Author response to Reviewer 2

We thank this reviewer for their very useful and carefully considered comments that will help to improve our paper. Their comments are repeated here in black text and our replies are in blue below.

General comments:

This manuscript investigates the seasonal evolution of supraglacial meltwater features in the Russell/Leverett glacier catchment, SW Greenland, with a focus on drainage distribution and characteristics from a low (2018) and high (2019) melt year and assess its implications, including ice velocity and potential drainage response in future warmer years. Of particular interest is the attempt by the authors to include small (i.e., <0.0495 km^2) and shallow meltwater features (e.g., slush), which can be overlooked in mapping studies, however important to consider. The authors use a pre-existing method (Corr et al., 2022) for all supraglacial meltwater feature extraction and then seek to partition these features into those that drain and refreeze, with links to ice velocity events.

The main findings are that (i) surface meltwater feature characteristics and distribution differ between a high (2019) vs low (2018) melt season, with meltwater features developing earlier (May) and occurring further inland (2000 m a.s.l) in the high melt season (2019); (ii); small meltwater features (<0.0495 km^2), predominately small SGLs, are important features of the system with their drainage prevalent at lower elevations and; (iii) the drainage of features, including those that are small, can generate an ice velocity response, with inference that a sustained speed-up in ice flow may occur at this catchment in the future.

We are pleased to see that this reviewer has understood the main findings of our manuscript and also that they appreciate our approach of including small meltwater lakes and understand the importance of these features.

Whilst I appreciate the effort put into the development of this study and manuscript, my view is that this study is not particularly novel in terms of the methods used (well-versed in literature) or the location of the study area in SW Greenland, which has been well documented and the focus of many supraglacial hydrology studies over recent years. Additionally, whilst you present the importance of small meltwater features (<0.0495 km^2), particularly small SGLs, and appreciate why they were included in terms of your findings (as agree, they are important!), I struggle with your use of the term '*all meltwater features'.* From Figure 1, it seems your river and stream network is lacking (even with the resolution of imagery used), with only larger portions of rivers extracted, often associated with either inputting or outputting an SGL (interpreted from Figure 1). Therefore I think your use of the term *'all meltwater features'* insinuates complete supraglacial drainage network maps and analysis (including smaller, shallower features such as the river and stream network) across the Russell/Leverett catchment, which is misleading as believe this is a basic supraglacial network at best. I therefore think there needs to be increased clarity of this or further mapping to be undertaken.

We agree that the specific methods we use are not particularly novel, however developing novel methods was not the aim of our study. Having said that, we note that we do adapt methods by the addition of extensive manual enhancement in order to accurately delineate small meltwater features, and in our revised paper, we also adjust NDWI thresholds to better distinguish shallow meltwater.

We agree that our original approach was limited in its ability to delineate channels. To address this, we will add delineated surface channels (defined as all linear meltwater features > 1000 m long) to our dataset using the automated methods from Yang et al. (2016). We also slightly adjust the NDWI threshold value in order to delineate shallower slush and better partition lake, channel and slush features.

In our responses below, we include more detail about channel and slush delineation methods, which we will also add to our revised paper.

I am also unsure as to the method used for partitioning meltwater that 'drains' and refreezes' as it has been shown in the literature that meltwater can stay active for much longer (i.e., weeks) post surface melt cessation. I think there needs to be some further clarification as to the simplicity of the method and acknowledgement that meltwater can linger for longer post surface melt cessation. Additionally, a figure showing this occurring in imagery (from your manual interpretation) may help you here, which could be placed in your supplementary information.

We agree that our previous method for partitioning meltwater lake drainage vs. refreeze was overly simplistic and poorly explained. We have now improved this method; please see our extensive response to Reviewer 1 for more details (pages 5-9 of that letter).

In addition, the link to ice velocity and drainage/refreeze events I believe, at times, is rather subjective.

We agree. We are careful to use language such as '<u>appears</u> to perturb ice velocity' within the text. We will ensure that the subjective link to ice velocity is made clearer in the manuscript. Please also see our longer response to Reviewer 1 (pages 4-5 of that letter).

I provide further comments on these issues below.

<u>Major comments:</u>

Feature extraction and terminology:

In Figure 1, you provide your mapped supraglacial meltwater features for 2018 and 2019 (only figure presenting these in the main body and supplementary information, which is a shame), however it mostly looks like only SGLs and some slush have been captured, with the caveat of some larger, wider sections of supraglacial rivers (these networks look rather fragmented and incomplete). After searching one of the images used via Copernicus Browser (2019-07-25) and comparing with other studies in this area which have captured supraglacial features, there looks to be a number of rivers and streams not captured, or fragmented, by your method.

This is a shame as you state in your *introduction 'we precisely delineate all surface meltwater features (i.e SGLs > 0.0018 km², as well as rivers and slush)'* (Line 85) and within your methodology you state: *'Our threshold values are lower than those used by Corr et al. (2022), which was a deliberate choice as we wanted to detect shallower meltwater features (including small streams and slush) than those considered in that study'* (Line 150-153). However I do not see many small, shallow streams or continuous river channels captured (perhaps a few within the slush regions at most). It is my understanding that a significant part of this paper was to map *all supraglacial meltwater features*, in particular those of small, shallow size, across the catchment to examine feature distribution, evolution and low-high melt year comparison, with an emphasis on their importance albeit their size. I therefore think there are a number of things that need to be addressed in this manuscript and a few avenues which could be taken to improve the dataset and/or clarity in this paper:

1) As stated already, it looks like you have only captured segments of some of the primary (larger) supraglacial river channels within your drainage network, mostly where they input or output an SGL. Therefore, I think you need to make this clear in your introduction and/or methodology that you only partially-capture these types of channels (i.e., primary rivers) and not smaller stream-type networks (i.e., secondary tributary networks which are shallower and transient) and explain why (method limitation?). I think to aid this, it would help to give brief definitions of these differences as per the literature (e.g., Pitcher and Smith, 2019) in your introduction and then, throughout the

manuscript, make sure you refer to these features as 'rivers', rather than interchangably between 'streams' or 'rivers/streams' to make it clear (as you have in some areas of text).

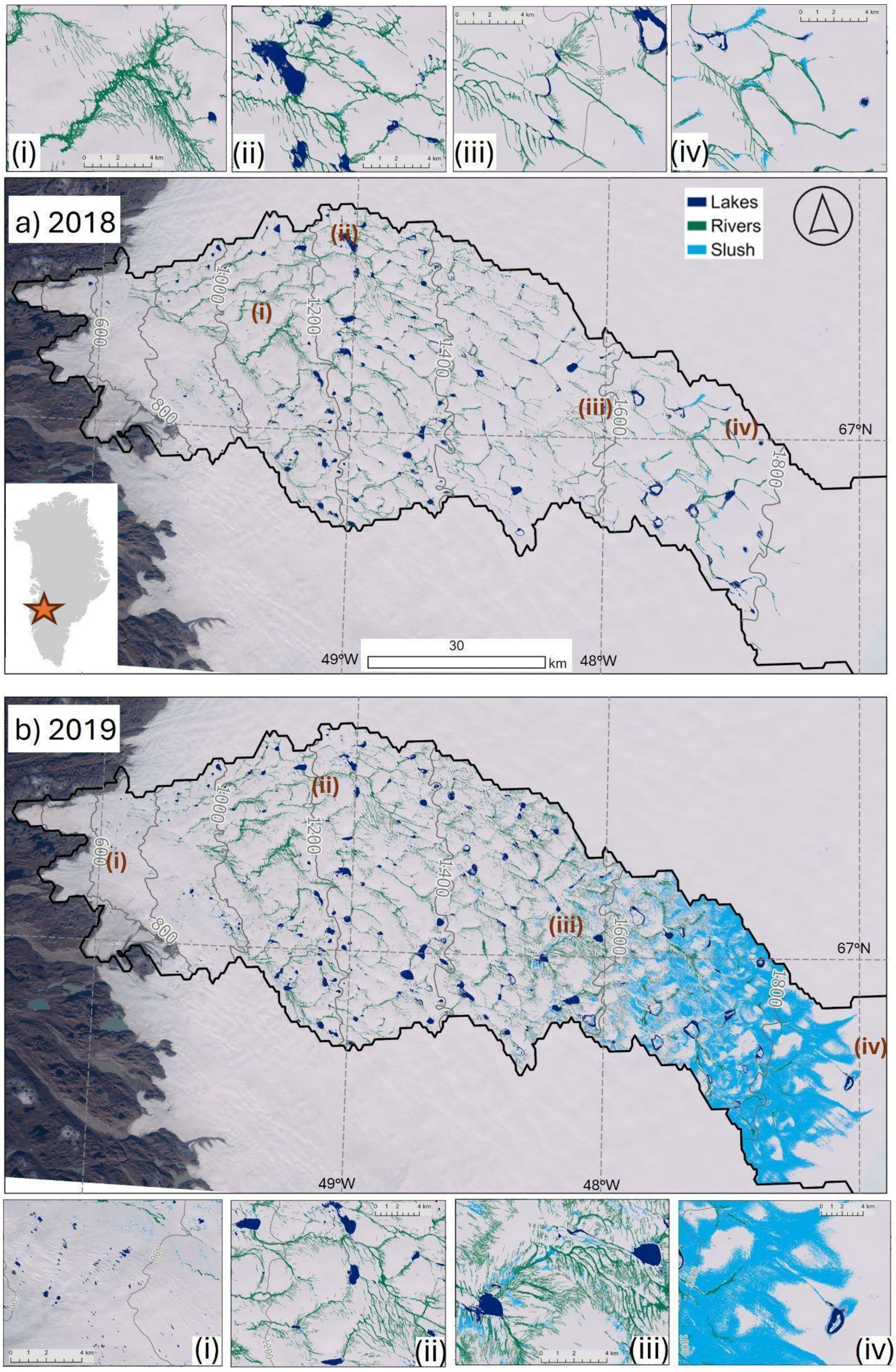
We apologise for the confusion in our original paper. In summary, 'channels' in our study include both rivers and streams, but we do not differentiate between the two. In our revised paper, we will add the following to the introduction: *'Supraglacial channels can be categorised as rivers or streams (Smith et al., 2015), however in this study we do not differentiate between these two types of channels. Instead, we define all channels as being linear meltwater features that are > 1000 m in length.'*

2) After performing NDWI and subsequent thresholding (via Corr et al., 2022), you state you partition your features into slush and rivers via manual interpretation of geometry and colour. I think an additional figure showing these partitioned features (lakes, slush and rivers) mapped would enable the reader to visually understand and assess their differences (i.e., the distribution of individual meltwater features, the overall collective drainage network characteristics and meltwater drainage behaviour – particularly that of smaller SGLs in lower elevations which are discussed) across the two melt years. This could be completed by including multiple mapped subsets in a new figure (within the results in either *Section 3.1* or *3.2*) showing the distribution and subsequent differences in features across selected dates and/or zoom in sections for both the 2018 and 2019 melt seasons.

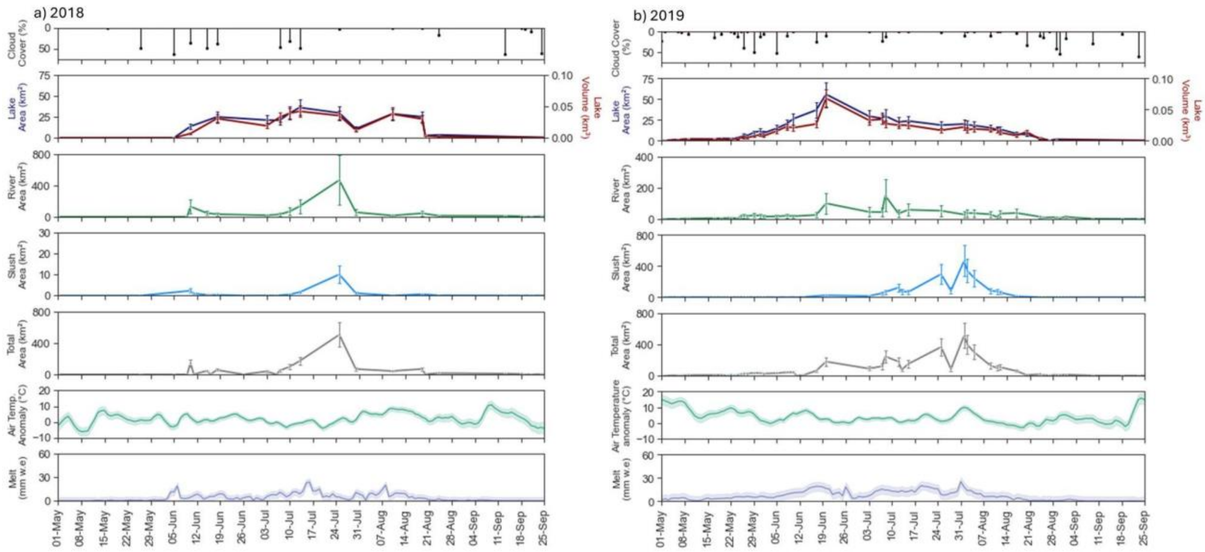
We agree that it would be useful to show the meltwater distribution and differences between 2018 and 2019 melt seasons. Below, we have included a revised version of Figure 1, which includes additional zoom in/out sections. This also clearly highlights the detail we are now able to capture by adding additional slush and new channel delineation methods

3) Following on from my previous comment about an additional figure, this would also help show how the network evolves seasonally across the two distinct years. A particular interest, as you discussed, is the drainage of small meltwater features (particularly at lower elevations) and how slush develops in these two years. In terms of slush, so far, I can only see your higher elevation slush in Figure 1 (from your maximum extent). It would be therefore interesting to see how slush develops during the melt season alongside your other features.

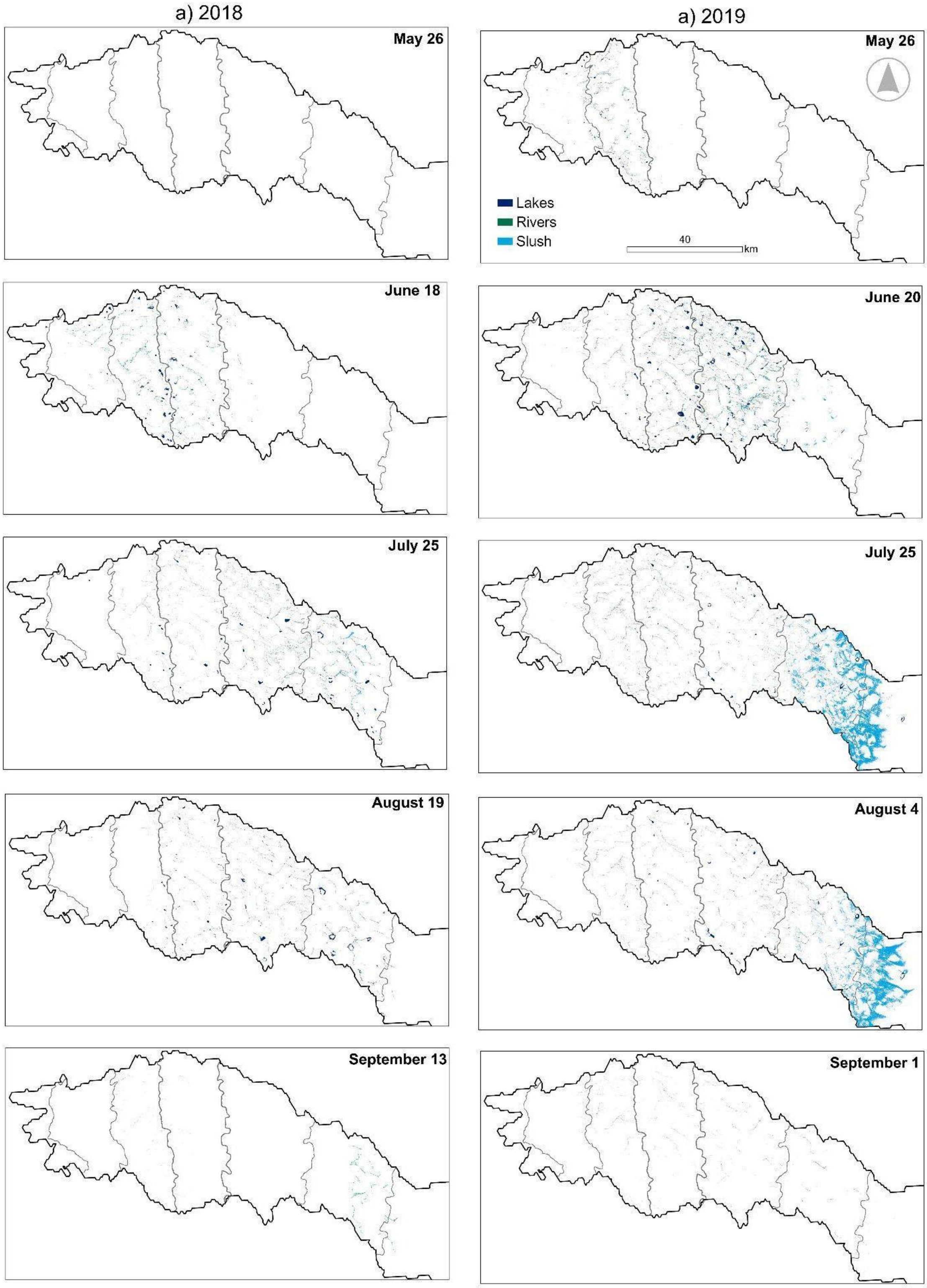
We have separated our lake, channel and slush features to produce a revised Figure 3 (below, on page 5). We have also created a new supplementary figure (see page 6 of this letter) that details the seasonal evolution of meltwater features throughout both melt years. We acknowledge that it is difficult to see the detail in this figure, so we will also upload a GIF version of this figure alongside our revised paper.



REVISED Figure 1: Maximum areal extent of supraglacial meltwater features in (a) 2018 and (b) 2019 within the Russell/Leverett Glacier catchment derived from ArcticDEM (black outline). All meltwater features are superimposed during each melt season in our dataset; slush is light blue, channels are green and lakes are dark blue. Elevation contours from the ArcticDEM are shown in grey (m a.s.l). Background is a true colour Sentinel-2 image acquired on 26/09/2019. Inset depicts the location of the catchment within the southwest GrIS. a(i) depicts a supraglacial channel system, a(ii) shows lakes linked with channels, a(iii) is an example of underdeveloped lakes in the ~1600 m region of the catchment, a(iv) depicts slush and channels in the percolation zone (~1700 m). b(i) shows small lakes close to the margins of the *catchment, b(ii) highlights linked channels and lakes, b(iii) shows interconnected lakes, channel and slush, b(iv) depicts high-elevation (˜1900 m) slush, channels and the highest elevation lake (1880 m) in our 2019 dataset.*



REVISED Figure 3: Time series of total areas of lakes (dark blue), channels (green), slush (light blue) and all meltwater features (grey) in (a) 2018 and (b) 2019 from L8 and S2 imagery. Area error bars represent uncertainty of automatically delineated features compared to a manually delineated dataset. Lake volume is given in red error along with an estimate of uncertainty determined by comparing lake depth to Melling et al. (2024). Also shown is cloud cover percentage (black bars), RACMO 2 m air temperature anomaly (light green line) from the 1958 - 2019 catchment average with the spatial standard deviation (light green shading), and RACMO total daily melt (mm w.e.; light blue line) with the spatial standard deviation (light blue shading). Note that the y-axis ranges are different for the channel and slush areas between (a) and (b).



NEW Supplementary figure: Areal extent daily snapshots of supraglacial meltwater features in 2018 (a) and 2019 (b) within the Russell/Leverett Glacier catchment derived from ArcticDEM (black outline). Slush is light blue, channels are green, and lakes are dark blue. Elevation contours from the ArcticDEM are shown in grey.(Note, we will also include a GIF version of this figure in the Supplement.)

4) You could, time- and review-dependent, try to adapt your thresholding method or perform further manual delineation to capture more of the smaller network (i.e., a more complete supraglacial river and stream network) alongside your other smaller features (SGLs) to give a more hollistic view of supraglacial meltwater, and its drainage as a whole, in this catchment. Supraglacial rivers and streams can make up a large portion of the supraglacial network, and so are important to consider alongside your captured, smaller SGLs. This is a suggestion to uphold the use of '*all meltwater features' to* elevate the paper, however, I understand that this may be a considerable undertaking.

We will remove any partially delineated channels from our original data set and replace them with the channels in our new separate channel dataset. To describe the methods we use to now delineate these channels, we will add text along the lines of the following to our revised methods: '*Supraglacial channels have different physical and spectral characteristics to SGLs and thus we delineate channels using methods developed by Yang et al. (2016). We extract channels based on their Gaussian-like cross-sections and longitudinal open-channel morphometry (Lu et al., 2020). Meltwater features are first enhanced by applying an NDWI to the image. A band-pass filter ramped between 1/200 and 1/40 m-1 (Yang et al., 2017) is then applied to remove low frequency background and high frequency noise. This is followed by Gabor filtering (set to < pixels 2 width) to amplify the cross-section of channels. A path opening operator (with a minimum length of 20 pixels) is then implemented for better connectivity. We then remove any features < 1000 m in length to reduce classification uncertainties. A global threshold of 5 (for T22WEV S2 and all L8 tiles) or 10 (for T22WFV S2 tiles) out of 255 was then used to extract the Channels (Rawlins et al., 2023; Lu et al., 2020). Finally, channel features were pologonized and manually cleaned up (e.g. by the removal of previously delineated lake and slush features) before subsequent analysis.*'

Additionally, we have now also added extra detail to the slush dataset by slightly decreasing the NDWI and NDWIice thresholds from 0.25 and 0.24 to 0.15 and 0.14, respectively. This is following Bell et al. (2017) and Yang et al. (2013) who use a lower threshold value to detect slush than we did previously.

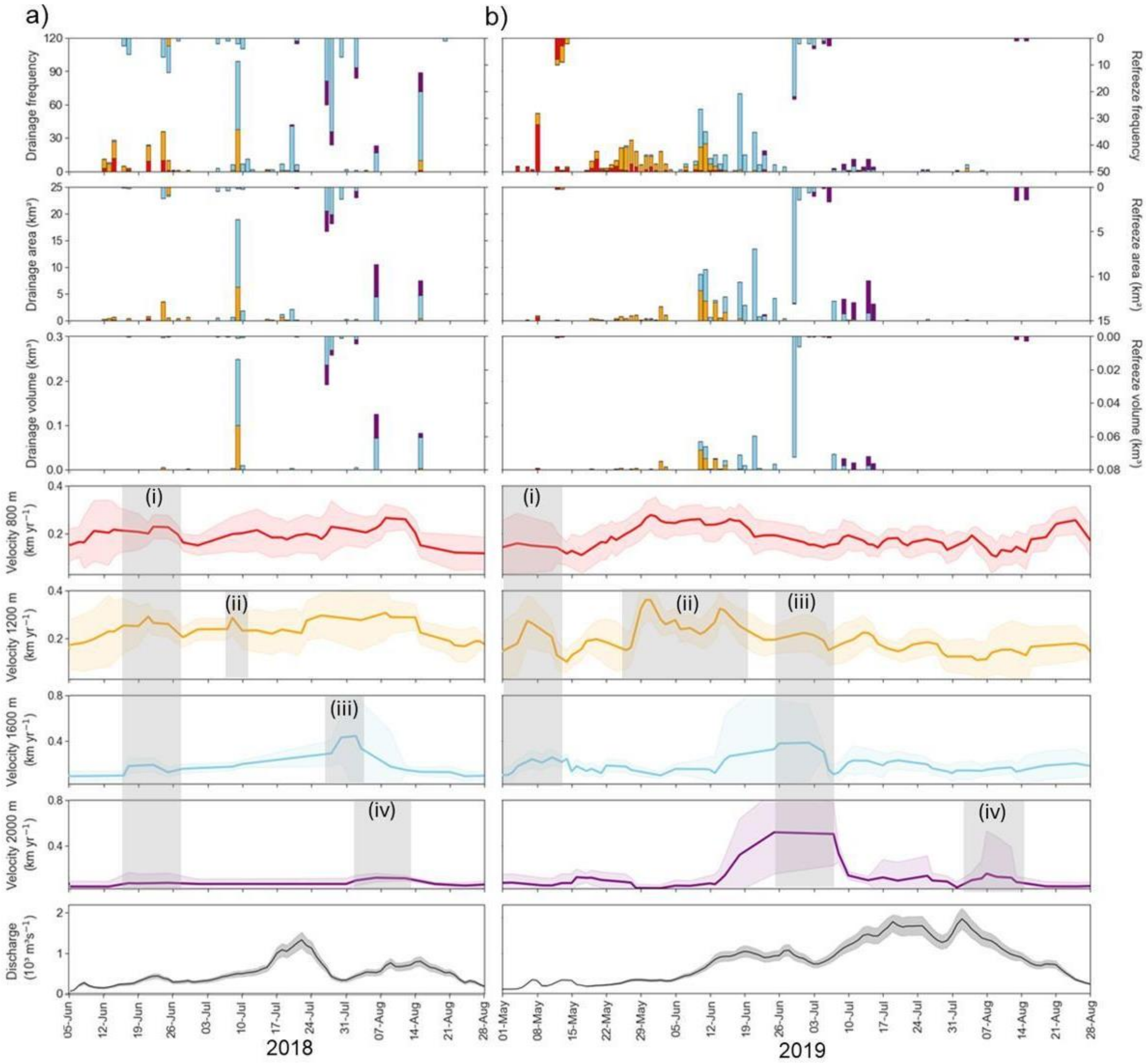
Ice velocity:

I have no problem with the use of NASA MEaSUREs ITS_LIVE data – it is a well-used and useful data resource. However, there is a lack of acknowledgement of the error and uncertainity regarding this data and implications this may have on your inferred results. For example, a lack of error envelopes for your ice velocity data presented in Figure 5 (particularly important for higher elevation, noisy data). You present an estimate of uncertainty in your Figure 3 – it would be good to do the same in Figure 5.

We have edited Figure 5 (pasted below) to include uncertainty calculations. Please also see our response to Reviewer 1 for more details (particularly pages 4-5 of that letter, which also includes a new supplementary figure).

Secondly, the link between your drainage/refreeze events and impact on ice velocity looks highly subjective and are difficult to interpet and verify from Figure 5 as you do not separate these events by elevation (like you have done with ice velocity) – consider improving this figure.

We have now edited Figure 5 by separating drainage/refreezing events by elevation REVISED Figure 5 below).



REVISED Figure 5: Time series of lake drainage and refreeze within the Russell/Leverett catchment in a) 2018 and b) 2019. From top to bottom: daily frequency of lake drainage/refreeze events (i.e., the number lakes that drained or refroze); total daily lake area loss; total daily volume loss; mean ice velocity at 800 m a.s.l (red), 1200 m a.s.l (orange), 1600 m a.s.l (blue) and 2000 m a.s.l (purple). Shading indicates the uncertainty taken directly from the ITS_LIVE data product (Gardner et al., 2018; 2023). Vertical grey shaded columns depict, and velocity perturbations discussed in the text (vertical grey shaded columns, labelled i, ii, iii, and iv); Daily values of meltwater discharge through the Watson River (black line) and associated uncertainty (grey shading). Note that the x-axis date ranges are different for each year, constrained by the first and last meltwater feature drainage events in each melt season. Also note that the y-axis for the velocity plots differ between elevation bands.

You also refer to an ice velocity increase coinciding with a period of refreezing in July 2019 (Line 391). How do these two mechanisms work?

We will remove this statement from the manuscript as we do not have enough information to speculate about these two mechanisms.

Minor comments:

Units: You interchange your use of units, from km^2 to m^2. For example, when defining small meltwater features you use km^2 (e.g., 0.0495 km^2), however when presenting your results, you refer to your meltwater features in m^2. Please choose one unit for consistency and comparison of results.

We will ensure that we have unit consistency in our revised manuscript.

Catchment reference: You refer to the Russell/Leverett catchment throughout the manuscript and provide its outline in Figure 1. Is this catchment delineated yourself (e.g., via flow routing) or is this an already pre-defined catchment? If the former, please provide a method as to how this catchment was delineated and what datasets were used. If the latter, please cite the appropriate data source.

This is a pre-defined catchment created using ArcticDEM, which is stated in our original manuscript, i.e.: '*The surface drainage basin is derived from ArcticDEM Digital Elevation Model at 1 km resolution' (L 100).*' However, we will change 'basin' to 'catchment' to make this clearer.

Specific comments:

Line 44 – *'SGLs generally form in early summer enlarge in area and depth between spring and summer as they accumulate water…'.* This sentence does not fully make sense. Maybe add an *'and'* before enlarge or *',enlarging in area…'*.

Done.

Line 60 – could include additional references to remote sensing studies here (Lu et al., 2021; Turton et al., 2021; Rawlins et al., 2023; Zhang et al., 2023).

Done.

Line 73 – *'…the drainage of meltwater features was not considered*.' Drainage how? I am assuming drainage subglacially, but could be more explicit here as some of the papers cited assess how meltwater moves or is 'supraglacially-drained' across the surface over a single/multiple melt seasons.

We will edit this to say: '*the vertical drainage of meltwater from the ice sheet surface to the bed was not considered*.'

Line 95 *(Figure 1)* - Your figure shows maximum areal extent of meltwater features in 2018 and 2019. Is this from a particular date in the season or an amalgamation of your features from separate mapped dates across the season into one map?

We will edit this to say: …'*All meltwater features are superimposed during each melt season in our dataset*'.

Line 102 – This study area is well known for its prevalent surface hydrology features including lakes, rivers, and moulins. Could you additionally provide an upper elevation estimate from previous studies (including refs)?

We will add: '*Supraglacial lakes and channels have been observed to drain into moulins at 1600 m a.s.l in our study area (Yang et al., 2021). Although, it is suggested that drainage by new hydrofracture events is restricted to elevations < 1600 m due to low surface strain rates in higher elevation regions (Poinar et al., 2015)'*.

Line 143 – the blue and green filter you use. What is this? A band combination? Some clarity would help.

We will edit to say: ' …as well as an additional blue and a further green filter.'

Line 146 – Include the citation and subsequent reference for McFeeters (1996) – paper for the traditional NDWI index (using green and NIR bands).

Done.

Line 171 – how narrow were the channels that were manually added? Are they still larger, primary rivers (as commented on earlier)?

See previous comment re: the change in our channel delineation methods.

Line 260 – would be helpful to give a clarifying statement as to the purpose of ice velocity data for the study to make this clearer.

We will : 'We use ITS_LIVE velocity as ancillary data to support our analysis. Its purpose is to infer links between lake drainage events and ice speed up through basal sliding.'

Line 285 – You refer to both linear stream and river features. Maybe just state rivers (as per my previous comments).

As mentioned earlier in this letter (page 7), we are now able to delineate both streams and rivers using our new channel delineation method, however, we do not see the need to differentiate between these two features. As such, we have changed our terminology to 'channels', which we define as river and stream features > 1000 m in length.

Line 412 – Whilst I think it is relatively clear the contrast between surface meltwater characteristics and distribution (which would be helped by an additional figure) between years, I think I would refrain from saying there is a 'clear contrast' for drainage dynamics, as this looks to be subjective.

We will ensure that the subjective nature of the contrast in drainage dynamics between years is represented in the revised manuscript and we will remove any phrasing that suggests otherwise.

Table S1 – From the main body it was stated that 'Images with > 50% cloud cover were omitted' (Line 122). However, in Table S1, scene IDs have been included with cloud cover >50%. Do these scene IDs need to be removed from the table? Or were these scene IDs (>50% cloud) used? If they were used, rectification in the main body is required.

We initially limited the cloud cover to < 50% based on the image metadata. However, after manual inspection, it appeared that the cloud cover algorithm used to create the S2/L8 image metadata misclassified some white ice/snow as cloud. Therefore, we manually checked all available images and included misclassified images in our dataset. We will update the text in our manuscript to explain this.

<u>Technical corrections:</u>

Line 126 – Capitalise 'Level' Done.

Line 131 – Missing bracket for citation Added.

Line 133 – decide whether to capitalise (or not) the word 'bands'. Some inconsistencies. Fixed.

Line 139 – you have already given the abbreviation for Normalised Difference Water Index (NDWI) on Line 89. You could therefore remove this on Line 139 if you wish (however, if retaining, please capitalise 'Normalised Difference Water Index' for consistency). Fixed.

Line 217 – replace 'ocean' with lake or SGL

'Ocean' is correct. See: Sneed and Hamilton (2007). We have added this reference to the text.

Line 296 – At the end of the sentence, either remove 'at' or the brackets.

We do not see this issue on line 296, so we wonder if the reviewer has the line number wrong.

In places, you have a citation and Figure number in separate brackets in immediate succession. Combine these using a semi-colon (Corr et al., 2022; Fig. 2).

Done.

References not in the original paper (which will be added to our revised paper)

Bell, R., Chu, W., Kingslake, J. *et al.* Antarctic ice shelf potentially stabilized by export of meltwater in surface river. *Nature* 544, 344–348 (2017). https://doi.org/10.1038/nature22048

Lu, Y., Yang, K., Lu, X., Li, Y., Gao, S., Mao, W. and Li, M.: Response of supraglacial rivers and lakes to ice flow and surface melt on the Northeast Greenland ice sheet during the 2017 melt season, J. Hydrol. 602, 126750, 2021. https://doi.org/10.1016/j.jhydrol.2021.126750

McFEETERS, S. K. (1996) 'The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features', International Journal of Remote Sensing, 17(7), pp. 1425–1432. https://doi.org/10.1080/01431169608948714.

Sneed, W. and Hamilton, G.: Validation of a method for determining the depth of glacial melt ponds using satellite imagery, Ann. Glaciol., 52, 15–22, https://doi.org/10.3189/172756411799096240, 2011

Turton, J. V., Hochreuther, P., Reimann, N., and Blau, M. T.: The distribution and evolution of supraglacial lakes on 79° N Glacier (north-eastern Greenland) and interannual climatic controls, The Cryosphere, 15, 3877–3896, https://doi.org/10.5194/tc-15-3877-2021, 2021. https://doi.org/10.5194/tc-15-3877-2021