Manuscript title: Hanging glacier monitoring with icequake repeaters and seismic coda wave interferometry: a case study of the Eiger hanging glacier

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Response to Reviewer 1

General comments

This article proposes a seismological study of a hanging glacier in Swiss Alps, which has been instrumented during five months in 2016. The authors recorded seismic data and used sophisticated methods to extract a lot of information from icequakes signals. Micro-seismicity analysis and coda wave interferometry have been used by aiming at evaluating the temporal evolution of seismic indicators, such icequakes rate, relative seismic velocity and attenuation.

A major break-off event occurred at the end of the monitoring period, inviting the identification of precursors before the event for improving early warning systems.

Although the technical challenge of seismic instrumentation, the main interest of the study lies in the investigation of physical processes in the subsurface of a hanging glacier, as a complementary method to forecasting technology focusing only the surface.

I found that some results are not always very convincing (eg, back-azimuth from signal polarization) or some interpretations are rather speculative (basal slip?).

Our response: We thank the Reviewer for this detailed and careful review. We performed some additional analysis to verify our results and to address the Reviewer's comments. We will also change the wording and rephrase our interpretations to make them less speculative following Reviewer's recommendations. We provide our detailed responses to each Reviewer's comment below. The Reviewer's comments are marked in blue, our responses in black, and parts of the manuscript are marked in *italic*.

I suggest several edits.

Specific comments

1) "repeating icequakes" ?

The term "repeating icequakes" or "repeaters" is present in many places in the manuscript, starting from the title. However, I don't think that this term is correct in this context, and I think it can be misleading.

Most "repeating icequakes" on glaciers have been detected at the base of glaciers or ice streams (see references on l36-38). These events have both highly similar waveforms and quasi-periodic recurrence times. This suggests that they are associated with the repeating rupture of asperities surrounded by aseismic slip. Repeating earthquakes are also defined as events having exactly the same rupture area, or at least an overlap of at least 50%.

See Uchida and Bürgmann (2019) for a review on repeaters in different contexts (faults, glaciers, landslides...).

In contrast, the events described in this study have similar waveforms but do not show any regularity in time. They have been detected using template matching with a correlation threshold of 0.5, while a threshold of 0.9 is generally used to define "repeaters".

This method thus groups together events that have similar waveforms in the frequency range 10-40 Hz. This implies that events in the same cluster are likely separated by distances much smaller than this wavelength of about 65 m, but likely much larger than their rupture length. There is no information on this study about the icequake magnitudes, so we cannot have an idea on the rupture length. The absence of regularity in time also suggests that icequake activity is not associated with basal slip, but rather by crevasse opening.

I thus suggest to remove everywhere the term "repeating" or "repeaters" or to replace it by "doublets", "multiplets" or "clusters", meaning events with similar waveforms.

Our response: We thank the Reviewer for this comment and pointing out this inaccuracy of our manuscript. We agree that with the Reviewer that our method groups together icequakes that have similar waveforms, although due to the use low cross-correlations threshold of 0.5 in the template matching, those events are “doublets” rather than “repeaters”. We will change the title of the paper to: “Hanging glacier monitoring with icequake doublets and seismic coda wave interferometry: a case study of the Eiger hanging glacier”, and replace the term “repeaters” with “doublets” in the manuscript. We also thank the Reviewer for mentioning the useful reference, we will add it to the manuscript. Also, we discuss the source separation between the two icequake doublets in below.

L90 : "*The repeating events imply sources in close proximity with the same source mechanism, resulting in highly similar waveforms (Poupinet et al., 1984)"*I don't agree with this statement, such events are defined as "doublets" or "multiplets" (Poupinet et al., 1984).

In contrast, "Ideal repeaters represent two or more events that have exactly the same fault area and slip and thus produce the same seismic signal or waveform. " (Uchida and Burgman, 2019).

Our response: As stated before, we thank the Reviewer for pointing out this inaccuracy in our manuscript. We will change the phrase to:

“Repeaters are two or more events that have exactly the same fault area and slip producing the same waveform with a threshold >0.9 (Uchida and Burgman, 2019). In our analysis, we

first define templates by searching for icequake repeaters with RedPy (cross-correlation coefficient >0.9), and then we extend the analysis to icequake doublets through template matching (cross-correlations coefficient >0.5). Doublets are closely-spaced events, with almost identical source mechanism, resulting in similar waveforms_(Poupinet et al., 1984). Repeaters are two or more events that have exactly the same fault area and slip producing the same waveform with a threshold >0.9 (Uchida and Burgman, 2019).”

2) Thermal regime and deformation mechanism

Eiger hanging glacier is a polythermal glacier but I don't understand which part of the base is cold.

- L66: "The Eiger hanging glacier is polythermal […], except the base of the frontal part which is cold (entirely frozen to the bed) (Lüthi and Funk, 1997)"

- L164: " […] the origin of most clusters either from the back of the glacier where a large crevasse is visible and where glacier is not frozen to the bed"

These two sentences suggests that the front is cold, while the back is not frozen, that is a bit surprising. I don't understand German, so the reference (Lüthi and Funk, 1997) does not help me.

Could you please clarify, and possibly indicate the transition between cold and temperate basal ice on a map?

How do you know the basal temperature, from boreholes to the base of the glacier ?

Could you also highlight the location of the crevasse mentioned on L164 on a map ?

Our response: The front of the glacier Eiger hanging glacier is cold, or at least it used to be in 1993. Unfortunately, the only study that performed measurements on the Eiger hanging glacier dates back to 1997 (Lüthi and Funk, 1997) and the results of this study were only published in German. A more recent study by Magreth et al. (2017) presents some of the results of Lüthi and Funk, 1997 in English.

In a field campaign lasting several days in the spring of 1993, Lüthi and Funk determined the thickness of the glacier by using a ground penetrating radar along several longitudinal and transverse profiles. In addition, seven boreholes were drilled in the glacier up to 70 m with hot-water drilling. The temperature of the glacier was determined using thermistors installed in the boreholes. Finally, 15 stakes were drilled into the ice as reference points and their position was measured several times with interval of three weeks to determine the flow velocity on the surface. Based on those measurements and using the finite element method, Lüthi and Funk provided a glacier model to determine the flow lines of the ice as well as the temperature and stress distribution in the hanging glacier (Figure R1).

Their results show that coldest area is on the glacier bed close to the unstable front. This may be surprising at first, but it might be explained by the glacier location. The shady location of the glacier front ensures low temperature and the ice cools down from the front. The rock underneath is often snow-free and transfers the cold to the glacier bed. As a results, the ice in the glacier front is frozen to the ground, which contributes significantly to the stability of the glacier.

We will add Figure R1 and the above explanations to the Appendix.

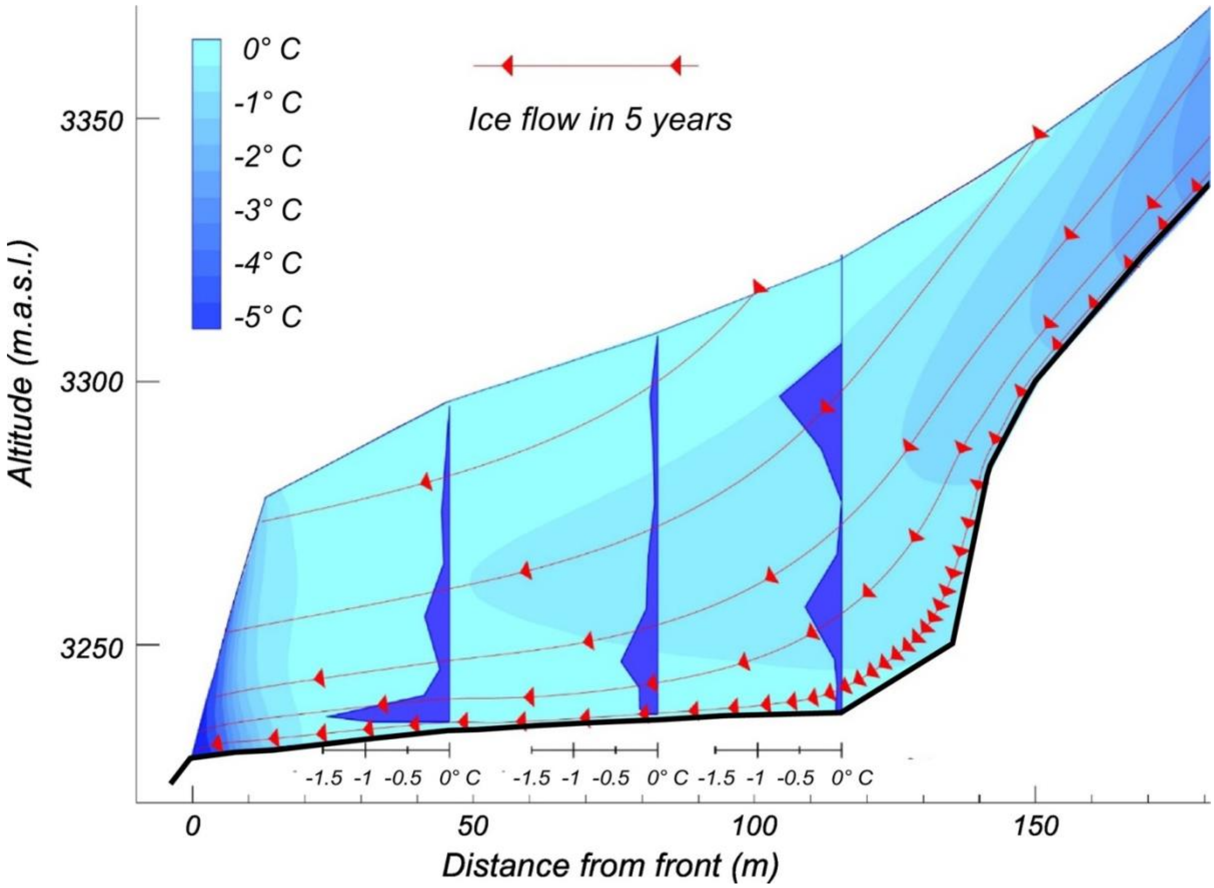

Figure R1: 2D section of Eiger hanging glacier. The cold glacier front (frozen to the glacier bed) is shown on the left side. This ice flow and temperature model was obtained through the finite element method. Englacial ice temperatures measured in three boreholes are also shown (reprinted with a permission from Margreth et al., 2017, the original can be found in Luthi and Funk, 1997).

We will mark the crevasse in Figure 1 and B1, and B2.

3) Signal polarization and back-azimuth analysis

I am not totally convinced by the polarization analysis.

Could you illustrate the method by adding a figure showing a seismogram with arrival times of the different waves, and back-azimuth and linearity as a function of time?

In several places you write that there is a 180° ambiguity in the estimated back-azimuth. I don't understand why? Using the method of Vidale (BSSA, 1986), there is no ambiguity if the source is at depth.

Furthermore, you use a sliding time window of 0.05s to estimate the signal polarization, but I suspect that this time window is too large to separate P, S and surface waves. For illustrating, Figure 1a suggests that seismic stations are located at about 50 m away from the crevasse. Assuming Vp=3600 m/s and Vs=1800 m/s, this gives a time delay of 0.014s between P and S arrival times. There are thus likely both P, S and surface waves mixed in the same time window, with different polarizations. Also, there is a very strong coda, starting just after the first arrival (Fig. A5B), with waves coming from different directions.

Moreover, why don't you also estimate the dip angle of P waves (corrected from free surface effect), in order to give an idea of the icequake depth?

L333: "The complex covariance matrix is formed over 0.05 s window of data to extract polarized seismic arrivals."

Can you specify "polarized"? Do you mean "linearly polarized"? What is the threshold you use for the linearity coefficient?

<u>Our response:</u> We thank the reviewer for these suggestions. We updated our polarization analysis and we follow exactly the steps presented by Vidale et al., 1986:

1) We first calculate the covariance matrix and the we perform a singular value decomposition.
2) The eigenvector (x_0,y_0,z_0) associated with the largest eigenvalue λ_1 points in the direction of the largest amount of polarization. However, the phase in the complex plane of the eigenvectors is initially arbitrary.
1) The eigenvector (x_0,y_0,z_0) is normalized to have length 1.
2) Then, we look for an angle α that maximizes the real component of the eigenvector associated with the largest eigenvalue. The angle α can be found by rotating the eigenvector by 0°to 180° in the complex plane. This rotation may be found by searching over α= 0° to 180° to maximize X, where X:

$$X = \sqrt{(\mathrm{Re}(x_0 \mathrm{cis}\alpha))^2 + (\mathrm{Re}(y_0 \mathrm{cis}\alpha))^2 + (\mathrm{Re}(z_0 \mathrm{cis}\alpha))^2} \quad \text{(Eq. 1)}$$

Where: Re(x) is the real part of x and $\mathrm{cis}\alpha = \cos\alpha + i\sin\alpha$
3) The (x_0,y_0,z_0) is rotated by the angle alpha.
4) We then calculate the elliptical component of polarization (P_e) as a ratio of the imaginary part of the eigenvector to the real part of the eigenvector. We represent linearity as P_l=1-P_e:

$$P_l = 1 - P_e = 1 - \frac{\sqrt{1-X^2}}{X} \qquad \text{(Eq. 2)}$$

5) The eigenvectors that correspond to the intermediate eigenvalue λ_2 and smallest eigenvalue λ_3 point in the directions of the intermediate and least amount of polarization, respectively. We use them to find the strength of the polarization signal P_S:

$$P_s = 1 - \frac{\lambda_2 + \lambda_3}{\lambda_1} \qquad \text{(Eq. 3)}$$

6) We determine the backazimuth of maximum polarization as (clockwise from the North in the range from 0° to 180°):

$$\phi = \frac{\pi}{2} + \arctan\frac{\mathrm{Re}(y_0)}{\mathrm{Re}(\mathrm{x}_0)} \qquad \text{(Eq. 4)}$$

7) And the dip of the direction of maximum polarization (clockwise from the vertical direction in the range from 0° to 180):

$$\delta = \frac{\pi}{2} + \arctan\frac{\mathrm{Re}(z_0)}{\sqrt{\mathrm{Re}(\mathrm{x}_0)^2 + \mathrm{Re}(\mathrm{y}_0)^2}} \qquad \text{(Eq. 5)}$$

Regarding the 180° ambiguity, Vidale, 1986, also mentions it:

"The polarization vector is ambiguous in that the vector (x, y, z) represents the same polarization state as the vector (-x, -y, -z). In this paper, the strike and dip defined in equations (6) and (7) range from -90° to 90°, where 0° strike and dip represents a vector which points horizontally in the direction back to the epicenter. The strikes in the range -180° to -90° and in the range 90° to 180° do not appear because of this ambiguity."

Regarding the duration of the sliding time window: We need to ensure a full rank covariance matrix to perform a singular value decomposition, meaning that the minimum duration of the sliding time windows should be 3 samples. The data we use is sampled at 100 Hz, therefore the minimum sliding time window duration is 0.03s. We initially decided to choose a longer time window (0.05s) to provide a better estimate of the covariance matrix, although we agree that such window duration potentially results in inclusion of two (or more) separate events. Therefore, we updated the length of the time window used for the polarization analysis and recalculated the results. Also, we perform the polarization analysis in the frequency band of (10-40) Hz (initially we did it on the raw data).

We thank the Reviewer for pointing out the time difference in individual arrivals of different seismic phase (i.e., P- and S-waves, Rayleigh waves). The frequency sampling of 100 Hz might be insufficient to distinguish relatively in between the arrivals of P and S waves. We will add the following sentence to the manuscript:

"The low frequency sampling (Fs=100Hz) might further complicate the polarization analysis since, the P and S wave arrivals might be separated by less than 0.3 s (e.g., assuming distance to the glacier front 50 m, Vp=3600 m/s and Vs=1800 m/s, this gives a time delay of 0.014s between P and S arrival times, and 0.017 s between P and Rayleigh waves, and 0.004s between

the S and Rayleigh waves). It is though possible that certain sliding time windows might mix P-, S-, and surface waves.”

We also estimate the dip as indicated in 7) although the distinct geometry of the glacier bed (Figure R2) complicates the interpretation of the dip values. We refrain from estimating the P-wave dip angle because the near-surface velocity profile of the glacier is poorly constrained. Estimating the P-wave dip angle requires knowledge of the velocity gradient, which we cannot provide at this moment. In contract to ablation zones where an equivalent technique has been applied (Helmstetter et al., 2015) our glacier’s near surface is characterized by snow/firn compaction and thus highly depth dependent.

Please find below the figure showing seismic waveforms recorded over Z, N, and E components, linearity, the strength of the polarization, estimated backazimuth, and dip as a function of time.

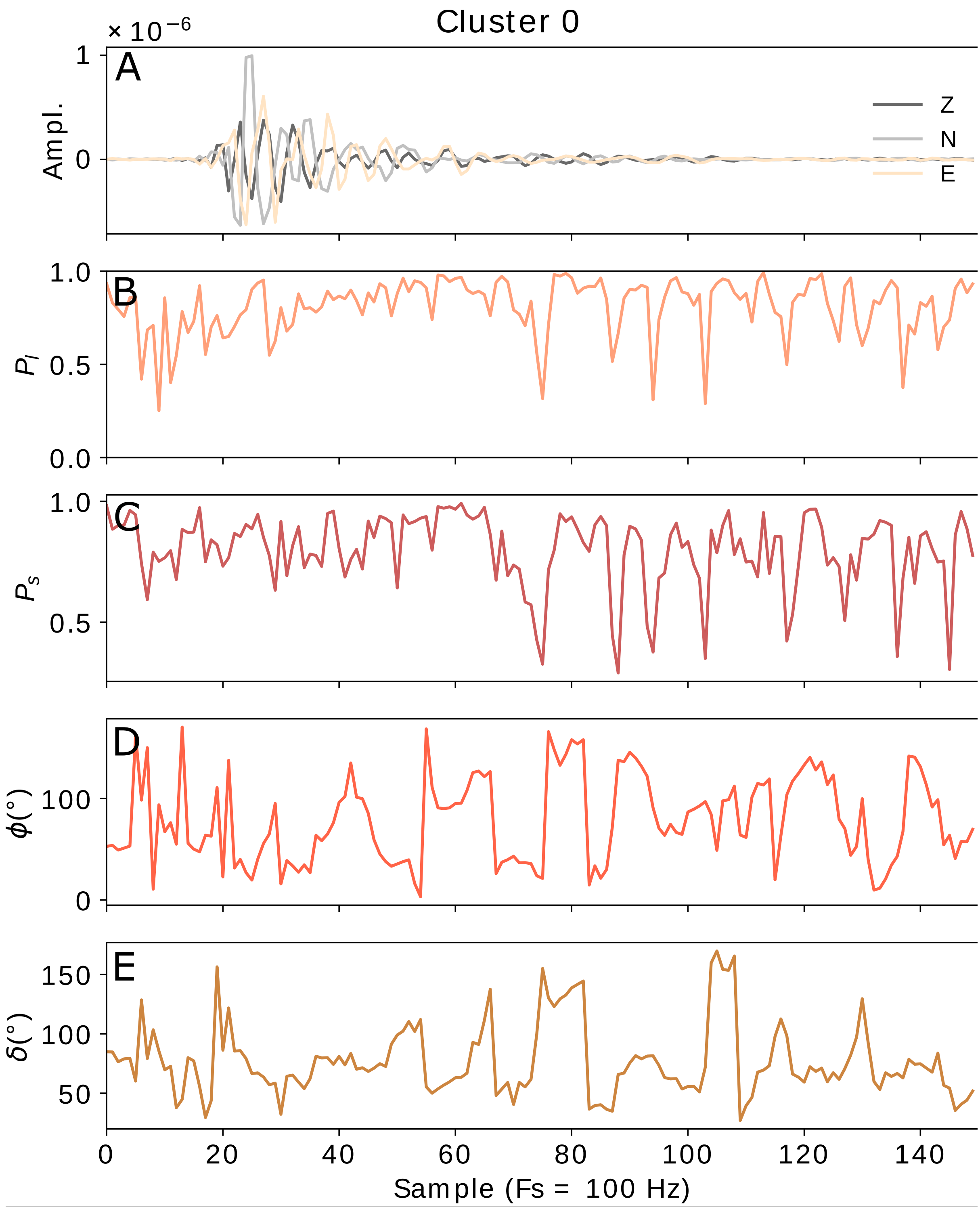

Figure R2: Polarization analysis for cluster 0. A. Waveforms recorded over Z, N, and E, component. B. linearity, C. the strength of the polarization, D. estimated backazimuth, and E. dip as a function of time.

To limit the influence of the coda waves and different modes of Rayleigh waves that might also result in linear polarization (Vidale et al., 1986), we limit the polarization analysis to the time window containing the first arrivals, between 0.05s and 0.25s from the beginning of the event (5 and 25 samples). We then choose the backazimuth value associated with the highest linear polarization and the polarization strength >0.9. See the example below:

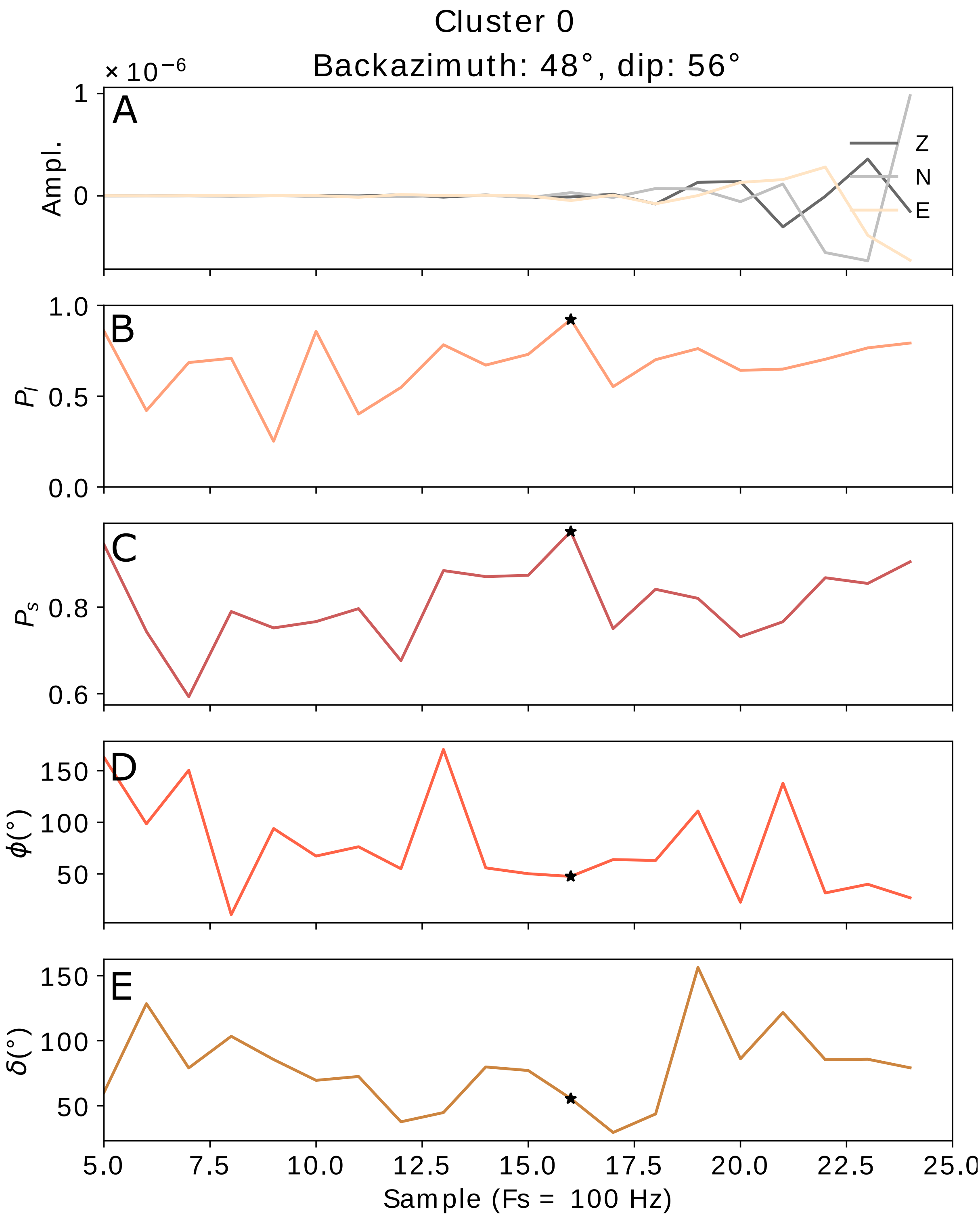

Figure R3: Polarization analysis for cluster 0 (limited to the time window containing the first arrivals). A. Waveforms recorded over Z, N, and E, component. B. linearity, C. the strength of the polarization, D. estimated backazimuth, and E. dip as a function of time. The black star marks the sample that corresponds to the highest linear polarization and the polarization strength >0.9 in the analysed time window. The estimated backazimuth and dip values are written at the top of the figure.

Finally, following a suggestion from the Reviewer 2, we perform a beamforming analysis to resolve 180° ambiguity in the backazimuth estimates. Since the beamforming analysis is based on four stations it potentially yields more robust results compared to the single-station polarization analysis. Also, the pre-event noise visible in Figure R2 have a strong polarization which raises a question on the reliability of the polarization analysis. In the revised manuscript, we will leverage the results of the two techniques to provide the most robust estimates of the backazimuth direction.

Also, following a comment from the Reviewer 2, we will calculate the final backazimuth values as a median over four frequency bands: (10-40), (10-20), (20-30), (30-40) Hz to improve the estimations of the backazimuth values more robust and to provide an uncertainty of these values (taken as a standard deviation of the measured backazimuth values). Please see the response to the Reviewer 2 for more details.

Finally, we will change the phrase to: "*The complex covariance matrix is formed over 0.03 s window of data to extract linearly polarized seismic arrivals.*" And we will add the above analysis and explanation to the appendix.

4) Icequakes location and source mechanism

L260: " The tendency of icequakes to form clusters of thousands of events and high waveform similarities (Figure 2C) all suggest repeated source (e.g., shear faulting), rather than irreversible fracturing process."

I don't agree with this statement, I don't think that these observations allow you to distinguish basal slip from fracturing processes.

Similar clusters, with thousands of events, high waveform similarities and also sensitive to melt water, have been detected on Bench Glacier (Alaska) and on Argentière Glacier (Mont-Blanc massif) and were associated with crevasse opening (Mikesell et al., 2012; Helmstetter Moreau et al, JGR 2015).

What do you mean by shear faulting ? Is that located at the base of the glacier or on the edges?

Were the fractures that appeared before the break-off mainly opening, or could you detect a shear displacement on the cameras ?

It is also inconsistent with the sentence L.265 "the cluster origin from the unstable glacier front due to crevasse opening".

Our response: We thank the Reviewer for those comments. We agree that our observations do not allows us to distinguish between basal slip and fracturing processes. We will remove this sentence from the manuscript. We will acknowledge in the manuscript that we do not have enough information to reliably determine the icequake doublets' source mechanism.

We will change the section "Repeating icequake interpretation" to "Icequake doublet interpretation" admitting that our observations do not allow us to reliably interpret the icequake mechanism behind the detected doublets:

"*Icequakes can arise from surface crevassing, hydraulic fracturing, opening and closing of tensile faults, and glacier stick-slip movement (Podolskiy and Walter (2016)). We detect ~10 times more repeating icequakes during the melt season, which indicates an influence of meltwater and subglacial water pressure on their activity. The tendency of icequakes to form clusters of thousands of events, high waveform similarities (Figure 2C), and sensitivity to meltwater has been associated with shear faulting at the glacier's bed (Gräff and Walter, 2021) and crevasse opening (Mikesell et al., 2012, Helmstetter et al., 2015). The lack of regularity in interevent time might suggest a crevasse opening rather than a stick slip movement, although the presented observations do not allow us to reliably determine icequake doublets' source mechanism. Using the threshold of 0.5 in the template detection with a single station provides us with a comprehensive catalog that we need for coda wave measurements. However, it makes the interpretation of individual icequake detections more uncertain. To resolve the origin and the source mechanism of the repeaters, an enhanced sensor coverage would be needed that could be obtained with, for example, a distributed-acoustic sensing (DAS) system deployed at the glacier surface (Walter et al., 2020). Located icequake doublets originating from the glacier bed would allow to monitor changes at the glacier-bed interface.*"

The photo camera seems to show mostly shows fracture openings, although due to the location of the camera on bedrock next to the glacier a shear displacement could be difficult to observe (Figure R4).

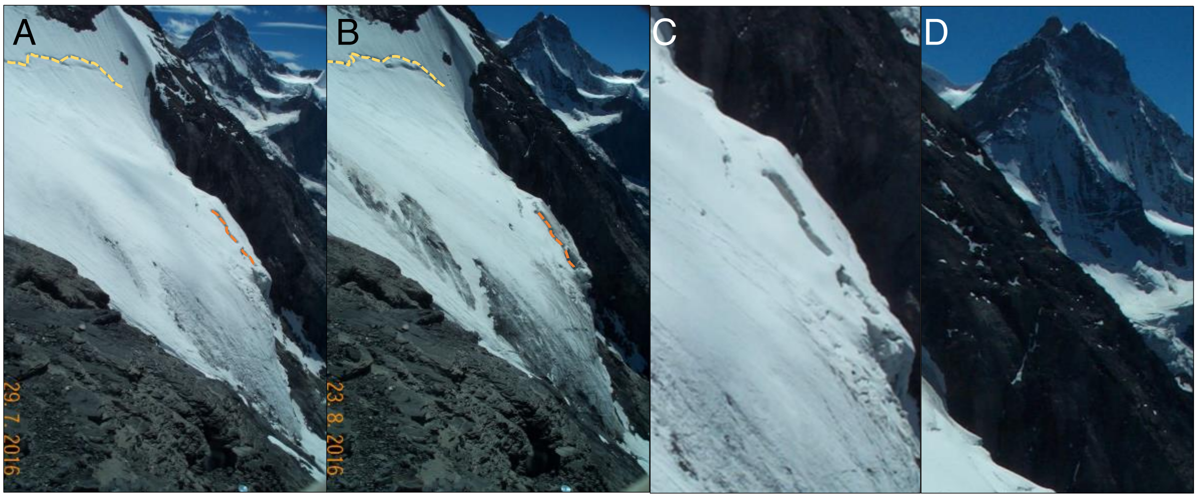

Figure R4: Lateral view of the Eiger hanging glacier from an automatic camera photographing the unstable ice mass on A. July 26, 2016; B. August 23, 2016 (<2 days before the main-break-off event). The crevasse located in the back of the glacier is marked in the yellow dashed line and the orange dashed line marks the unstable lamella. Zoom on the unstable lamella on C. July 26, 2016; D. August 23, 2016.

5) Coda wave interferometry

You estimated phase time differences between individual signals and a stacked signal (section 3.2).

Assuming that all events of a cluster have exactly the same location, you interpret these variations only due to changes in seismic waves velocities.

However, the relatively small correlation threshold and low frequency content means that the cluster size could be of several tens of meters.

Is it possible to interpret the same observations by a migration of icequake locations rather than a change in seismic wave velocity? Could this interpretation be consistent with observations of crevasse propagation?

- L391: "Assuming that the position of sources is stable over the monitoring period, changes in station position […]"

In this sense, you should also discuss uncertainties associated with possible icequake migration inside the cluster size, which are likely more important than uncertainties associated with station position.

Our response: We thank the reviewer for pointing out this uncertainty in our analysis. Indeed, changes in the coda waves can be caused by the changes in the medium velocity, source position, and scatterer position. Snieder et al., 2002 and Singh et al., 2019 showed that we can distinguish between the medium velocity and source position perturbations and CWI allows an independent estimation of those two perturbations.

This is because these two attributes can be observed independently: velocity perturbation is related to the consistent phase information along the waveforms, whereas the source separation can be retrieved from the variance of inconsistent phase perturbations and hence from the maximum value of the cross-correlation value (Singh et al., 2019). When the icequake positions change from the original unperturbed location to a new perturbed location, some of the wave paths become longer and some shorter, and thus, the contribution from some wave trajectories arrives early and some later.

The change in arrival times summed over all wave trajectories is approximately zero, but the variance of the changes in arrival times increases if the source location moves further (Snieder and Vrijlandt, 2005). The travel time variance provides an estimate for the displacement of the icequake location over time. Travel time variance can be obtained from the maximum cross-correlation coefficient between sliding time windows of the coda of the two waveforms, where each window gives a separate estimate scattered around a mean value (Snieder et al., 2002).

Following Snieder et al., 2002 and Singh et al., 2019 the separation *r* in the source location for isotropic sources in a three-dimensional acoustic medium can be calculated as:

$$r^2 = \frac{1}{3\alpha^2}\sigma_\tau^2 \quad \text{(Eq. 6)}$$

Where: σ_τ^2- the variance of the travel time perturbations, α-an estimate of the velocity in the medium.

And for double couple sources on the same fault plane with the same source mechanism in elastic media, the source separation *r* reads:

$$r^2 = \frac{7\left(\frac{2}{\alpha^6}+\frac{3}{\beta^6}\right)}{\left(\frac{6}{\alpha^8}+\frac{7}{\beta^8}\right)}\sigma_\tau^2 \qquad \text{(Eq. 7)}$$

Where: α, β-are estimates of the P and S wave velocities in the medium (Snieder & Vrijlandt, 2005).

The variance of the travel time perturbations σ_τ^2 can be estimated from:

$$\sigma_\tau^2 = \frac{2(1-R_{\max})}{\omega_\tau^2} \qquad \text{(Eq. 8)}$$

Where: ω_τ^2 is the dominant mean square angular frequency and R_{max} is the maximum correlation-coefficient. The dominant mean square angular frequency is calculated as a ratio of the sum of squares of the temporal derivative of the reference trace and the sum of squares of the reference trace in a sliding time window.

We now investigate an average source displacement for all clusters using icequake doublets stacked with a moving average over 72h time windows with a step of 1h (similar to the dv/v measurements) taking as a reference the first trace in the dataset. The above analysis suggests that the average icequake doublet separation within a cluster ranges within 0.3 λ-0.4 λ of the shortest wavelengths at (10-40) Hz, with 24($\pm$2)m on average. Moreover, the above results seem to suggest seasonal changes in the source separation (stronger changes in source position from winter to summer season). A different source mechanism or different seismic velocities change the magnitude of the source displacement, but not the relative variations over time (Figure R5 and Figure R6).

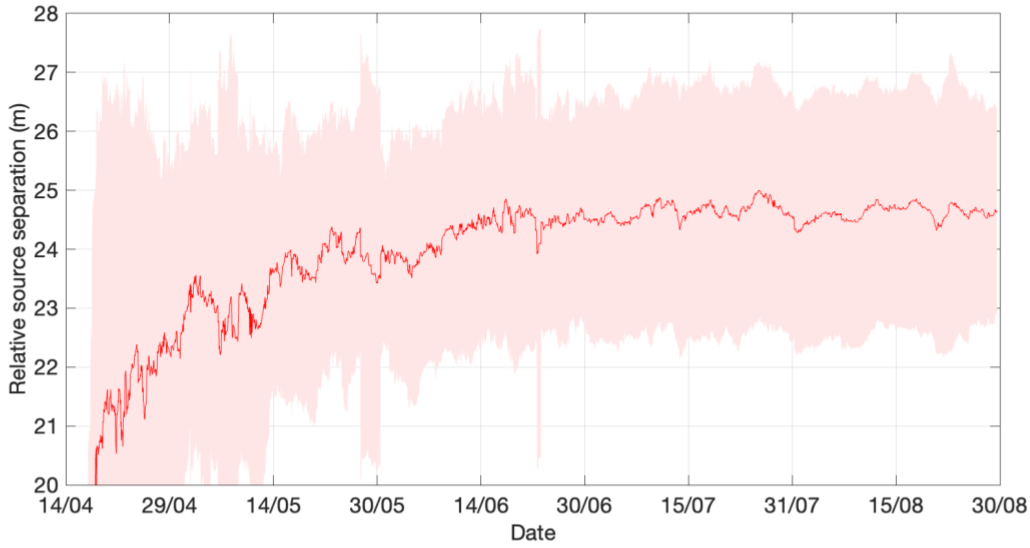

Figure R5: Average source separation and its standard deviation assuming isotropic sources in a three-dimensional acoustic medium with Rayleigh wave velocity=1600 m/s.

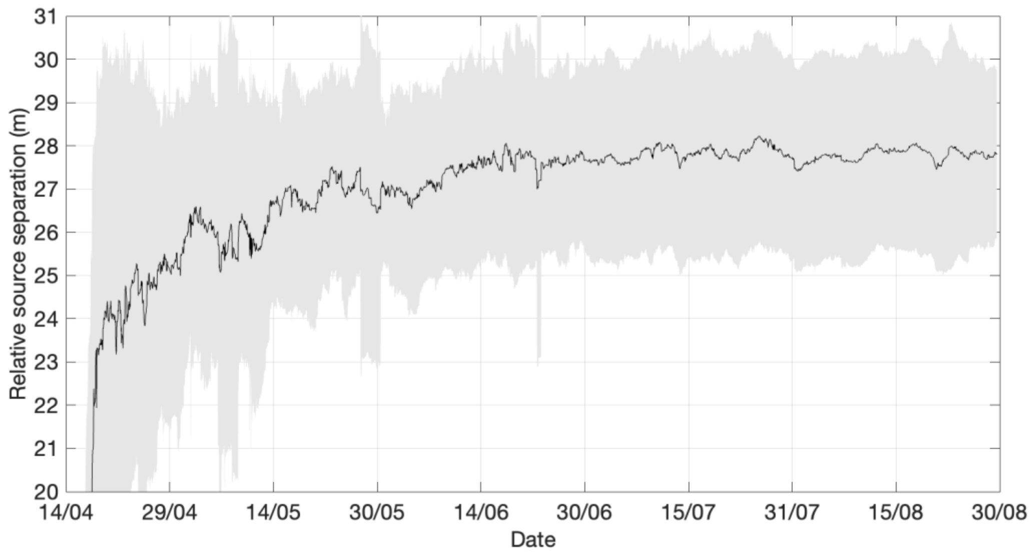

Figure R6: Average source separation its standard deviation assuming double couple sources in an elastic medium with P- ans S-wave velocities 3600 m/s and 1800 m/s, respectively.

For the crevasse propagation, we investigated source displacement for cluster 18 (only icequakes with a cross-correlation coefficient>0.7 as explained in the original manuscript) which goes inactive after the break-off event, and we interpret this cluster as potentially related to a crevasse opening. For that, we take as a reference the daily stack of icequakes on 19 July and we perform the source displacement measurements over the icequake data that are stacked over 24h windows with a 1h average (Figure R7).

The initial steep increase in the source displacement from the reference trace is related to the use of the moving average in data pre-processing. The first 23 measurements in Figure R7 (71 for Figure R5 and R6) are highly similar to the reference trace because they include the same icequake waveforms. Moreover, we also note that there is a minimum source displacement which we can resolve at the dominant mean frequency of 25Hz depending on the cross-correlation coefficient. Assuming the minimum wavelength of Rayleigh waves of ~65m, and R_{max}=0.5, r_{min}=18m and for R_{max} =0.9, r_{min} = 8m. If the dominant mean frequency is lower than 25Hz it will further increase the minimum source displacement that can be resolves within the cluster.

Assuming that cluster 18 is related to the crevasse propagation, we can estimate that the fracture extends around 2.3(±1.4)m between July 24 and August 22. One day before the small break-off event, the results shows a strong acceleration in the relative source displacement of another 3.1(±1.6)m, and a less pronounced acceleration after the small break-off event and the main break-off event 1.7(±0.9)m. This suggests that the most of the fracture extension occurred before the small break-off.

The interpretation of results of dv/v and source displacement measured with CWI need to be taken with caution. Singh et al., 2019 showed that source separation estimates are mostly unaffected by the velocity perturbation, however CWI estimates of the relative source locations are more precise and are more accurate up to approximately 0.2–0.4 λ, where λ is the dominant wavelength. Therefore, we are at the limit of the interpretation with an average icequake doublet separation within clusters of 0.3 λ-0.4 λ. Also, velocity change estimates are much more sensitive and might become inaccurate in the presence of larger source perturbations possibly due to cycle skipping.

We will add this discussion and Figures to the revised manuscript, and we will further address the source separation estimates for other clusters.

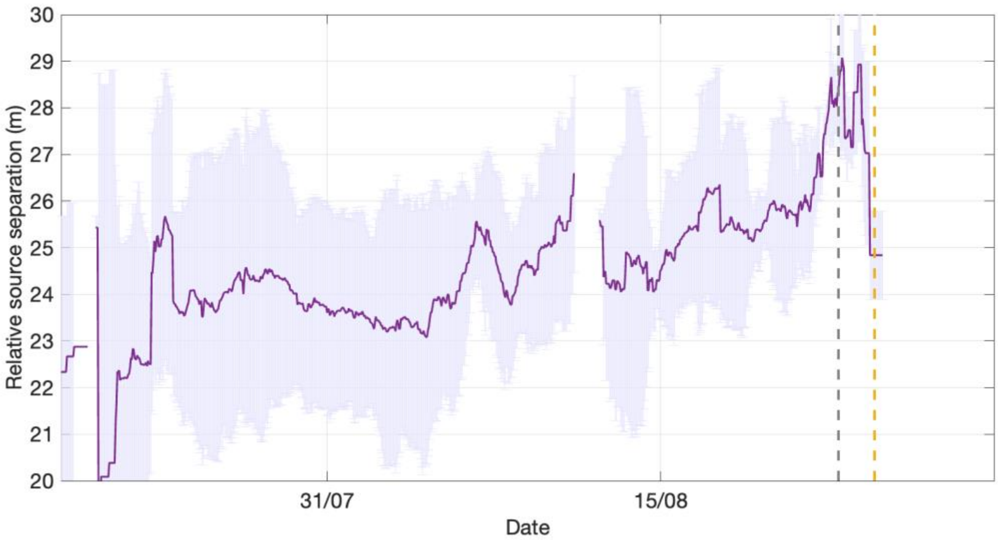

Figure R7: Average source separation and its standard deviation for cluster 18 potentially related to the crevasse extension, assuming isotropic sources in a three-dimensional acoustic medium with Rayleigh wave velocity=1600 m/s. The gray vertical dashed line marks the small break-off event and the orange dashed line mark the main break-off event.

L. 185 : you link the dV/V drop to an englacial damage due to rapid freezing of meltwater near the surface. But can you observe this melting, for example at diurnal scale ? Actually the refreezing of a melting water should increase the rigidity of the subsurface, thus increasing the dV/V. How do you deal with this process ? Do you any hint to favor the englacial damage effect rather than the latter ?

Our response: We link only this particular drop in dv/v around July 10 to englacial damage since there was a small break-off event that occurred on July 11, and we also observe crevasse opening at the glacier front (Figure R8). We will add this information to the manuscript.

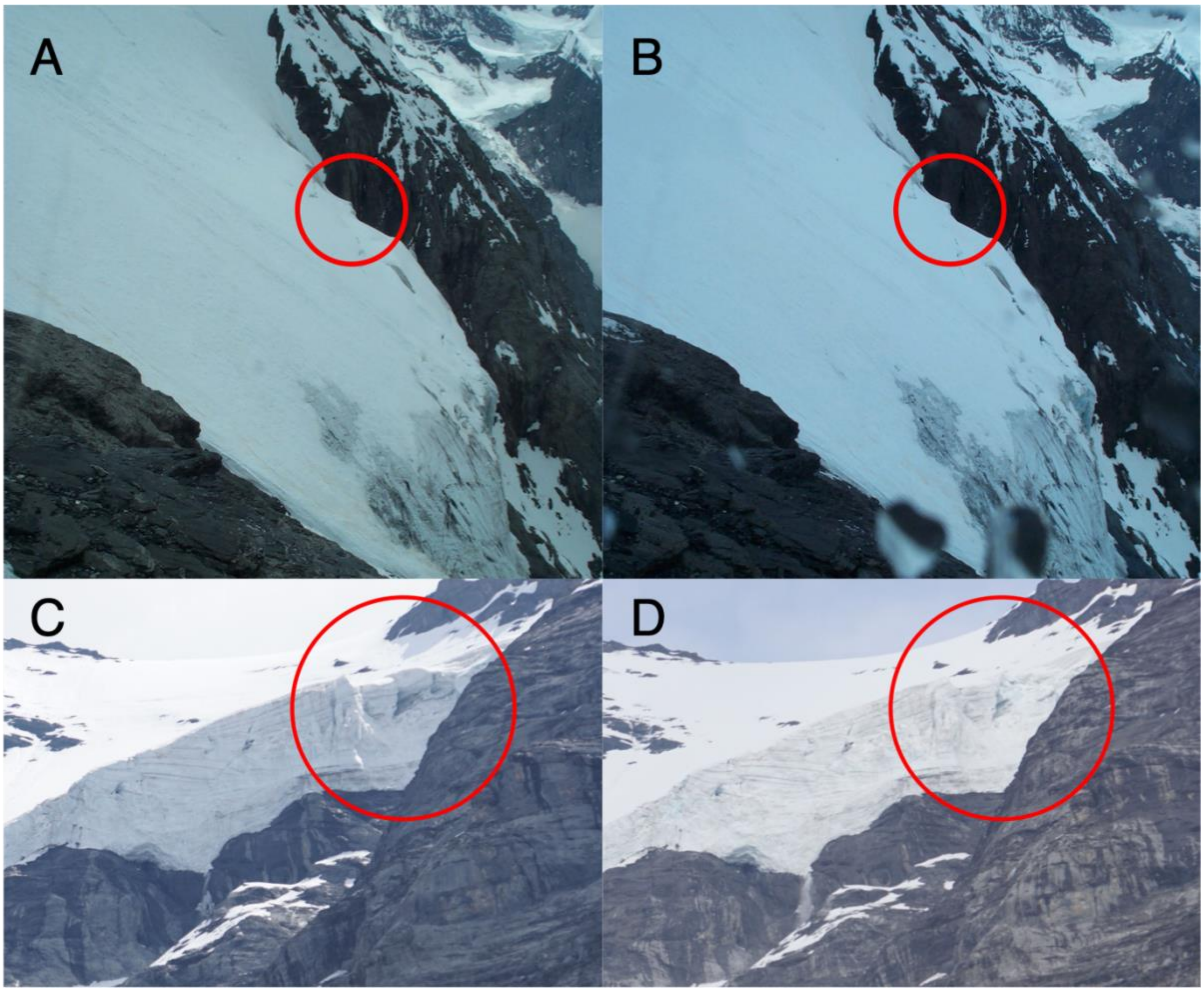

Figure R8: View on the Eiger hanging glacier before and after a small break-off event that occurred on July 11. Lateral view of the glacier on July 11 at 15h (A) and July 12 at 8h (B). Bottom view on the unstable glacier front on July 11 at 12h (C) and at 18h (D). The position of the ice chunk that detached is marked in red circles.

Uncertainties of dV/V values are poorly investigated in the study. In Figure 3 you show error bars related to standard deviation of results, but you should precise the order of magnitude of uncertainties when dV/V variations are mentioned. Also, L. 201 : is a diurnal variation of 0.01% significant ?

<u>Our response:</u> Thank you for noticing that. We will specify the order of magnitude of the uncertainties every time we mention dV/V variations.

Diurnal variations of 0.01% are weak velocity changes that have been detected previously with CWI (Roberts et al. 1992; Weaver et al. 2009; Mao et al. 2019). Such small dv/v variations can be due to diurnal thermal effects, as recently shown by Mao et al. 2019 for the shallow crust. We will add this comment to the manuscript.

L.254 : "This stress accumulation could possibly explain the dV/V increase"

I don't understand where this stress is accumulated : In the base of glacier, or more shallower ? Usually when meltwater penetrates into fractures, pore pressure increase and effective pressure decrease, leading to a decrease of dV/V.

<u>Our response:</u> This stress could have accumulated in the base of glacier front that is frozen to its bed. However, we will mention in the manuscript that this is a concurrent process with meltwater penetration into fractures, which would cause pore pressure increase and effective pressure decrease, leading to a decrease of dv/v. Therefore, we would need more observations (e.g., a GPS sensor measuring glacier surface velocity in the stable part of the glacier or dv/v measurements around other break-off events) to confirm or infirm this hypothesis.

6) Triggering by Amatrice M6.2 earthquake

L136: "our results show elevated seismicity two hours after the passing of the teleseismic waves of M 6.2 Amatrice earthquake"

This is both surprising and potentially very interesting. Can you show the rate of activity for a few days before and after the M6.2 earthquake?

Usually, distant triggering occurs during the passage of teleseismic surface waves, not several hours later. Are you sure this is not a simple coincidence?

How can you explain this triggering at larges distances and with a large time delay?

L.138-139 : Do you have an explanation about these recurrent bursts of seismic activity ? If you observe a correlation with melting, maybe you can assume an interpretation based on this statement.

<u>Our response:</u> The rate of icequake activity a few days before and after the earthquake is shown in Figure 1A in the manuscript and a few hours before and after the earthquake is shown in Figure R9 in this rebuttal letter. In the revised manuscript, we will also add the rate of cluster activity to the panel C in Figure R9.

We agree with the reviewer that distant triggering occurs during the passage of teleseismic surface waves, not several hours later. We did not want to suggest that this burst of the seismic activity was triggered by the Amartice earthquake. We are sorry for this misunderstanding and we will clear this misunderstanding in the manuscript saying that we cannot reliably interpret this seismic burst as triggered by the earthquake due to a large time delay between the passage of the teleseismic surface waves and the bursts of icequake activity.

Similar recurrent bursts of icequake activity have been observed by Preiswerk, 2018, in summer months at the Bisgletscher in Switzerland, which is a heavily crevassed temperate avalanching glacier. By using a 6-station seismic array, Preiswerk, 2018 located two of those bursts revealing their origin from the unstable glacier tongue. The exact source mechanism of the bursts of icequake activity remain elusive: they could be related to a slow emptying of a large en- or subglacial water reservoir, a series of small internal glacial structures or snow bridges collapsing and subsequently triggering more such events could cause such a signal, or to a mini-surge or active phase, i.e. a short-term speed-up as previously observed on other glaciers [such as on Allalingletscher (Röthlisberger and Kasser, 1978), or Unteraargletsche. (Iken et al., 1983)]. We will add this discussion to the manuscript. We believe that a more detailed analysis of these bursts of icequake activity on hanging glaciers deserves a separate study and it is beyond the scope of this paper.

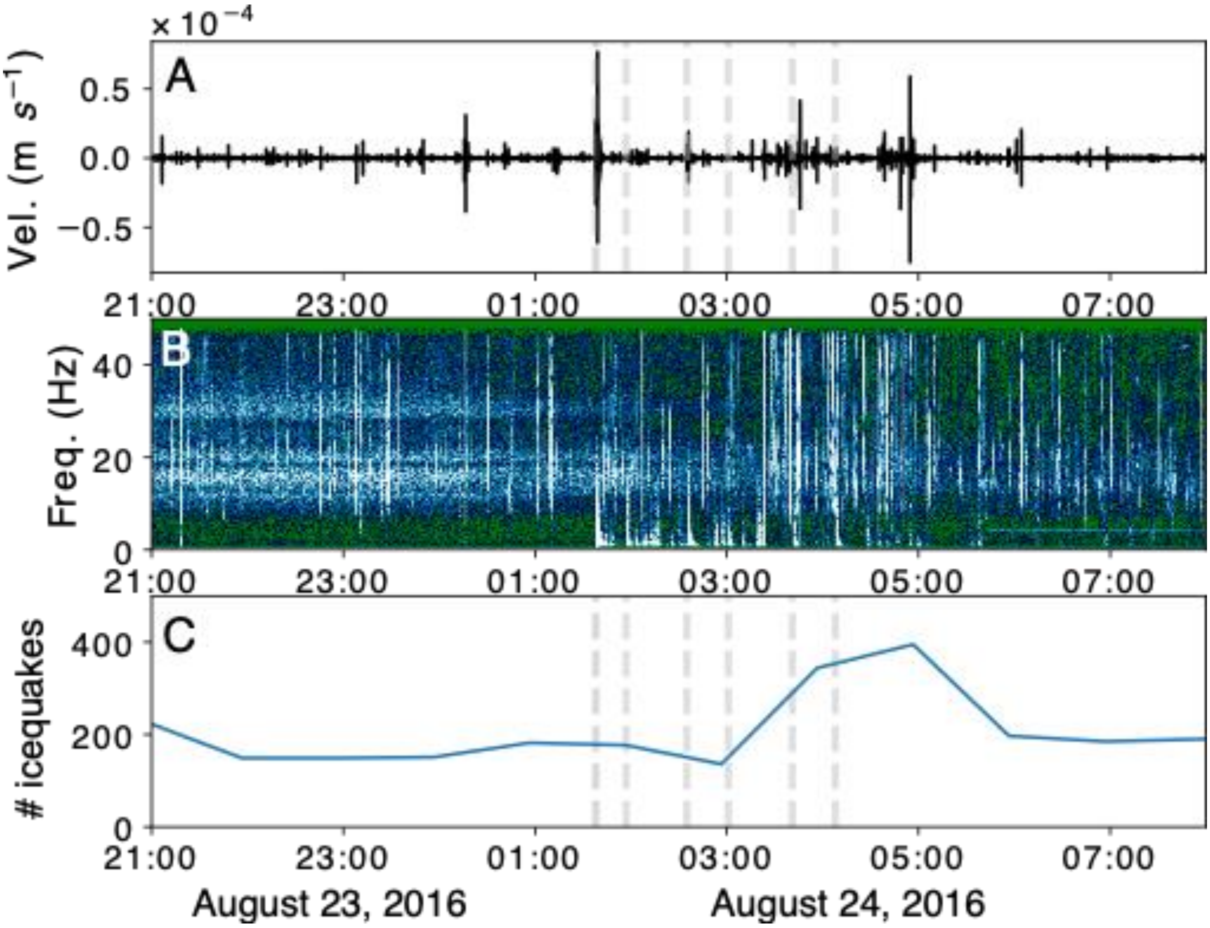

Figure R9: The rate of icequake activity for a few days before and after the M6.2 Amatrice earthquake. A. Vertical ground velocity recorded at the EIG2 station, B. the corresponding spectrogram, C. icequake activity between 21:00 August 23 and 08:00 August 24, 2016. The main shock and the aftershocks are shown in dashed gray lines (M6.2, M.5.5, M4.6, M4.3, M4.3, M4.4).

Technical corrections

Our response: Thank you for these technical corrections, we will correct all of them in the new version of the manuscript.

L.7 : Replacing “strong” by “long” or “significant” coda waves ?

L.22 : A timely warning -> timely warning

L.32 : icequake -> icequakes

L.33 : move the comma : “and the medium through which they travel, which can be been exploited”

L.62 : mountain -> summit

L.75 : “failure” or “rupture” ? In other cases the term “rupture” is used. If both refer to the same type of event, please clarify this by choosing one single word.

L.78 : snow fall -> snowfalls

L.87 : occurrence -> occurrences

Fig. 2 : please recall what depicts the orange dashed line (main break-off event ?). In this figure the mention “coda changes” and “frequency changes” are not straightforward for the reader. Is the change visible on the figures, or these range of values arbitrarily fixed, or after a preliminary study ?

L.130 : The values of mean measured velocity are not clearly conform to Figure 1e (I read rather 10 cm/day before break-off events)

L.207 : crevices -> crevasses

L.219 : shown -> showed

Caption Fig. 1 : Ortophoto -> Orthophoto

Caption Fig. 2 : showed -> shown

L.199 : places -> place

L.248: “Atmospheric effects might be the same order of magnitude as surface velocities” -> this sentence is not clear for me, you should reformulate.

Figure 3 : the date of break-off events could be more highlighted.

L.294 : moving-time -> moving time

L.294 : the short time window -> short time window

L.299 : removing the comma between m and s^{-1}

L.312 : exceed -> exceeded

L.346 : by lack of scatterers -> by a lack of scatterers

L.367 : crosspectrum -> cross-spectrum

Caption Fig. A8 : clusterts -> clusters

L.387 : coda wave arrival times -> coda wave phase times

Caption Fig. B1 : 4 3-component -> Four 3-component

Caption Fig. B2 : I suggest “Lateral view of the glacier from an automatic camera photographing the unstable ice mass, (A,B) before the small (23/08/16) and the main break-off event (24/08/16) correspondingly, and (C) after break-off events (25/08/16).

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