

**Editor Decision: Publish subject to minor revisions (review by editor)**

Dear Editor,

We want to thank you again for all the critical and constructive comments on our manuscript. We have carefully considered your comments. Our point-by-point response to the reviewers' comments follows below. Our replies/actions are indented and given in blue font.

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Line 11: "...and that allow glacier-specific calibration". Unclear what "that" refers to.

In this case "that" refers to the areas that have become ice free. Changed that to "therefore" for clarity.

Line 32: Change "illustrate" to for example "found"

Changed wording as suggested.

Lines 42-44: I suggest changing to: "The change in surface height between 2000 and 2011 was found by differencing a merge of two TanDEM-X radar images (28 January 2011, 4 April 2011) and the SRTM DEM."

Changed the sentence as suggested.

Line 57: Strictly speaking, isn't this an extrapolation? The surface elevation change is extrapolated to the point in time when the GPR thicknesses were acquired.

Yes, the editor is correct. We changed "interpolating" to "extrapolating" in the manuscript.

Lines 58-65: I am not sure that this (very useful) paragraph belongs in the Data section. Consider if this would be a better fit in Section 3 (for example under the description of the experimental set up) or in the Discussion section.

Moved the paragraph to Section 3.3 Ice thickness reconstruction.

Line 71: change: "...being driven by..." -> "...driven by..."

Removed "being".

Line 73: delete "observed"

Deleted "observed".

Section 3.2: This section is now very short and one of the lines is basically repeating what has already been mentioned in Section 2. Consider merging this section with the data description, since the manuscript does not deal with the details of TanDEM-X processing anyway.

Merged this section with the data description.

Line 135: It is good to remind the reader that Experiment 3 is in a different year than Experiment 1+2. For example, the sentence could say "In Experiment 3 (Fig. 1) we now move forward in time to 2011. Here, KG is split into two parts... "

Adjusted sentence as suggested.

Line 141: Change "orientation" to "guideline" otherwise a reader might think that it is the orientation of the glacier.

Changed wording as suggested.

Lines 154-155: Does the consensus map use a constant viscosity? If yes, is that the explanation for the similarity?

The thickness distribution of Experiment 2 is similar to that of the consensus estimate, but it is difficult to explain solely via the viscosity parameter, as the models included in the consensus estimate show non-negligible methodological differences.

Line 161: Which Experiment is being discussed? Exp 1?

Yes, this sentence refers to Experiment 1. Added reference to the text.

Lines 164-165: "Increased mismatch values, especially for borehole C3, might as well be explained by the very flat plateau." What does this sentence refer to? It implies a change between two values but the mismatches decrease from Experiment 1 to 2. Please clarify. Should "Increased" be "Large"?

"Increased" refers to "large" in this case.

Lines 171-173: This sentence: "Despite that no GPR measurements were considered on Mt. Kilimanjaro, the complex topography posed a similar challenge for the models participating in the consensus." combines two seemingly unrelated sentences. It is not clear how the absence/presence of GPR measurements is coupled to the topography. Please clarify.

Changed the sentence to "The complex topography posed a similar challenge for the models participating in the consensus, especially because no thickness observations were considered for Mt. Kilimanjaro."

Line 180: Please mention the mean ice thicknesses found in Experiment 2: "..increased in comparison to Experiment 2 from XXm to 9.3 m and from 23.4m to 26.6 m, respectively."

Added the mean ice thicknesses from Experiment 2 as suggested.

Lines 181-182: "Resolution can be excluded from a 25 m reconstruction in 2011 (not shown)." - > "Resolution can be excluded based on results from a 25 m reconstruction in 2011 (not shown)."

Adjusted sentence as suggested.

Lines 182-185: "Concerning the 2011 outlines, some internal ice-free areas (on both NIF and KG), present in the RGI, could not be confirmed from the coarse Landsat imagery, resulting in thicker ice. The quality difference between SRTM and KILISoSDem is certainly also a contributing factor explaining part of the larger thickness values. "

This part is really crucial in order to understand why there is a difference between the 2000 and 2011 reconstructions. The present version leaves several questions unanswered. Firstly, are the ice-free areas real? If yes, is the difference then due to the (incorrect?) outline from the Landsat imagery? Wouldn't you then have gotten better results if you had incorporated the RGI ice-free areas in your 2011 outline? Secondly, what is meant by quality difference? Quality in what? How do the DEMs differ and how does their difference impact your results?

The ice-free areas on KG and NIF are located very close to the glacier margin, or in areas that have become ice-free by 2011, which means these areas are indirectly accounted for in the reconstruction.

We did however notice ice-free areas mapped in Bohleber et al. (2017). Bohleber et al. digitized their outline and the ice-free areas from a GeoEye-1 satellite image from 2012, which has a higher resolution than the Landsat image we used so we were unable to detect these smaller ice-free spots.

The quality difference between the two DEMs is largely based on different ground resolutions. The SRTM DEM is a global dataset with a 30 m ground resolution, whereas the KILISoSDEM only covers the Kilimanjaro area, but has a 0.5 m ground resolution. With a higher DEM resolution, we can also run the ice thickness reconstruction at a higher resolution, which is especially important to accurately reconstruct areas such as the vertical ice cliffs.

Changed “The quality difference...” to “The difference in resolution...” .

Lines 196-197: The term "data assimilation" is not used in the methods description at all. Considering that the reviewers also asked for more details on this, I ask that you explicitly mention this method, for example, in Section 3.5, e.g., "The method of Fürst et al. uses data assimilation to...". Alternatively, rephrase this part in the conclusion.

We added a brief explanation for the term “data assimilation” to Section 3.3.

Lines 210-211: "We therefore speculate that thickness information from retreat is most useful in areas that have been dynamically more active in the past." This is a very important point and I think it should also be directly mentioned in the Discussion. As it is now it is buried.

We briefly mentioned it in the Discussion Section as well (l. 184f. in the tracked-changes manuscript).

Section 6: This section could do with some streamlining and tidying up. At the moment, report on results is mixed with discussions of the utility of retreat observations and ice thickness measurements. I am also confused by the word "assess" - the new ice thickness map is compared to the consensus map but since the latter is likely wrong it seems counterintuitive to assess with consensus map?

I suggest restructuring the section:

Firstly, report on the findings. Mean ice thicknesses for 2000 and 2011 and how the results compare to the consensus map.

Secondly, the use of observations of glacier retreat to constrain ice thicknesses. From your results it would seem that direct ice thickness measurements are most valuable, then glacier retreat observations and then (in the absence of any data) the consensus model approach.

Thirdly, outlook: In the future multi-temporal satellite information might aid in reconstructing glacier thicknesses with the caveat that complex topography (or other factors) might complicate matters.

We restructured the conclusion as per your suggestions. We assess how our reconstruction is performing in comparison to the current best estimate, which is the consensus estimate.

Fig. 2: I don't see any coloured dots with a magenta outline? I can see magenta contours. Please revise figure caption.

Adjusted the figure caption.

# Brief communication: Glacier thickness reconstruction on Mt. Kilimanjaro

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## Abstract.

Glaciers on Kilimanjaro are unique indicators for climatic change in the tropical mid-troposphere of Africa, but their disappearance seems imminent. A key unknown is their present ice thickness. Here, we present thickness maps for the Northern Icefield (NIF) and Kersten Glacier (KG) with mean values of 26.6 m and 9.3 m respectively in 2011. In absence of direct  
10 measurements on KG, multi-temporal satellite information was exploited to infer past thickness values in areas that have become ice-free and ~~that~~ therefore allow glacier-specific calibration. In these areas, KG is unrealistically thick in the existing consensus estimate of global glacier ice thickness.

## 1 Introduction

Tropical glaciers at high elevations are unique climate indicators for the tropical mid-troposphere (e.g. Kaser 2001, Mölg et al. 2009). As one of few tropical locations with still existing glaciers, Mt. Kilimanjaro, a stratovolcano with an elevation of  
15 5895 m.a.s.l., is located in East Africa close to the Tanzania-Kenya border (3°04' S / 37°21' E) (Fig. 1, overview). In addition to the very high elevation, the free-standing nature of the mountain causes the glacier on top of the summit to be directly exposed to tropospheric flows at higher altitudes, minimizing the forcing of local climate on the glacier and creating a unique opportunity to study the mid-troposphere climate.

20 The modern glacier recession on Kilimanjaro has been well documented and mapping approaches have shown that from an estimated ice extent of 11.4 km<sup>2</sup> in 1912, only 1.76 km<sup>2</sup> remained in 2011, constituting a severe 85% reduction in glacier area (Cullen et al. 2013). While glaciological research on Kilimanjaro has focused on mapping glacier area and retreat (e.g. Cullen et al. 2013), as well as quantifying the mass and energy balance (Mölg et al. 2003, 2008, 2009), the research on the ice thickness of different glaciers on Kilimanjaro has been comparably sparse (Bohleber et al. 2017). However, in light of severe glacier  
25 recession, an assessment of current glacier thickness is important to better determine future recession. A recent effort was made to reconstruct the distributed ice thickness for all glaciers outside Antarctica and Greenland using a consensus of up to 5 models (Farinotti et al. 2019). This estimate generated ice thicknesses for Northern Icefield (NIF) and Kersten Glacier (KG) using ensembles of 2 and 3 models, respectively. The consensus estimate produces a similar mean ice thickness of 21.5 m for NIF, which is in fair agreement with the observations by Bohleber et al. (2017), considering that the consensus was not

30 informed by local thickness observations (Farinotti et al. 2019). Moreover, the recently observed separation of KG into two fragments (e.g. Landsat 5 scene 2011-08-22; Image courtesy of the U.S. Geological Survey) is not in agreement with the high thickness values ~~illustrated~~ found in the consensus estimate.

Here, we present the first well constrained thickness maps for KG and NIF using a mass conserving reconstruction approach introduced in Fürst et al. (2017) that readily assimilated thickness measurements (Section 3.34). In two different experiments  
35 we test the influence of varying input of ice thickness observations for the glacier state of 2000, where we rely on surface mass balance (SMB) data from a physically-based model developed by Mölg et al. (2008, 2009; Section 3.1) and digital elevation data with global coverage (Shuttle Radar Topography Mission; SRTM; USGS), pursuing a new calibration strategy that uses multi-temporal satellite information on geometric changes in absence of observational ice thickness data on KG. These resulting thickness estimates are then compared to the consensus estimate (Farinotti et al. 2019). In a third experiment, we  
40 combine the very high resolution digital elevation model KILISoSDEM (0.5 m ground resolution; Sirguey et al. 2014) with the calibration strategy from the previous 2000 experiments to produce a best estimate for the 2011 glacier state.

## 2 Data

To apply the distributed surface mass balance (SMB) model (Sect. 3.1; Mölg et al., 2008, 2009) and the thickness reconstruction (Sect. 3.34), the following input data was used: climate data measured by the automatic weather station (AWS)  
45 located on KG (Section 3 c in Mölg et al. 2009), digital elevation information from the SRTM digital elevation model (DEM) from 2000 and the KILISoSDEM from 2012 (Sirguey et al. 2014), the RGI6.0 glacier outlines from 21 February 2000 (RGI Consortium 2017), as well as digitized outlines based on a Landsat 5 image from 22 August 2011. The change in surface height between 2000 and 2011 was found by differencing a merge Surface height change was generated by differencing a merge of two TanDEM-X-radar images from 2011 (28 January 2011, 4 April 2011; Suppl. Fig. 2; for details on the processing refer to  
50 Braun et al., 2019) and the SRTM DEM.

The central plateau area of NIF drains westward into two glaciers, Drygalski Glacier in the south and Credner Glacier in the North. In anticipation of a future separation of NIF, we redefine Credner Glacier (CG) to comprise the northern part of NIF (Fig. 1). Ice thickness measurements on Kilimanjaro are limited to NIF, where three ice cores were drilled to bedrock in 2000, with lengths from 49.0 m (C1) to 50.9 m (C2) and 50.8 m (C3) (Thompson et al. 2002; Fig. 1 for borehole locations). In  
55 addition, ground penetrating radar (GPR) profiles from September 2015 (Fig. 1) were collected by Bohleber et al. (2017). Using a kriging interpolation and the KILISoSDEM, the authors estimated the mean thickness to be between  $21.2 \pm 1$  m and  $27 \pm 2$  m. For the anticipated reconstruction in 2000 and 2011, the GPR thickness measurements for NIF are adjusted by linearly interextrapolating the above-mentioned elevation change information to the elapsed time between the DEM date and acquisition date of the thickness measurements. ~~To account for different availability of thickness measurements, Fürst et al. (2017) conducted experiments withholding 1%—99% of the available point measurements on several test geometries on Svalbard. Aggregate errors typically exceed 10–20% of the mean glacier ice thickness when most measurements are withheld~~  
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but error values quickly reduce as measurements become available. Between the two end-member experiments (1% and 99%), volumes of the test geometries differ by at most 10%. Considering input uncertainties from the DEM and the SMB fields, sensitivity tests revealed that ice volume differences remain below 5% (only shown for the ice cap geometry). For more details on associated uncertainties and input sensitivities, we refer the interested reader to Fürst et al. (2017). Here, the focus is rather on assessing the utility of multi-temporal satellite information in a glacier-specific calibration.

## 3 Methods

### 3.1 Mass balance modelling

The mean annual climatic surface mass balance fields were generated using version 2.4 of the distributed, physically-based mass balance (MB) model by Mölg et al. (2008, 2009), being driven by meteorological input from the aforementioned AWS (Suppl. Fig. 1). The full MB model has already been calibrated and validated for KG. For the application on NIF, surface meltwater is not expected to run off but rather refreeze over the very flat plateau areas (Mölg & Hardy, 2004). To properly reproduce these conditions on NIF, we revised the model code so that refreezing of meltwater can occur on a bare ice surface with a slope angle below 5 degrees (not captured before). With these changes, the model is capable of reproducing the observed surface height changes observed by a Sonic Ranger mounted to the AWS.

### ~~3.2 TanDEM-X processing~~

~~First a DEM with 30 m resolution was generated from the 2011 TanDEM-X imagery (for details refer to Braun et al., 2019). Surface elevation changes between 2000 and 2011 were inferred from DEM differencing with respect to the SRTM DEM (Suppl. Fig. 2).~~

### 3.3.2 Margin thickness generation

For KG, no in-situ thickness measurements are available. Therefore, multi-temporal DEM and glacier outline information is used to infer past ice thickness. First, glacier retreat is delineated from outline information in 2000 and 2011 (Fig. 1 hatched area). In the currently ice-free area, contemporaneous elevation changes (2000-2011) then give information on past ice thickness. Positive values, which indicate a height gain in the TanDEM-X layer, were removed as a height gain outside the 2011 glacier extent implies an increase in glacier thickness from 2000 to 2011, which is unlikely. In total we removed 92 of 602 grid cells with a mean height gain of 0.19 m/a for NIF and 14 of 254 grid cells with a mean height gain of 0.25 m/a for KG.

### 3.4.3 Ice thickness reconstruction

Here, we apply an inverse method to infer the glacier ice thickness by assimilating surface observations and ground-truth thickness measurements. A detailed description of this two-step ice thickness reconstruction data assimilation, of which we only used the first model step as surface velocities were not available, can be found in Fürst et al. (2017). The reconstruction approach is based on the principle of mass conservation and computes a glacier-wide flux field from the difference between the surface mass balance (Section 3.1.2) and contemporaneous elevation changes. The flux solution is converted into thickness values using the Shallow Ice Approximation (SIA; Hutter, 1983). This conversion involves the ice-viscosity parameter  $B$ , which is a-priori unknown. This parameter stems from assuming a Glen-type flow law, linking deviatoric stresses to strain rate components  $\dot{\epsilon}_{ij}$  via the effective viscosity  $\eta = 0.5 B^{-1/n} \dot{\epsilon}^{(1-n)/n}$ . Here,  $\dot{\epsilon}$  is the second invariant of the strain rate tensor (for further information on the equation see Pattyn 2003) and  $n=3$ . After the flux solution is obtained,  $B$  is calibrated at locations where thickness measurements are available. This point-information is then expanded to the entire glacier domain using a Natural Neighbor Sibsonian Interpolation, resulting in a spatially variable field. Before interpolating the  $B$  values from each measurement location to the entire glacier basin, an average value is prescribed along the glacier outline to avoid spurious extrapolation effects.

To account for different availability of thickness measurements, Fürst et al. (2017) conducted experiments withholding 1% - 99% of the available point measurements on several test geometries on Svalbard. Aggregate errors typically exceed 10-20% of the mean glacier ice thickness when most measurements are withheld but error values quickly reduce as measurements become available. Between the two end-member experiments (1% and 99%), volumes of the test geometries differ by at most 10%. Considering input uncertainties from the DEM and the SMB fields, sensitivity tests revealed that ice-volume differences remain below 5% (only shown for the ice-cap geometry). For more details on associated uncertainties and input sensitivities, we refer the interested reader to Fürst et al. (2017).

For the reconstruction in 2000, a nominal mesh resolution of 25 m was chosen. With the higher DEM quality in 2011, the resolution was iteratively increased from 25, via 10 and 5, to 2 m. The processing was conducted separately for NIF and KG. To smooth the surface slope during reconstruction, we use a coupling length parameter (introduced in Fürst et al. 2017), which is defined as a multiple of the local ice thickness. In this way, flux streamlines become less erratic and their alignment increases. For KG, the parameter is set to 1, a typical value for valley glaciers (Kamb & Echelmeyer, 1986). For NIF, it had to be reduced so that the steep elevation increase at the vertical ice cliffs is depicted in the thickness field. A compromise value of 0.3 was chosen to still guarantee sufficient smoothing of the flux streamlines.

### 3.4.5 Experimental Setup

The general strategy is to reconstruct a thickness field for KG and NIF by combining SMB, elevation changes and glacier geometry with in-situ measurements of ice thickness for two points in time, namely 2000 (Experiment 1 and 2) and 2011 (Experiment 3). In Experiment 1, we reconstructed the glacier state for 2000 with the generated margin thickness data (Section

120 3.23) for both NIF and KG. As KG is rather small, we expect a homogeneous ice viscosity. In Experiment 2, we therefore decided to simply average the point information on ice viscosity and use a constant viscosity value over the entire glacier basin. In this way, lateral thickness values are no longer reproduced but spurious spatial viscosity variations stemming from the generic margin data are suppressed. For NIF in Experiment 2, we chose to use the thickness measurements from Bohleber et al. (2017) as input, to check how observational data influences the glacier-wide ice thickness in comparison to only using  
125 margin thickness information. In Experiment 3, the aim is to benefit from the 2011 KILISoSDEM showing very high resolution. For NIF, the reconstruction can still be calibrated by GPR measurements from Bohleber et al. (2017) acquired in central areas. For KG, the retreat information falls outside the ice-covered domain in 2011. Therefore, we use the mean viscosity information as inferred for the reconstruction in year 2000 (Experiment 2). The KILISoSDEM is further exploited to investigate the resolution influence. Table 1 summarizes the three different experimental setups (Tab. 1).

## 130 4 Results

Results show generally larger ice thickness for NIF than for KG in all three experiments. For Experiment 1 (Fig. 2 A), KG shows thickest ice of up to 15 m at the flat plateau parts of KG. For the central areas on the mountain flank thickness values show a mean of 6.2 m and locally reach up to 7.5 m, with patches of thinner ice towards the glacier margins. NIF is up to 40 m thick in its center, decreasing towards the glacier margins and towards CG and has a mean ice thickness of 13.7 m. At the  
135 borehole locations C1, C2 and C3 ice thicknesses of Experiment 1 are 19.9 m, 23.9 m and 36.6 m thinner, respectively (see Suppl. Table 1).

Results from Experiment 2 show a similar thickness pattern on KG (Fig. 2B). For NIF, the magnitude differs significantly. Now one large part of NIF's flat area and two smaller parts of CG exceed 40 m. Moreover, the ice thickness in the steeper western areas of NIF and CG has increased by a factor of 2. The mean ice thickness also increases to 23.4 m. At the borehole  
140 locations C1, C2 and C3 ice thicknesses of Experiment 2 are 4.4 m, 8.3 m and 26.1 m thinner, respectively (see Suppl. Table 1). Concerning the GPR surveys from Bohleber et al. (2017), the thickness map of NIF (Fig. 2D) largely reproduces these measurements. Turning to the consensus estimate map (Farinotti et al., 2019), larger discrepancies prevail (Fig. 2E), especially towards the eastern part. KG shows a similar thickness, but the ice body on the mountain flank becomes thicker in the central parts. As before, the thickest ice patch remains on the plateau. The mean ice thickness with 6.9 m is very similar to  
145 Experiment 1. ~~For In~~ Experiment 3 (Fig. 1) we now move forward in time to 2011. Here, KG is ~~now~~ split into two parts and shows an ice thickness of up to 10 m at the flat top part and most of the slope being between 5 and 7.5 m thick. KG's mean ice thickness is 9.3 m. NIF's thickness distribution is similar to Experiment 2, with the thickest areas of over 40 m at its flat part on the plateau. For NIF, the decrease in thickness is less noticeable than the lateral retreat and decrease of glacier area. The mean ice thickness of NIF in Experiment 3 is 26.6 m. At the three ice-core locations, the thickness mismatch remains  
150 comparable to Experiment 2 (see Suppl. Table 1), with a mean relative absolute difference of 26%. This value is rather large



and exceeds inferred error estimates for the majority of glacier on Svalbard (Fürst et al., 2017). Here, we want to use it as a rough ~~orientation guideline~~ for the overall uncertainty of the 2011 reconstruction.

## 5 Discussion

We will first discuss the reconstructions for the year 2000 (Fig. 2): Generally, our experiments produce results with a higher difference in thickness magnitude between KG and NIF as compared to the consensus thickness map (Fig. 2C; results from Farinotti et al. 2019). For KG, no ice thickness measurements are available, and it is uncertain to what extent the generated thicknesses along the glacier margin (Section 3.32) are useful to inform the reconstruction. We find that the margin values result in a spatially varying viscosity field, which is transmitted into the ice thickness field (Experiment 1; Fig. 2 A). As no strong viscosity variations are expected for the small KG, a second run was conducted with constant viscosity (Experiment 2; Fig. 2 B). Results indicate a thick central flow unit, as one might expect for a steep glacier, as well as a smoother ice thickness distribution, with higher thickness in the center of the glacier and thinning towards the margins. In the absence of ground truth data, it is unclear, which thickness field is more plausible. However, as the thickness of most glaciers on Earth is unsurveyed, the use of margin thickness information, generated from outline differences enabled a local glacier-specific viscosity tuning which might be preferential to an empirical temperature relation (Huss and Farinotti, 2012). The consensus map shows a similar thickness pattern as Experiment 2. The most notable difference is found for the thickness magnitude of KG. For the consensus estimates, thickness values exceed 35 m both for the flat top part and the central steep slope part. The consensus mean thickness of 27.1 m, is more than twice as large as in our reconstruction. Since there are no actual thickness observations for KG, it is not certain that the ice was only up to 15 m thick in the year 2000. However, KG split in two parts by 2011. The separation line follows a contour line just below the plateau. Mean elevation changes between 2000 and 2011 of -0.64 m/yr suggest that not more than 7 m of ice was present in 2000. With 35 m ice in this area, the consensus estimate seems too large. NIF's peculiar geometry poses a challenge and it is difficult to reconstruct the ice thickness distribution using generic thickness observations around the margin (Experiment 1, Fig. 2A). The ice is much too thin in the interior (Fig. 2 A), which underestimates the ice core lengths from Thompson et al. 2002 by 48, 52 and 71% for the core locations C1, C2 and C3 respectively. When the interior GPR measurements are used as model input (Experiment 2; Fig. 2 B), differences decrease to 10, 17 and 53%. ~~Increased-Large~~ mismatch values, especially for borehole C3, might as well be explained by the very flat plateau. Therefore, ice motion is expected to be rather slow. Stagnant and flat areas are challenging for a reconstruction based on ice-flow and Fürst et al. (2017) show that uncertainties in the reconstructed thickness values significantly increase towards the ice divide of an ice cap. They further show that measurements along divides and ridge areas are most valuable to constrain the reconstruction approach used here. Although GPR measurements are available on the NIF plateau, we expect that uncertainties increase quickly away from these measurements. This can partly explain the mismatch with C3. Turning to the consensus estimate the mismatch is significantly larger with relative underestimations of 34%, 38% and 72% for boreholes C1, C2 and C3. ~~Despite that no GPR measurements were considered on Mt. Kilimanjaro,~~ The complex topography posed a

similar challenge for the models participating in the consensus, especially because no thickness observations were considered for Mt. Kilimanjaro. This is also reflected in the similar mean ice thicknesses, which are 27.1 m for the consensus estimate (Farinotti et al. 2019) and 23.4 m for Experiment 2. The results for KG and NIF point towards glacier margin data as thickness information being more useful in dynamically more active areas, such as KG, instead of more stagnant and flat areas, such as the flat plateau area of NIF.

Experiment 3 repeats the reconstruction for the year 2011 at a very high resolution. The general distribution of ice thickness is barely affected by the increase in resolution. This stability under resolution increase is assuring and illustrates the effects of inherent smoothing via the coupling length parameter that scales with the thickness. For NIF however, resolution is key, and the cliff geometries are much better imprinted in the final thickness map. Further experiments with 10 and 5 m model resolution (not shown) showed barely any difference in thickness distribution, verifying this effect. The mean ice thickness for KG and NIF have increased in comparison to Experiment 2 from 6.9 m to 9.3 m and from 23.4 m to 26.6 m, respectively. As observed elevation changes do not support an increase, remaining explanations comprise model resolution, outline differences and DEM quality. Resolution can be excluded based on results from a 25 m reconstruction in 2011 (not shown). Concerning the 2011 outlines, some internal ice-free areas (on both NIF and KG), present in the RGI, could not be confirmed from the coarse Landsat imagery, resulting in thicker ice. The four holes in the RGI outlines for KG and NIF either stay ice-free in the 2011 outline, connect to the lateral ice-free area or are located very close to the 2011 margin. Therefore, the reconstruction accounts for these indirectly. Bohleber et al. (2017) show more even smaller ice-free spot in the western part of NIF, which could not be confirmed from the coarse Landsat imagery thus explaining thicker ice there. The quality difference between SRTM and KILISoSDEM is certainly also a contributing factor explaining part of the larger thickness values.

Finally, we want to briefly discuss the reconstruction approach, used here, with respect to other strategies for inferring distributed thickness information. The Ice Thickness Models Intercomparison eXperiments (IMTIX; Farinotti et al. 2017) concluded that as long as no thickness measurements are available, no single strategy generally outperforms the others. In this case, an ensemble result from multiple models is preferable. Yet here, observations are either available or are inferred from multi-temporal satellite imagery. Measurement availability was used in the global consensus estimate to infer performance scores for the participating models (Farinotti et al., 2019) and the approach by Fürst et al. (2017) was attributed the highest value. Yet, with regard to applications on individual geometries as for Kilimanjaro, comparable results, as presented here, might well be attainable with various approaches. Regarding input requirements, approaches based on the perfect plasticity assumption are least exigent, only requiring information on the ice geometry (e.g. Frey et al., 2014).

## 6 Conclusion & Outlook

This study has a multi-disciplinary character as we apply modelling approaches for glacier surface mass balance, infer remotely sensed elevation changes and utilize available information in a data assimilation. The aim of the assimilation is to accurately determine the thickness and distribution of ice for NIF and KG on Mt. Kilimanjaro.

215 In the reconstructions for 2000 we assessed the utility of this margin thickness information in constraining glacier thickness by comparing our reconstructions to the recent global consensus estimate (Farinotti et al. 2019). For Kersten Glacier, we report significantly smaller thickness values as compared to the consensus estimate, which is shown to be inconsistent with the observed glacier separation between 2000 and 2011. Our reconstructions for 2011 show mean ice thicknesses of 9.3 m for KG and 26.6 m for NIF. A comparison of modelled thickness to the ice core lengths (Thompson et al. 2002) results in a mean

220 relative absolute error of 26%. For NIF, our reconstruction (Experiment 2) and the consensus estimate both show a very similar mean ice thickness, which is surprising as the consensus estimate was not informed by any thickness measurements. As ice thickness observations were not available for KG, the reconstruction approach was calibrated with past thickness values inferred from multi-temporal satellite information in areas that became ice-free in the last decade. In absence of ground truth data on KG, it remains unclear if the retreat information is best used spatially distributed or as a bulk average. Yet we can state

225 that increased quality and resolution of more recent DEMs are key for capturing sharp transition zones (e.g. cliffs). The lateral glacier retreat information seems less utile as central ice thickness is strongly underestimated. Reasons for this worse performance might be the complex topography and the dynamic inactivity of NIF. We therefore speculate that thickness information from retreat is most useful in areas that have been dynamically more active in the past. But we also have to acknowledge that the unique glacier settings on Mt. Kilimanjaro are certainly not ideal for this first assessment of utilizing

230 glacier retreat information to allow a glacier-specific calibration of thickness reconstruction approaches and should be tested elsewhere to verify our results.

To conclude, glacier retreat is palpable all around the planet and it will continue in the future (e.g., Hock et al., 2019). As time progresses, the suggested strategy to infer past ice thickness values from multi-temporal satellite information will produce an increasing wealth of calibration data. Moreover, the approach is readily transferable and provides a means for glacier-specific

235 calibration of reconstruction approaches on regional or even global scales. This study has a multi-disciplinary character as we apply modelling approaches for glacier surface mass balance, infer remotely sensed elevation changes and utilize available information in a data assimilation. The aim of the assimilation is to accurately determine the thickness and distribution of ice for NIF and KG on Mt. Kilimanjaro. As ice thickness observations were not available for KG, the reconstruction approach was calibrated with past thickness values inferred from multi-temporal satellite information in areas that became ice-free in

240 the last decade. Our reconstructions for 2011 show mean ice thicknesses of 9.3 m for KG and 26.6 m for NIF. A comparison of modelled thickness to the ice core lengths (Thompson et al. 2002) results in a mean relative absolute error of 26%.

In the reconstructions for 2000 we assessed the utility of this margin thickness information in constraining glacier thickness by comparing our reconstructions to the recent global consensus estimate (Farinotti et al. 2019). For Kersten Glacier, we report significantly smaller thickness values as compared to the consensus estimate. The latter reconstruction is shown to be

245 inconsistent with the observed glacier separation between 2000 and 2011. For NIF, our reconstruction (Experiment 2) and the consensus estimate both show a very similar mean ice thickness, which is surprising as the consensus estimate was not informed by any thickness measurements. The lateral glacier retreat information seems less utile as central ice thickness is strongly underestimated. Reasons for this worse performance might be the complex topography and the dynamic inactivity of

250 ~~NIF. We therefore speculate that thickness information from retreat is most useful in areas that have been dynamically more active in the past.~~

~~The unique glacier settings on Mt. Kilimanjaro are certainly not ideal for this first assessment of utilizing glacier retreat information to allow a glacier-specific calibration of thickness reconstruction approaches. In absence of ground truth data on KG, it remains unclear if the retreat information is best used spatially distributed or as a bulk average. Yet we can state that increased quality and resolution of more recent DEMs are key for capturing sharp transition zones (e.g. cliffs).~~

255 ~~To conclude, glacier retreat is palpable all around the planet and it will continue in the future (e.g., Hoek et al., 2019). As time progresses, the suggested strategy to infer past ice thickness values from multi-temporal satellite information will produce an increasing wealth of calibration data. Moreover, the approach is readily transferable and provides a means for glacier-specific calibration of reconstruction approaches on regional or even global scales.~~

### **Acknowledgement**

260 CS received primary funding from the project BR2105 /14-1 within the DFG Priority Program "Regional Sea Level Change & Society". JJF was funded by the German Research Foundation (DFG) under grant number FU1032/1-1. Results presented in this publication are based on numerical simulations conducted at the high-performance computing center of the Regionales Rechenzentrum Erlangen (RRZE) of the University of Erlangen-Nürnberg. We would also like to thank Nicolas Cullen and Pascal Sirguey (both at University of Otago, NZ) for constructive discussions and for providing the KILISoSDEM.

### 265 **Author contribution**

CS led writing of the manuscript, in which she received support from all authors. The research aims and setup were developed in regular discussion with JJF, TM and MB.

### **Competing interests**

The authors declare no competing interests.

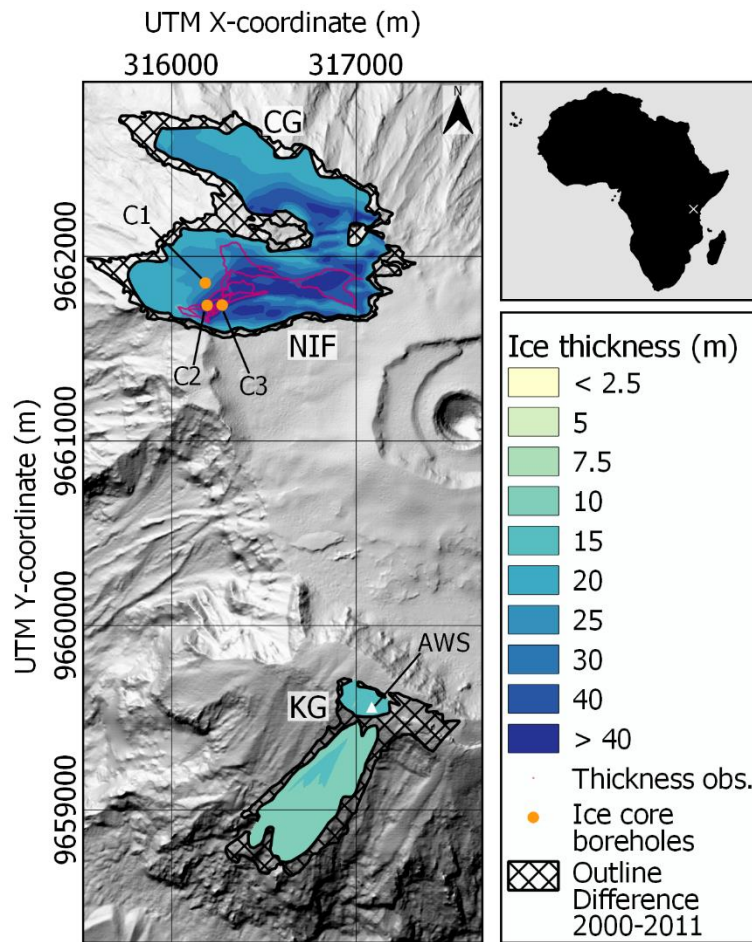
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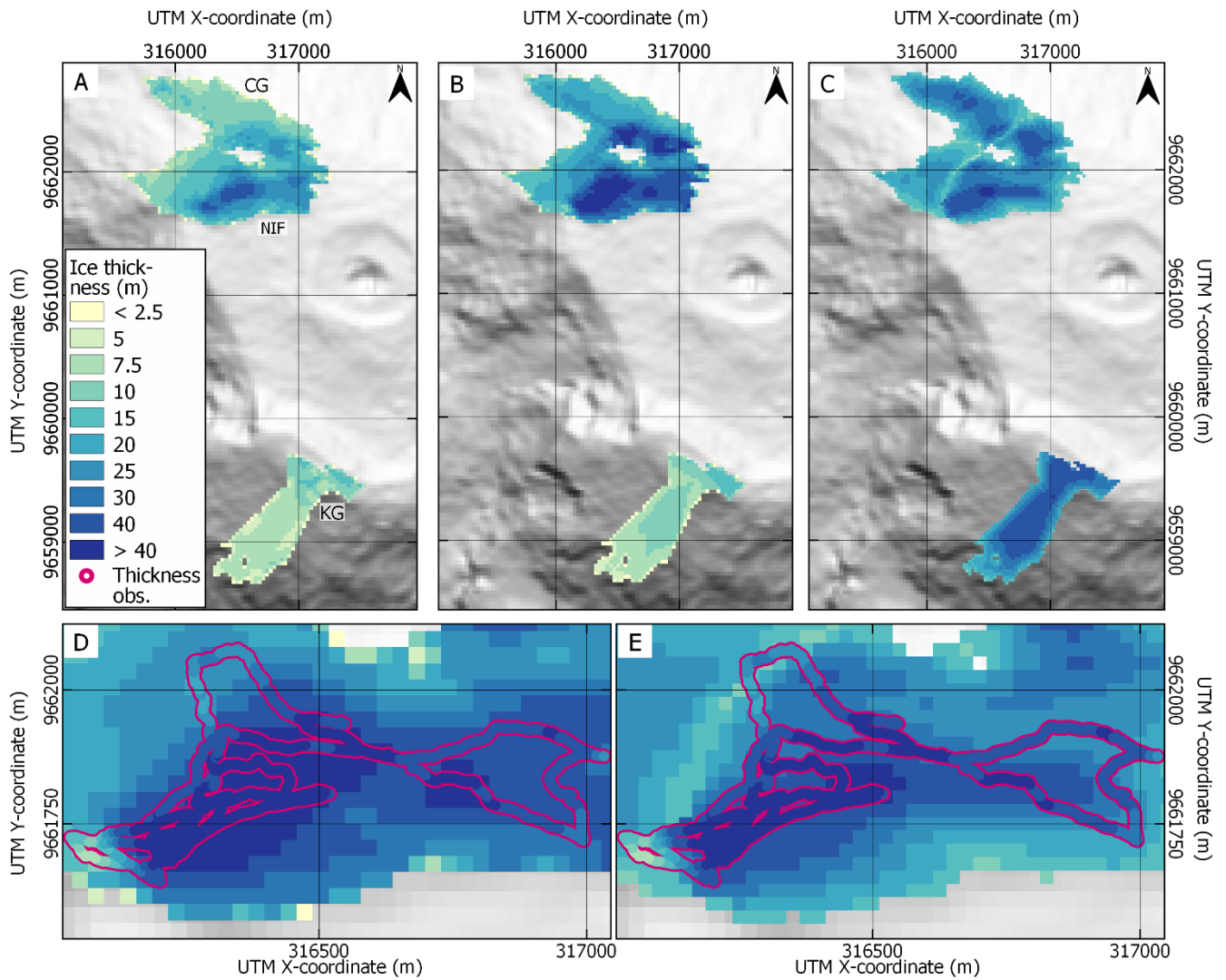
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325 **Figure 1: Reconstructed ice thickness (m) for Northern Icefield (NIF) and Kersten Glacier (KG) for the year 2011, based on thickness observations (NIF) and mean viscosity (KG) with a model resolution of 2 m (Experiment 3). The magenta path on NIF represent the GPR ice thickness measurements by Bohleber et al. (2017). Orange dots (C1-C3) indicate the drill locations of the ice cores from Thompson et al. (2002). The AWS location from Mölg et al. (2009) is marked by the white triangle. Background: KiliSoSDEM hillshade. The overview map depicts the location of Mt. Kilimanjaro (white cross) on the African continent.**



330 **Figure 2: Reconstructed ice thickness (m) for Northern Icefield (NIF) and Kersten Glacier (KG) for the year 2000. Panel (A) shows**  
**results for Experiment 1 making exclusive use of past thickness information in nowadays ice-free areas. Panel (B) presents results**  
**from Experiment 2, which uses a bulk viscosity inferred from the retreat information on KG, whereas for NIF, the reconstruction**  
**is only calibrated by in-situ GPR measurements (see Table 1).As comparison panel (C) depicts the composite ice thickness from**  
**Farinotti et al 2019. Panel (D) shows a closeup of NIF, overlying the thickness map of Experiment 2 with the GPR thickness**  
**measurements (colored dots with magenta outline, magenta contour, showing measured values in the same colourbar) by Bohleber**  
**et al. (2017). Panel (E): same as Panel (D) but showing the consensus thickness map (Farinotti et al., 2019; cf. Panel C). Background:**  
335 **SRTM DEM hillshade.**



**Table 1: Experimental setup of the ice thickness reconstruction (Section 3.4~~5~~).**

	<b>Representing the glacier state for the year</b>	<b>Thickness input KG</b>	<b>Thickness Input NIF</b>	<b>Surface Elevation Information (year of acquisition)</b>	<b>Glacier Outlines (acquisition date)</b>	<b>Mean ice thickness KG (m)</b>	<b>Mean ice thickness NIF (m)</b>
<b>Experiment 1</b>	2000	Generated margin thicknesses	Generated margin thicknesses	SRTM DEM (2000)	Randolph Glacier Inventory 6.0 (2000/02/21)	6.2	13.7
<b>Experiment 2</b>	2000	Mean viscosity	Observations from Bohleber et al. (2017)	SRTM DEM (2000)	Randolph Glacier Inventory 6.0 (2000/02/21)	6.9	23.4
<b>Experiment 3</b>	2011	Mean viscosity	Observations from Bohleber et al. (2017)	KILISoSDM (2012)	Digitized from Landsat 5 Image (2011/08/22)	9.3	26.6