Anonymous Referee #1

Referee: General Comments

Overall, this is a good paper that requires only minor revisions. The paper documents two types of frost-related seismic activity: frost quakes and frost tremors. The methods are adequately described. The evidence from the timing of the events in relation to meteorological data and from the location of the events in relation to water and wetlands make a good case that the signals do indeed derive from the proposed freezing-related mechanisms. The recognition of this phenomenon is significant for the hazard that may pose to infrastructure and for understanding the sources of ambient seismic noise in the critical zone. I have only one major comment, regarding the use of HVSR to identify a frequency band of interest (see below), for which the explanation does not really make sense to me.

Specific Comments

Lines 117-124 : I am confused by this. Okkonen et al. (2020) Fig. 2B shows significant vertical as well as horizontal motion, and in the accompanying text they state that the signal is "depleted in body wave energy but having large-amplitude Rayleigh waves". If the signal is dominated by Rayleigh waves, shouldn't it have both horizontal and vertical motion and be elliptically polarized in a vertical plane?

Authors: In the case described in Okkonen et al. (2020) the frostquake was recorded only by single permanent OUL station, located at 14 km from the source. The source of the event appeared as a crack on the road of significant size (about 1m deep and half meter wide). The time of this event was reported by locals as the crack was formed exactly near their house. We found the record of this event on the seismogram of closest seismic OUL station (14 km from source) using this knowledge. On the same day, this station recorded huge number of impulse-like events. They appeared in OUL seismogram during this day only, when the air temperature significantly and abruptly dropped. This was unusual signal, as this station is located in a very quiet area on the bedrock. We analyzed the swarm of these impulses and found out similarity between waveforms of events from the swarm. We noticed from analysis of 3-component recordings that they mainly have horizontal polarization. Assuming that all of these impulses were produced by local sources (because they were presented only by surface waves), we suggested that the main source mechanisms of these events are vertical fracture opening. The recording of the strongest event, mentioned in Okkonen et al. (2020), had strong enough Rayleigh wave. But this is because of the relatively large distance from the source and the effect of propagation. In our pilot study in 2019-2020 as well as in the study described in the current paper, we analyse the events (tremors) with much smaller epicentral distances (less than 1000 m). Assuming that they should have the same polarization as impulses, detected in 2016, we used the HVSR as so-called "polarization filter" to detect frequency band of these events. This is possible because considered tremors look like a continuous swarm composed of events originating almost every second. Therefore, we could consider this process as continuous emission. Calculating the HVSR is working as averaging these impulses over time. Therefore, the HVSR maxima should correspond to the dominating frequency range of impulses.

Referee: From your results in this paper, it also looks like it is only the P waves that are horizontally polarized (Figure 6), and the Rayleigh waves as well as the high-frequency tremor in Figure 9 are elliptically polarized. I do agree that the change in HVSR at freezing temperatures is

significant, but it could also be explained by a change in the elastic properties of the subsurface due to ground freezing, rather than by a change in the noise source.

Authors: When we detected such HVSR behavior, the hypothesis about changing mechanical properties of soils was the first we tested. Practically, our first idea was to use the HVSR to understand changing in soils mechanical properties with time (namely, depth of the frozen layer). But when we calculated the time series of HVSR, we found significant disagreements with our original hypothesis. Firstly, the frequency band of HVSR maxima was too low. We had a soil station co-located with the seismic sensor during experiment. From this data we knew that the soil has been frozen only from ground surface down to 5 cm. In that case HVSR peak should be significantly higher (in order of 1kHz). In our case, the frequencies of 120-180 Hz would correspond to a layer of more than 1 m thickness. Moreover, the HVSR maxima in considered frequency range disappeared during about 6 hours after the air temperature became positive. The soil conditions could not be changed so fast. Before making conclusions, we checked the seismograms in the considered frequency range. These seismograms were quite similar to those we observed in 2016: a swarm of horizontally polarized impulses. This significantly supports origin of the HVSR maxima.

Referee: Instead of HVSR, or in addition to it, I would suggest plotting a spectrogram of the ambient noise over time. (This could be done with one or both of vertical and horizontal components, or an average of them.) If frost quakes and tremors are a major source of noise in this frequency band, then the same pattern should appear: The noise should occur only when the meteorological conditions are suitable, but the change will be more clearly related to the source, not the medium.

Authors: We analysed these spectrograms. But we did not detect such obvious correlation between spectrograms and air temperature. This is because of anthropogenic noise, as both sites are seismically not quiet. To find a way to reduce the effect of anthropogenic noise, we used the HVSR method, assuming the source mechanism as vertical opening and taking into account that we record seismograms in near-field area. We found correlation between air temperature and the HVSR behavior. To be sure that the frost tremors correspond to the frequency band detected by the HVSR, we tried to detect tremors in other frequency bands, but without success (they disappeared or no correlation with temperature was observed).

Referee: Technical Corrections

- The word “the” is sometimes missing. In the abstract I counted four instances: On, line 8 before “so-called,” line 10 before “relationship,” line 13 before “municipality,” and line 24 before “strongest”. The error doesn't appear to be as frequent in the rest of the manuscript, but it would be good to go through and check.

Authors: The text has been checked and corrected.

Referee: Line 26: Missing “and” before “cargo trains”.

Authors: Corrected

Referee: Line 34: Hyphenate "snow-dominated"

Authors: Corrected

Referee: Line 40 “stats” should be “starts”

Authors: Corrected

Referee: Line 80: “is” missing before “located”.

Authors: Corrected

Referee: The Figure 1 caption says “(Mention that units are in metres, X is Easting and Y is Northing)”. This looks like some editing comment that wasn’t fully implemented.

Authors: Corrected

Referee: Line 152: “moth” should be “month”

Authors: The typo has been corrected.

Referee: Line 167: “such significantly” should probably be “so significantly”.

Authors: Corrected.

Referee: Figure 11 caption: The meaning of the blue dot is repeated (and “being” is misspelled in the first instance).

Authors: Corrected.

Referee: Line 325: The comma after latitude is not needed.

Authors: Corrected

Referee: Line 362: “shacking” should be “shaking”.

Authors: Corrected

Referee: Line 366: “1-store buildings” should be “1-story buildings”.

Authors: Corrected

Referee: Line 418: “phenomenon” should be “phenomena” since it is referring to two things.

Authors: Corrected

Anonymous Referee #2

Referee: This is an interesting paper on "frost quakes and tremor" detected in Finland.

I had never heard of such signals before.

The topic is interesting both for seismologists (as a new source of seismic signals), because of the associated damage and hazard and for researchers interested in the Cryosphere.

I recommend this manuscript for publication after minor modification.

I believe that several points should be clarified or improved but that the main results are correct.

Earlier experiment during winter 2019-2020 (l115-116).

Could you describe the experimental setting and the results?

Authors: The description has been added to the text.

Referee: l115-120, you wrote that "the frequency band of 120-180 Hz was selected based on results of our earlier pilot experiment in Talvikangas during winter 2019-2020.

In that experiment we recorded three component continuous seismic data by a single station in Talvikangas equipped by broadband Trillium compact seismometer, by Nanometrics Inc. (USA).

The results of our pilot frost quake study (Okkonen et al., 2020) suggest that the seismic signal excited by fracturing in the uppermost soils would have mainly horizontal polarization, as the main fracturing mechanism in that case is vertical fracture opening."

This paragraph (l115-120) is rather confusing for several reasons.

First, I did not find any description of the 2019-2020 experiment in the paper of Okkonen et al. (2020).

Authors: The paragraph had problems with formulation. From our observations described in Okkonen et. al., 2020, we assumed that the main source mechanism of considered events were vertical opening, as we observed a crack on the road and analysed polarization of impulses in the swarm on 6.01.2016, when the air temperature abruptly dropped and frostquake was reported by locals in Talvikangas. To check this assumption, we organized a pilot experiment in 2019-2020. We installed a broadband seismometer in Talvikangas and detected a swarm of impulses, but in another frequency band (120-180 Hz). They also had horizontal polarization. The swarm was looking like a continuous signal composed of events originating almost every second. That is why we decided to use the HVSR as co-called “polarization filter” to understand behavior of these swarms. Using this approach, we found some correlation with air temperature. Based on this, we assumed that these swarms are frost tremors, but we could not study origin of them, as we had records of only single station in our pilot experiment. When we obtained the data from our experiment in 2022-2023, we checked our hypothesis, by locating sources of signals in considered frequency band. We found that locations of sources correlate with wetlands as well as with reports by local inhabitants about new cracks and noise.

The text has been corrected.

Referee: Okkonen et al. (2020) describe data recorded in 2016 with a single sensor. It does not mention tremor.

Authors: The text has been changed. See previous comment.

Referee: It also assumes that these quakes were induced by fracture opening based on direct observations of cracks on buildings and roads, not from the analysis of seismic signals.

Is this reference wrong?

Authors: This reference is not wrong, but it is not describing all the details, related to seismic data analysis, as this work aimed to explain mechanism of frostquakes using numerical simulation.

Referee: Also, the polarisation of the seismic signal depends not only on the source mechanism, but also on the type of waves (P,S, Rayleigh...) and on the source azimuth.

This is explained latter (l195), so that the discussion on the signal polarization could be removed from section 2.

Authors: That is correct, but in section 2 we explain our assumptions which have been done from direct observations and results of our pilot experiment in 2019 (HVSR). The features of the signals, which we found in 2023 are partially proving our assumptions.

Referee: The frequency band of 120-180 Hz mentioned on l115 corresponds to the tremor signal but the quakes have a lower frequency content.

Could you please clarify this part?

Authors: Because the sources of these events are of different scales. In our paper we did not aim to explain everything related to these events. We just detected, located them and estimated ground motions produced by them. We found that only events in frequency bands 2-20 Hz and 120-180 Hz have correlation with air temperature and originating during these extreme weather events.

Referee: Figure 2: the largest peak of seismicity occurred on 2016/2/10 but is not discussed in the text.

Do you know what was the source of these events? Are the signals similar to frost quakes?

Authors: They are like impulses from swarm, recorded 6.01.2016. We could not check their origin, because we had records of only single permanent OUL station. We used detector based on correlation analysis to detect them and we just can say that waveforms of these events look quite similar to thoss of events from swarm, recorded in 6.01.2016. However, these events in 2016 motivated us for more detailed instrumental study in 2022-2023, which we report in our present paper.

Referee: Figure 3b.

Nice tremor signal with a clear correlation with temperature data!

How do you interpret the lower frequency 50 Hz signal when the high-frequency tremor stopped?

Authors: We investigated the seismograms in the frequency range near 50 Hz as well, but did not find a correlation between air temperature and this maxima behavior. Probably the origin of this maxima is not related to considered phenomena.

Referee: Could you show the spectrogram of the signal for the full duration of this 2019-2010 experiment and a zoom on the time window when tremor was detected?

Could you also show a spectrogram for the 2022-2023 experiment for comparison?

Authors: We analysed these spectrograms, but they are not very informative, as both sites are noisy (urban areas). We did not find clear correlation between spectrograms and air temperature. This was one of the reasons why we used the HVSR diagrams instead of spectrograms.

Referee: Source mechanism

Did you try to estimate P wave polarity to constrain the source mechanism?

Authors: We did not analyse records in such details. The main goal of current paper is to report about a new type of seismicity we observed as well as about possible hazard, related to this seismicity. We will do detailed analysis of seismograms in our further research, using the whole dataset of our experiment.

Referee: Vertical motion should be up on all sensors for crack opening. Is it what you observed?

Authors: We did not analyse records in such details. See previous comment.

Referee: Could you also estimate magnitude (local or moment magnitude)?

Authors: In our opinion, ground velocities and accelerations are more informative for seismic hazard assessment in considered cases, as we recorede events in near-field area. In our further study, we are planning to estimate magnitudes as well as to study source mechanisms in more detail.

Referee: Temporal evolution of tremor and quakes

Did you observe tremor at both sites?

Authors: Yes (see figure 12)

Referee: Fig 13 shows the "number of seismic events": does it includes both quakes and tremors?

Authors: It means number of frost quakes. Fig. 13 caption has been corrected.

Referee: Could you show a figure with the number of events per hour for each class (tremor, quakes) and the temperature at each site?

Authors: A sub plot, that illustrates number of frost tremors per hour has been added to figure 13.

In our paper we analysed a single frost quakes episode during 6.01.2023, aiming mainly to locate events and to evaluate ground motion produced by them. As our previous study shows (Okkonen et al., 2020), the air temperature is important factor that could initiate episodes of frost quakes, but it is not the only one. Also snow depth and soil moisture content are important factors. In our next paper, which is now under preparation, we are analysing the whole winter period and the number of events not only for freezing, but also for melting periods. In the next study we take into account not only temperature variations, but also those other factors. The paper will include also detailed thermomechanical modelling. It is not possible to include everything into one single paper.

Referee: Quake detection

l190. What do you mean by "seismograms were ... stacked using beam forming algorithm"?

Could you provide a reference or describe the beamforming method you used?

Is it a simple stack (sum) or do you shift the signals in time? How is this time shift estimated?

Does it really improve the signal quality and the location accuracy compared to picking the raw signals?

Authors: We used a method described in Schweitzer et al., 2012 and the reference has been added to the text. We shifted seismograms in time, according to recommendations given there. This procedure helped to improve signal-to-noise ratio and we used these stacked seismograms only on visual inspection (detection) stage. To calculate source location, ground velocities and accelerations, we used seismograms recorded at each sensor.

Referee: Figure 6: What are the signal shown in (a): the stack for each array or individual signals? Did you filter the signals?

Same questions for Fig 8.

Authors: Figure 6 shows seismograms, stacked for each array using beamforming, mentioned above. The same is for Figure 8. There are averaged ground velocities and accelerations over the array.

Referee: Figure 7. Could you add the sensors on these figures?

Authors: Done

Referee: Tremor location

The description of the location method is a bit confusing.

Could you explain what signal you correlate? I think you correlate each sensor with the central sensor of the same array but it should be written more explicitly.

Authors: That is correct. But this was not always the central sensor. To avoid errors in detection because of low quality of records of central sensor, our algorithm randomly selects several candidates to “virtual source” and tests them. If correlation coefficients are always lower than the threshold (for all candidates to “virtual source”), then the algorithm reports no events in the interval considered. Otherwise, the seismic event is detected and the sensor with the highest correlation coefficient is selected as a “virtual source”.

Referee: The term "virtual source" is also misleading. If I understood correctly this is the central sensor of each array?

Authors: This is not always the central sensor, but those with which all other records correlate (the first record in cross-correlation procedure). We are selecting this sensor by tests. If low correlation is detected between all sensors and the central one, the algorithm selects randomly another one as a possible “virtual source” (see previous comment). The term “virtual source” is commonly used in seismic interferometry. We think that usage of this term is justified in our case, as we are using interferometric approach too. We transform seismograms in such a way that after this transformation they look like impulse response of the source, located in point with the “virtual source” cooordinates.

Referee: Did you also try to use this method to locate frost quakes?

Authors: We tried, but in our study we preferred to use visual inspection of seismograms and a manual picking of arrivals, as a more reliable method, because we deal with unique data showing quite new phenomenon.