General Comments

The paper uses machine learning to identify and extract flexural-gravity (FG) wave signals recorded on a small lake, and then uses these signals for an MCMC inversion of ice thickness, based on the dispersive nature of FG waves.

I have only passing knowledge of ML and thus cannot evaluate those portions of the paper. Details on the MCMC inversion were specified in another paper, which I did not track down, and so I also cannot evaluate the specifics of that. The core results of the ML clustering and MCMC inversion, as presented, do appear realistic. FG wave sources are back-located to the grounding lines of the lake ice and are likely icequakes. Lake ice thickens during the first two weeks of the study period, and stabilizes during the last two, consistent with stated (but not provided) temperature readings.

The manuscript has a marked lack of supporting ancillary data, specifically temperature and tidal observations. Despite this, the authors make a geophysical interpretation of their icequake as being thermally-driven, as opposed to tidally-driven. As outlined in the specific comments below, based on publicly-available temperature and tidal data, I disagree with this interpretation.

The manuscript mentions that it produces results that are in agreement with another study by the same group of authors (Serripierri et al., 2022). From a quick readthrough of that work, it appears that it uses the same methods, but with greater rigor and scope. It mentions a future publication (assumed to be the current manuscript) that will attempt to replicate their results using fewer stations and wave modes. In that context, the current work appears to be a companion paper, yet does not address the work done by Serripierri et al. (2022), or make any explicit statement of the differences between the two works. The current manuscript should make a clear statement on how it is substantially different from the prior work.

I believe the core results (ML extraction of events and MCMC inversion of FG waves) are sound, novel, and notable. However, I recommend revisions to address the points raised in the specific comments below. In particular, the lack of ancillary data and the related geophysical interpretation, and the implications for an assumption of an infinite-depth water column in a borderline shallow-water setting.

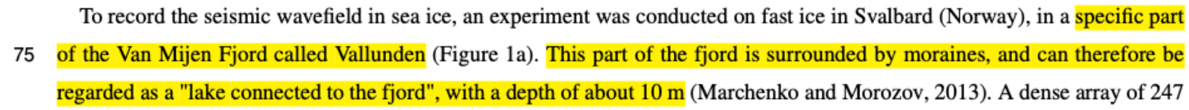
We thank the reviewer for such an in-depth review, and in particular for the help in interpreting the icequakes occurrences in conjunction with tides. We have accounted for all the comments (see detailed answers thereafter), and modified the manuscript accordingly.

A quick note about the comparison between the method in Serripierri et al. (2022) and that in the manuscript. In Serripierri et al. (2022), a frequency vs wavenumber analysis is performed via a Fourier transform on the time and space dimensions. The inversion is based on wavenumber inversion (phase velocity). This requires a dense line of geophones for spatial sampling. In the present paper, we use waveforms inversion, which is a very different approach, which allows to recover the ice thickness with only 5 stations instead of 50, which is an order of magnitude less. However, thickness values are consistent.

Specific Comments

Lines 11, 70, 92 : The authors state that they installed their seismic array on sea ice in Van Mijen fjord. Figure 1 shows that the field site is actually Vallunden Lake. While there is a short (100 m) channel connecting the lake to the fjord, the lake is geophysically distinct from the fjord. The authors do not provide any geologic context for the lake nor provide relevant references. The depth of Lake Vallunden is ~10 m (Marchenko et al. 2013), which is also not mentioned by the authors, but is an important consideration for their modeling (addressed further below).

We have added the reference Marchenko and Morozov (2013) to provide the depth of the Lake, and we have more specifically explained that the location of the experiment is at Vallunden.



To record the seismic wavefield in sea ice, an experiment was conducted on fast ice in Svalbard (Norway), in a specific part of the Van Mijen Fjord called Vallunden (Figure 1a). This part of the fjord is surrounded by moraines, and can therefore be regarded as a "lake connected to the fjord", with a depth of about 10 m (Marchenko and Morozov, 2013). A dense array of 247

Line 13 : “calibrated seismic sources”. The seismic sources, as described on line 221, appear to be more “estimated” than “calibrated.” Addressed further below.

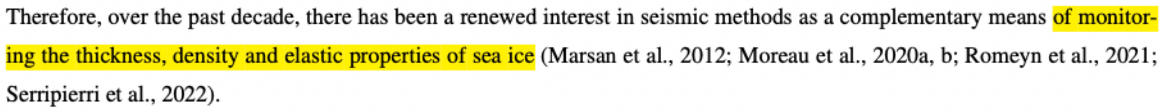
The height of the jumps was 1m, but unfortunately we cannot be as accurate as to go down to the cm. We have replaced “calibrated” occurrences by “artificial”.

Lines 18–19 : Citation needed. https://nsidc.org/arcticseaicenews/charctic-interactive-sea-ice-graph/ ?

This cannot be cited as a reference paper, so we have added the hyperlink to the text.

Lines 31–33 : The densities of snow and ice are also a source of error for seismic measurements, so this statement is a little misleading in the context of putting forth seismology as an alternative to freeboard measurements. In my opinion, the greatest advantage of seismic methods vs satellite is orders of magnitude greater spatial and temporal resolutions, at the expense of spatial scale. The authors appear to agree with this, though not explicitly.

In Serripierri et al (2022), we demonstrated that the density of sea ice can be accurately evaluated through passive seismic methods, and this is one important novelty of the approaches that we develop. We have modified this part of the introduction to remind that density can be monitored as well.



Therefore, over the past decade, there has been a renewed interest in seismic methods as a complementary means of monitoring the thickness, density and elastic properties of sea ice (Marsan et al., 2012; Moreau et al., 2020a, b; Romeyn et al., 2021; Serripierri et al., 2022).

It is true that we have not yet demonstrated that the density of snow can be constrained too. The impact of this parameter on our inversions is very minor at the frequencies of interest. However, we intend to make use of the higher frequency content to constrain the snow properties, by using a forward model that accounts for the snow cover. This is out of the scope of this paper, but a new paper where we investigate this issue will be submitted in the coming months.

Line 35 : “The first seismic experiments on sea ice date back to the late 1950s…” Ewing and Crary (1934) on Saylor’s Lake and Crary (1954) on Fletcher’s Ice Island should not be overlooked.

We thank the reviewer for these references, which we were unaware of. We have added reference Crary (1954) to the manuscript. However, we have not added the other reference, because it does not concern sea ice.

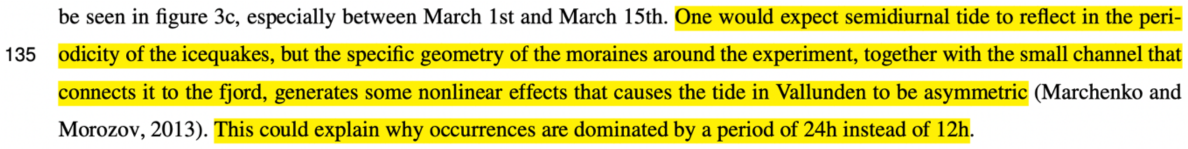
Lines 122, 273–274, 283–284, Fig 5 caption : “Icequakes (in the 0–7 cluster family] are likely produced by thermomechanical forcing.” This interpretation is not substantiated by the data presented.

The reviewer is right, and since thermomechanical cannot be completely ruled out, we have modified this sentence such that: “Icequakes are produced by \hl{tidal and} thermomechanical forcing”.

Hourly temperature data are not included in this manuscript, nor any of the references that I checked. Hourly temperatures recorded at Lufthavn, 50 km away, for March 2019 (https://meteostat.net/en/station/01008) do not show a diurnal cycle, consistent with a perpetually overcast Arctic coastal climate where temperatures are dominated by weather rather than solar heating. In the absence of locally recorded data, one could assume that Lake Vallunden has similar temperature trends. The noted 24-hour peak in icequake occurrence cannot be attributed to thermomechanical fracturing without an hourly-scale time domain correlation between temperature at Vallunden and icequake occurrence rates. Arguably, a spatiotemporal correlation would be most appropriate.

Fig. 3d does not show a consistent 24-hour recurrence pattern for the 0–7 cluster family. The deficit at 9 AM (local? UTC?) can be attributed to tides, as explained below.

We agree with the reviewer, and we have added a new figure with the temperatures recorded in March 2019 at Sveagruva (~ 1.5 km from the place of the experiement). Reviewer 1 also pointed out this issue. We have modified the manuscript to explain that icequakes are more likely a consequence of tidal forcing than temperature changes.


be seen in figure 3c, especially between March 1st and March 15th. One would expect semidiurnal tide to reflect in the periodicity of the icequakes, but the specific geometry of the moraines around the experiment, together with the small channel that connects it to the fjord, generates some nonlinear effects that causes the tide in Vallunden to be asymmetric (Marchenko and Morozov, 2013). This could explain why occurrences are dominated by a period of 24h instead of 12h.

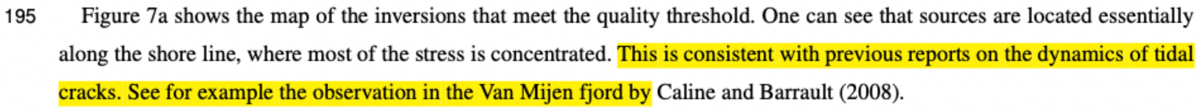


Figure 7a shows the map of the inversions that meet the quality threshold. One can see that sources are located essentially along the shore line, where most of the stress is concentrated. This is consistent with previous reports on the dynamics of tidal cracks. See for example the observation in the Van Mijen fjord by Caline and Barrault (2008).

Fig. 5 : In the absence of any collaborating geophysical data to the contrary, I would suspect that the n*24-hour peaks are binning-related artifacts.

Now that the manuscript has been modified to correlate the icequakes with tides, it appears that these peaks are actually associated to tides that repeat every ~ n*24-hour

Fig. 6 indicates that the icequakes in the 0–7 cluster family were overwhelmingly back-located to the lake ice grounding zones. This is more suggestive of tidally forced fracture (e.g., Cole, 2020). One would expect thermomechanical fracturing to occur uniformly distributed throughout the interior of the lake ice. An argument could be made for solar heating of exposed geology at the shorelines, but would require in situ temperature and solar radiance data to validate.

We agree with the reviewer, and this was also pointed out by reviewer 1. The manuscript was modified accordingly and a reference to tidal cracks was added.

Lines 122–123, 273–274 : “[S]emidiurnal tide reaches 10-20 cm, so it is likely that tides have less effect than changes in temperature….” The opposite interpretation is suggested by the data presented. The stated tidal range is 0.1–0.2 m, potentially 30–40% of the 0.45–0.6 m inverted ice thicknesses presented in Fig. 6. Given the steep bathymetry suggested by Marchenko et al. (2021), this seems to be a substantial tidal deflection relative to the ice thicknesses.

We agree with the reviewer. The modified manuscript (see above lines 134 -137 and 195-197) now states that cracks are tidal cracks.

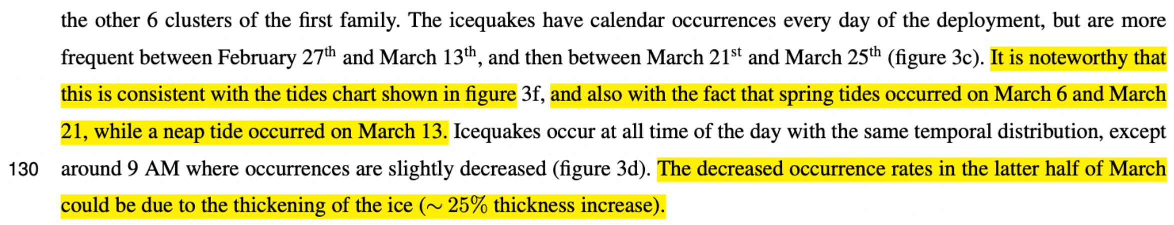
Fig. 3c shows calendar day occurrences for icequakes. The authors note that “The icequakes have calendar occurrences every day of the deployment, but are more frequent between February 27th and March 13th, and then between March 21st and March 25th” (lines 118–119). Spring tides occurred on Mar 6 and Mar 21, 2019, and a neap tide on Mar 13.

Hourly tidal data from Nylesund, 157 km away, shows tidal heights that are visually well-correlated with the icequake occurrence plots in Fig 3c (http://uhslc.soest.hawaii.edu/data/csv/fast/hourly/h823.csv) The decreased occurrence rates in the latter half of March 2019 may be due to the thickening (and, presumably, strengthening) of the lake ice (Fig. 6b).

We thank reviewer 2 for pointing towards the tides chart at Ny Alesund. With have added this chart to figure 3 (see figure 3-f) to make it comparable with figure 3c. There is a correlation with icequakes occurrences indeed.

The roughly uniform occurrence of icequakes throughout the summed days shown in Fig 3d for cluster family 0–7 could be explained by the hourly precession of high tides throughout the month. Tidal minimums during the Mar 13 neap tide occurred at 0800–0900 UTC, coincident with the 9AM (local? UTC?) decrease in icequakes noted on line 120.

This is a very good point and this is now mentioned in the manuscript:

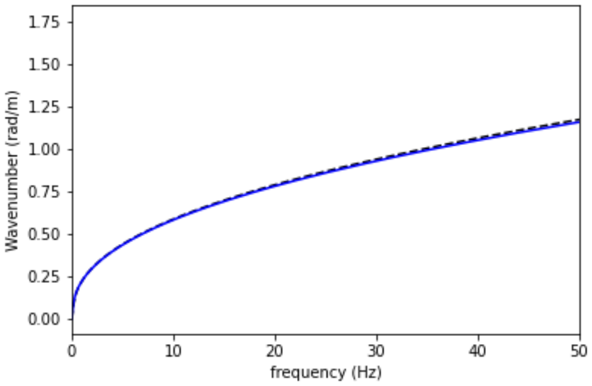


the other 6 clusters of the first family. The icequakes have calendar occurrences every day of the deployment, but are more frequent between February 27th and March 13th, and then between March 21st and March 25th (figure 3c). It is noteworthy that this is consistent with the tides chart shown in figure 3f, and also with the fact that spring tides occurred on March 6 and March 21, while a neap tide occurred on March 13. Icequakes occur at all time of the day with the same temporal distribution, except around 9 AM where occurrences are slightly decreased (figure 3d). The decreased occurrence rates in the latter half of March could be due to the thickening of the ice ($\sim$ 25% thickness increase).

Lines 150–154 : Forward modeling uses the flexural-gravity wave dispersion relation from Stein et al. (1998). This equation assumes an infinite depth water column. Vallunden Lake has a depth of no more than 10 m (Marchenko et al. 2013). Ewing and Crary (1934) provide a formulation for FG waves in shallow water. Based on a comparison of the two dispersion relations, the Stein formulation diverges from the shallow water case for frequency-thickness products less than 1 Hz m. The current study uses icequakes in the 1–50 Hz range, with a peak at 8 Hz (presumably; the authors do not explicitly state the frequency band for their inversions). Their results are likely not significantly impacted by the assumption of infinite depth. However, the regime change—and their avoidance of it—should nonetheless be acknowledged, especially given that they do acknowledge the high frequency regime change for frequency-thickness > 1000 Hz m.

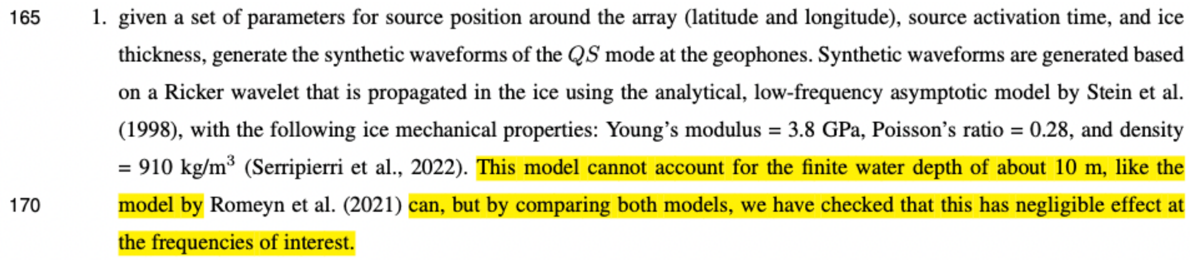
Reviewer 1 also asked to clarify this assumption. We are copying here the answer made to reviewer 1.

We assume that ignoring the finite water depth of 10 m has a negligible effect on the inverted thickness, based on a comparison between the model used in the manuscript by Stein et al. (1998) and the model by Romeyn et al. (2021). See for example the following figure. Wavenumbers are almost identical in the frequency range of interest.



Wavenumber vs frequency for the QS mode, calculated in a 60 cm-thick ice sheet floating on water. Blue solid line: model by Stein et al. (1998) based on an infinite water depth. Black dashed line: model by Romeyn et al. (2021), based on water with a 10 m depth.

We have added the following sentence, at the beginning of section 3.1 to explain this.

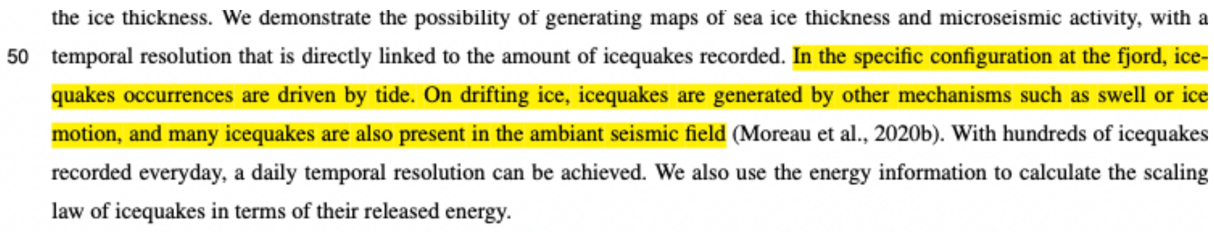


1. given a set of parameters for source position around the array (latitude and longitude), source activation time, and ice thickness, generate the synthetic waveforms of the QS mode at the geophones. Synthetic waveforms are generated based on a Ricker wavelet that is propagated in the ice using the analytical, low-frequency asymptotic model by Stein et al. (1998), with the following ice mechanical properties: Young's modulus = 3.8 GPa, Poisson's ratio = 0.28, and density = 910 kg/m^3 (Serripierri et al., 2022). This model cannot account for the finite water depth of about 10 m, like the model by Romeyn et al. (2021) can, but by comparing both models, we have checked that this has negligible effect at the frequencies of interest.

Future investigations will be made using a forward model based on the spectral element method, that accounts for finite water depth and for snow cover.

Lines 208–209, 296–298 : The authors state that their method could be adapted for near real time monitoring of ice thickness. What actual time scales are envisioned for a data product? Hourly? Daily?

It is possible that the reviewer did not have the latest version of the manuscript. The latest version mentions: "it could be possible to generate a similar map for each day, hence achieving near real-time maps of sea ice thickness evolution". But this is actually dependent on the number of icequakes recorded every day. We also recorded many icequakes on drifting pack ice (See Moreau et al. 2020b). The text was modified to emphasize this point:



the ice thickness. We demonstrate the possibility of generating maps of sea ice thickness and microseismic activity, with a temporal resolution that is directly linked to the amount of icequakes recorded. In the specific configuration at the fjord, icequakes occurrences are driven by tide. On drifting ice, icequakes are generated by other mechanisms such as swell or ice motion, and many icequakes are also present in the ambiant seismic field (Moreau et al., 2020b). With hundreds of icequakes recorded everyday, a daily temporal resolution can be achieved. We also use the energy information to calculate the scaling law of icequakes in terms of their released energy.

Line 221 : The jumps are stated to be 1 m. How was this guaranteed? Was the jumpee stepping off a 1 m platform? Was the impact onto un-groomed snow & ice, or onto a strike plate? A standing jump does not have sufficient repeatability to be classified as a "calibrated source."

We made standing jumps directly on the ice after removing the snow, hence we cannot guarantee that the height is accurate down to the centimeter, but the goal here is to study the repartition of the orders of magnitude of the icequakes. In this context, an error of a few centimeters would be negligible. We did not realize that the term “calibrated“ would be controversial. We have replaced it by “artificial.”

Line 260 : The authors mention expanding further work to include longer period ice waves, to the order of 0.1 Hz m. Such waves would absolutely interact with the lake bottom and thus necessitate the Ewing and Crary (1934) or similar formulation.

The frequencies of investigation were adapted to the dimensions of the Lake. This statement is about applying the method to drifting pack ice. We have made the sentence clearer: “Hence, on drifting pack ice, by adjusting the size of the geophones antenna…”

References

Cole, Hank M. Tidally Induced Seismicity at the Grounded Margins of the Ross Ice Shelf, Antarctica. Diss. Colorado State University, 2020.

Crary, A. P. "Seismic studies on Fletcher's ice island, Tâ□□3." Eos, Transactions American Geophysical Union 35.2 (1954): 293-300.

Ewing, Maurice, and A. P. Crary. "Propagation of elastic waves in ice. Part II." Physics 5.7 (1934): 181-184.

Marchenko, A. V., and E. G. Morozov. "Asymmetric tide in Lake Vallunden (Spitsbergen)." Nonlinear Processes in Geophysics 20.6 (2013): 935-944.

Marchenko, A. V., et al. "Ice thickening caused by freezing of tidal jet." Russian Journal of Earth Sciences 21.2 (2021): 5.

Technical Comments

Due to the revisions recommended, this is section is withheld. In general, the grammar and organization are clear and concise.