Dear Editor

Many thanks for overseeing the review of our paper: '*Unravelling the long-term, locally-heterogenous response of Greenland glaciers observed in archival photography*'. We are very pleased to see the positive comments made by both reviewers on our work. We appreciate the recognition of just how much work has gone into the processing of this imagery, and our focus on lesser-studied glaciers. We were particularly pleased to read that Reviewer 2 considered our work to be 'an important scientific contribution' and that our 'results deserve to be published', while Reviewer 1 considers that (with some changes) our paper 'can provide an impactful contribution'. We are also appreciative of the thorough reading of our work by both reviewers, and as a result, they have raised a number of issues and concerns which we now deal with one by one. Each relevant statement from the reviewers is indicated by red text, whereas our responses are in black text. Here we provide responses to Reviewer 2 only. We respond to Reviewer 1 in a separate document.

Reviewer 2

It is unclear to me why first a orthomosaic is created after which it is georeferenced to a DEM. This seems like an inaccurate approach. It would result in a more accurate result if GCPs were introduced earlier in the flow, during SfM-processing. Perhaps I am misunderstanding your workflow… Under all circumstances, then I would like to see a work-flow diagram, to be sure that I have understood to process chain correctly.

Thank you for this comment, we agree that the description of the processing pipeline was insufficiently detailed in the original version of the manuscript. We will improve the explanation in the revised version to incorporate the additional details below and add a work-flow diagram (to supplementary material if space in the main paper does not permit).

In fact, GCPs *were* used during the structure-from-motion processing. In detail, our pipeline was as follows. We produced an initial 3D model using Agisoft Metashape without GCPs in order to check if there was enough overlap between images and to analyse the images in terms of their quality. We also produced masks where they were needed: we removed parts that might have changed between images like icebergs on water, photographic plate boundaries, sky and mountains in the distant background. In the case of the 60s images we masked parts of the image that we were not planning to use, due to the size of these images, this procedure significantly reduced the processing time.

When usable images were chosen and masked we placed GCPs on the images with corresponding 3D locations on our reference DEM (ArcticDEM), then we allowed the SfM algorithm to additionally find tie points between the images. At this point we analysed the GCPs. If their reprojection errors were significant we double checked if their placement over the series of images was correct. If so, and the error was still large, we removed them from processing (assuming the error resulted from errors in ArcticDEM described for example in Meddens et al. 2018). After that check we processed tie points again and produced orthomosaics from the 3D models. So, to clarify the specific question: orthomosaics are georeferenced as part of the SfM processing pipeline, not as an independent step afterwards.

Since you are not producing a DEM, then why are you not using an image source as master for the GCPs? It seems like an inaccurate approach for rectification of an image.

Again, the improved explanation we propose above will help clarify this misunderstanding. Some of our images (specifically from the 1930s BAARE dataset) are highly oblique. An orthomosaic cannot be produced from these images without going via a 3D model to compensate for the significant occlusions and perspective changes to produce a top-down orthomosaic. Hence, we require 3D GCPs for structure-from-motion and cannot rely on calibrated/georeferenced satellite images. In addition, due to the highly variable appearance over the large time spans we work with, image-based features were rarely useful for matching GCPs. Using a reference DEM and 3D GCPs allowed us to use topographic features for GCPs which were more easily identified and matched in our images and reference DEM. Finally, for consistency we wanted to have one unified ground truth model across all datasets and so using ArcticDEM (and overlapping sets of GCPs) for all datasets was the best choice.

Why are you producing a 1985 ortho with GCPs from ArcticDEM, when an ortho already exists with GCPs from in-situ measured points? You are also referenceing the correct paper, Korsgaard et al. 2016, from which the ortho and DEM was published.

Thank you for this comment, which is certainly a valid question. As mentioned above, we wanted to use the same processing pipeline and reference model for all the data sets. Thus instead of using a ready product we processed the images on our own. Also, we wanted to have more freedom in producing the mosaic with textures and pixel size that we could compare to other data and our own processing pipeline allowed for that.

You mention 58 images used in the text but only 30 in the table. You also mention GCPs from SDFE associated with the images - are these the ones you have used?

There were 58 images originally obtained but due to various reasons described above and also lack of coverage (images of sea or ‘white-on-white’ Greenland ice cap images) we had to limit the number of actually used images.

We do not mention anywhere in the text anything about GCP from SDFE and we did not use either the existing GPS (GNSS) points nor Doppler points as GCP. We used only GCP from ArcticDEM and, as often as possible, we used the same points between all models. The 1930s images covered a relatively small area since the oblique images were taken from low height and the photo cover is not continuous over the shore. Taking all this into account the double coverage of those GPS and Doopler points would have been extremely poor thus we decided to work with a more flexible data set (ArcticDEM) that allowed us to more freely choose GCP positions.

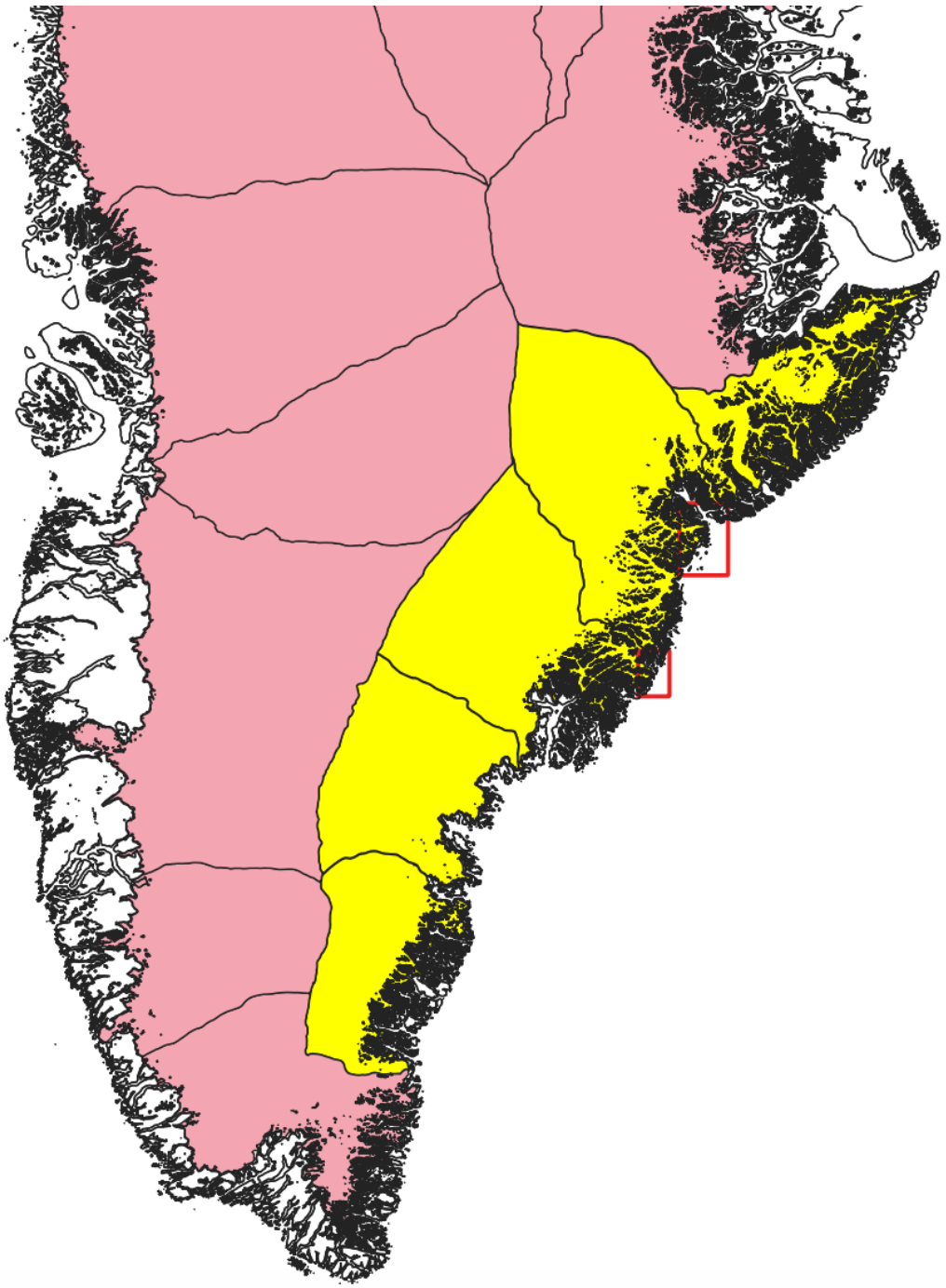
There is no information provided on how you reach the 2D and 3D errors in table1. From the way I understand your processing, I don't see how you can have a 3D error, when you state that: "For geolocalisation of the orthomosaic….. the ArcticDEM model was used. If you have a georeferenced 3D product (DEM) than it would be very nice to see it included in the manuscript.

We used Agisoft Metashape for the creation of orthomosaics. We use 3D GCPs and thus Metashape produces a 3D error for them. We agree that, in the case of orthomosaics, this 3D error does not carry significant information and will be removed from the next version of the manuscript. The DEM model is being produced in the further steps of this project however due to the complexity of the datasets we are still improving its production. Also we feel that with the amount of information that we already have from the orthomosaic and additional temperature data, showing preliminary results related to a DEM would overcrowd the manuscript and take the attention away from interesting results of already fully processed orthomosaic data.

I would like some more information on the SMB model and specifically the area of the model the results that you are showing here represents. Since it is shown as a point/line graph does it represent the combined glacier area studied or a point in the region? Would be interesting to see the SMB plotted on a map.

The SMB results are taken from the *SE region*; Greenland wide SMB model performed and presented in Box (2013), Box et al. (2013) and Box and Colgan (2013). Since they are the results of a modeling procedure they cannot be considered strictly as observations. The *SE region* is defined by portioning the ice sheets' drainage basins (we have attached a screenshot of the basins we believe are used for this region - highlighted in yellow). According to the mentioned papers, the cross validation with GEUS/ Denmark Meteo institute of 'SE Greenland' meteorological records proves the models of this region to be highly accurate. We do agree that a spatial SMB plot provides an extremely suggestive visual representation of this dataset. However, those plots have already been done in Box (2013), thus this would not add any extra information for our study. We will make explicit reference to these plots in the revised version. The value provided in the graph is an average for this region. We choose that since it allowed for better time step visual correlation of used temperature and mass balance and also better accompanied box plots showing magnitude of change over the different time-steps (fig. 6).

- Box, J. E. and Colgan, W.: Greenland Ice Sheet Mass Balance Reconstruction. Part III: Marine Ice Loss and Total Mass Balance (1840–2010), Journal of Climate, 26, 6990 – 7002, https://doi.org/10.1175/JCLI-D-12-00546.1, 2013.
- Box, J. E.. Greenland Ice Sheet Mass Balance Reconstruction. Part II: Surface Mass Balance (1840–2010), *Journal of Climate*, *26*(18), 6974-6989. Retrieved Jan 4, 2022, https://journals.ametsoc.org/view/journals/clim/26/18/jcli-d-12-00518.1.xml, 2013
- Box, J. E., Cressie, N., Bromwich, D. H., Jung, J., van den Broeke, M., van Angelen, J. H., Forster, R. R., Miège, C., Mosley-Thompson, E., Vinther, B., & McConnell, J. R.. Greenland Ice Sheet Mass Balance Reconstruction. Part I: Net Snow Accumulation (1600–2009), Journal of Climate, 26(11), 3919-3934.https://journals.ametsoc.org/view/journals/clim/26/11/jcli-d-12-00373.1.xml, 2013



It appears that very few of the glaciers studied have data from the 1930s. Table 2 shows only 7, while fig 3 shows 18. How come have you chosen not to focus only on the glaciers that have the long record. I agree that adding more glaciers gives the dataset more value, but I am missing a justification and most importantly some criteria for your selection of additional glaciers.

Thank you for this comment. We agree that the criteria used there are a bit vague however after much deliberation we decided to include more glaciers than only the 30s data set glaciers. This was dictated by two factors: first was the use of the 60s data set from the

CORONA mision. Due to its complexity this dataset is rarely used and has never before been used to produce data for this part of Greenland, thus it is an interesting result on its own. Second, while mostly focusing on the areas covered by 30s data we produced orthomosaics of the surrounding glaciers and then observed that, even with fewer time steps, these interactions are interesting. We observed that neighbouring glaciers react very differently in similar circumstances and thus decided that this is worth exploring. Also in some cases we were missing some time steps - for example we had 30s and 80s data but no 60s data (due to snow/cloud coverage) thus the lack of one time set is not limited to only 30s data. To summarise, taking into account an enormous time sweep that we are covering and the technical capabilities of each era of photography it is understandable that some data will be missing and we did not want to limit our data set even further just in order to unify the time steps.

Fig 6 is great – would it be possible to combine it with fig 7, 8, and 9, for a better overview?

Thank you for this suggestion. As described in our response to reviewer 1, we agree with the suggestion to combine figures 7, 8 and 9 into one figure (and we show a preliminary version of how this combined figure will look). However, it is not possible to also include figure 6 and still fit all of the content onto one page. So we propose to keep this figure separate.

It would be nice to see on a map from where the temperature is coming – both air and SST. There is no information provided from which grid cell you have extracted the SST. I am not sure what is meant by mean annual maximum and minimum temperatures – can you please explain?

Thank you for this comment. Air temperature used in this paper is coming from Tasilaaq weather station (65.60°N, -37.63°E). This is the longest air temperature record in the region thus is the most representative data source. SST temperature is a combination (average) of values taken from the 1 degree grid cells (67°N and - 31°E -32°E) closest to our study region - this information will be added to the text. The mean annual maximum and minimum temperatures (wrt air temperature) are the average (mean) of the maximum and minimum temperatures recorded for that year (annual).

Several places in the text is mentioned mass loss, you are not providing data to support these statements, and can with what presented only describe retreat.

We have removed mention of mass loss where this was based on a reading of retreat rates. However, we retain mentions of mass loss when we are discussing surface mass balance changes.

In your conclusion you write that there is been a temptation to differentiate between region. I suggest you reword this. Subdivision into regions makes perfectly sense, as climate, ocean

currents, landscape and geology varies on a regional scale. While there may be variations within the regions, there are plentiful patterns that warrant these subdivisions.

We agree, and reviewer 1 also raised this point (see response to their comment). We made some modifications so that it is clear that we acknowledge the importance of regional studies. We reinforce this point in several locations (see reviewer 1) and finally state in the final paragraph of the conclusions: ‘In the past, regional investigations across the Greenland Ice Sheet have been key (e.g. Mouginot et al., 2019, King et al., 2020). This has been important for exploring broad scale regional behaviour and responses. However, our work here, in which we have focused on glacier-to-glacier heterogeneity, shows that within regions there is great complexity, with even adjacent glaciers behaving very differently.’

Additional changes

Towards the end of the first paragraph of section 4.2, we list a series of variables that control glacier behaviour. These are listed and labelled a, b, c etc., but previously we had multiple variables listed as ‘c’. This has now been corrected so the list reads a, b, c, d, and e.