Inversion of Seismic Waveforms to Study the Dynamics of Sea Ice

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Context

Arctic Sea ice is an essential element of climate regulation, which is declining by 13% per decade. At small scale, it affects the ecosystem, working and living conditions, and Arctic warming. At large scale, the result is disruption of normal ocean circulation and change in global climate.

For these reasons, the study of sea ice is of great importance. Field data are essential for understanding the rapidly evolving dynamics of sea ice, such as ice thickness, density, elastic properties, porocity, snow cover, etc.

Some of the common methods for collecting data include satellite imaging (providing an average thickness, but with poor spatial resolution), ice profiling sonar (data with good accuracy, but the data is rare and expensive), and **seismology** (active and passive data).

- ✓ Seismic studies on sea ice are based on the propagation of multimodal seismic guided waves recorded at 3C geophones.
- ✓ The analytical models describing these waves are based on low-frequency approximations and for a homogenuous mdeium, showing that:
- ▶ At **low frequencies** (< 100 Hz.m) - wavelengths greater than the plate thickness - we have 3 fundamental modes as (Moreau et al, 2020a):
  - ▶ Symmetric mode (QS_0) $\Rightarrow$ longitudinal/axial wave (dispersive mode, and mostly seen on Z component)
  - ▶ Anti-symmetric mode (QS) $\Rightarrow$ flexural wave (non-dispersive, seen on horizontal channel, here in green)
  - ▶ Shear-horizontal mode (SH_0) (non-dispersive, seen on horizontal channel, here in orange)

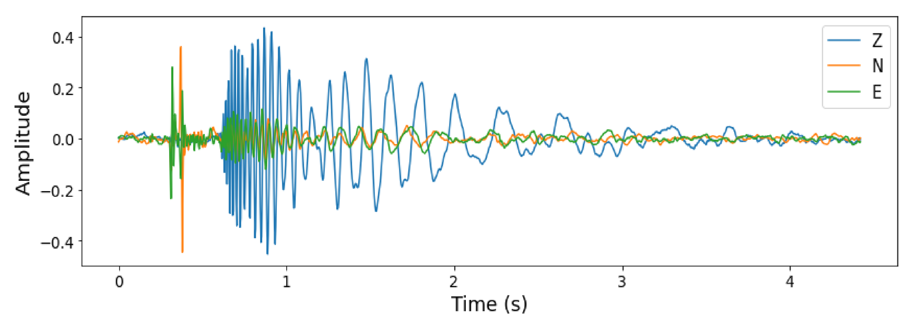


Figure 1: Example of an icequake recorded on March 8, 2021, using a 3C geophone, Lammi, Lake Pääjärvi, Southern Finland.

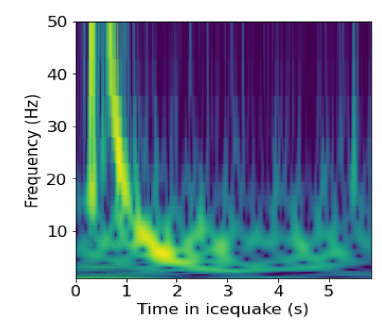


Figure 2: The time-frequency representation of the icequake.

While some studies are based on these analytical models (to create synthetics) to derive elastic properties and ice thickness, others used wavenumber integration (Miller et al., 1991) and finite element method (FEM) (Moreau et al., 2020b) to create synthetics in the inversion. Similarly, Johnson et al. (2019) (using wavenumber integration method) and Landschulze (2018) (using FEM) performed full wavefield modeling in sea ice, showing the limiations of analytical models in high frequencies.

Methods - Forward Modeling

Analytical modes are based on the assumptions of low-frequency approximation and for a homogeneous isotropic ice layer.

How to evaluate these limitations? Thanks to numerical method, **spectral element method (SEM)**, we can evaluate these limiations.

How to proceed? The comparison is done in two steps:

First, forward modeling using SEM is performed for

- ▶ floating ice layer (90 cm)
- ▶ floating ice layer (90 cm) with overlaying snow layer (50 cm)

Then, the results are compared with 2 analytical models (**Model 1**: Stein et, 1998; **Model 2**: Squire et al, 1996).

Spectral Element Method

The SEM code used is a 2D-coupled acoustic-elastic wave modeling in time domain (developed by Cao et al, 2021).

- ✓ Vertical force - 10Hz Ricker wavelet
- ✓ As it is in 2D, we only have flexural (QS: dispersive mode on both channels) and longitudinal (QS0: on horizontal channel) waves
- ✓ Use of adaptive mesh size and absorbing boundaries for an infinite medium and water depth

The V_p, Vs, and ρ for ice are 2284 m/s, 1282 m/s, and 910 kg/m^3, and for snow 194 m/s, 112 m/s, and 160 kg/m^3, respectively.

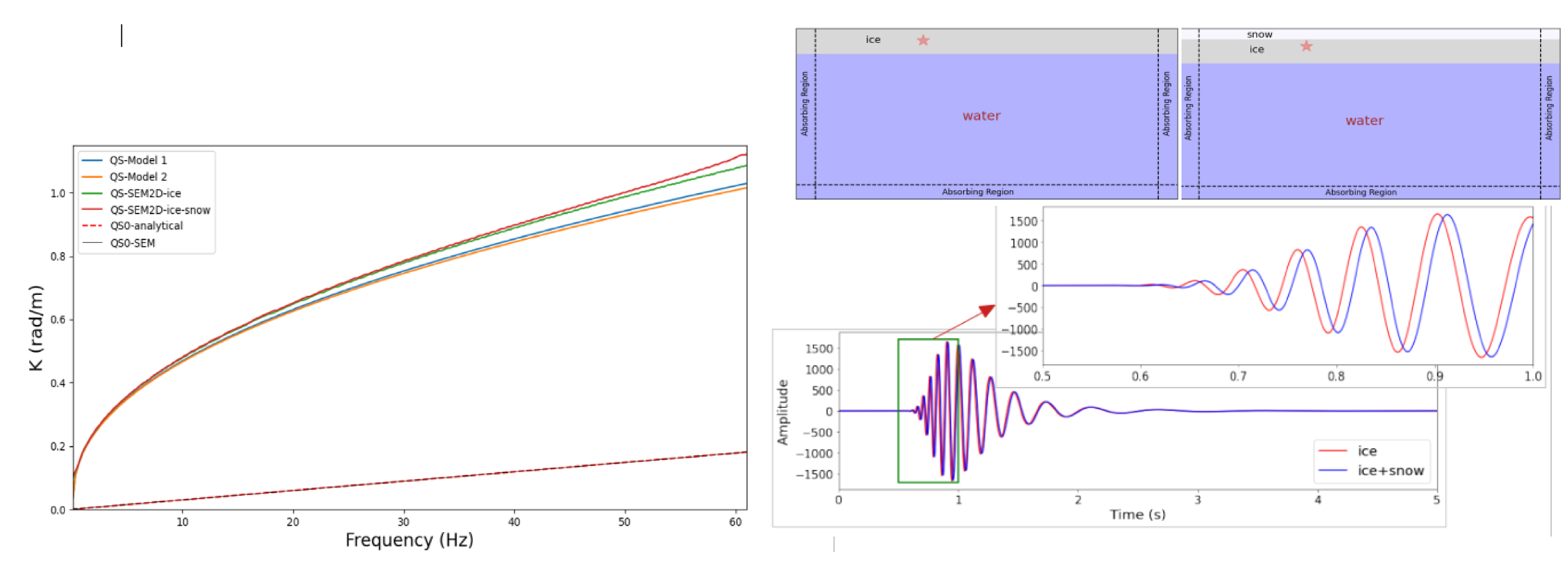


Figure 3: (Right) comparison of dispersion curves obtained from 2D-SEM with Models 1 and 2. QS0-SEM shown here is for the case of ice. 2D-SEM waveforms are recorded at 300 receivers with spacing of 1 m, and both vertical and horizontal components are used for derving dispersion curves. (Left) example of forward modeling using 2D-SEM, vertical channel.

Methods - Inversion

We observed that dispersion curve of flexural wave is different from those of Model 1 and 2. This difference is larger at high frequency and when there is a snow layer. Snow layer can also reduce the velocity of longitudinal wave (not considered here).

Knowing elastic constants (from non-dispersive modes of SH0 and QS0), Moreau et al. (2020b) used icequakes to estimated ice thickness and source locations from flexural waves.

So we expect an under/over-estimation of ice thickness and source location when using Model 1 and 2 in case of having

- ▶ a snow layer
- ▶ high frequency content

The idea is that to use 2D-SEM data as observed data to test the limitations of these analytical models.

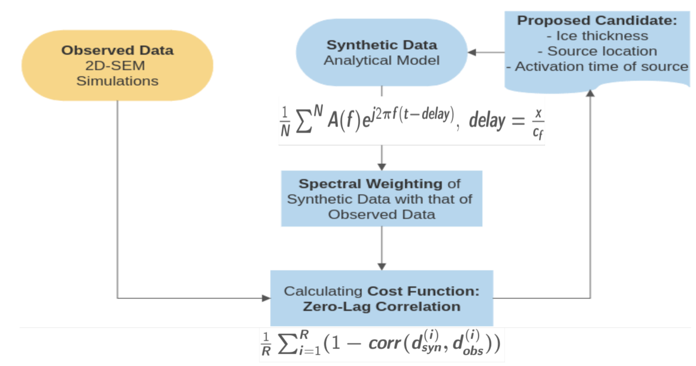


Figure 4: The inversion procedure. The observed 2D-SEM data include simulations for floating ice and ice-snow layers using sources with different central frequencies. 4 receivers (at 50, 150, 200, and 250 m from the source) were used for inversion.

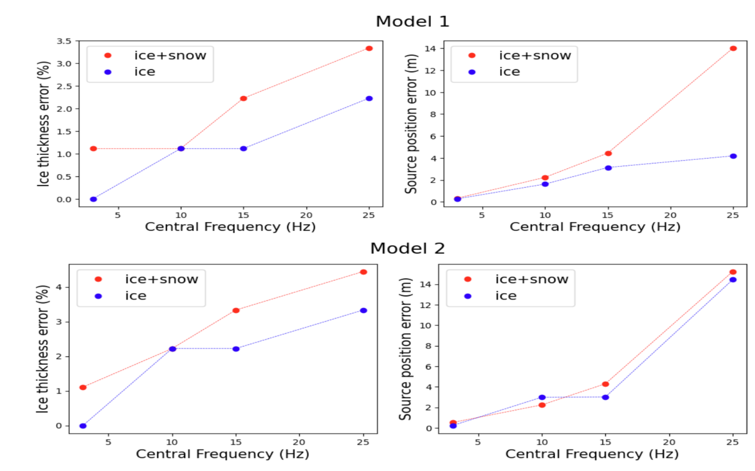


Figure 5: Inversion results: the sensitivity analysis for Model 1 and Model 2: ice thickness (left) and source location (right) errors

We observe that with increasing frequency content the error in estimation of ice thickness and source location increases. These error are slightly larger when there is a snow layer.

2D-SEM database

In the inversion process (Fig. 4), the forward modeling is basically solving analytical models numerically.

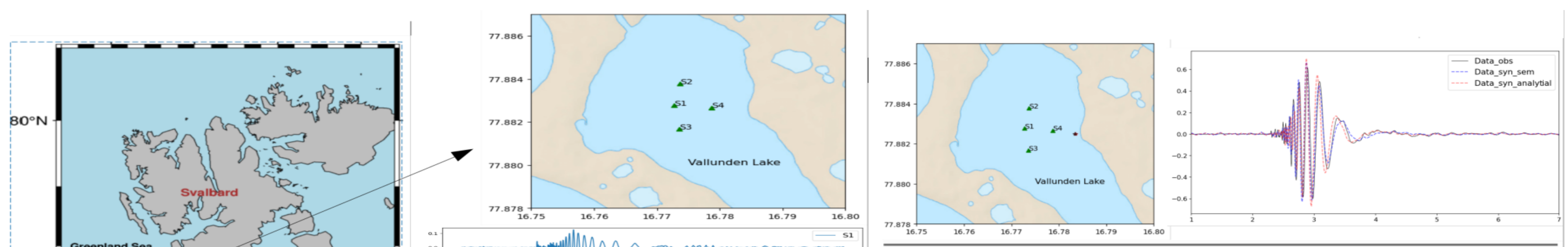
In the next step, a large database of waveforms for different models of ice-snow was created using a vertical point source (10Hz Ricker wavelet) for:

- ▶ ice ranging from 20-100 cm with a step of 1 cm
- ▶ snow ranging from 10-50 cm with a step of 2 cm
- ▶ waveforms recorded at 300 receivers with a step of 1 m

This database can be used for:

- ✓ inversion without solving the forward problem (when using analytical models for creating synthetic waveforms), for different combinations of parameters including ice thickness, snow thickness, and distance $\rightarrow$ grid search approach
- ✓ reducing the computational cost: Here the inverse problem is a based on searching in the database

Application of the database to real data:



Category	Ice thickness	Snow thickenss	Misfit
SEM-Database	0.59 m	0.32 m	0.066164
Anaytical approach	0.59 m	-	0.080115

Figure 6: (Right) The icequake data recorded at 4 stations. (Left) The source location found (star), and waveform fitting for station S4, and the results for inversion using the database and analytical approach.

Both the inversions give similar ice thicknesses with slightly different source locations (3 m difference). In addition, searching in the database gives an estimation for snow thickness. In general,

- ▶ In the frequency band of the real data, which is mainly between 0-10 Hz, the analytical approach gives comparatively results
- ▶ Real data with high frequency content can better highlight the limitations of analytical approaches

Next Steps:

- ✓ Using the 2D-SEM database, the inversion for the case of a floating ice layer with increasing/decreasing thickness showed an overestimation/underestimation in ice thickness and source location.
- ▶ Furthermore, the effect of snow can change depending on its density and thickness.

Prospectives: More field data applications, taking into account viscoelasticity and a gradient in elastic constants of ice and snow, as well as the 3D effects, and full waveform inversion for recovering ice-structure with local optimization

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