Title: Towards the systematic reconnaissance of seismic signals from glaciers and ice sheets - Part A: Event detection for cryoseismology
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Below the Editor and Reviewer 1 Comments (Second Review) are copied in grey with Author responses continuing in blue.

Editor Comments

Thank you again for submitting your revised manuscript entitled "Towards the systematic reconnaissance of seismic signals from glaciers and ice sheets - Part A: Event detection for cryoseismology".

Your manuscript has now been seen by 2 referees. While Referee #2 was fully satisfied by your revisions and replies to the other referee and recommended this work for publication as is, some important points were raised by Referee #1 (please see below). In brief, Referee #1 did not find your previous replies satisfactory, questioned the innovative nature of the paper, and was not convinced by the demonstration of the advantage of your approach versus other algorithms. The Referee also raises additional specific points that need to be addressed for the paper to be acceptable for publication.

Response to Editor
Many thanks for this reply. We are cautiously enthusiastic about the high potential of the workflow that we present, for the reconnaissance of mixed glacier/ice sheet environments, across the Part A and Part B papers. We are also pleased that the two reviewers for Part B now recommend publication. We're very pleased that Referee #2 was fully satisfied by our revisions to our Part A manuscript.

We're happy to address Referee #1's second review and have structured this according to the Editor's summary, that is:
a) innovative nature,
b) advantage of approach vs other algorithms (includes response to previous replies) and
c) other points raised.

We hope that following the changes outlined below, especially noting our 'Prelude' clarification of the difference between reconnaissance and high-resolution studies, our Part A m/s will be considered suitable for publication in TC.

(... continued overleaf)

Response to Reviewer #1 (second review) Comments (reordered as per the Editor's summary)

Prelude)

As a key clarification for this second revision (in response to Reviewer 1), we newly expand the distinction between the 'reconnaissance' scope of our method for large glaciers and widely spaced recording sites, and the 'high-resolution' capability of other work (we add the suggested 'Nanni et al., 2022' and related references). We also add text regarding the utility of our Part A – Part B workflow for targeting subsequent deployments, suggesting that readers could logically make use of such high-resolution methods (as in the references suggested by Reviewer 1) in locations targeted using our workflow. Clarifications in the m/s are noted as part of the response below.

a) Innovative nature

- … just I don't think this study is very interesting and innovative.
- The method is not new, it has already been published (Turner et al 2021). This work is only an application to a special case study.

R1.2ndRev.01

Our focus is on expansive glaciated areas, and/or widely space recording sites, and is innovative (together with the Part B machine learning component) in progressing knowledge for those settings. To correct a misunderstanding, we confirm that the current m/s *is* the first presentation of the multi- STA/LTA algorithm, i.e. it has not been previously published. This is explained in the main text, lines 201-203, quoted below, so we make no change but we are happy to rephrase (or clarify at a different point in the m/s) if there is some ambiguity remaining.

(Extract from line 201) We use the waveform handling pipeline for automated analysis developed by Turner et al. (2021), adding the multi-STA/LTA as a new option, with a view to subsequent signal reconnaissance using unsupervised learning (Part B, Latto et al., 2023).

b) Advantage of approach in comparison to other algorithms

- What is an "event" anyway?

R1.2ndRev.02-1

We agree that it is important to be clear what is meant by an event, and therefore move the definition (previously provided at line 98) to the earliest logical point in the main text. We also re-order some text from the paragraph beginning at line 26.

Text inserted at line 27 (after '… noise'): We use the term 'event' broadly to include impulsive signals, and waveform changes (such as an amplitude increase or frequency content change) with a less distinct onset. In some glacier environments, event-like noise is of as much interest as impulsive cryoseismic events, as both signal types yield insight into glacier and/or ice shelf processes.

Also, we modify the text previously at line 98 to avoid direct repetition. Modified text: Our broad use of the term 'event' includes both impulsive signals and waveform changes with a less distinct onset.

We also discuss this point in a later section (line 300), and make a slight modification for consistency. Modified text: The varied nature of cryoseismicity raises the question of how an 'event' should be defined for inclusion in the catalogue.

- Their goal is to bust a "catch-all" catalog, but there are better methods for this.
- Tremor and all event types can be simultaneously detected and located by migration based or beam-forming methods (eg, Nanni et al GRL 2022).
- It's not that I did not understand their goal …
- They usually answer by referring to "part B"…
- … But the interpretation of the results is left for a future paper.

R1.2ndRev.02-2

Many thanks for pressing these points. As per the note in the 'Prelude', we now better state the distinction between the 'reconnaissance' scope of our study (14 broadband stations, approx. 55 km aperture, events often recorded by less stations, median=6 stations, with some significant coupling differences being notable) and the

suggested recent 'high-resolution' work (98 Nodal-type stations, approx. 600-800 m aperture). It is exciting that our Part A + Part B workflow could help target locations within large areas that would merit a future high-resolution study, so there's certainly a nice link to the citation suggested by this review, which we are happy to include.
Last sentence of the abstract modified: The new algorithm and workflow will assist in: the comparison of different glacier environments using seismology, the identification of process change over time, and the targeting of possible following high-resolution studies.
Text modified with small additions (line 30): This workflow aims to enable the reconnaissance of ice-covered environments, such as outlet glaciers of ice sheets, some of which supply ice shelves. It provides a consistent and repeatable approach that will work with a modest number of stations deployed over a wide, remote area to provide an initial appraisal of seismicity across a given region. Such a reconnaissance could facilitate either 1) a comparison of the processes active in different locations; and/or 2) the monitoring of glacier processes over time; and/or 3) the targeting of following high-resolution studies.
Citations added (line 84): Where high-resolution sensor coverage is desirable and possible, source locations and glacier processes may be determined directly (e.g. Nanni et al., 2022 make use of a dense, ~800 m aperture array), with the reconnaissance-level approaches that we describe enabling the targeting of such detailed studies.
https://doi.org/10.1029/2021GL095996
Text modified with small additions (line 85): The wide variety of techniques for the detection of icequakes highlights the extent of analytical challenges in event-based cryoseismology. Where the area of interest is an ice stream or other ice sheet outlet glacier, the challenge is increased by the remote location together with the need to undertake a reconnaissance across a relatively large area. The diversity of event types in glacier environments therefore suggests the need for a workflow comprising…
References added for consistency (line 409): …to examine or locate a more specific event (glacier process) type (e.g. Nanni et al., 2022, Umlauft et al., 2023, Hudson et al., 2023).
https://doi.org/10.1029/2021GL095996
https://doi.org/10.1029/2023JF007280

- For instance, the authors claimed that "Our experience is that varying the parameters mentioned results in a full catalogue". How do you know that you detected all events? Just because you detected all previously known "stick-slip"events? But there could be smaller stick-slip events that you missed, or other types of events. How to be sure?

R1.2ndRev.02-3

In the text of the m/s we consistently use the term 'near-comprehensive' catalogue (i.e. not 'full'). We apologise for the use of the word 'full' in our previous response. We handle the question of detected vs missed events, and also false detections, through the discussion of high confidence and low confidence events (Section 3.2.1). Given the 'catch-all' approach that we use, false detections are more of a concern than missed events, however, the general findings of the Part A m/s are not impacted in either case.

- The multi-STA/LTA method only detect impulsive events and cannot detect tremor, which occurs frequently on glaciers.
- The multi-STA/LTA method is also not better than other methods at detecting small events, template-matching methods can detect much smaller signals.

R1.2ndRev.02-4

We have expanded the examples of the multi-STA/LTA algorithm shown in Supplementary Figure S2, now S2a and S2b to illustrate the above points. As implemented in this reconnaissance for the Whillans Ice Stream (i.e. station separation approx. 10 km) the multi-STA/LTA method detects both emergent and impulsive small events quite well (Fig. S2b) and achieves what we intend, i.e. that the wide variety of events would be captured by the algorithm, e.g. contrast the large events (Fig. 2a). We do see tremor-like signals, although with the 10 km station separation, they appear in the catalogue in connection with other signals (e.g. lower plot in Fig. S2a). Text modified (line 256) to point to the updated Fig. S2a, b.

We agree that template matching is a great choice of method for high-resolution studies with a particular event type in mind (see text at lines 49-52, with small modifications), and hope that readers are inspired to carry out well-targeted follow-up studies having carried out a reconnaissance for large glaciers aided by our Part A/Part B workflow, as in the title of the two papers.

- o I still disagree that the proposed method outperforms a simple STA/LTA algorithm. Indeed, the authors have not shown that their method is better than "any other simple STA/LTA method", just that it is better that a simple STA/lTA algorithm with extreme unrealistic values of short and long time windows.

As above, the strength of the multi-STA/LTA is that it captures a wide variety of events, and we hope that the updated Fig. S2a) and b) now provide a better sense of that. The variety of events are then explored using the machine learning (Part B) of the workflow, by design. Relevant text has been added in various locations as in the response to **R1.2ndRev.02-2.**

- o The main advantage of the method is that it searches automatically for the optimal values of some model parameter (time windows), but some other important parameters (triggering and detriggering thresholds) are adjusted by trial and error. The proposed method thus does not remove the need to visually optimize some model parameters.

R1.2ndRev.02-5

We agree with this comment, and slightly modify our existing text on this topic (line 325).

In this study we use the Monte Carlo approach to optimise the five key model parameters that have the strongest conditional interplay when applying the multi-STA/LTA method (sta, lta, Δsta and Δlta, and ε) as previously described (Fig. 2). Secondary parameters, which will vary based on study environment (i.e. background noise and seismic signal amplitudes) include the trigger and detrigger values. These values were set in this study following a brief, visual-based analysis as this was a straight-forward process. Whilst any parameter choices could be optimized through the Monte Carlo analysis, the needed visualization and appraisal process for the trigger values could become unwieldy. In general, the parameters that are used should be recorded and supplied with the resulting catalogue.

c) Other points raised

- o the tone of their manuscript and response letter is slightly pretentious and patronizing

To correct this misunderstanding, we are cautiously enthusiastic about the potential of our Part A – Part B workflow for reconnaissance of seismic signals from glaciers and ice sheets. We aim for clarity of presentation and offer our responses with respect for other methods that are well-suited to other glacier environments..

- o For known stick-slip events, the method is not able to detect the correct start and end times (see response letter and electronic supplement).

R1.2ndRev.03-1

As we explain (line 206) our reconnaissance method provides a reference arrival time. This is appropriate to the sparse recording networks that enable knowledge generation for large expanses of glaciated areas. We hope that such insights could enable subsequent high-resolution studies as in our response to R1.2ndRev.02-2.

- o Figure S2 is supposed to show a high confidence stick-slip event not previously identified.
  What represent the pink areas? The time window when the event is detected at each station?
  I don't see any event when looking at these seismograms. I can't believe that there is an increase in energy ratio SA/LTA larger than the chosen threshold of 3. Or the event may be in a different frequency range than the bandpass filter 0.001-1Hz used in fig S2? Could you show the spectrogram of this event at one or more stations? And add a plot to show the temporal evolution of STA, LTA and STA/LTA? This event is identified as stick-slip just because it shows 3 successive pulses (electronic supplement). This is not very convincing. It could also correspond to 3 successive events. It also has a different frequency range than known stick slips events. You should at least locate this event before making a claim like that. Or show that this event repeats at regular time intervals.

R1.2ndRev.03-2

We have changed the presentation of Figure S2a, and figure caption, as per **R1.2ndRev.02-4.** We didn't intend the strong claim implied by the referee's response, rather, we suggest that a different kind of slip mechanism would be plausible.

- I understand why you filter seismograms, but why spectrograms (fig S5)?

R1.2ndRev.03-3

We modify the figure caption to explain that the same filter is applied to the spectrogram in this case as it relates directly to the seismogram (in this case removing a low frequency signal that overlaps with the event).

- The authors do not filter the signal or deconvolve the data by the instrument response because it leads to "artificial detections". I have never seen that. What kind of signals did you detect? Are these real signals (ambient noise...) or numerical problems?

R1.2ndRev.03-4

The most important part of our original response (we use very limited frequency-based filtering prior to applying the algorithm) is the fact that we are searching for events across a wide range of frequencies, so we need to retain that wide frequency range . As a less important remark, a single event with different frequencies at different times sometimes appeared as separate multiple events if we presented differently pre-filtered data to the algorithm (as per 'common sense'). We withdraw the phrase 'artificial detections' as this wasn't in our original text and did not help the explanation.

We again thank Reviewer 1 for providing a second review, and hope that the above responses have now provided satisfactory explanations of the context of the work, or corrections. It has strengthened the paper to make a better link to the high-resolution work as per the suggested citations, and we look forward to using both reconnaissance and high-resolution methods in Antarctica in the future.