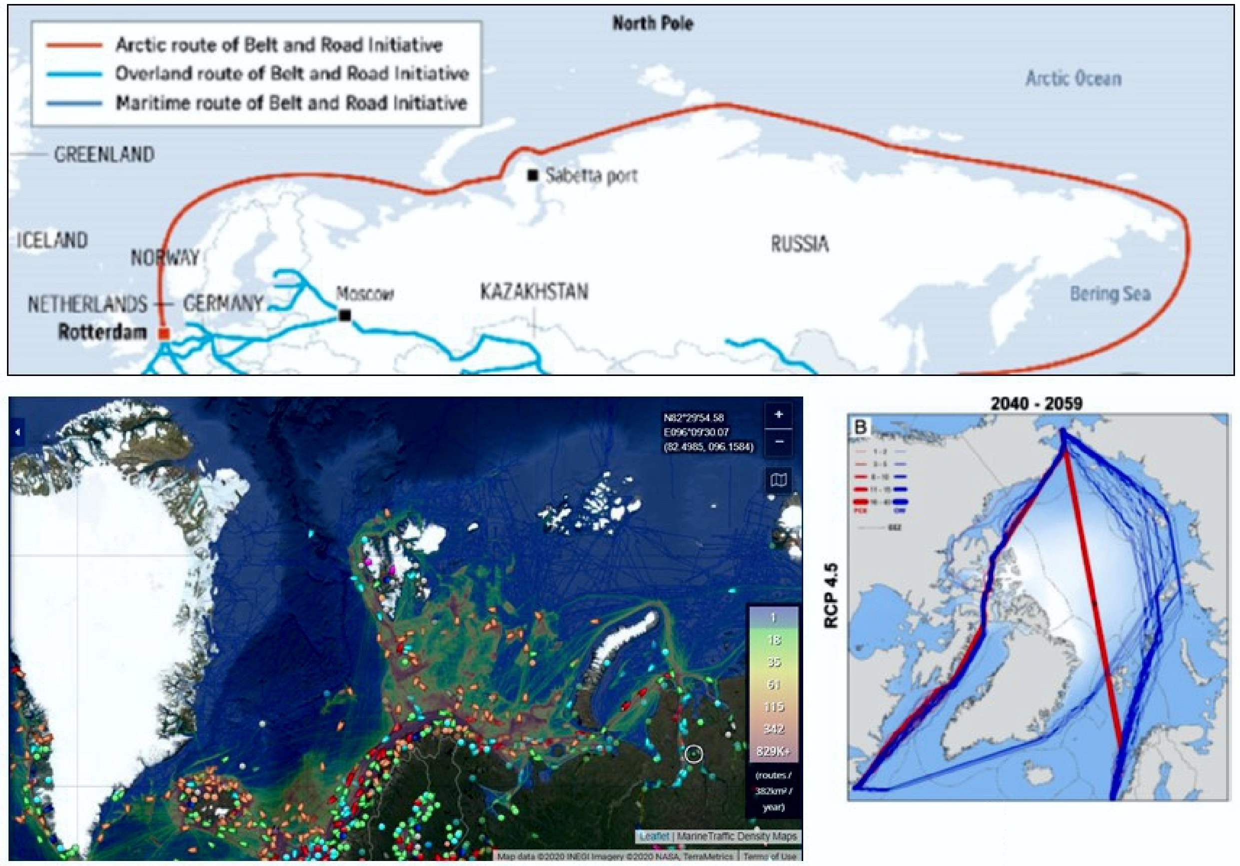


Figure 1: Top: Arctic route of the Belt and Road initiative.[2] Bottom left: snapshot of daily traffic (17/09/2020) around the European Arctic region, overlaid on density map of vessel measurements in 2017,[3] showing fishing vessels (orange), tugs and special craft (blue), general cargo (green) and tankers (red). Bottom right: projected trans-Arctic shipping routes[4] if climate change follows the intermediate Representative Concentration Pathways scenario with emissions stabilised at 4.5 W/m^2 (RCP 4.5). Both present and projected shipping are associated to marked soundscape changes.

Arctic soundscapes already combine natural background noise and marine life vocalisations with noise from ship cavitation (from icebreakers) and noise from seismic airguns (sometimes audible more than 800 km away, propagating from licensed areas to protected areas)[5–8] . As climate change makes Arctic waters more accessible, the development of the Northern Sea Route (Fig. 1, top) is strongly encouraged by some countries[2,9] and already visible in current marine traffic (Fig. 1, bottom left). Shipping along trans-Arctic routes (Fig. 1, bottom right) will also increase significantly, with different projections according to the likely climate change scenarios.[4] This will be associated with shore infrastructures (e.g. harbours, new settlements), several of which are currently planned or under construction. The rich natural resources of the Arctic include mineral resources (30% of the world's undiscovered gas and 13% of its undiscovered oil[10]) and increasingly attractive fisheries. Increased shipping will be accompanied with new infrastructure (e.g. harbours and offshore platforms) and expansion of human presence in general (e.g. Arctic tourism, currently on hold because of the worldwide Covid-19 restrictions). Most of this noise is in the frequency range 10 Hz - 1 kHz, in particular the third-octave frequency bands centred on 63 Hz and 125 Hz (”shipping bands” of the *European Marine Strategy Framework Directive*[11]).

Contributors to the Arctic soundscapes will therefore overlap in frequencies:

- Shipping: 10 Hz - 1 kHz, with important ”shipping bands” centred on 63 Hz and 125 Hz;
- Ice (mostly sea ice): 10 Hz - 10 kHz (and possibly higher in a few cases);
- Weather: 100 Hz to 20 kHz and higher, well constrained (e.g. Wenz curves);
- Biophonics: 100 Hz to more than 100 kHz (for some animals).

Some of these sounds will be long and relatively regular (e.g. ship noise, weather) whereas others will be short and irregular, sometimes with loud transients (e.g. animal vocalisations, ice processes). Warming of the Arctic seas extends deep, affecting long-range propagation and potentially affecting the attenuation of some frequencies. The long time series now routinely measured over timescales of months to years are extremely useful in understanding the affects of climate change and/or human activity on Arctic soundscapes, but they need to adequately distinguish between these processes, It is therefore important to use the right kind of measurements. We will compare standard metrics on two contrasting datasets, from the Arctic and from a temperate region, over a one-year timescale.

2. ACOUSTIC DATA AND METRICS

A. OCEAN OBSERVATORIES

The reference observatory is located in a temperate and well studied part of the NE Pacific (Fig. 2). The Folger Deep observatory was selected because it has been studied[12,13] with some of the metrics presented in the next section and because of the large amount of supporting data available. This observatory is operated by Ocean Networks Canada (ONC) and part of a larger array of nodes at different depths and ranges from the shores, covering all key environments of the NE Pacific.[14] Folger Deep lies off the coast of Vancouver Island, 100 m deep and 40 km from a busy shipping channel on the edge of a bay also popular with pleasure crafts. Large volumes of fishing vessels pass through this stretch of water when travelling to and from the harbour of Vancouver, and it is characterised by a rich and diverse ecosystem.

The acoustic measurements extend back from the present to late 2009. Due to gaps of varying sizes in the dataset, the date range which most easily enabled analysis of all seasons over a year was from May 2010 to April 2011.[15] The hydrophone used was placed close to the seafloor, composed of sandy sediments and some boulders. The raw audio measurements were in WAV format, sampled at 96 kHz. The generally quiet background is marred by regular pings from a neighbouring ADCP transmitting around 30 kHz. Short and regularly spaced, they produce varying echoes and harmonics. They were removed by bandpass filtering to the frequency band between 10 Hz and 2 kHz, to get a comparable frequency range to the next dataset. Analyses made use of the higher-frequency content, drawing on the previous studies[12,13] mentioned earlier.

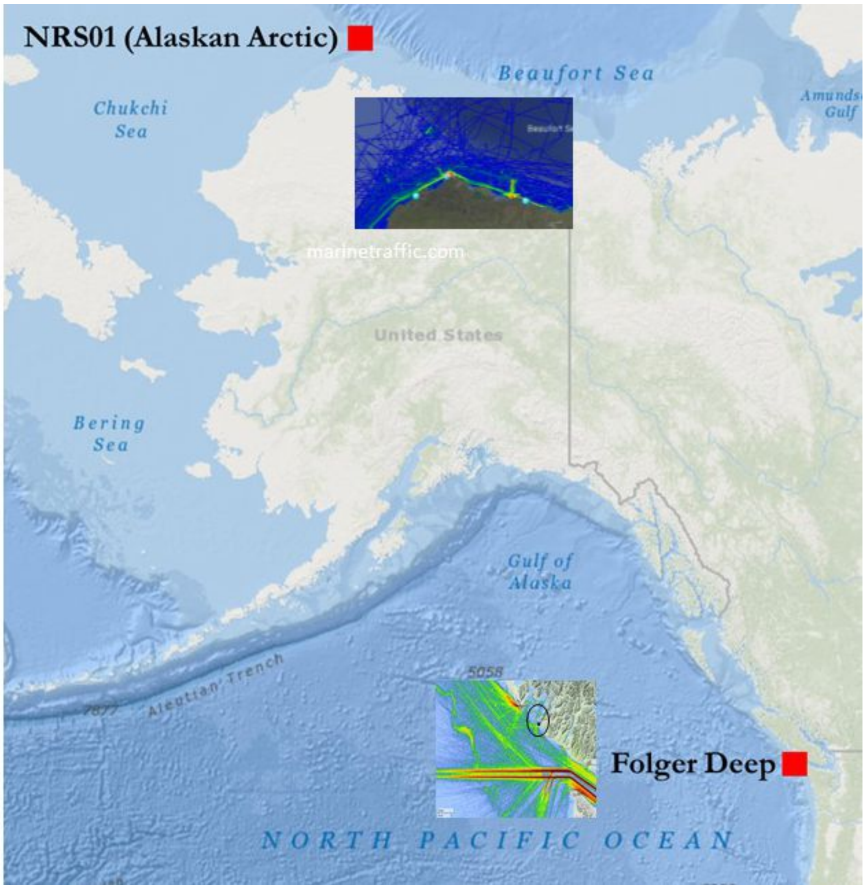


Figure 2: Location of the two datasets used in this study. Top: NOAA's Noise Reference Station NRS01, in the Alaskan Arctic. Bottom: Ocean Networks Canada Folger Deep observatory, in the North Pacific Ocean. Density maps of 2017 vessel traffic[3] show their contrasting levels of shipping (from blue: very low, to red: very high).

The US National Oceanic and Atmospheric Administration (NOAA) and the US National Park Service operate a Noise Reference Station (NRS) network of underwater observatories.[16] Station NRS01 is located north of Alaska in a region of complex bathymetry, on the steep transition between the Chukchi and Beaufort Seas, and the significantly deeper Arctic Ocean (Fig. 2). This region experiences a dramatic shift between near-total ice cover in the peak of winter, and open water during the summer, although its winter sea ice extent has seen a continuing decrease in the last 40 years, with 2019 the lowest on record.[17] Biodiversity is lower throughout the year than at the Folger Deep observatory, with most animals, such as whales, present only for only a brief time as part of long migration routes; the drastic seasonal change caused by ice build-up and melting renders the environment impractical for continuous inhabitation. Shipping is generally very low (The hydrophone at NRS01 was positioned mid-water (500 m deep) and recorded ambient noise at a sampling rate of 5 kHz, with the dataset extending from October 2014 to October 2015.[16] In practice, the period studied was limited to that between October 2014 and September 2015. This was due to persistent anomalous artefacts in the audio beginning from early October 2015, with regular and loud mechanical noises identified as a hydrophone fault (NOAA, pers. comm., 2019). To allow for investigation of the effect of ice cover on shipping activity, biodiversity, and potential affects on the general ocean soundscape, data from NOAA's Multisensor Analysed Sea Ice Extent – Northern Hemisphere (MASIE-NH) project were used to identify the periods of ice freezeup, ice breakup, and maximum ice cover in the region near NRS01.

These data were collected through observations from a number of satellite sources, and provided daily sea ice extent values from 2006 onwards over the whole Arctic Ocean, with datasets available for specific regions such as the Chukchi Sea.[18]

B. ACOUSTIC METRICS

Passive Acoustic Monitoring traditionally makes use of broadband Sound Pressure Levels (SPLs) and to compare like with like, we have reduced both datasets to a maximum frequency of 2 kHz. The frequency content of acoustic processes often contains important clues as to their origin or their impact, for example on marine life. We are therefore using Third-Octave band levels (TOLs), in particular around the ”shipping bands” of 63 Hz and 125 Hz identified by the European Marine Strategy Framework Directive.[11] Power Spectral Densities (PSDs) provide more information into how the power of a signal varies with its frequency content, The use of percentiles helps to define background noise levels by excluding ‘peaks’ that are loud but very infrequent: the x^{th} percentile signifies noise that appears $(100 - x)$ percent of the time (i.e. the 99th percentile is present 1% of the time), along with root mean square (RMS) values. This is done with the PAMGuide software,[19] using similar analysis parameters and the full calibration of each hydrophone. Biodiversity is more complex to assess, as it relies on vocalisations by animals close enough to each hydrophone to be heard. Because of time constraints, detailed analyses of individual calls was eschewed in favour of a more generic approach. The Acoustic Complexity Index (ACI) was developed[21] to quantify soundscape complexity by measuring the average absolute fractional change between time segments, based on their Short-Term Fourier Transform (STFT) and absolute differences between adjacent values of intensity. Originally designed and successfully used in terrestrial environments, an increasing number of studies[20] aim to extend it to underwater soundscapes.The ACI was computed with similar parameters[13] to compare both datasets. using its implementation in the R *Seewave* package.[21,22]

3. RESULTS

The Sound Pressure Levels in each area are presented in Fig. 3, averaged over months to better show the variation over the course of a year. For each month value, the tops and bottoms of each box show the 25th and 75th percentiles, i.e. the values that are present between 75% and 25% of the time. The distances between the tops and bottoms are the interquartile ranges. The line in the middle of each box corresponds to the median value, and outliers (infrequent events) are represented as red crosses. The top bars in each plot indicate either the amount of ice (Fig. 3, top) for the Arctic station or the generic season, for the NE Pacific station, simplified as summer/winter (Fig. 3, bottom).

The Folger Deep variations in SPLs (Fig. 3, bottom) show lower values, between 60 and 80 dB re 1 μPa at most, but with a large number of outliers associated to nearby shipping (louder but for shorter times of passage, and generally clearly audible in the WAV data). The SPLs are fairly constant throughout the year. April 2011 saw very heavy precipitations, with 35.6 to 41.6 mm/day recorded on 3rd-5th April 2011 at the weather station in neighbouring Port Renfrew, BC (https://climate.weather.gc.ca/). Apart from this, both frequency bands are at similar levels throughout the year, with the 125-Hz band generally slightly louder than the 63-Hz band. These relative variations are contrary to MSFD expectations for deeper areas[13] but they match other studies in similar environments.[23] They need to account for other contributions in these frequency bands, though, for example from weather.

Conversely, the Arctic measurements (Fig. 3, top) show louder averages, varying between 80 and 90 dB re 1 μPa, with fewer outliers. Interestingly, these outliers appear at the end of ice freeze-up, are more frequent during the period of maximum sea ice, decrease around March-April and increase again significantly as ice breaks up. In this case, the 125-Hz band is slightly louder (a few dB re 1 μPa) than the 63-Hz band, in line with MSFD expectations for deeper waters (which is the case here). However, the attribution to

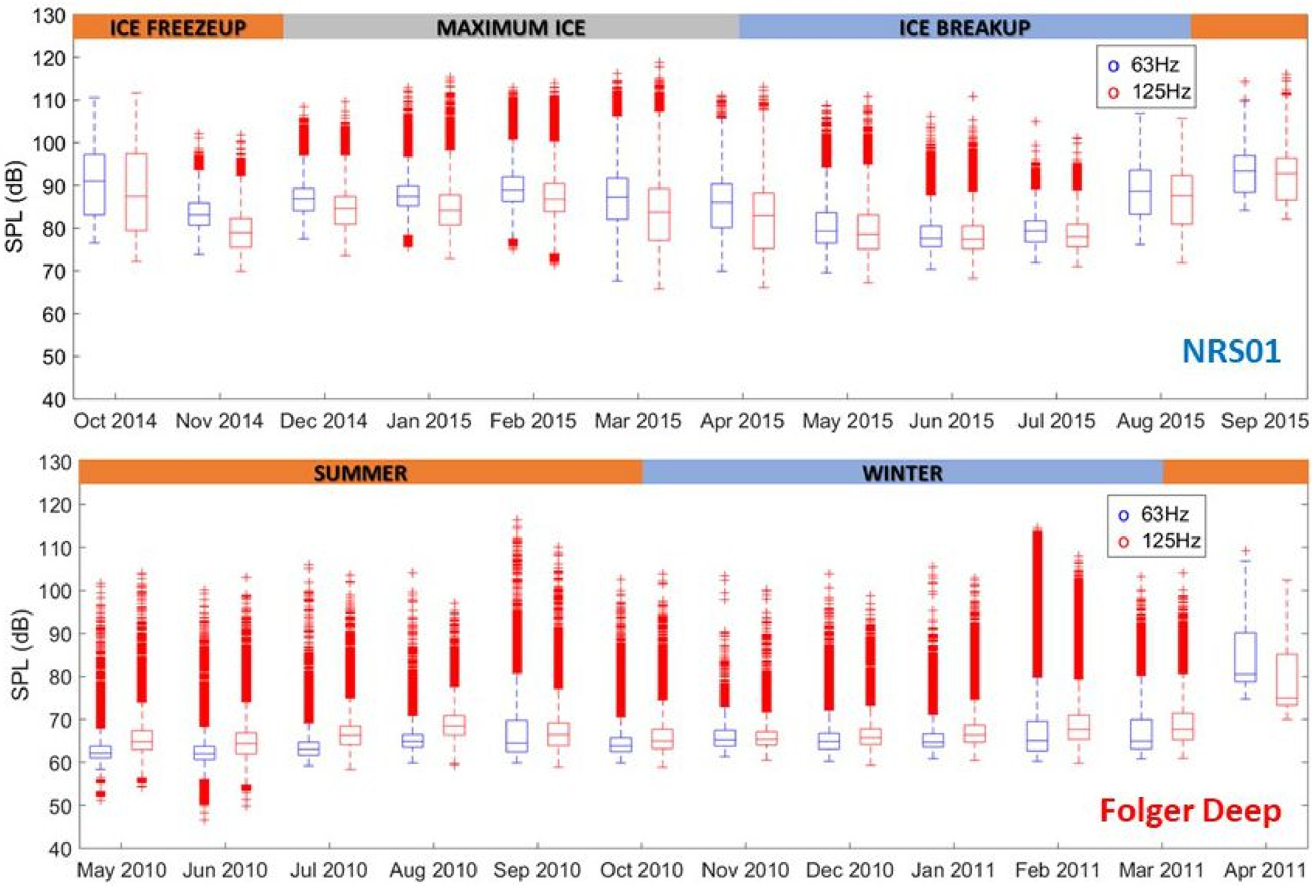


Figure 3: Comparison boxplots of Third-Octave levels in the two ”shipping bands” for each location (outliers are represented as red crosses).

shipping must be relativised, as during the period of maximum ice, only a few icebreakers would be likely to have accessed these areas.

Analyses of SPLs in these ”shipping bands” reveal other key differences . SPLs are louder in the Arctic region although there is little to no traffic (Fig. 2, top inset) compared to the Pacific region ((Fig. 2, bottom inset). The spread in SPLs is also larger at all times, although restricted at the onset of maximum ice cover (December 2014) and again in the middle of the ice break-up season (June 2015).

The significance of these ”shipping bands” is better seen by comparison with other third-octave bands, chosen here as centred on 500 Hz, 800 Hz and 1,000 Hz to encompass other processes.[1,8,24] Fig. 4 shows the spreading of SPLs at these frequencies through their standard deviations (σ_{SPL}, in dB re 1 μPa). Measurements at the Folder Deep hydrophone (Fig. 4, bottom) show large variations, up to 20 dB re 1 μPa, at all frequencies. This corresponds to very high precipitations, starting on 19th May 2010 and peaking in the period of 31st May - 2nd June 2010 (according to measurements from the Port Renfrew weather station). Overall, the shipping bands are slightly louder than the other bands, showing the expected acoustic influence of shipping from the neighbouring shipping lanes. The higher variations, up to 10 dB re 1 μPa, in February-March 2011 are also associated with sustained high levels of precipitations (2nd February to 14th March 2011, with a short break in the middle).

This can be usefully compared to the spreading of third-octave bands in the Arctic (Fig. 4, top). The ”shipping band” peaks are associated with higher peaks in all other bands, following their variations with seasons but with generally smaller variations. Considering the expected absence of shipping, particularly during the season of maximum ice cover, this limits the usefulness of the 63 and 125 Hz bands as single indicators of shipping. All frequency bands must be considered in the analyses of the soundscapes, at least in Arctic regions where ice processes have strong acoustic signatures.

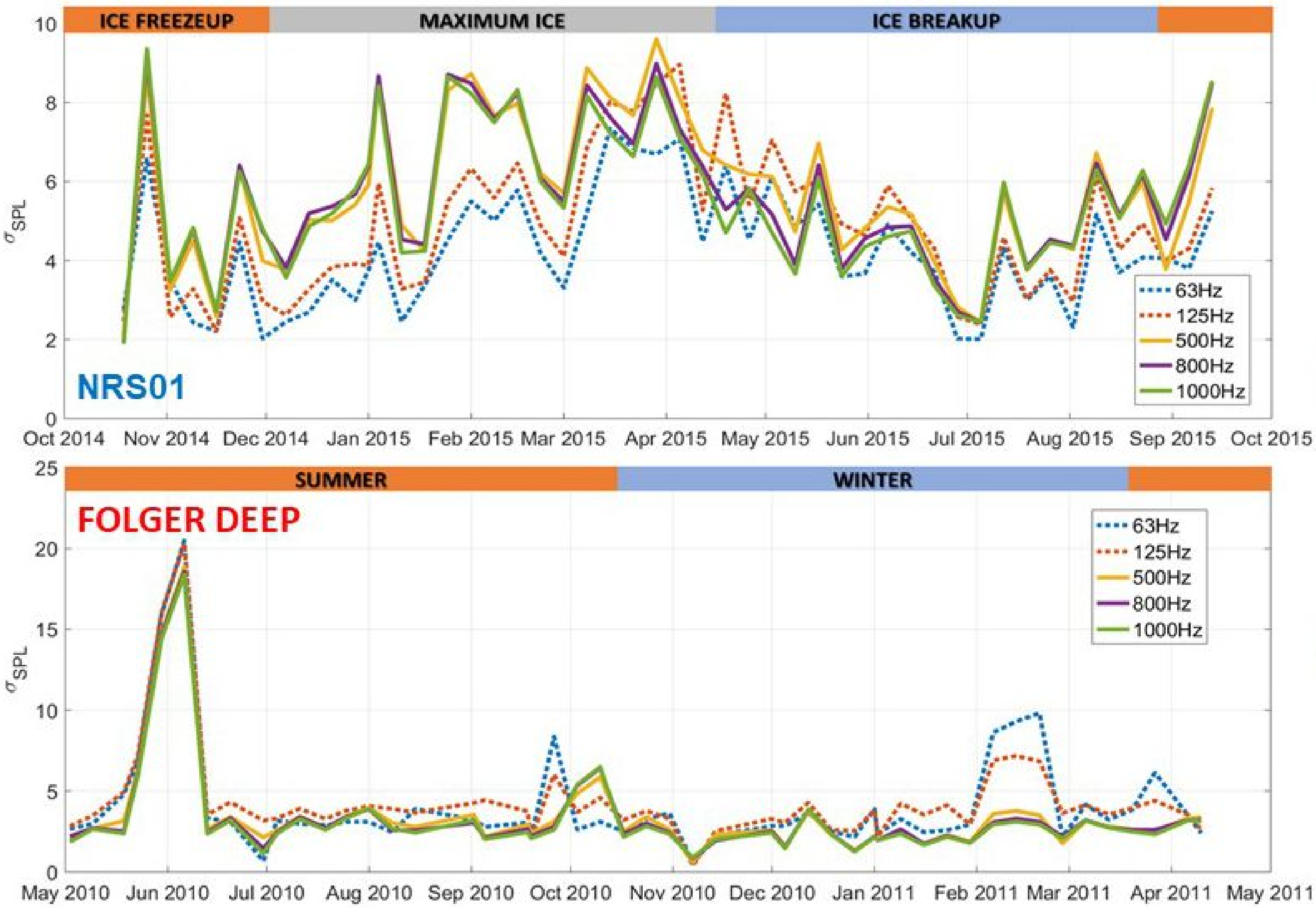
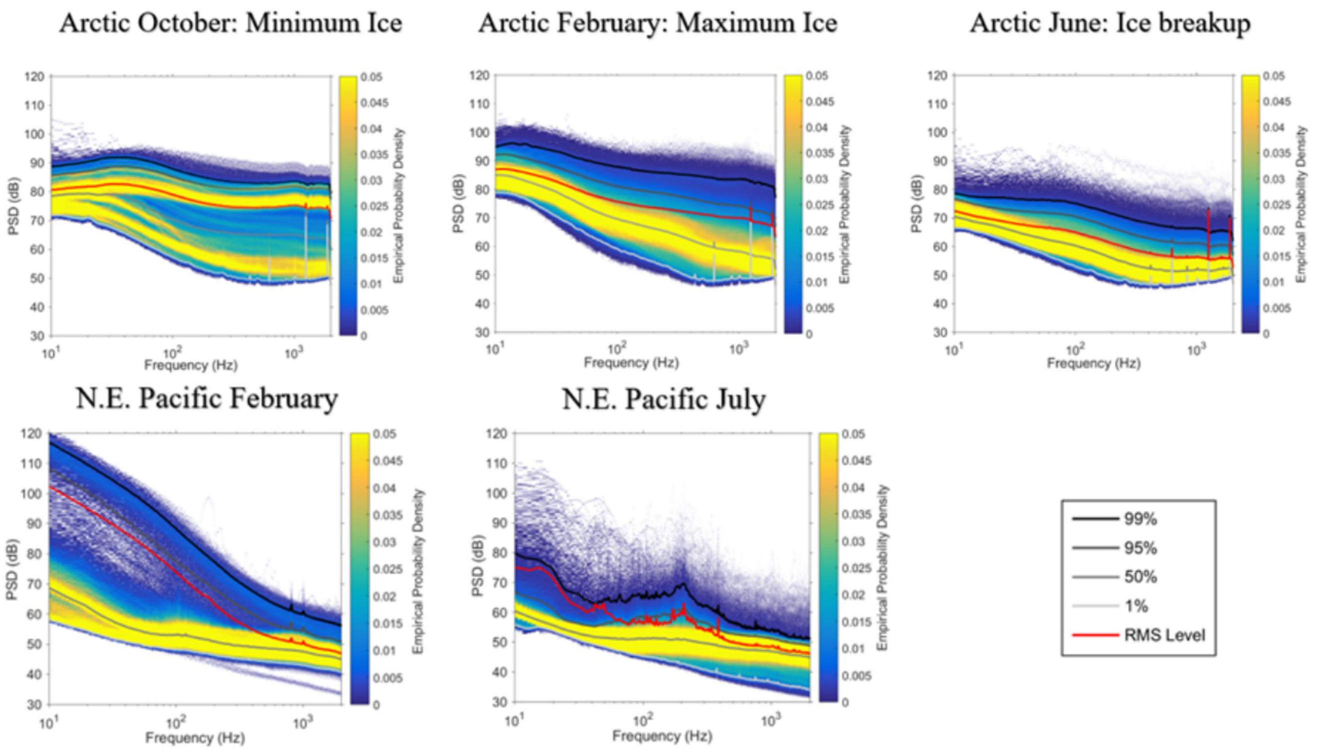


Figure 4: Variations along selected third-octave bands are better compared using their standard deviations. See text for explanations.

Exceedance levels, in combination with rms levels, are often used to distinguish between ambient and impulsive noise. The 99th exceedance level, labelled L_{99}, corresponds for example to sound levels present 1% of the time. Power Spectral Densities (PSDs) have been plotted as a function of frequency for periods corresponding to minimum ice, maximum ice and ice breakup in the Arctic, and winter/summer months in the NE Pacific (Fig. 5). These have been overlain with exceedance levels L_1, L_{50}, L_{95} and L_{99}, to better assess the prevalence of different frequency bands.

Measurements in Arctic waters (Fig. 5, top) show relatively similar levels throughout the frequency range, but with interesting differences associated to the amount of ice cover. In October (still with minimum ice), the PSDs vary between 70 and 90 dB re 1 μPa^{2}Hz^{-1} at 10 Hz, and 50 to 90 dB re 1 μPa^{2}Hz^{-1} at 2 kHz. Lower sound levels are more prevalent at higher frequencies, and the empirical probability densities show (in yellow) what are likely to be different processes. In February (maximum ice cover), the PSDs vary between 80 and 95 dB re 1 μPa^{2}Hz^{-1} at 10 Hz to 50 - 85 dB re 1 μPa^{2}Hz^{-1} at 2 kHz (i.e. louder at lower frequencies, related to ice processes). Empirical probability densities are relatively uniform and only hint at a single physical process (which is plausible, considering that the uniform ice cover decouples the underwater environment from wind and precipitations). In June (ice breakup period), sound levels spread much less: from 65 - 80 dB re 1 μPa^{2}Hz^{-1} at 10 Hz to 50 - 70 dB re 1 μPa^{2}Hz^{-1} at 2 kHz. The small peaks visible in October and February around 1 kHz become more pronounced, and might be associated to ice flexure and fracturing.[24] The relatively stable noise levels in February and June are dominated by this single physical process.

In contrast, the measurements in the more temperate waters of the NE Pacific show a marked difference between winter and summer (Fig. 5, bottom).In February, PSDs vary between 60 and 120 dB re 1 μPa^{2}Hz^{-1} at 10 Hz. The higher PSDs reduce with frequency down to 40 - 60 dB re 1 μPa^{2}Hz^{-1} at 2 kHz, with small peaks around 800 Hz and 1 kHz. In July, PSDs vary mostly between 55 and 80 dB re 1 μPa^{2}Hz^{-1} at 10 Hz, with a lower frequency gradient down to approximately 32 - 55 dB re 1 μPa^{2}Hz^{-1} at 2 kHz. The summer month also sees a high number of peaks between 40 and 400 Hz and a high number of loud outliers, generally associated with shipping and other infrequent noise sources.


Arctic October: Minimum Ice

Arctic February: Maximum Ice

Arctic June: Ice breakup

N.E. Pacific February

N.E. Pacific July

Figure 5: Monthly averaged exceedance levels as functions of frequency overlaid with the empirical probability density. Months have been chosen to represent different seasons and sea ice levels. A greater spread between L_1 and L_{99} can be seen between the Arctic months than the NE Pacific months. October has similar weather and little ice cover yet in the Arctic. July in the NE Pacific shows a greater number of transient events, seen by small variations in the rms and 99th percentile.

Principal-Component Analyses of the third-octave band levels in the NE Pacific[13] showed indeed that shipping was the most important component by far, with weather the second most important component. Along with a previous study,[12] it had shown that the Acoustic Complexity Index (ACI) followed several distinct timescales (e.g. time of day, tide, seasons). ACI was therefore attractive in open water. But its pertinence to ice-covered waters, with potentially less biodiversity and loud ice processes competing with biophonics in the same frequency ranges, still needed investigating.

ACIs were computed with the same processing parameters across the entire year for the Arctic data (Fig. 6). Exact numerical values are less meaningful in the absence of recognised standards for ACIs across different environments, and relative variations are much more important. ACI increases as the Arctic environment transitions to maximum ice, and decreases to previous levels as the ice cover becomes permanent (December-January). It then peaks in the middle of the maximum ice period (February), before decreasing again as the ice starts to break up (but peaking again, nearly at the same level, in the middle of the ice-breakup period). It then decreases drastically toward September 2015, at levels much smaller than October 2014. The decrease in acoustic complexity, were it related only to biodiversity, would therefore look odd if happening when the ice disappears and the waters become navigable again.

Comparison with Sound Pressure Levels (Fig. 6) does not show identifiable links. The Spearman's ρ correlation between the ACI and each TOL band was different when calculated for maximum ice cover; -0.2 for frequencies <200 Hz increasing to +0.2 above 200 Hz, and -0.7 for transitions in global ice cover as well as minimum ice cover (with no frequency dependence). During the maximum ice cover period, ρ is frequency dependent, but with a value indicating no significant correlation. This can be considered as further evidence of the contribution of ice noise to the "shipping bands", but also an indication of the limits of a blanket assessment of biodiversity only from using Acoustic Complexity.

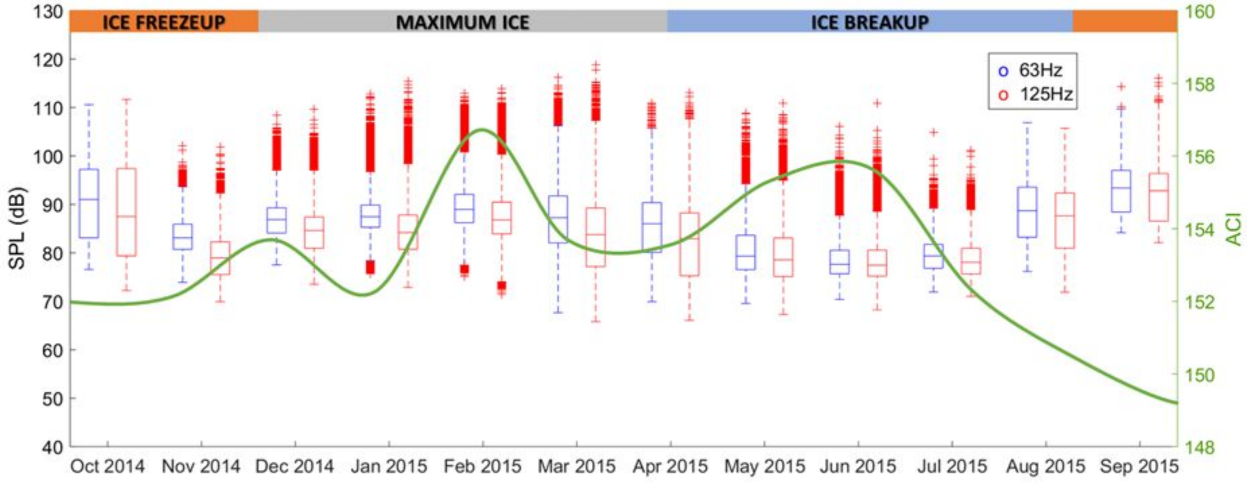


Figure 6: Yearly variation of the Acoustic Complexity Index (bold green line), compared with the Sound Pressure Levels in the two "shipping bands" centred on 63 Hz and 125 Hz. See text for explanations.

4. CONCLUSIONS

Acoustic signatures of specific processes like shipping, weather and marine life are relatively well constrained, but there are strong variations with the oceanographic environments and the relative amounts of human activities. We have compared a full year of ambient noise measurements in two contrasted settings, namely the Arctic Chukchi Sea (NOAA Noise Reference Station NRS-01) and the NE Pacific (ONC Folder Deep observatory). We compared standard metrics like Sound Pressure Levels, third-octave band levels (focusing on the 63-Hz and 125-Hz bands associated with shipping), Power Spectral Densities and their percentile contributions, with the emerging Acoustic Complexity Index (ACI).

Measurements at Folger Deep show that shipping is the most significant contributor to ambient noise, with weather second (except in summer, when biophonics becomes more important). This confirms earlier results,[13] with relative contributions of the 63-Hz and 125-Hz bands similar to those in other coastal locations.[23] ACI is strongly correlated with weather but also with the apparent bioacoustic activity. The shipping bands can therefore be used as intended, and ACI is a potentially useful metric in open waters and non-Arctic environments.

Measurements in Arctic deep waters show that the shipping bands have high levels when there is little to no shipping but maximum ice cover. This is correlated with high noise levels at higher frequencies, associated to ice processes. The ACI peaks at ice formation and break-up, but also at maximum ice cover. It is inversely correlated with the shipping bands when there is no ice. The MSFD shipping bands should therefore be used with caution in icy environments, and the significance of ACI in Arctic waters needs to be further investigated.

In conclusion, the metrics designed for open waters are not directly applicable to icy environments, or at least not on their own. They must as often as practicable be supplemented with multivariate analyses of third-octave bands in the entire frequency range.

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