Review of tc-2020-195 "Modal sensitivity of rock glaciers to elastic changes from spectral seismic noise monitoring and modeling » by Guillemot et al.

The study presents a new methodology that uses the resonant frequency of rock glaciers extracted from continuous ambient noise records to monitor the seasonal and interannual changes in the structure of the vibrating glacier. The seismic modal analysis is coupled to a poroelastic model of a 2D porous medium representing the rock glacier, supported by other geophysical measurements. The results indicate the thawing-freezing cycle effects on the resonance of the glacier. This comprehensive study highlights well how the structural changes of rock glaciers can be tracked and monitored with passive seismology, when other geophysical methods are time-consuming and hardly repeatable at such time resolution.

Major comments:

(1) I miss somewhere an explanation of the origin of the ambient seismic noise (at frequency > 1Hz). Many studies agree to say that it takes its origin in fluvial processes when the water flow from ice melting in spring/summer creates transient forces on the Earth at the glacier base or on the surrounding ice in englacial channels. The noise recorded in winter may come from other sources in the area. Many studies on ambient noise suggest that a change in the noise sources could lead to a change in the noise spectrum. This renders monitoring studies difficult, especially for ambient noise correlation method. Here you use a modal analysis which should be less sensitive to noise source changes. But still, there remains an open question: are the seasonal variations of the resonant frequencies influenced by changes in the noise or actual structural changes ? I am quite concerned about the abrupt resonant frequency shift you observe at the onset of the melting.
Personally, I am absolutely confident in the interpretation of actual changes in elastic properties of the structure underneath the sensor. However, this question should be raised and discussed.

(2) As a proof of concept and to approve the interpretation of the results, I suggest to try to actually reproduce the seasonal variations of the resonant frequencies with the poroelastic model (as stated in the conclusion Line 542 but wrong). This would strengthen the discussion and the capability of the method. The interpretation is finally based on Fig 14 which represents measured resonant frequencies as a function of the temperature of the ground surface, while this temperature does not tell the whole story on what is happening at depth. So having a hint on the evolution of the active layer and the rigidity of the structure thanks to the best-fitting model output would definitely strengthen your conclusions. In addition, this figure would be very great to track the interannual changes. Finally, I miss a figure showing the temperature time-series (in this additional « proof of concept » figure, or in Fig 3 for example). This would ease the reading of Fig 14 and also highlight melting seasons versus winter.

(3) Sometimes, I think that the structure of the sentences is not smooth enough and lead to confusing statements in English. I have listed some in the comments below which need to be reformulate. In general you should try to keep the sentences short.

Other comments:

L48: in depth -> at depth ?

L57-59: References are needed here for both methods (ambient noise vs microseismicity). I understand this is the output of the study by Guillemot et al 2020 as detailed in the following sentence, but other studies have also proven this in glaciated environment.

L89: I suggest to specify « France » after the « Laurichard catchment »

Figure 1d: Please indicate the flow direction with an arrow.

Section 2.1.3: How were the seismometers maintained (leveling, orientation) ? Are they three-component sensors ?
You should also specify somewhere here the glacier thickness beneath the stations (ice thickness was also not specified in the previous section)

L137: « The long periods » -> the longest periods ?

L139: What is the distance between these two stations ?

L140: It could be interesting to have the results for the seismic measurements at the other stations in the appendix.

L144: I suggest to specify « Switzerland » after « Wallis Alps »

L157: Please specify here if the geophones are one or 3 components. Are they deployed directly on the ice ? Were they maintained ?

L169-171: This is the right place to be more specific for glacier microseismicity and glaciological applications (location of crevasses, basal interface and asperities, water channels) with appropriate referencing.
For ambient noise studies on glaciers, you could refer to the studies of Preiswerk and Walter 2018, Sergeant et al 2020 (for the imaging part) and Lindner et al 2018 (for the monitoring part)

Preiswerk, L. E., & Walter, F. (2018). High−Frequency (> 2 Hz) Ambient Seismic Noise on High−Melt Glaciers: Green's Function Estimation and Source Characterization. *Journal of Geophysical Research: Earth Surface*, *123*(8), 1667-1681.
Sergeant, Amandine, et al. "On the Green's function emergence from interferometry of seismic wave fields generated in high-melt glaciers: implications for passive imaging and monitoring." *The Cryosphere* 14.3 (2020): 1139-1171.
Lindner, F., Weemstra, C., Walter, F., & Hadziioannou, C. (2018). Towards monitoring the englacial fracture state using virtual-reflector seismology. *Geophysical Journal International*, *214*(2), 825-844.

L171: add « to » before monitor.

L174: « on it » -> « on site »

L176: « tracking dynamic parameters » -> « tracking the evolution of »

L180: « The seismic noise averaging properties » What does this refer to ?

L182: « The PSD is simply defined by averaging the intensity of the FFT » You average it by what ? The (inverse of) time of integration ? I do not see any averaging in the proposed equation.

L185. Preiswerk et al 2019 also investigated the resonant glaciers with different geometries which imply 1D, 2D and 3D resonances through HVSR, time-frequency dependent polarization and modal analysis. This study should be cited, here maybe or elsewhere.

Preiswerk, L. E., Michel, C., Walter, F., & Fäh, D. (2019). Effects of geometry on the seismic wavefield of Alpine glaciers. *Annals of Glaciology*, *60*(79), 112-124.

L191: « in absence of geometrical changes » maybe specify here « (i.e. ablation/accumulation) »

L191: missing comma after Young's modulus.

L195: Which component ?

L200-204: The picking method is not clearly described. Additionally, please specify why you expect to have frequency peaks above 10 Hz on the glacier ? Is it related to the glacier morphology and more specifically to the ice thickness ?

Figure 2d: It seems that you still see the 23 Hz anthropogenic peak at station C05 (as expected) but it is not obvious because of the normalization. Maybe indicate this in the caption.

L212: « The results of PSD » -> « The spectrograms of PSDs »

L218: « no subglacial resonating water-filled cavities was known on the site ». I suspect you refer to moulins which extend from the glacier surface to (probably) the glacier base (this is what it sounds as you cite Röösli et al 2016) ? If yes, the part of the sentence Line 2018 should me modified to point out to moulins. If no, how do you know that there is absolutely no channels in the glacier ?

L225: « resonating structure of the sensor » -> « beneath the sensor » ? Do you refer to the glacier or the shelter around the sensor ?

Section 3.2: see major comment: I miss somewhere an explanation of the origin of the ambient seismic noise (at frequency > 1Hz). Many studies agree to say that it takes its origin in fluvial processes when the water flow from ice melting in spring/summer creates transient forces on the Earth at the glacier base or on the surrounding ice in englacial channels.
You say later (Line 224) that water filling of the resonating structure could be responsible for changes in PSD. Then you say Line 229 that no water was present in the sensor settlement. In fact, the presence of meltwater inside the glacier does affect the seismic noise with strong noise generated in spring/summer and little englacial noise in winter. The noise recorded in winter may come from other sources in the area. This should appear on non-normalized spectrograms. In this case, there remains an open question on the cause of the resonating frequency shift from winter to summer. Is it related to source effects or structural changes ? I am confident in the interpretation of actual changes in elastic properties of the structure underneath the sensor. However, this question should be raised at the end of this section or in the discussion.

Figures 3/4: The blue boxes indicating the melting season are present only for spring. On what observations is it based on ? Generally in Alpine glaciers, the melting seasons spread from spring (April/May) to the end of summer (september/october).This would also be consistent with the seasonal cycle you observe for the seismic dominant frequency.
Also related to this comment, I would say in Line 233: « a sudden drop of frequency occurs at the time when melting processes [start to occur in spring and stay stable to lower frequency over the course of the summer]. »

Figures 3-4: I would here display the time series of air or ground temperature + periods of snow cover. This would ease the interpretation in the discussion and Fig 14

Figure 4: Nice observation !

Line 247: I would add « at [spring and] summer time »

Line 261: Do you have a reference for the software ?

Figures 5-7: I suggest to move these figures to the appendix section as I think that the study should be focused on the modal analys/modeling methodology.

Line 391: « appling » -> applying

Line 446: « as shown in Fig 13 for Laurichard and not presented here but similar for Gugla »
Results for both glaciers are presented in Fig 13, so you should revise this sentence.

Line 449: Section number missing (and elsewhere)

Line 450: « and compare them to the maximum values of the observed ones ». You should indicate here that data are indicated by squares and rephrase this as the text alone is confusing. Say that you represent here the maximum and minimum bounds of the resonance frequencies you measure for each mode, for the two years - if I understand correctly.

Line 452-453: « Resonance frequencies of these modes match the freq band of measurements below 50 Hz, and generally decrease with thawing ». There is no relation between the two parts of this sentence so you should split it in two. The first part is a bit redundant with the previous sentence of the text. In general I think that section 4.5 could be better rewritten and reorganized with clearer description of the glacier seismic behavior.

Line 454: I would add at the end after « for all cases » « i.e. Gugla and Laurichard »

Line 455: You should remind here that C05 is towards the glacier tongue (on thinner ice H=8m according to your velocity model) and C00 is more upstream (H=14 m).

Figure 13: You could add arrows: one which points toward higher depths of thawing indicating summer, one which points toward 0 indicating winter

Line 465: I would replace « melting periods » by « at the onset of the melting period in spring » (summer is also a melting period).

Line 471: « observed seasonal freq variations » -> observed freq seasonal variations

Lines 487-488: « in 2019 … frequency is lower than is 2018 » Give values !!

Line 488: « In addition to an earlier snow cover period in 2019 than 2018 … » I would reformulate. Did snow falls started earlier in 2019 or was the period for snow cover shifted earlier in time ?
« frozen » -> « refrozen » ?

Lines 475-489: I think this paragraph could be improved with some reorganization. You should highlight your conclusion which is that, on average, resonance frequencies are more sensitive to the intensity of internal thawing (which is influenced by …) than to the air temperature as …
Also you use both the present and the past to describe the observations. You should homogenize this.
Could you explain those differences with your model ? Can different level of porosity and depth of thawing mimic different intensity of thawing ? It would be very great to have a figure showing the time series of the observed resonance frequencies with the model results for different states of thawing.

Lines 489-498: I suggest to remove this paragraph from the discussion which is focused on the thawing-freezing cycle.

Line 499: I would remove « non-linear ».

Line 500: « over the year » -> along the year

Line 501: I would remove « dry » as we do not know if you are referring to the air or the rock glacier.

Lines 521-522: « for ambient noise correlation method, the theoretical relative velocity change of the Rayleigh wave is computed by dispersion curve difference using the Geopsy package» -> I would say « for … corr method, we compute the dispersion curves of the Rayleigh wave using the Geopsy software. The theoretical relative velocity changes are computed by measuring the differences of the dispersion curve with the reference one at each frequency. »

Figure 15: For the modal analysis, you say « first mode » while everywhere in the text you refer to the fundamental mode. This could be confusing. You should specify the resonance frequency, and also in the main text.

Line 538: I would say « continuous seismic noise measurements »

Line 539: This is minor but I would say something like « These freq show seasonal variations that are to be related with changes in elastic properties of the structure underneath the recording sensor, due to freeze-thawing effects ».

Line 541: « which fit well the recorded frequencies » I would specify here or next sentence on what the resonance freq depend in the poroelastic model. Basically the take-home message I keep from your analysis is that the freq depend on the maximum depth of thawing in a porous medium.

Line 542: « we have reproduced the observed seasonal variations » This is a strong statement, you did not reproduced the seasonal cycle exactly but only reproduce the maximum freq in winter due to maximum freezing and minimum freq in summer due to maximum thawing. See my major comment.

Line 551: « insight to other deeper processes » -> into other processes at greater depth