Changes to manuscript of *Detection of glacier surge activity using cloud computing and Sentinel-1 radar data* based on TCD review comments

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1 Review 1, doi: 10.5194/tc-2021-89-RC1

1.1 General remarks

The paper demonstrates a method for detection of glacier surge events that is straightforward, well described/presented, and (to my knowledge) novel. The authors demonstrate how the Normalized Difference Index of SAR backscatter may be a useful measure both for the detection of potential surge events as well as in the interpretation of a specific event when combined with optical satellite imagery and ice velocity measurements. The method provides a way to detect potential surge events on a global scale using relatively straightforward and fast processing, especially with the use of the GEE platform. While it is difficult to exactly estimate the accuracy and false alarm rate of the proposed method in detecting surges (due to the limited amount of validation data sets), the authors have presented a comparison with SAR surface velocity data for two of the areas of interest, which does show encouraging results. The authors also describe the (current) limitations to the method, namely that visual inspection of the NDI images along with auxiliary data such as optical images is required to identify surge events and that other physical phenomena than surges could lead to similar signatures in the NDI measurements. My comments mainly concern clarifications on the used data (e.g. polarization, resolution) and validation.

author reply: *We thank the reviewer for the careful reading of our paper and the constructive comments that helped to improve the paper. We have inserted answers to his comments in italics below.*

1.2 Specific comments

Line 26 + Line 36 (+Supp. Mat. Section 1): The GRD images are "detected" SAR images, meaning that they measure intensity (i.e. not amplitude, but amplitude squared). The intensity images must then be calibrated and converted to the unitless backscatter coefficient (which is almost always converted to dB scale). This pre-processing is done automatically in GEE, as far as I can tell from the documentation. Therefore, "amplitude images" should be changed to "backscatter images".

author reply: *Good point, changed as suggested (line 27, 39, SupMat section 1)*

Line 36: Maybe it is worth noting that Sentinel-1 coverage depends on the acquisition plan, meaning that certain areas of interest may have infrequent coverage.

author reply: *We included this remark on the Sentinel-1 coverage depending on the acquisition plan (line 40–41).*

Line 41: How much multi-looking (i.e. spatial averaging) is applied to the SAR images? (For the GRD images in IW mode, they are provided either as "Medium Resolution, MR" or "High Resolution, HR", dependent on the amount of multi-looking). Did you test multiple levels of multi-looking to determine if the reduction in speckle noise and/or the reduction in resolution affect your results significantly?

author reply: *We found only HR images for the IW images used within GEE. Thus, we could not test the impact of multilooking. We, however, apply moderate filtering (a 3x3 median filter) on the normalized difference results (added to the method description in line 55) and find this reduces the effect of speckle noise while at the same time maintaining important details. We agree that testing filters such as multilooking on the individual stack images might be worthwhile to try in further refinements of the method.*

Line 47: You mention using only cross-polarization images (VH or HV) for all your NDI measurements. Is there any specific reason for this? Since you are looking for general changes in the surface roughness, I would not necessarily expect cross-polarization to yield a much different/better result than co-polarization (VV/HH). Have you looked at an example event using both cross-polarization-based NDI and co-polarization-based NDI for comparison (similar to how you investigated the difference between ascending/descending tracks in Supplementary Material Section 2)?

author reply: *We did look at difference images using HH and VV co-polarization as well. But, in general, we found these work less good than cross-polarization. HH and VV difference images have more noise and in some regions the signal we are looking for is obscured by this. For some areas the results would be the same, though. In the paper we focused on the method and settings that work best and are therefore used for the results we present and didn't mention the HH and VV option further. In the revised version we have added a paragraph to the Discussion where we indicate that we have used a setup that works well for the detection of surge activity, but that other choices can be made to either improve the method or apply it to other purposes (line 148–156). We agree it would be an interesting question by itself why cross-polarization works better for crevasse changes. We think however that detailed analysis of this exceeds the purpose of our Short Communication. One speculation would be that as cross-polarization typically stems rather from volume scattering processes, it might be that for crevasses it reflects strong but multiple backscattering from the crevasse walls within a resolution cell. This effect could be significantly stronger than volume scattering processes in the uncrevassed snow/firn/ice pack surrounding the crevasses. See also the comment on Line 40 by reviewer 2 (Section 2.3).*

Line 50: I would consider specifying more explicitly that, based on your experiments, for a given area you expect to see (roughly) the same detection of surge activity from descending and ascending tracks, as SAR acquisition artefacts tend to affect glacier surroundings more than the glacier surface (with a reference to your Supplementary Material Section 2). This is an important result for a potential operational/automated implementation of your method.

author reply: *We have added this point to the Discussion section (line 153–156).*

Line 149: "We compare the results from our method with surge detection from surface velocity measurements for Alaska and Svalbard. The two methods largely identify the same surge activity." I think this sentence could be slightly misleading. My impression (based on Supplementary Material Section 4) is that for Alaska, you did not check the velocity fields of all glaciers in the region for surges, which is what you did for Svalbard. This means that, potentially, there could be a number of 'False Negatives' in the Alaska region (i.e. surges indicated by surface velocity measurements but not by your method). I would suggest mentioning more explicitly that you do not check for these False Negatives for the Alaska region (under Section 3.3 or in the Discussion).

author reply: *There is indeed a difference in validation in the two regions. In Alaska we only studied the glaciers we found to have surge activity and we checked if the development in surface velocity, derived from Landsat images, supports the detection of surge activity from backscatter differences. We only control for false positives, in the words of the reviewer. For Svalbard we included the development in surface velocity for all glaciers and thus checked if the detected surges have a corresponding change in surface velocity, and if there are no marked changes in surface velocity that indicate surges which we missed. In Svalbard we controlled both for false positives and false negatives. We have made this distinction more clear in the revised paper. We added a remark on this in the Methods section (line 78–80), and made this point more explicit in the Results Section 3.3 (line 119), Discussion (line 126–128) and Suppl. Mat. Section 4.*

Supp. Mat. 4.1/Fig. S5: I think you should add a table containing an estimate of the change in velocity for the various Svalbard glaciers (for instance computed as a spatial average over a specific part of the glacier). It is difficult to see the magnitude of the velocity change for many of the glaciers, due to the wide color scale. For the Alaska cases, where the colorbar is adjusted per glacier, it is easier to visually note velocity changes, so a table with estimates is not as necessary (in my opinion).

author reply: *We included a 4th panel in Figure S5, rather than an additional table, that shows the difference in surface velocity between January 2018 and January 2019 to display the change in velocity more clearly (SupMat Fig. S5). Meanwhile, the surface velocity data are also available from the website of NVE. We included a link to this website in the revised version of the paper (SupMat Section 4.1)*

Supp. Mat. 4.2 (Fig. S7): You mention that Walsh Glacier Tributary shows a strong decrease in surface velocity during 2015-2017, but as far as I can tell from Figure S7, the velocity shows little change from 2015 to 2016, then an increase from 2016 to 2017.

author reply: *Thanks for pointing out this mistake. The Walsh Tributary should indeed be included in the list of glaciers that have an increase in surface velocity in 2017, along with Turner, Hubbard, La Perouse and Le Comte Glacier. This is corrected in the revised version. (SupMat Section 4.2)*

future research (Purely as a suggestion for future investigations (not to be incorporated in the current paper): I wonder if interferometric coherence could provide additional useful information, e.g. by estimating coherence for a number of 6- or 12-days pairs during one winter and comparing with estimates from the following winter).

author reply: *We and others have previously worked using coherence (loss) for detecting motions, and the method is very successful for distinguishing debris-covered glaciers from surrounding glacial debris. For surge detection, the method would only detect velocity changes on VERY slow (almost stagnant) glaciers as most glaciers would show coherence loss even for normal*

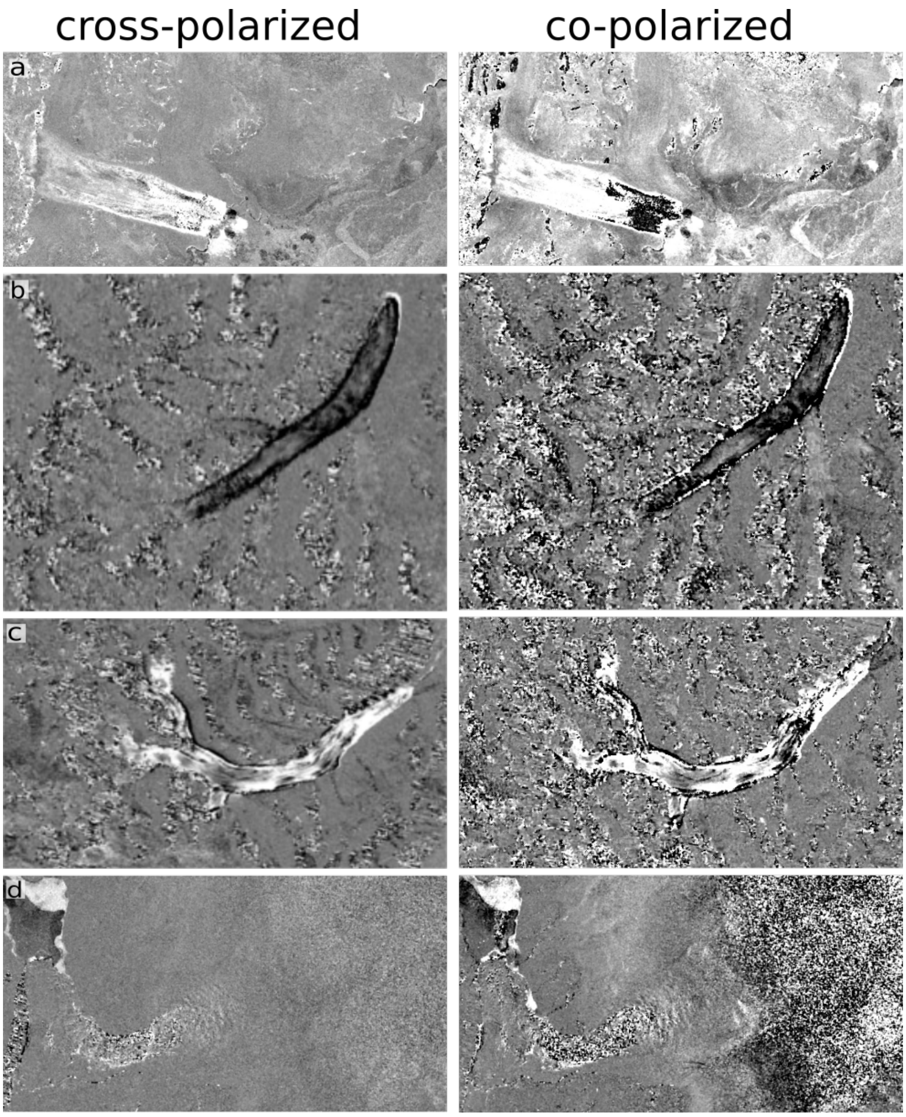

Figure 1: Examples of glacier surge activity derived from cross-polarized (HV or VH) as used in the paper, and co-polarized (HH or VV) for **a**) Negribreen (also shown in Fig. 2 of the paper), **b**) the glacier with GLIMS ID G077483E35705N, and **c**) Kluane Glacier (both shown in Fig. S3), and **d**) the glacier with GLIMS ID G278750E77768N (Canadian Arctic).

quiescent phase speeds. We agree the method could be tested to see whether it could add information to our approach, e.g. earlier detection of surge onsets. As phase is not available in GEE, the approach would have to be implemented locally.

1.3 Technical corrections

Figures 1+2: I would suggest increasing the resolution/size of the images (it is difficult to see the insets in Figures 1d and 2c).

author reply: *We have increased the resolution of both images, and increased the size of Fig 1 by making it a two-column image.*

Figure 1 text: I would change "maximum brightness" to "maximum backscatter" to be consistent.

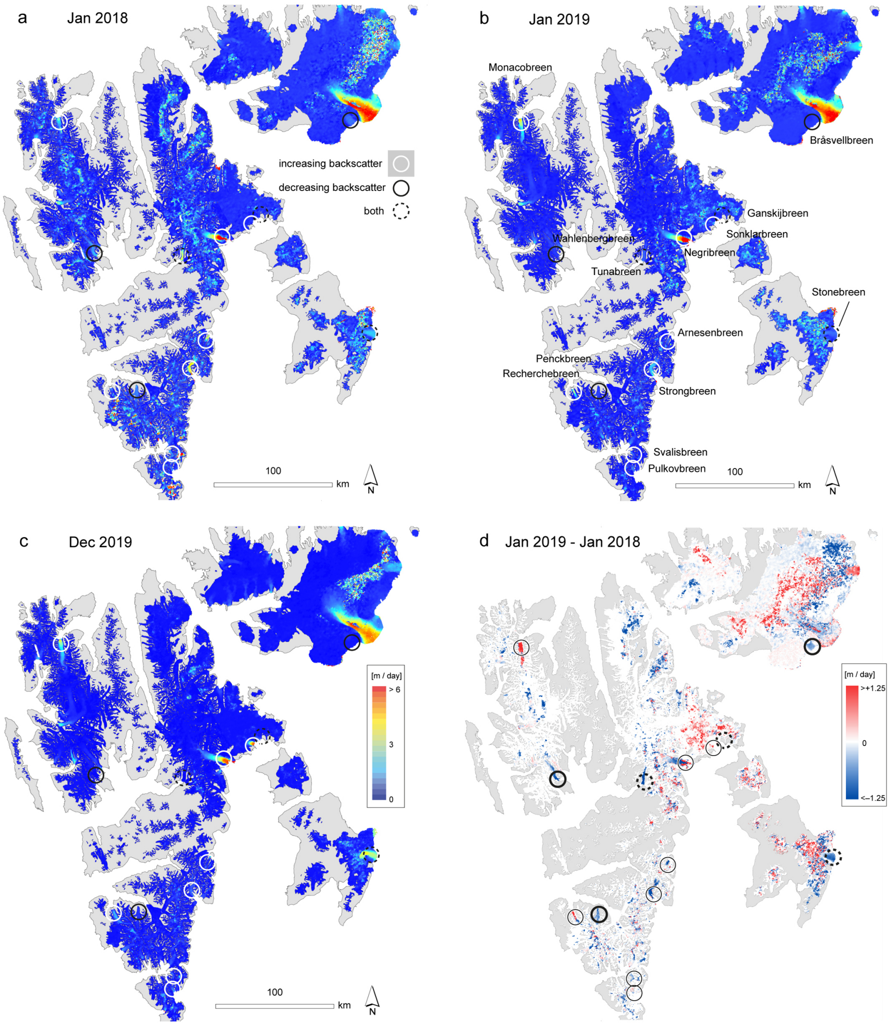

Figure 2: New version of Figure S5 including change in glacier surface velocity between January 2018 and January 2019.

author reply: *Changed as suggested. We have also added the names of the surging glaciers in the caption such that they can be found in Table S1.*

Supp. Mat. Fig. S3: the LOS arrow is hard to distinguish from the background. I would consider changing the color/size of it

author reply: *We have increased the size of the arrows in Fig S3, and the position for some, to make them better visible.*

2 review 2, doi: 10.5194/tc-2021-89-RC2

2.1 general remarks

The authors have proposed a simple method to detect surges at a global scale with an annual time scale. It is very well known that an active phase can significantly change the morphological features of a surge-type glacier and this study compares a sequence of radar backscatter images from the Sentinel-1 C-band mission in order to identify morphological changes corresponding to surge events. I really endorse the use of cloud based Sentinel-1 data inventory for glacier applications on a global scale, but this study missed many critical points that makes it eligible for publication at this stage. I was expecting a reasonable argument why such a framework is needed in addition to approaches based on continuous velocity observations, glacier area and surface elevation changes. Such approaches not only detect glacier surges but thoroughly quantify surge behaviors.

author reply: *We thank the referee for his review effort and comments. We believe most comments are due to misunderstandings and we attempted to be more clear at a number of places. Please see details below. We would also like to stress that referee 1 finds the study well designed and described so that we at places had to decide whether to follow ref 1 or 2.*

2.2 Major points

Major points are as follows:

1. *Reviewer 2's first major point consists of several questions, which we answer one by one:*

1.1 The Method section is inadequately explained. Few questions remain unanswered. What is the rationale behind interpreting decrease in radar backscatter values as a surge activity?

author reply: *There might be a misunderstanding, we use both increase and decrease of backscatter. In the Method section (lines 31–32), we expect the glacier surface gets less crevassed, and therefore backscatter decreases, at the end of an active surge phase when glacier flow velocities go down. Increase in backscatter is interpreted as rising surge activity. We tried to clarify better and added a general sentence on the enhanced radar backscatter over crevasses. (line 33–36)*

1.2 How does the algorithm detect surge automatically in three different scenarios?

author reply: *The method is not an automatline 31, ic algorithm. The NDI images are calculated and then visually inspected using the Google Earth Engine interface. During this inspection the researcher (us) has to determine whether backscatter differences, either increase or decrease in backscatter or a combination of the two, are an indication of surge activity. As written in the Discussion, we envision that this method could be automated with the use of some form of object-oriented classification or machine learning. The results presented here could serve as a training data set in such an effort. The current Short Communication is rather an initial proof of concept for the approach, as it has not been shown before, to our best knowledge.*

1.3 A surge activity was detected using data two years after the event, which means the timing of the surge activity cannot be detected using this technique. It is also not clear how the authors found out that the surge occurred two year prior to the technique applied in this particular case. Have you applied any thresholding?

author reply: *It is not entirely clear to us what the reviewer means with the timing of the event. A surge event can stretch out over multiple years, with first an increase in velocity and, typically, glacier front advancement, which can take several years, and subsequently a period with declining surface velocity. If the reviewer refers to the timing of the maximum surface velocity, we agree that our method does not measure changes in surface velocity directly, and therefore it is difficult, or even impossible, to derive the timing of maximum velocity from the backscatter images. This is mentioned in the paper (line 85–89 and 133–134). Referring to the example of Negribreen described in Section 3.1 "Detailed example", we found an increase* *in backscatter for the year 2018-2019, while we know from surface velocity measurements published in Haga et al. [2020] the the velocity peak was in 2017. Haga et al. [2020] found that, even though the surface velocity declined, surface crevassing continued to increase after the peak in surface velocity. This explains that we found an increase in backscatter in our study period 2018–2019. We have not used a threshold in determining whether the NDI image shows increased or decreased backscatter.*

2. The study claims that it has identified 18 new surge-type glaciers, which are not yet documented. Given the presented algorithm has been misinterpreted at many instances, more evidence (e.g. velocity changes, dh/dt) is required to further confirm the claim. I suggest making such comparisons in different regions, which is currently limited to two glacier locations.

author reply: *We have detected surge activity for 45, not 18, glaciers that are not classified as surging glaciers in the RGI (which is based on Sevestre and Benn [2015]): 35 glaciers are not classified (class 9) and 10 are classified as not having evidence of surge (class 0). The 18 cases the reviewer probably refers to are cases in which we are uncertain whether the backscatter changes could be classified as surge activity. Many of these cases are calving glaciers in the arctic region for which the backscatter change could be related to velocity changes that are caused by calving processes rather than surge activity (see also reviewer's third major comment). As the reviewer asks for more evidence of surge activity in the form of surface velocity and surface elevation changes, we assume the reviewer means with "the presented algorithm has been misinterpreted at many instances" that we incorrectly identified surge activity in* many *cases with the presented method. We (and referee 1) do not see justification for such statement. The goal of this paper is exactly to present a method that can be used to relatively quick and straightforward detect glacier surge activity at a global scale. Comparison with surface velocity measurements for the two regions with most cases of surge activity, containing 32 of the total of 69 cases we detected globally, shows that this method works well. We identified two possible false positives, where we have to take into account that the velocity measurements contain uncertainty as well. We have found one possible false negative for Svalbard, the region where we studied surface velocity for all glaciers not just the ones for which we detected surge activity. We trust that this comparison gives enough confidence that the method is useful for glacier surge detection and we believe that extension of the comparison to all other regions to include the other 37 cases will not change this. Comparison of the velocity fields, and possibly elevation changes, of all glaciers world-wide to detect false negatives globally is beyond the scope of this study, and it is exactly the purpose of our method to provide a much simpler and faster method for surge detection. That said, we envision that specific interesting cases, after being detected with the method presented here, can be further studied in detail using velocity and elevation changes in future studies.*

3. Ice velocities of many ocean-terminating glaciers significantly vary due to ice frontal changes and do not correspond to a surge activity. However, the former scenario also results in heavy crevassing. It is not clear from the manuscript how the framework makes such a distinction.

author reply: *The method detects changes in surface roughness that we relate to crevassing. It is from the radar backscatter alone very hard to determine the cause of detected changes in crevassing such that it is hard to discriminate between acceleration, or deceleration, caused by surge activity or calving dynamics. In Table S1, we have included 18 cases for which we see a backscatter change that could be surge related, but where this is not certain (line 104–106). As can been seen in Table S1, most, 12 out of 18, of these glaciers are located in the Arctic.*

For many of these the problem raised by the reviewer is exactly the reason why we are not certain whether the backscatter changes are caused by surge activity, and calving instabilities are also explicitly mentioned in the manuscript as a possible alternative explanation (line 107 and 139–140).

4. Line 30: "radar backscatter is increased during an active phase" is contradictory to the three scenarios used for identifying glacier surges.

author reply: *Assuming the reviewer refers to the division of surge activity detection in 1) increasing, 2) decreasing, and 3) combined increase and decrease in radar backscatter, we do not see why this should be contradictory as we state in the next sentence (line 32) that "the glacier surface get[s] less crevassed and therefore backscatter decrease[s] at the end of an active surge phase". See also responses to comments 1.1 and 1.3.*

5. Line 130: It is also not clear how the study deals with misclassification and what needs to be done - manual intervention or thresholding? It means one needs to thoroughly check whether the glacier surged or not, which requires the use of optical images as well. In my view, this does not suit the purpose of proposing such a framework. It should have rather been proposed as a data fusion approach to detect glacier surges.

author reply: *We assume this comment is in parts based on misunderstandings regarding manual interpretation and thresholding that we tried to clarify above. The method we present here is based on visual inspection on the NDI images (the backscatter difference images). All results are therefore based on "manual intervention". We do not use a threshold in the proposed method. After visual inspection of the NDI images leads to detection of surge activity, we suggest the use of optical images, and possibly the aggregated stack maximum images and NDI images from other periods, to support the identification of surge activity. The GEE platform is well suited to this combined use of different satellite imagery. However, despite the fact that we use these optical images to support the results, the principal component in the detection of surge activity are the Sentinel-1 derived NDI images. Therefore, we are not inclined to describe the method we present as a data fusion approach. We deduce from this comment that the approach we use is not described clearly. So we have reorganized the Method section, and added an explicit example of the role of supporting evidence from optical images (line 58–63, 72–73 and Fig 1d).*

6. Limitation of the proposed framework to detect the surge of small glaciers should be discussed too.

author reply: *It is true that the Sentinel-1 resolution makes application of our approach to very small glaciers and ice patches difficult. At the same time such small glaciers typically don't surge (see addition on size distribution of surging glaciers to the revised Discussion line 132–133). What our approach would probably miss are instabilities of very small ice bodies. In general, we wouldn't call those "surges", though.*

2.3 Other comments

Line 30: How did you check whether there was any influence due to rain or not - especially in HMA

author reply: *The way we calculate the backscatter differences limits the influence of rain, or other forms of liquid water, on the NDI images. Firstly, we limit the acquisition of the Sentinel-1 images to the winter months when most of the glaciers, or glacier area, is likely the be* *frozen. Secondly, we compare the stack maximum of the backscatter. As water reduces the backscatter [Winsvold et al., 2018], we can expect the melt or rain events do not impact this result. Only if a glacier surface would be wet the entire winter in one year, and not the other year, this would show up in the result. But then we expect to see this on several glaciers at the same elevation band and in the same region. We did not see this in our study period 2018–2019, also not for the glaciers in High Mountain Asia.*

Line 30: How did the algorithm distinguish between existing and newly formed crevasses?

author reply: *The method does not distinguish between the two. It only refers to more or less backscatter, which is related to a more, or less, crevassed glacier surface. We tried to clarify the Methods section accordingly (line 33–36)*

Line 40: "We create ... winter periods" should be better explained. I understood that you stacked all the images within 3 winter months and created a raster image with pixels containing the maximum values of the stacked images. What is the rationale to use the maximum of the image stack?

author reply: *This is indeed what we do. We found that the maximum is the stack statistic that gives the best difference image in the detection of surges when testing the method on a number of known surges. We tried other simple statistics, such as mean or median, but they didn't give an as clear signal. A stack maximum works especially well for crevasses as it promotes permanently strong scatterers, which crevasses are. In addition has the use of the stack maximum the advantage that it reduces the sensitivity to rain or melt events. We by no means exclude that the method can be improved or fine tuned with more sophisticated stack statistics. We have included a paragraph in the discussion on this issue (lines 148-156).*

Line 45 I was informed by the scientific community that the Sentinel-1 radar images available at GEE have georeferencing issues. This should be tested and clarified.

author reply: *We carefully checked for such issues, which would be visible as duplicated features in our NDI results, but didn't find any. Overall georeference issues that would shift the entire dataset a bit do not affect our results. By comparison to optical images, we didn't find any large overall georeference issues. In sum, we cannot confirm the problems the referee heard about.*

Line 100: These classes must be explained earlier.

author reply: *We have rewritten this paragraph and removed the reference to the RGI surge classes in the text of the manuscript (line 108-111). We included the classes in the text of the supplement, Section 1, and the classes are still included in Table S1.*

Line 140: Another limitation is that the algorithm fails in cases where glacier surge does not change the geomorphology to an extent which can be detected using radar backscatter changes.

author reply: *We agree with the reviewer that if a surge does not change the surface roughness of the glacier, this surge will not be detected by comparing Sentinel-1 backscatter. At the same time, we doubt it is very likely that a surge does not result in a different glacier surface roughness. Does the referee have a specific case of such a surge in mind?*

– Lake drainage events abruptly result in elevated radar backscatter as water-filled lakes (specular reflection: low backscatter) empty and expose the icy lake bottom surfaces (high backscatter).

author reply: *We completely agree. In fact, we show an example of changes in a lake detectable in the NDI image in Figure S3d, as described in the second paragraph of Section 2 in the Supplementary Material. Note, however, that this example is a proglacial lake, not a lake on the glacier itself. We have added an arrow to Figure S3 to draw more attention to the lake changes.*

3 pers. commun. H. Jiskoot

1 I think a reference/comparison to Herreid & Truffer (2015: https://doi.org/10.1002/2015JF003502) is in order, as you do discuss several other "static" methods of detecting surge-type glaciers from morphological evidence, but this is an automated method based on medial moraine displacement amount.

author reply: *We included a reference to this paper in the introduction (line 19).*

2 In your comparison to reported glaciers you only use the RGI 6.0 classification (thus Sevestre and Benn, 2015). First, there are gross errors in their classification and they were very selective in certain regions: in East Greenland they only classified glaciers as surge-type when there had been an observed surge even though they used my Jiskoot et al (2003) database. If you compare your "newly found" Greenland surge observations in your Appendix table to my maps in Jiskoot et al. (2003; is your reference list) then you can see that several of the glaciers that you list have indeed been reported as having surge evidence. This includes Rosenborg and several nearby glaciers. Further, Sevestre and Benn's classification is now old (we have >10 more years of observations) and glaciers such as Wykeham Glacier South in the Canadian Arctic (which was already classified as surge-type by Copland et al., 2003: https://doi.org/10.3189/172756403781816301, but not in RGI) has now had some further observations of surging (Van Wychen et al., 2021: https://doi.org/10.1080/07038992.2020.1859359). So; these are just two examples of where your detection of surge-type glaciers is not really a new detection, but rather an independent confirmation of what had already been observed as surge-type by others. I suggest you are a bit more thorough and careful in your reporting on specific glaciers.

author reply: *Both Rosenborg Glacier and Wykeham Glacier South are not among the 69 glaciers where we detected surge activity, but among the 18 where we detected backscatter change that we didn't classify as surge activity (last part of Table S1). Those we did not classify as such as we were not sure the backscatter change was due to surge activity or to another process such as calving instability. If we understand Wychen et al. [2020] correctly, they ascribe the recent acceleration of this and other Arctic Canadian glaciers to dynamic thinning caused by climate change or calving instability, not to surge activity. This supports our choice not to classify this backscatter change as indication of surge activity. In addition is Wykeham Glacier South included as a surging glacier in the RGI (class 3). So these two specific examples do not directly affect our results. Nevertheless, it is a fair point that also among the 45 glaciers we found to have surge activity but were not classified as such in the RGI there could be glaciers that have been identified as surge-type in literature without this being included in the RGI. An example of this is the glacier in East Greenland with GLIMS ID G330976E68786N that is classified as "likely surge-type" in Jiskoot et al. [2003]. We included a few sentences on this issue in the Discussion (line 162–166).*

References

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