

# Mechanisms leading to the 2016 giant twin glacier collapses, Aru range, Tibet

Adrien Gilbert et al.

## Response to reviewer comments

We would like to sincerely thank the referees for their careful feedback on our study that certainly helped to improve its presentation. We believe we can sufficiently respond to all comments made and improved the manuscript accordingly

Reviewer comments in normal font.

Response in *italic blue* font

- **Reviewer 1 (M. Truffer)**

### General Comment

This paper discusses the catastrophic collapse of two glaciers in Tibet within a few months of each other; one of the most astonishing glaciological events ever recorded. The paper provides a thorough analysis of the glaciers' development in the years prior to the event using satellite data and climate models interpreted with a thermomechanical 3D ice sheet model. The paper reaches substantial conclusions that might even be a bit counter-intuitive (i.e. it is not just melting of a previously frozen bed). It should be published after some modification. Most importantly, it needs thorough editing. There are many grammatical mistakes including long convoluted sentences, missing pronouns, misused prepositions, confusing singular and plural, and third person singular.

*We have now significantly improved the grammar throughout the manuscript and believe its language is now good enough for the final language editing done by the publisher.*

## Specific Comments

- 1- The method for deriving basal friction is not well explained. It is not very common to use vertical velocities for the cost function in an inversion. There is a reference to Gilbert et al (2016), but that paper uses both vertical and horizontal velocities, which is likely to constrain the friction parameter much better.

*Gilbert et al. (2016) do validate the method by providing both velocity field inferred from emergence velocity only (figure 8A of their manuscript) and from combination of emergence and horizontal velocities (figure 8C of their manuscript). They show this method is working well. We provide now new additional results based on horizontal velocity measurements from TerraSAR-X offset tracking between 2013-11-30 and 2013-12-11 that give a new validation of the method. As discussed in the manuscript we do not see signs of strong seasonal variability and these results should be similar to the ones obtained by TanDEM-X DEM differences between 2013-04-14 and 2014-04-01. Comparison between these two results shows a good accordance in the reconstruction of surface velocities (Figure R1) which validates our method. Furthermore, horizontal velocities obtained after friction inversion from DEM differences between 2015-09-06 and 2015-11-25 match well the observed horizontal velocity between January and April 2016 providing another validation of our method (see Figure 7 of the manuscript). The detailed comparison of modeled sliding velocities between the two methods shows that the localization of sliding zone are in reasonable agreement despite some differences in magnitude (Figure R2). In particular, sliding velocities are underestimated in the upper half of the Aru-1 detachment zone. This highlight a lack of accuracy in the emergence-velocity-based method that show a standard deviation of  $13.1 \text{ m yr}^{-1}$  ( $0.036 \text{ m day}^{-1}$ ) compared to the horizontal velocity inversion (Figure R2-D).*

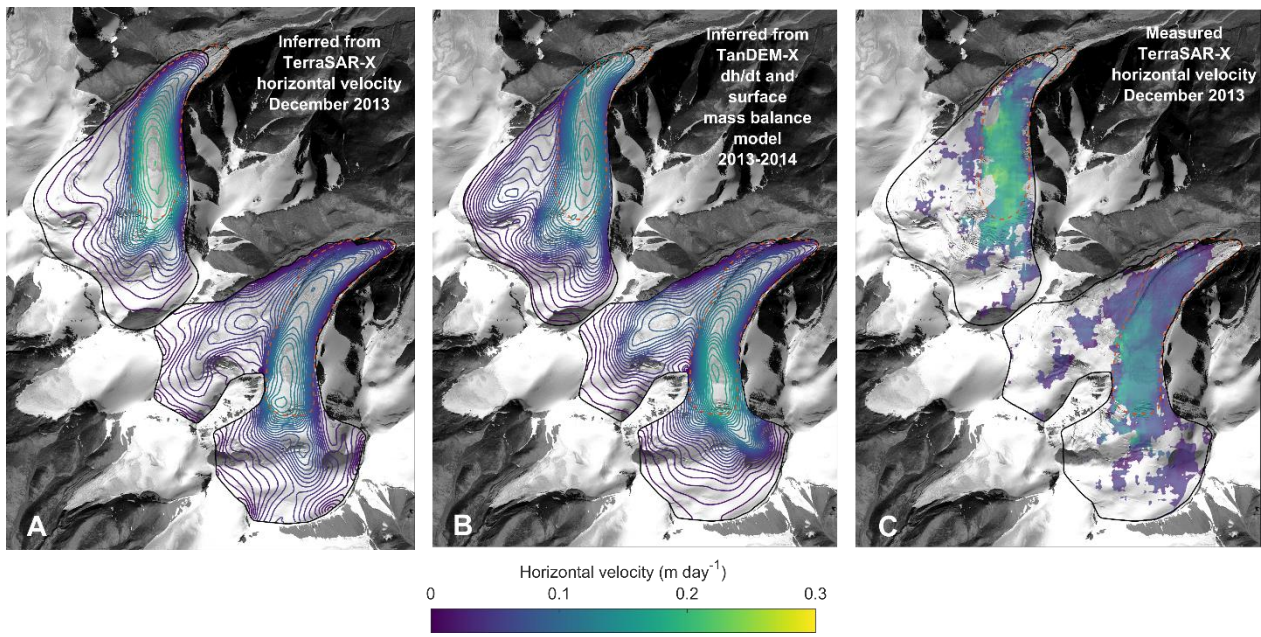


Figure R1 – Surface horizontal velocity modeled after basal friction inferred from horizontal velocity measurement (A) and from emergence velocity estimation (B). (C) Measured horizontal velocity between 2013-11-30 and 2013-12-11 from TerraSAR-X offset tracking.

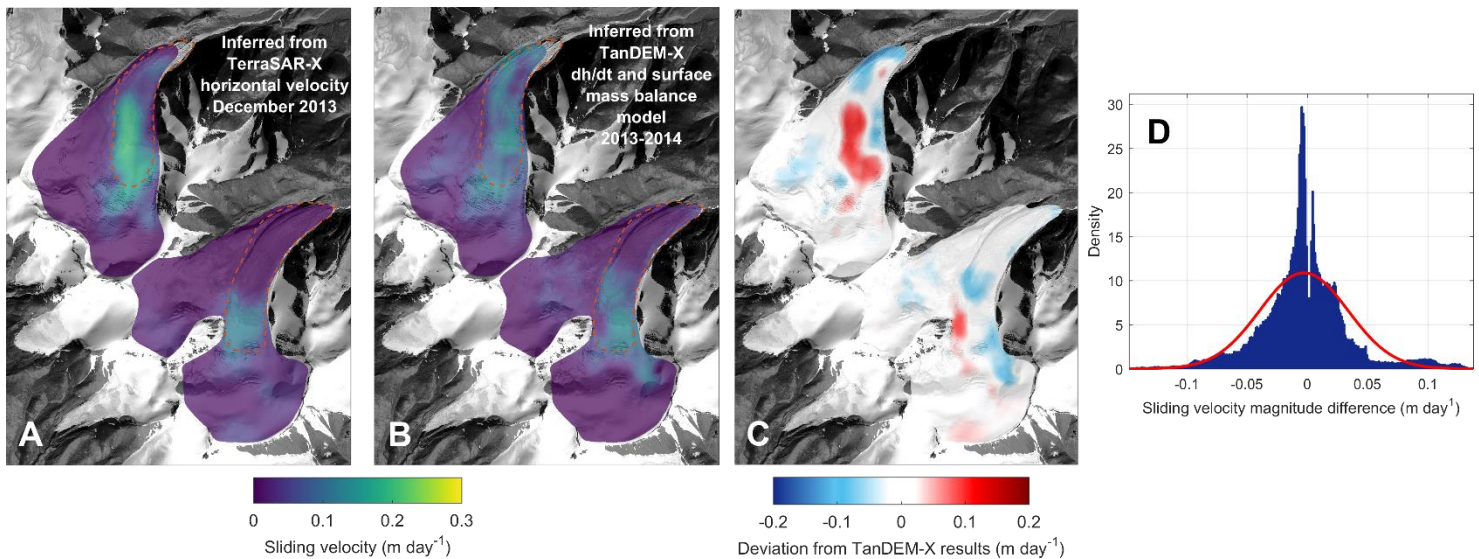


Figure R2 - Sliding horizontal velocity modeled after basal friction coefficient inferred from horizontal velocity measurement (A) and from emergence velocity estimation (B). (C) shows difference between (A) and (B) and (D) is the associated error distribution (blue) and Gaussian fit (red).

However, due to not completely spatially resolved horizontal velocity measurements, especially in slow flowing glacier zones (see Figure R1-C), the friction coefficient is better-constrained using emergence velocity in those zones. This leads to significant difference in those regions between the two reconstructions in terms of friction coefficient (Figure R3). We believe that our method based on emergence velocities is a powerful method for small, slow moving glaciers since it is complex to obtain accurate horizontal velocities from remote sensing in such cases. Indeed, slow surface motion requests large time periods between two images to capture the displacement at a sufficient signal-to-noise ratio. During such longer time periods, visual (for optical data) and radar (for interferometry) coherence is often lost due to surface changes. However, it is easier to quantify surface elevation change and in turn emergence velocities after correcting for surface mass balance. Furthermore, it can be done for long time periods, up to several years, since the geodetic (DEM differencing) method is not sensitive to surface state. The accuracy of the emergence velocities method is good enough for the purpose of our paper but should be combined with horizontal velocity if a more precise localization of the frictional changes are intended. In the revised manuscript, we added details to the method and a new paragraph about method validation in the result uncertainties discussion (section 5.1).

Figures R1, R2 and R3 added to supplementary information.

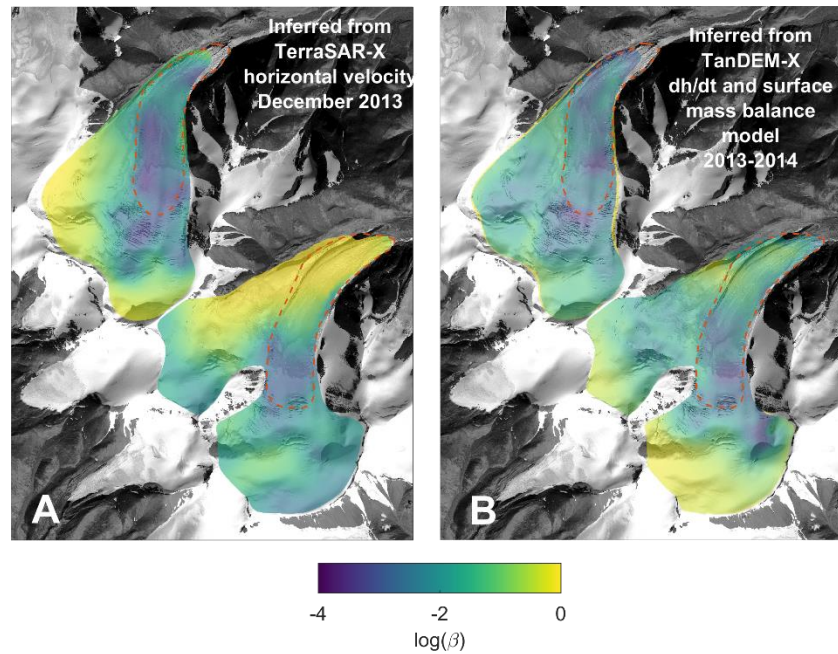


Figure R3 - Basal friction coefficient inferred from horizontal velocity measurement (A) and from emergence velocity estimation (B).

If I understand correctly, vertical velocities are derived from DEM differences (yielding  $dh/dt$ ) and a mass balance model? If so, why is there a discussion of surface-normal velocities? Both  $dh/dt$  and  $b_{\dot{}}$  are generally evaluated in the vertical direction, so there is no need for this? Intuitively, I'm surprised that this method works so well, but the results do look encouraging. But there should at least be some discussion of errors (which is missing for any of the results).

*Yes, you understood correctly. The quantity we derived is actually the vertical component of the surface-normal velocity, also called emergence (or subsidence) velocity. Vertical velocity would refer to vertical component of the velocity vector, which is a different quantity. We now only use the term "emergence velocity" to avoid confusion. Discussion of errors is extended in the revised manuscript (section 5.1) and new figures have been added in the supplementary material.*

2- There are conflicting assumptions in the paper that are not always discussed. For example, the derivation of bed topography is based on 'no sliding' (this is shortly discussed).

*The assumption on 'no sliding' for deriving bed topography is done for the glacier state in 2000 before the surging anomaly. Even with no flow instability going-on at this time, this is probably a rough assumption since we show that the two glaciers were temperate in the detachment area. However, this seems to provide good enough results when comparing with surface topography after the collapses. In the upper glacier parts, the no-sliding assumption is in agreement with the high friction inferred from inverse modeling. This assumption is now discussed in more detail.*

Friction parameters are derived from a linear sliding law, but the discussion is entirely in terms of a plastic till.

*Deriving friction parameters from a linear sliding law does not imply any choice of the physical processes behind the friction since the inversion is done at fixed times. The friction coefficient  $\beta$  can be expressed in the framework of plastic till theory which would give:*

$$\beta u_s = N \times \tan(\phi) + c$$

*We do not think that inverting the friction using a linear sliding law is incoherent with a plastic till behavior since a linear sliding law can be viewed as a parametrization where the coefficient  $\beta$  includes the physics behind the processes taking place. However, in such approach, the value of  $\beta$  is only valid at the time for the inversion. For example, Minchew et al. (2016) used a linear sliding law to provide evidence of plastic behavior. We clarified this point now in the manuscript:*

*“The use of a linear friction law in our inversion is a parametrization where  $\beta$  includes these physics and is only valid at the time of the inversion. The change in friction coefficient  $\beta$  can here be therefore interpreted in terms of a plastic till.”*

- 3- I would like a bit more information about how stresses are divided between basal shear stress and lateral stress. In a valley geometry, the bed-parallel stress can be both lateral and basal.

*In our study, the force balance analysis is done on the part that detached. This means the existence of a western margin linking the detachment to the glacier body, which provides lateral stresses. See also our response in Technical Corrections. In the manuscript, lateral stress always refers to the stress within the part that detached and does not apply to the whole glacier. This has been clarified in the manuscript:*

*“The analysis of the dynamics and force-balance evolution on an area restricted to the detachment zone (dashed lines in Figure 8) reveals both similarities and differences between the two events (Figure 9). Further references to “lateral stress” apply to the detachment zone and not to the whole glacier. It refers to the stress provided by the shearing interface between the stable and the instable part of the glacier”*

- 4- The Kolka Glacier case is interesting with a rock fall on it. There is a simple argument to be made that for a plastic till the addition of a mass on top of the glacier will lead towards instability if the glacier slope is larger than the friction angle of the till, without invoking pore water pressure changes. Is this potentially the case here?

*From satellite observation, we do not observe any evidence of external loading on the top of the glacier in the previous years. Such event would have been visible and is unlikely given that there is no steep rockwall overlooking the glaciers. However, bulging (due to surge-like behavior) associated to strong melting increase in the tongue area has steepened the glacier surface in the*

*tongue region (Kääb et al., 2018). This could also act as a trigger if the tongue surface slope would have reached the friction angle but changes in pore water pressure still have to be invoked to initiate the instability. We computed driving stress at different periods on the detachment from surface slope and thickness (Error! Reference source not found.9B of the manuscript). It shows an increase of 17% of the driving stresses that may have contribute to reach still strength. We mention it, in the manuscript.*

5- The abstract mentions that this is a response to recent increases of surface melting and rain. Neither is shown in the paper. This is an important conclusion and only enters the paper via a mass balance model that is discussed elsewhere. For such a substantiative statement it seems like there needs to be at least some amount of backup (e.g. a figure of temperature/precip changes)

*Yes, this result comes from the previous study of Kääb et al. (2018), a figure is already published in their supplementary material (Figure S10). We added a reference in the discussion (section 5.3).*

### **Technical corrections**

I won't list grammatical issues, there are too many. This paper needs a very careful editorial revision.

*This has been done.*

Some other comments:

p.2, l.7: unique -> rare (it's not unique you mention another example in the next sentence...)

*Done*

p.3, l.10: are the two X-band images from the same time of year? Otherwise could the penetration depth change with snow wetness?

*The TanDEM-X images were acquired in June 2011, April 2013 and April 2014 (specified in Table 1). So there could be some penetration depth change between 2011 and 2013. However, ERA-interim reanalysis and Sentinel-1 backscatter images over the period 2015-2016 (warmer than 2011) show that no melt occurred in the accumulation area (above 5800 m a.s.l.) before mid-June (see Figure R5). Changes in penetration depth are therefore likely not significant between June 2011 and April 2013. We modified the manuscript:*

“The effect of uncertainty linked to radar penetration in the TanDEM-X data should be minimized when comparing same wavelength data (X-band) at similar times of the year. Change in penetration depth between the TanDEM-X data of 2011 (early June) and of 2013 (mid April) due to different snow wetness should be also limited because surface melting in the accumulation area of the Aru glaciers only occurs from around mid-June on (Kääb et al., 2018).”

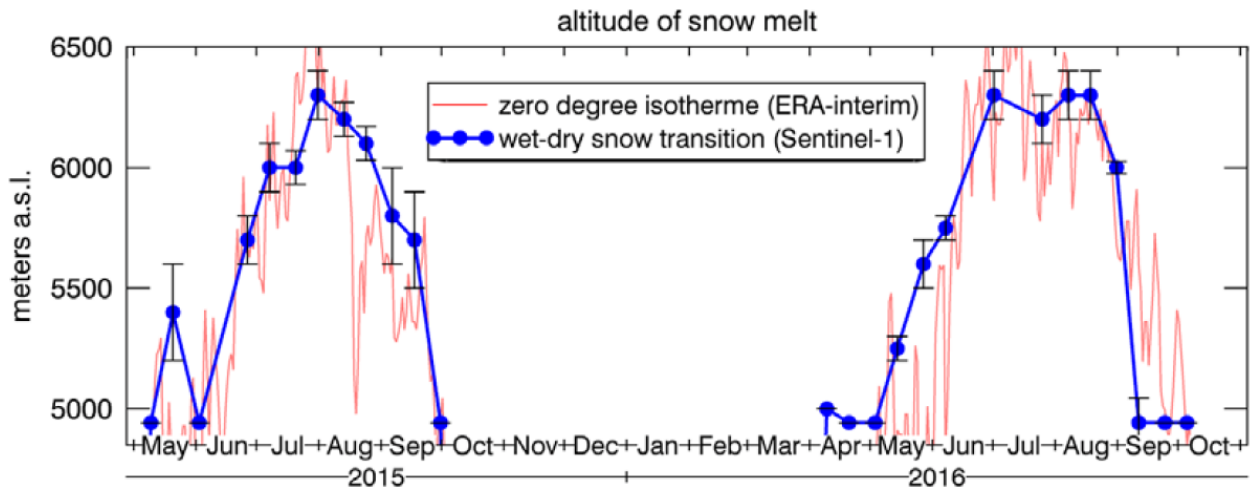


Figure R4 - Elevation of the wet-dry snow transition in 2015 and 2016. Figure taken the supplementary material of (Kääb et al., 2018).

eqn (2): d should be y

Done

p.6, l.2: which two cases?

We mean here the cases of Aru-1 and Aru-2. This is now clarified in the manuscript.

p.7, l.31/32: I don't understand that sentence at all (.. external side of the curve ..)

The sentence has been clarified: « Along the left bank of the glacier, close to the terminus of Aru-1, shear stress is about 6-7 kPa and was not more than 15 kPa at the terminus. »

p.10, l.2: sec 5.2 is a self-reference...

We wanted actually refer to sec 5.3... The manuscript has been corrected.

p.10, l.10: How did you observe bedrock roughness. I thought this was all till covered?

This is a qualitative statement based on field pictures (see Figure R5). You are right that we do not really observe the bedrock interface but rather the failure plan, which can be different. However, this provides evidence for a rather smooth interface between the glacier and its substrate. Manuscript has been updated.



Figure R5 – View of Aru-2 after collapse (November 2016, Picture: T. Yao).

p.10, l.17/18: The MacAyeal and Tsai references don't quite seem appropriate here; they don't show plastic till, they assume it in their models.

*Yes, we removed these two references.*

p.10, last paragraph: I find some of the discussion here confusing. What do you mean when you state that “plastic rheology becomes the only source of resisting forces”? Or “increasing pore pressure ... quickly reduced basal shear stress”? Increasing pore water pressure reduces effective stress (not shear stress) and through that the strength of the till. In a plastic rheology you can't reduce the shear stress to the strength; till strength is a limiting stress.

*We mean that when the failure occurred at the detachment margin and lateral stresses are not able anymore to contribute to force balance, the only source of resisting force became the basal friction, which behaves plastically when till strength is reached. In other word, as you say, the resisting stress became limited to the till strength which is not able to compensate driving stress anymore, leading to collapse.*

*Yes we exactly mean what you wrote here. Increasing pore water decrease effective normal stress and therefore till strength. Because till strength is the limiting stress and driving stress is superior to this limit, basal shear stress actually takes the till strength value and locally decreases as the till strength decreases.*

*We clarified this paragraph in the reviewed manuscript.*



p.11, l.17: What would cause higher lateral stresses? See also my earlier comment: when does a basal stress become a lateral stress in a valley geometry?

*In our study, we refer to lateral stress at the detachment margin and not over the whole glacier. Therefore, our force balance analysis is done on the part of the glacier that detached. On this delimited area, lateral stresses exist along the western glacier margin where the detachment is connected to the glacier body over a significant thickness of ice. In particular, the ice body, west of the detachment, is likely cold based and provides significant lateral resistance to flow in the detachment area. In this case, higher lateral stress would be caused by greater ice thickness or more likely by less damaged ice at the detachment margin, confirmed by the much less developed crevassed area on Aru-2. The manuscript has been clarified on this point. See also response to specific comment no 3.*

#### *References:*

*Minchew, B., Simons, M., Björnsson, H., Pálsson, F., Morlighem, M., Seroussi, H., Larour, E. and Hensley, S.: Plastic bed beneath Hofsjökull Ice Cap, central Iceland, and the sensitivity of ice flow to surface meltwater flux, *Journal of Glaciology*, 62(231), 147–158, doi:10.1017/jog.2016.26, 2016.*

- **Reviewer 2 (I. Rogozhina)**

This paper presents a model-based interpretation of temporal changes in the internal dynamics, basal friction and stress states of two glaciers in western Tibet to explain their catastrophic collapses in 2016. The inversion method used to derive glacier model results is rather unusual in this I agree with reviewer 1 – but it seems to yield rather good results. I still think that this method should be validated on a glacier that has measurements of horizontal velocities, vertical surface changes and ideally bedrock topography to make the case that it is operational. There are quite some examples of such glaciers, especially in the European Alps. Inversion methods can be quite tricky, since they derive whatever one wants to obtain, especially when multiple parameters are estimated in parallel. Nevertheless, this study is an impressive contribution to the state-of-the-art understanding of the glacier dynamics and addresses the challenge of the glacier model initialization in a neat manner, even though it has a significant overlap in terms of motivation and conclusions with the paper featuring the same authors (Kääb et al., 2018). The language is quite remarkable, as reviewer 1 has pointed out, and I am rather surprised to see so many experienced co-authors – including native speakers who do not seem to have read the paper. With this review I encourage them to have a look at it. I believe that this paper will merit publication in TC after moderate revisions.

#### **MAJOR POINTS:**

1. As I mentioned in my summary, the authors should prove that their inversion method is operational by validating it on a glacier with more measurements (see above).

*We compare the results obtained by our method (2013-2014) with a more standard inversion method based on horizontal velocity measured in December 2013 by TerraSAR-X offset tracking. This shows good agreement and validates our inversion method. See also response to reviewer 1 (specific comment no 1). A paragraph has been added in the main manuscript as method validation (section 5.1) referring to new figures in the supplementary material.*

2. I absolutely agree with reviewer 1: All the points he has raised are valid and I am looking forward to seeing responses to his concerns. In addition, I feel that his specific point 2 needs further exploration: It would be worth looking at how friction angle in equation 4 (in addition to friction coefficients) changes over time leading to the collapses of the glaciers. In addition to showing how the subglacial till changed its properties in response to warming and increased meltwater supply, this experiment will provide an estimate of the yield stress needed to enable such a failure. A very useful exercise for the future diagnostic experiments that will empower predictions of similar glacier failures and an important exercise to support the conclusions of this study.

*See response to reviewer 1. Concerning friction angle: this is unfortunately not possible since we do not know the water pressure and effective normal stress. The friction angle is actually a constant through time that depends on the material property. The yield stress is then only a function of the effective normal stress. Assuming a typical value of friction angle and that basal shear stress reached the yield stress in most of the detachment, we could infer water pressure from equation 4. This would have to be analyzed by additional investigations based on subglacial hydrological models to be relevant. This is beyond the scope of the paper but inferring subglacial water pressure would be clearly a valuable next step of studying the Aru collapse.*

3. I don't believe much in the climate forcing provided by ERA-Interim in such high-topography, steep-gradient environment, especially after I learned from this paper that the precipitation rate had to be multiplied by a factor of 4. Could the authors compare ERA-interim fields with High Asia Refined (HAR) analysis (MauSSION et al., 2014)? I suggest that the authors perform sensitivity tests to assess the uncertainties in their results coming from the mass balance estimates using HAR.

*In our study, surface mass balance modeling is only used to compute surface-normal velocities from elevation change measurement and infer basal friction. We assessed the sensitivity of our results to surface mass balance by inverting basal friction during the period 2013-2014 under different surface mass balance reconstructions: (i) No surface mass balance correction, (ii) Modeled surface mass balance divided by two and (iii) Modeled surface mass balance multiplied by two. These hypotheses are rough and introduce greater variation in the surface mass balance than the actual uncertainty on this reconstruction constrained by satellite measurement and field data (see (Kääb et al., 2018), sup. mat.). The friction field variability presented in Figure R7 is therefore a conservatively large estimate of the uncertainty introduced by the surface mass balance. It shows that friction in the detachment area where surface-normal velocities are high,*

due to unbalanced geometry, is not very sensitive to surface mass balance reconstruction. This makes our results reliable in this glacier part, which is the focus of the study.

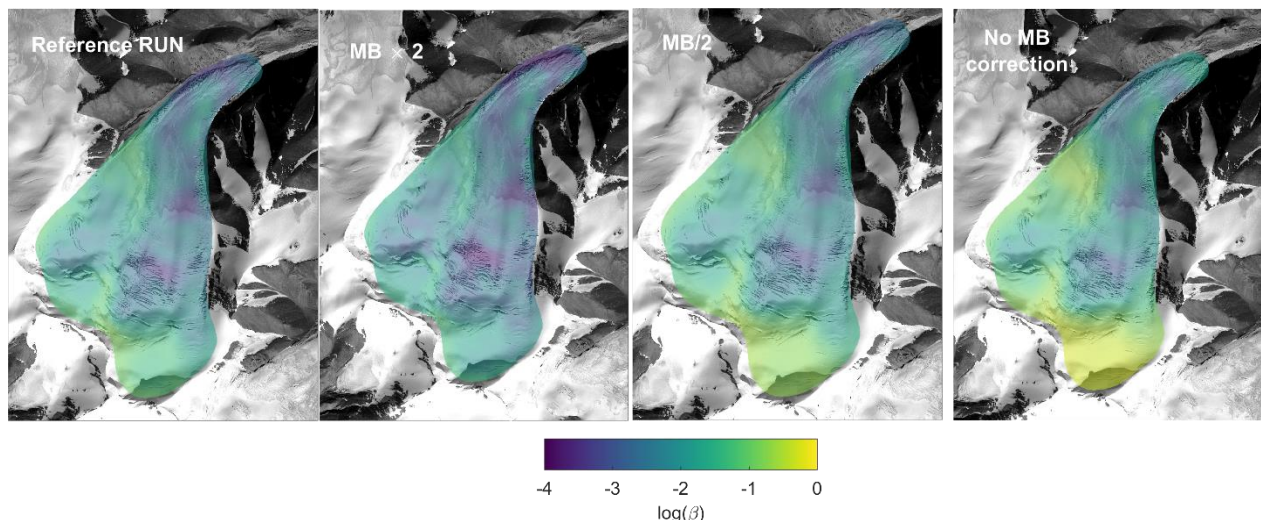


Figure R6 – Friction coefficient  $\beta$  inferred for different surface mass balance modifications on Aru-1 between 2013 and 2014. Absolute values.

This figure is now included in the Supplement of the manuscript.

The ability of ERA-interim reanalysis to reproduce observed mass balance has been already compared to MERRA-2 and HAR reanalysis in (Kääb et al., 2018). ERA-interim provides the best mass balance agreement with observations compared to the two other products. This is mainly due to a sudden increase of precipitation in the mid-nineties that is not captured by MERRA-2 (see Figure R8). HAR reanalysis gives an unrealistic trend in precipitation that makes mass balance modeling not able to reproduce the observations. However, the mean values of precipitation provided by HAR are in good accordance with our corrected ERA-interim precipitation (factor 4) (see Figure R9). The factor 4 is also confirmed by high elevation AWS measurement in the region (200 km away). Please refer to the sup. mat. of Kääb et al. (2018) for greater details.

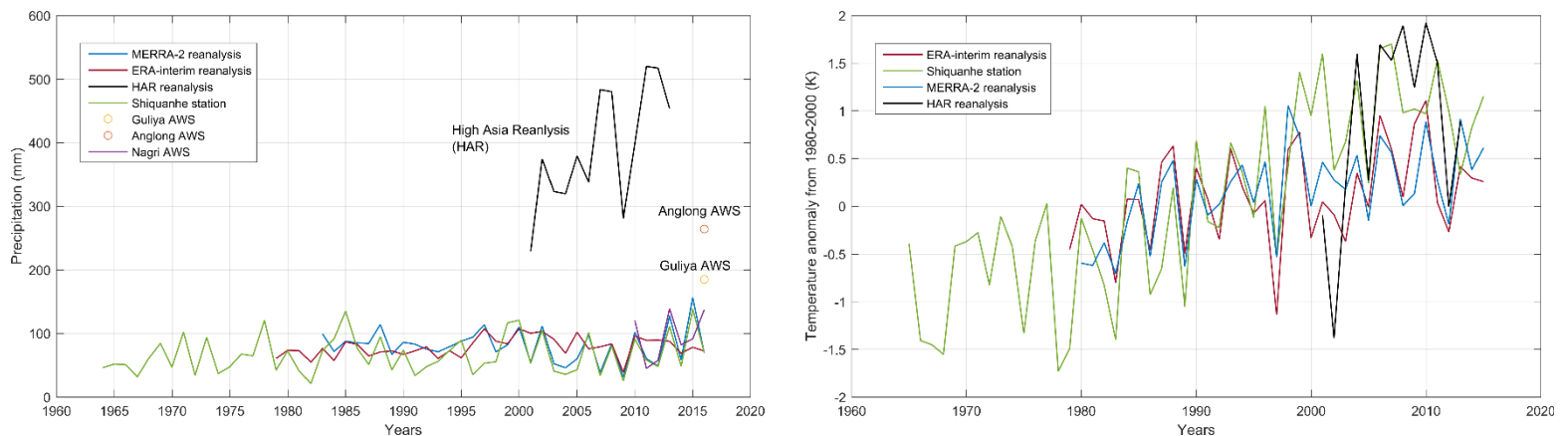


Figure R7 – Left :Annual precipitation at the different weather stations and from reanalysis at the location of the Aru range (see Kääb et al. (2018)). Right :Annual temperature anomaly relative to the 1980-2000 mean at the different weather stations and from reanalysis at the location of the Aru range (see Kääb et al. (2018)).

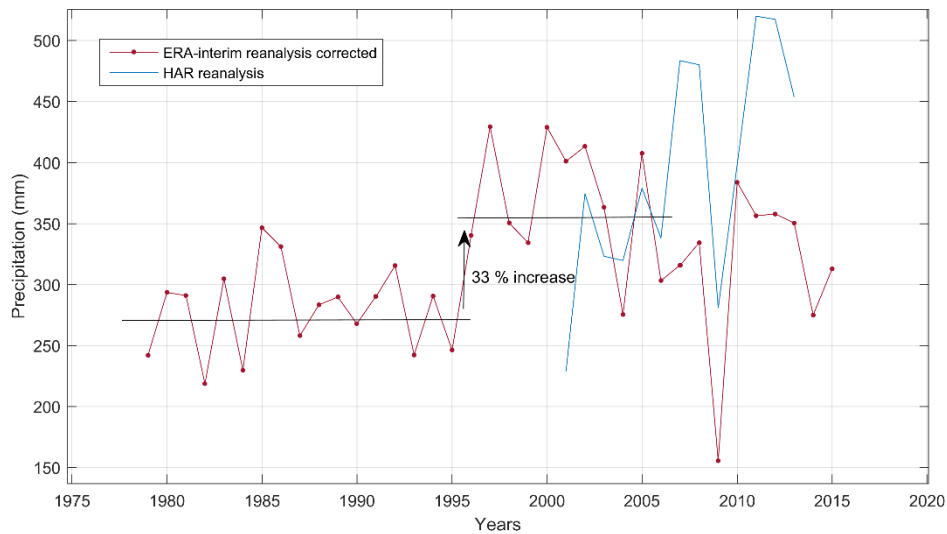


Figure R8 - Corrected ERA-interim annual precipitation (red line) using glacier geodetic mass balance observations compared with the 10km resolution HAR reanalysis (blue line) (see Käab et al. (2018)).

#### MINOR POINTS:

The methods section is sloppy. For example, I am missing a table with model parameters. In general, the methods have to be more detailed. This is not a Nature paper, there is space for the description of methods. The supplementary materials are no accessible through the online system. There are some citations of materials in the supplement, which I cannot access.

*We did not find any issues to access the supplement through the article webpage; this should be accessible to all. We made the choice to not describe the model in details and focus on the application of it since both mass balance and thermo-mechanical model are already described in other published studies (Gilbert et al., 2014, 2016; Käab et al., 2018). In the revised manuscript we added a table with model parameters and described more the methods (see also response to Major point 1).*

Page 7, lines 13 – 14: Cannot it be influenced by a larger error in the bedrock estimate?

*This is unlikely since bedrock topography is quite well constrain in the detachment area by the post-collapse Pleiades DEM. Also high friction on the tongue of Aru-2 is confirmed by the fact that the Aru-2 front never advanced before the collapse contrary to the Aru-1 front. We added a sentence in section 5.1 about uncertainty. “Bedrock topography is well constrained in this part from the post-collapse Pléiades DEM, giving additional confidence in the friction reconstruction over the detachment area.*

Page 9, line 9 – 13: This requires a proof.

See response to major point no 3. An additional figure has been added in the supplementary information.

Page 9, line 27: “from temperate to cold basal conditions” - the other way around?

Yes. The manuscript has been corrected.

Page 10, section 5.3: The field data are only available for Aru 1. Are the authors sure that Aru 2's bed has the same lithology?

This is shown by multi-spectral lithological analysis from satellite images. See (Kääb et al., 2018).

Page 11, lines 4 – 5: Any evidence from the little ice age glacial moraines to support this statement?

No we did not find any. But melt rates are already very low in this kind of cold/dry environment. It makes relative melt rate increase significant in a context of climate warming as soon as a melt threshold is reached; especially in the accumulation area where water likely entered the glacier body (crevassed area, warmer ice temperature due to firn). Considering the current melt rate in the accumulation area ( $< 0.25 \text{ m w.eq. yr}^{-1}$ , see Figure R10), it is likely that no melt occurred at similar elevation during the Little Ice Age.

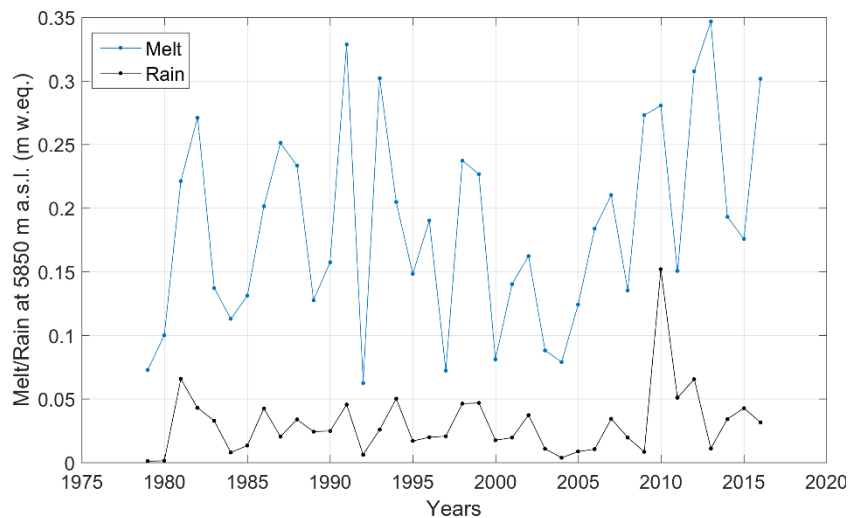


Figure R9 – Modeled annual melt and rain at 5850 m a.s.l. (Kääb et al., 2018)

## References:

Kääb, A., Leinss, S., Gilbert, A., Bühler, Y., Gascoin, S., Evans, S. G., Bartelt, P., Berthier, E., Brun, F., Chao, W.-A., Farinotti, D., Gimbert, F., Guo, W., Huggel, C., Kargel, J. S., Leonard, G. J., Tian, L., Treichler, D. and Yao, T.: Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability, *Nat. Geosci.*, 11(2), 114–120, doi:10.1038/s41561-017-0039-7, 2018.

Maussion, F., D. Scherer, T. Mölg, E. Collier, J. Curio, and R. Finkelburg: Precipitation seasonality and variability over the Tibetan Plateau as resolved by the High Asia Reanalysis, *J. Climate*, 27, 1910-1927, doi:10.1175/JCLI-D-13-00282.1, 2014.

# Mechanisms leading to the 2016 giant twin glacier collapses, Aru range, Tibet

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**Abstract.** In northwestern Tibet (34.0°N, 82.2°E) near lake Aru Co, the entire ablation areas of two glaciers (Aru-1 and Aru-2) suddenly collapsed on 17 July 2016 and 21 September 2016, respectively, ~~and~~ The masses transformed into ice avalanches with volumes of 68 and 83  $\cdot 10^6$  m<sup>3</sup> ~~mass flows that and~~ ran out up to 7 km in horizontal distance, killing nine people. The only similar event currently documented is the 2002 130  $\cdot 10^6$  m<sup>3</sup> Kolka Glacier mass flow rock/ice avalanche of 2002 (Caucasus Mountains). Using climatic reanalysis, remote sensing and 3D three-dimensional thermo-mechanical modeling, we reconstructed in detail the Aru glaciers' thermal regimes, thicknesses, velocities, basal shear stresses and ice damage prior to the collapse. Thereby, we highlight the potential of using emergence velocities to constrain basal friction in mountain glacier models. We show that the frictional change leading to the Aru collapses occurred in the temperate areas of the polythermal glacier structures glaciers and are is not linked related to thaw a rapid thawing of cold-based ice. The two glaciers experienced a similar stress transfer from predominant basal drag towards predominant lateral shearing in the later detachment areas, and during the 5-6 years before the collapses, ~~though with a collapses.~~ A high-friction patch is found on the Aru-2 tongue which is inexistent on, but not for Aru-1. The latter This difference led to distinctly disparate behaviour behavior of both glaciers, making the development of the -instability more visible for the Aru-1 glacier compared to Aru-2 through enhanced crevassing over a longer period and terminus advance, compared to Aru-2, where such signs were observable only over a few days to weeks (crevasses), or absent (advance). Field investigations reveal that those two glaciers are flowing on a were underlain by soft, highly erodible, and fine-grained sedimentary lithology ies. We propose that specific bedrock lithology played a key role in the two Tibet, and also in the Caucasus gigante glacier collapses documented to date by producing low bed roughness and

large amounts of till, rich in clay/silt with a low friction angle. The twin 2016 Aru collapses would thus have been driven by a failing basal substrate linked to increasing water pore-pressure in the subglacial drainage system in response to recent increases in surface melting and rain preceding the collapse dates.

## 1. Introduction

5 In the Aru mountain range on the Western Tibetan Plateau, on July 17 2016, the entire ablation zone of a nameless unnamed glacier (termed here Aru-1) spontaneously collapsed on 17 July 2016, this despite its low slope angle (of only  $13^{\circ}$ ) (Tian et al., 2016) compared to classical typical ice avalanches sourced occurring from the failure of much steeper hanging glacier failure glaciers (Faillettaz et al., 2015). The Aru-1 glacier collapse produced a high speed an ice avalanche exceeded with speeds exceeding 200 km h<sup>-1</sup> and spread out over a 7 km long and 3 km wide deposit, killing and killed nine people herders and hundreds of their animals (Kääb et al., 2018). This event was followed by the collapse of the closest adjacent glacier south of Aru-1 two months later, on 21 September 2016, producing a similar low-slope-angle gigantic avalanche (see Figure 1B). These Such catastrophic glacier collapses are unique by their extremely rare in size and mobility. Only one similar case has been documented before, the Kolka/Karmadon glacier collapse in the Caucasus mountains in 2002 (Evans et al., 2009; Huggel et al., 2005; Kääb et al., 2003). In order to anticipate potential similar hazards in other populated mountain areas we need it is crucial to understand in detail the mechanisms involved, and identify potential triggers and factors responsible for these extreme events-mass movements. Among others, such the collapses raise the question of their occurrence in the whether similar future with respect to the on going events affecting other glaciers might be influenced by ongoing climate change.

Applying satellite imagery analysis and glacier mass balance modeling, Kääb et al. (2018) explored the long-term behaviour of the two Aru glaciers leading prior to the collapse. They show that the two collapsed glaciers started a surge-like instability around 2010, probably in response to both increasing precipitation and temperature in the region, and related positive mass balances. Their preliminary analysis of the two-dimensional (2D) thermal glacier regime shows a polythermal structure for the two glaciers that. Such a structure likely would have played a role in the collapses by providing downstream provided resisting forces against whole-glacier sliding and promoting, but would have promoted englacial drainage to the bed only in the lower temperate part of the accumulation zone, with possible local sliding and contributing to swelling or inflation of the glacier toe above and behind the frozen part. Facing the enigma of two neighbouring glaciers undergoing—close in time—a similar catastrophic behaviour that otherwise is globally almost unique, Kääb et al. (2018) also point out the possible role of a specific that soft bedrock lithologies and glacier till production—perhaps due to local glacier sliding in the temperate part of the glaciers—played in the instabilities by reducing of glacier basal friction involved in the instability.

In this study, we significantly extend the quantitative numerical analysis of the Aru glacier instabilities and discuss in detail the mechanisms leading to the collapses. We used a three-dimensional (3D) full-Stokes thermo-mechanical model in order to (i) reconstruct the bedrock topography, (ii) analyse in 3D the thermal regime of the glaciers, (iii) infer the evolution of the basal friction prior to the collapse, and (iv) quantify the stress distribution that led to the final collapses. We then combine the



modeling results with field investigations to further ~~develop~~elaborate on the role of bedrock lithology and discuss the related origin of the twin collapses. Finally, we ~~provides~~summarize key-characteristics, to recognize similar on other glaciers, lithologic and thermal regimes ~~for other glaciers~~similar to the Aru glaciers to help identify new potential collapses in the future.

## 2. Observations

5 The Aru range is located on the remote Western Tibetan plateau (34°N, 82°E) where very few glaciological or meteorological observations are available (Figure 1). Prior to Kääb et al. (2018), the two collapsed glaciers were never studied before and the entire modeling work of this study is therefore based on remote sensing data and climatic reanalysis. DEM differencing provided both the observations on the glacier transient dynamics and the mean mass balance over different time periods needed to calibrate the models. (Kääb et al., 2018) compared different sources of local climatic data in order to reproduce remote-  
10 sensing based mass-balance observations and concluded that the ERA-interim reanalysis provides the best estimate of the Aru range climate, if the respective precipitation amounts are corrected by a multiplying factor of about 4. ~~We~~Here, we use ~~here~~ their mass balance model for constraining the thermo-mechanical model described in section 3.2.

### 2.1. Digital Elevation Models (DEMs)

We used seven different DEMs derived from different satellite missions between 2000 and 2016 (see Table 1). The SRTM C-  
15 band radar DEM from mid-February 2000 (Farr et al., 2007) ~~was~~is used as the steady-state reference of the two glaciers for reconstructing bedrock topography. A Pléiades optical satellite stereo DEM from 1 October 2016, after the collapse, allows us to, ~~in parts, validate~~ evaluate the modeled bedrock reconstruction over the detachment zone. We ~~computed~~compute ice emergence velocities by differencing pre-collapse high-resolution DEMs from ~~Tandem~~TanDEM-X, Spot7 and ~~Worldview~~ WorldView data and correcting these for mass balance following the approach described in Gilbert et al. (2016) (Figure  
20 2). ~~Uncertainty~~The effect of uncertainty linked to radar penetration in the TanDEM-X data should be ~~minimiz~~ed when comparing same wavelength (~~data (X-band-X) since~~) at similar times of the year. Change in penetration length would be similar depth between the TanDEM-X data of 2011 (early June) and 2013 (mid April) due to different snow wetness should be also limited because surface melting in the accumulation area of the Aru glaciers only occurs from around mid-June on (Kääb et al., 2018). X-band penetration into glacier ice (i.e. the Aru ablation areas) is very limited anyway (Dehecq et al.,  
25 2016)~~two images~~. Comparing Spot7 (2015) and ~~Tandem~~TanDEM-X (2014) elevations likely introduces uncertainty from TanDEM-X penetration in the accumulation area leading to higher emergence velocities in this part (visible in Figure 3). This problem only influences our friction reconstruction in the higher part upper parts of the glacier and glaciers but not on the detachment areas. Details on DEM accuracies and acquisition methods can be found in Kääb et al. (2018).

## 2.2. Field observations

We investigated glacier till properties by analyzing samples collected from the Aru-1 avalanche deposit in the gorge close to the former glacier tongue. We collected these samples one year after the collapse on 18 July 2017. Rainy conditions on that day highlighted the behaviour of the surrounding lithology that quickly turned to soft and unstable slurries in the presence of water. Additional information about our samples can be found in supplementary material to this article (Figures S3S8 to S5S10).

## 3. Modeling methods

### 3.1. Mass Balance

Our mass balance model for the two Aru glaciers is based on a degree-day model described in Gilbert et al. (2016). It has been calibrated ~~in~~ for the Aru glaciers by using satellite-derived glacier mass balances and is fed by ERA-interim climate reanalysis (Kääb et al., 2018). The model output, taken from Kääb et al. (2018), provides the ~~spatial~~ spatio-temporal distribution of surface mass balance, firn thickness, and available surface melt water for percolation/refreezing in the firn to constrain the thermo-mechanical model below.

### 3.2. Thermo-mechanical model

Our thermo-mechanical ice-flow model is based on the Stokes equation coupled with an energy equation using the enthalpy formulation (Aschwanden et al., 2012; Gilbert et al., 2014). Changes in the glacier geometry are computed using a free surface equation (Gilbert et al., 2014). We adopt a pure viscous isotropic ice rheology following Glen's flow law (Cuffey and Paterson, 2010). The model is solved using the finite-element software Elmer/ice (Gagliardini et al., 2013). Parameters and variables of our model set-up are summarized in Table 2.

We adopt a linear friction law as a basal boundary condition for the Stokes equation that reads:

$$\tau_b = \beta u_s \quad (1)$$

where  $\tau_b$  is the basal shear stress (MPa),  $u_s$  is the sliding velocity ( $\text{m yr}^{-1}$ ) and  $\beta$  the friction coefficient ( $\text{MPa yr m}^{-1}$ ). This coefficient is inverted using a control inverse method to minimize a cost function defined from the misfit with measured surface data and a regularization term (Gagliardini et al., 2013; Gillet-Chaulet et al., 2012). Following Gilbert et al. (2016) we used here the surface normal emergence velocity  $U_{N_z}^{obs}$  ( $\text{m yr}^{-1}$ ) to compute this cost function:

$$J_0 = \int_{\Gamma_s} \frac{1}{2} (\|U_{N_z}\| - \|U_{N_z}^{obs}\|) d\Gamma + \lambda J_{reg} \quad (2)$$

$$J_{reg} = \frac{1}{2} \int_{\Gamma_b} \left( \left( \frac{\partial \beta}{\partial x} \right)^2 + \left( \frac{\partial \beta}{\partial y} \right)^2 \right) d\Gamma \quad (3-This)$$

5 where  $U_{N_z} = (\mathbf{u} \cdot \mathbf{N}) N_z$  is the modeled emergence velocity (m yr<sup>-1</sup>),  $\mathbf{u}$  the surface velocity vector (m yr<sup>-1</sup>),  $\mathbf{N} = (N_x, N_y, N_z)$  the unit vector normal to the surface,  $\Gamma_s$  is the surface boundary,  $J_{reg}$  is the regularization term,  $\Gamma_b$  is the bedrock surface boundary and  $\lambda$  is a positive number. The emergence velocity is obtained by removing the mean modeled mass balance from the elevation change rate measured from our repeat satellite-derived DEMs over the same periods (Figure 2):

$$U_{N_z}^{obs} = \frac{dh}{dt} - M \quad (4)$$

where  $dh/dt$  is the measured elevation change rate (m yr<sup>-1</sup>) and  $M$  the mean surface mass balance during the corresponding period (m yr<sup>-1</sup>).

10 The surface boundary condition is set as a stress-free boundary for the Stokes problem and using a Dirichlet condition for the enthalpy equation. In order to take into account water percolation and refreezing within the firn, we follow the approach by Gilbert et al. (2015), in this case using a 6-month time step. Latent heat due to refreezing is released every year during a time steps that includes the summer time step. The firn-thickness distribution is estimated from the mass balance model following Gilbert et al. (2016) and the firn density is computed using a linear density profile set to:

$$\rho(y) = \rho_0 + \frac{d}{H_{firn}} (\rho_{ice} - \rho_0) \quad (5)$$

15 where  $\rho$  is the density (kg m<sup>-3</sup>) at depth  $d$  (m),  $\rho_0$  is the surface density,  $\rho_{ice}$  is the ice density and  $H_{firn}$  the firn thickness (m). The lateral boundary condition is set to a no-flux condition for both the Stokes and enthalpy equations. We assume a basal heat flux of 8.0·10<sup>-2</sup> W m<sup>2</sup> for the enthalpy equation according to heat flux measured in boreholes at that Guliya ice cap (6200 m a.s.l., 200 km north of the Aru range) (Thompson et al., 1995) and geothermal heat flux modeled in the region (Tao and Shen, 2008).

### 3.3. Modeling strategy for the steady state glaciers

25 The first step of modeling the dynamics and thermal regime of the Aru glaciers is to obtain/establish a steady-state glacier as initial condition for 1970 (start of the climatic reanalysis used). Landsat satellite images of the glacier area and the mass balance model suggest that the two glaciers were close to equilibrium from 1970 to 1995 (Kääb et al., 2018). We therefore assume that the surface topography measured in February 2000 by the SRTM mission (oldest available DEM) is representative of the glaciers being in equilibrium with the mean climate over this period, although the positive mass balance between 1995 and 2000 probably thickened the glacier by a few meters in the accumulation area. We use the mean mass balance between 1980

and 1995 as an equilibrium mass balance considering that modeled mass balance is close to steady-state during this period before becoming positive from 1995 to 2008 (Kääb et al., 2018).

We first run the model on a 2D flow line until a steady state is reached, ~~using the Pléiades DEM from after the collapses as deriving~~ bedrock topography in the detached parts ~~from a post-collapse Pléiades DEM,~~ and by reconstructing the bed at the ~~higher upper~~ glacier parts -assuming a constant basal shear stress (plastic approximation, ~~see~~ Cuffey and Paterson (2010)). This initial step allows for the first approximation of the steady-state thermal regime which we presented already in Kääb et al. (2018). We ~~use~~ then use the 10m-depth temperature modeled by the flow line model to define the steady-state surface enthalpy as a function of elevation which includes meltwater percolation and refreezing effects. This relationship is used to define a Dirichlet surface boundary condition for enthalpy in order to solve the steady-state thermal regime of the glaciers in 3D in the bedrock inversion procedure (section 3.3.1). Because the effects of meltwater percolation and refreezing ~~is~~ are already included in the surface enthalpy value, ~~it avoids solving meltwater percolation and refreezing there is no need to solve for these effects~~ in diagnostic runs. The final 3D steady-state glacier solution is ~~properly~~ properly obtained ~~at the end~~ by running a transient simulation using the inverted bedrock topography and solving water percolation and refreezing until surface topography and the enthalpy field reach equilibrium with the imposed climatic condition.

### 3.3.1. Reconstructing bedrock topography

Using constant climatic conditions associated with the balanced glacier conditions ~~for~~ corresponding to the SRTM DEM, we determined the bedrock topography allowing the best match between modeled and observed (i.e., SRTM DEM) surface topography (van Pelt et al., 2013). For this purpose, we run a 3D transient simulation assuming no sliding, fixed surface topography (SRTM DEM), and constant surface forcing (mass balance and enthalpy). The no-sliding assumption is likely a good assumption in 2000 since the glacier was not surging at this time (Kääb et al., 2018). Mesh horizontal resolution is set to about 50 m with 15 vertical layers. The evolution of the free surface is taken into account by varying the basal mesh elevation instead of the surface elevation. The mesh surface topography remains thus constant while the bed topography is updated by solving the equation

$$\frac{\partial(z_{bed})}{\partial t} + \vec{v}_s \cdot \vec{\nabla}(z_{bed} - z_{bed0}) = \vec{v}_s \cdot \vec{\nabla}z_{s0} - MB - w_s \quad (6)$$

where  $z_{bed}$  is the bedrock elevation (m),  $\vec{v}_s$  is the surface horizontal velocity (m yr<sup>-1</sup>),  $z_{bed0}$  is the initial bedrock topography (m),  $MB$  is the surface mass balance (m yr<sup>-1</sup>),  $w_s$  the vertical component of the surface velocity (m yr<sup>-1</sup>) and  $z_{s0}$  is the measured surface elevation (m). The right side of Eq. ~~36~~ vanishes once bedrock topography satisfies the required topography to keep  $z_{s0}$  constant for a given mass balance  $MB$ . The advective term in the left side of Eq. ~~36~~ allows smoothing  $z_{bed}$  in the flow direction. The enthalpy field is solved at each time step by solving the steady-state equation for the current velocity field and mesh. We initially start with a uniform 200 m ice thickness (rough maximum expected thickness on the glacier) and run the

model until reaching steady bedrock topography. This ~~gives~~generates a new  $Z_{bed0}$  value to ~~start again~~re-run the ~~procedure~~model until reaching a new steady state. After only two iterations, we validate the modeled bedrock topography by running the model with the ~~new fixed~~new inferred bedrock topography and free surface evolution. The resulting surface topography is in excellent agreement with the measured one (Figure 3) ~~meaning~~indicating that our method to infer the bedrock topography works well   
 5 ~~in~~for these two ~~eases~~glaciers.

We use the opportunity provided by the exposed detachments to compare the reconstructed bedrock topography with the measured Pléiades DEM from after the collapses (Figure 3). On Aru-2, the points where the bedrock is clearly visible in the Pleiades images match well with the locations where our reconstructed bedrock topography matches the Pléiades DEM (dots in ~~Figure~~Figure 3). Elsewhere in the Aru-2 detachment zone, the modeled bedrock is deeper than the observed surface elevation,   
 10 ~~but~~; this is likely due to the remaining ice debris ~~so that overlying the actual bedrock, so~~ the Pléiades DEM ~~is~~elevations are expectedly higher than the actual bedrock. This is confirmed by the good continuity between debris thickness measured outside of the former glacier tongue and the one inferred from our bedrock reconstruction (see Figure 3, profile 6). On Aru-1, the reconstructed bedrock on profiles 2, 3 and 4 is systematically deeper than the Pléiades DEM, even on the steep side close to the margin of the glacier where no ice remained after the collapse. This means that ice flow is not accurately modeled in this   
 15 part, likely due to the premise of no sliding, which is probably not accurate considering that the glacier may ~~be~~have been temperate at its base here (see section 4.1). This~~The error in the modeled bed topography of Aru-1 is however < 30 m and will only slightly affect the absolute value of the friction coefficient inferred during the instability development (see section 4.2), but not its relative changes, which are the focus of this study. The assumption of no sliding should also affect the result on Aru-2, which has a similar thermal regime, but where the no-sliding condition seems to work. This~~ ~~indicates~~suggests the existence of different sliding conditions ~~in~~at the two glaciers prior to collapse, ~~as~~which is also supported by the friction inversion analysis presented in section 1.1. In the upper parts of both glaciers, the no-sliding assumption is however supported by the friction inversion analysis.   
 20 by the friction inversion analysis.

## 4. Results

### 4.1. Steady state configuration of the two glaciers

25 The Aru glaciers are representative of a cold and semi-arid climate regime, and as such show under normal conditions little ~~dynamics~~dynamic behaviour under mostly cold-ice conditions. The steady-state equilibrium line is located around 5750 m a.s.l. (minimum glacier elevations around 5200 m a.s.l., and maximum elevations around 6100 m a.s.l.) with a maximum accumulation of 0.6 m w.eq. yr<sup>-1</sup> at 6100 m a.s.l. and a maximum ablation of -2.5 m w.eq. yr<sup>-1</sup> on the tongue (Figure 4B). Both glaciers are composed of two similar catchments characterized by a smaller western branch that joins the main stream in the   
 30 ablation area. The western branch of each glacier is thinner and ~~is~~ less dynamic compared to the main branches that collapsed in summer 2016 (Figure 4A). Maximum surface horizontal velocity reached 20 m yr<sup>-1</sup> in Aru-2, which is thicker than Aru-1 due to a wider accumulation area (1.7 km<sup>2</sup> vs 1.2 km<sup>2</sup>) converging in a similarly narrow gorge.

As previously concluded by Kääh et al. (2018), our results- show that the main branches of the two glaciers are characterized by a polythermal structure with a cold accumulation zone above 5900 m a.s.l. and a temperate-based ablation area surrounded by cold ice (Figure 5). However, ~~thanks to a~~through the more accurate bedrock topography ~~derived in this study~~ and ~~a~~the 3D approach, we show here that the temperate ~~parts~~zones likely ~~extend in~~extended into significantly larger areas beneath the detachments than previously thought. Temperate ice forms in the lower part of accumulation zones due to a significant amount of percolation and refreezing of melt water, which increase the temperature of the near-surface firn. This warmer ice is then advected into the ablation zone contributing, together with basal heat flux, to create ~~a~~temperate basal conditions in the ~~deeper~~lower parts of ~~each glacier~~the two glaciers. Cold surface conditions due to absence of water percolation in the ablation zone (cold impermeable ice) lead to a significant cold surface ~~cold~~-layer that eventually reaches the glacier base in the shallowest ~~region~~zones of the glacier tongues (Figure 5). The western branches of the two glaciers have a significantly smaller temperate area with an ablation zone almost entirely cold-based (Figure 5). This thermal structure ~~explains~~may explain why the western branches remained stable after the collapses even though each branch lost its downstream supporting buttresses formed by the ~~collapsed~~detached glacier tongues. The modeled spatial extent of the temperate basal ice, under steady-state-conditions coincides with the detached areas and suggests that friction changes leading to the collapse occurred in temperate ice rather than being produced by a ~~thermal~~change from cold to temperate thermal conditions at the glacier beds. However, the large amount of cold ice, especially along the side of the gorge, could have provided significant lateral drag that built up high driving stress which was able to balance gravitational force ~~in case of friction~~under the frictional change ~~in~~at the temperate ~~core-~~parts of the beds.

#### ~~4.2. Friction change at the glacier base over the last 5 years before the collapse~~

#### 4.2. Basal friction change since 2011

The surge-like behaviour of the two glaciers identified from DEM comparison in Kääh et al. (2018) documents a change in the glacier dynamics during the five years prior to the twin collapses. By removing the elevation change due to surface mass balance we ~~quantified~~the surface normalemergence velocity for constraining the basal friction parameter (Gilbert et al., 2016) ~~on~~for different periods: 2011-2013, 2013-2014, 2014-2015 and September/November 2015 (see Table 1 and Figure 2). Our results highlight a contrasting behaviour between Aru-1 and Aru-2 where friction decreased progressively in magnitude through time in both glaciers, but over significantly different areas (see Figure 6). Frictional changes over the five years prior to collapse are also more significant on Aru-1, resulting in a higher increase in surface velocity than on Aru-2 (Figure 7). Similarly inferred friction for Aru-2 for annual means (2011-2013 ~~on~~and 2013-2014) and a 2-month mean (Sept/Nov 2015) suggests low seasonal variability of the basal condition. Similarly, modeled surface velocities on Aru-1 in Sept/Nov 2015 correlate well with those measured for Jan/Apr 2016 by using satellite image correlation (Kääh et al., 2018) (Figure 7FF), also suggesting low seasonal variability.

### 4.3. Force balance analysis

To evaluate how resisting forces acted and evolved to balance the driving forces, we computed the mean basal shear stress during different periods from the inverse method. ~~Thereby we assumed~~ We therefore assume that basal shear stress is mainly constrained by the global stress balance and should not be influenced by the sliding law that we used (eq. 1) (Joughin et al., 2004; Minchew et al., 2016). The steady-state condition shows a basal shear stress between 100 kPa and 200 kPa in both glaciers with a mean shear stresses of 137 kPa and 150 kPa for Aru-1 and 2, respectively (Figure 8A). In comparison, mean driving stresses are 152 kPa (Aru-1) and 213 kPa (Aru-2) ~~meaning indicating~~ that 10% (Aru-1) and 30% (Aru-2) of the driving force is accommodated by normal force along the sidewalls. ~~This~~ These levels of driving stress ~~is~~ are at the higher end of the observed range of driving stresses on mountain glaciers (Cuffey and Paterson, 2010) and reflect the presence of strong resisting forces due ~~to~~ mainly to cold-ice conditions combined with the resistance of the valley walls.

The inversion ~~from of~~ mean elevation changes between September and November 2015 (Figure 8B) reveals that basal shear stress on Aru-1 decreased to only 20 to 10 kPa in large areas, and basal resistance ~~on the detachment zone~~ became mainly achieved by a few sticky spots (Stokes et al., 2007) in the detachment zone where shear stress exceeded 250 kPa. ~~On~~ Along the ~~external side left bank of the curve which both glaciers form glacier,~~ close to the terminus of Aru-1, shear stress ~~is~~ was about 6-7 kPa and was not more than 15 kPa at the terminus. In comparison, Aru-2 behaves differently with more localized friction changes that ~~produce~~ produced a smaller change in the distribution of the basal shear stress during the same period (Figure 8C). The analysis of the dynamics and force-balance evolution on an area restricted to the detachment zone (dashed lines in Figure 8) reveals both similarities and differences between the two events (Figure 9). Further references below to “lateral stress” apply to the detachment zone and not to the whole glacier, and refer to the stress provided by the shearing interface between the stable and the unstable part of the glacier. On the one hand, as already highlighted in Figure 7, the mean detachment velocity prior to collapse behaved differently for the two glaciers (Figure 9A). While the Aru-1 detachment significantly accelerated, following behaviour typical for slope failure (Voight, 1990) over several years (blue dashed line in Figure 9A), Aru-2 showed very little acceleration. On the other hand, force balances evolved similarly in the two detachments with a large increase of lateral stresses along the detachment margin due to both an increase in the driving stress ~~increasing~~ and reduction in basal friction ~~reducing~~ (Figure 9B). Interestingly, lateral resistance overcomes basal resistance in both detachments with a delay time (81 days) close to the actual delay between the two final collapses ~~(66 days)~~ (Figure 9C). On Aru-2, it seems that smaller changes in friction ~~were~~ were compensated by a higher change in driving stresses resulting in a similar increase of stress at the detachment margin compared to Aru-1 (Figure 9B). The difference in surface velocity response to these similar stress transfers ~~relies on~~ was a consequence of different basal drag repartitions in the two glaciers. Basal drag decreased uniformly on the whole detachment of Aru-1 with the appearance of localized sticky spots, whereas basal drag decreased only in the higher part of the detachment of Aru-2. This led to more intense bulging and a lower velocity increase (Kääb et al., 2018) due to the high-friction patch remaining in the tongue (Figure 6).

To evaluate the impact of the friction change on the mechanical property of the ice, we compute the maximal principal Cauchy stress and compare it with a threshold value (set to 0.1 MPa (Krug et al., 2014)) to identify the damage production (crevasse opening) (Krug et al., 2014; Pralong and Funk, 2005) (Figure 10). ~~This~~The modelled stress fields clearly ~~highlight~~highlight zones where a progressive intensification of cracks opened around the detachment zone of Aru-1 (Figure 10C) as observed on satellite images (Kääb et al., 2018) ~~that~~; these fractures led to the final collapses. In comparison, Aru-2 again behaves ~~again~~ differently with less damage (cracks) that only affects the upper part on the detachment (Figure 10C). This means that ~~sudden~~ damage ~~of~~at the shear margin would ~~had to occur~~have occurred suddenly in Aru-2 in 2016 which is confirmed by the observed sharp crack surrounding the detachment only a few days before the collapse (Kääb et al., 2018). In sum, Aru-1 and Aru-2 underwent a similar stress ~~transfer~~transfers, transitioning from basal drag to lateral shearing in their respective detachments, but ~~with~~showed different responses in terms of damage (i.e. crack production) and sliding speed due to different basal drag repartition. Aru-1 progressively evolved towards collapse whereas Aru-2 accumulated stresses until a sudden release led to collapse. This indicates that critical stress transfers, precursory to ~~the~~such collapses, may occur without observable phenomena (i.e., surface velocity increase, crevassing) in the preceding years.

## 5. Discussion

### 5.1. Result uncertainties

The modeled thermal regime is sensitive to basal heat flux, which is poorly constrained. However, sensitivity tests (see supplementary material, Figure S1) show that the temperate area remains similar/stable for a basal heat flux ~~comprised~~ between  $6.0 \cdot 10^{-2}$  and  $1.2 \cdot 10^{-1}$  W m<sup>-2</sup> and ~~disappear~~disappears only at  $\leq 2.0 \cdot 10^{-2}$  W m<sup>-2</sup>. Measurements in the Guliya Ice Cap (Thompson et al., 1995) and reconstructions from Tao and Shen (2008) both give a value of  $8.0 \cdot 10^{-2}$  W m<sup>-2</sup>, making a low value of  $\leq 2.0 \cdot 10^{-2}$  W m<sup>-2</sup> very unlikely. ~~Also~~, Kääb et al. (2018) have also shown that firn thickness has a great influence on the modelled thermal regime around 5900 m a.s.l. where melting occurs in the accumulation zone. Firn thickness is, however, hard to estimate without field investigation; following Kääb et al. (2018), we applied an intermediate scenario where firn thickness linearly increases from the ELA to the glacier top where it reaches a 15 m maximum. Sensitivity test showed that only very little firn thickness (< 5m at 6000 m a.s.l.) would lead to an almost cold glacier (supplementary material, Figure S2). ~~Nevertheless, the~~ modeled thermal regime and the friction reconstruction, which are both almost independent, ~~show a from each other, are in~~ good accordance between/agreement with the localization of sliding and modeled temperate areas ~~giving~~ lending confidence in our results despite uncertainties in basal heat flux and surface boundary conditions (see section 5.2).

The uncertainty in the reconstruction of basal friction ~~reconstruction~~ mainly depends on the accuracy of measured elevation ~~change accuracy~~changes, which is generally higher over longer time period/periods (increased signal-to-noise ratio), making the 2011-2013 reconstruction the most reliable one. The measured September/November 2015 elevation change is subject to higher noise level/a lower signal-to-noise ratio and is thus poorly resolved in the accumulation area (see Figure 2) ~~making~~, leaving however the reconstruction ~~more~~ reliable on the detachment area where elevation changes are statistically well



significant. ~~Same~~ thanks to the high-resolution optical satellite stereo method used for these DEM differences. A similar conclusion applies to the 2014-2015 reconstruction where the ~~higher upper~~ part of the glacier is affected by penetration of the X-band ~~X~~ signal, leading to an overestimation of the ~~surface normal~~ emergence velocities. ~~The~~ (see Section 2.1). However, the influence of ~~this~~ uncertainty ~~is on~~ the modeled mass balance used to compute ~~surface normal~~ emergence velocity is also low in the detachment ~~part~~ zone, since elevation changes due to surface mass balance are relatively small compared to the dynamical height changes linked to the surge-like instability (<20%). ~~This makes our~~ (see sensitivity tests in the supplementary material, Figure S4). Our results are therefore, least-affected by uncertainties, and most reliable, at least in the detachment area, which is the focus of this study. In addition, bedrock topography is well constrained in the detachment areas from the post-collapse Pléiades DEM, giving additional confidence in the friction reconstruction there.

Using emergence velocities to constrain basal friction is not a commonly used method, and has been successfully tested only on a slow-flowing ice cap by Gilbert et al. (2016) ~~the study~~. We therefore provide additional validation of this method in the supplementary material (Figures S4 to S6) by inverting the friction on both glaciers using horizontal velocities inferred from offset tracking obtained from repeat TerraSAR-X data in December 2013. This test reveals good agreement between our emergence-based approach and the more common method based on horizontal velocities. In particular, sliding zones are similarly localized in both methods. Using the inversion based on horizontal velocities as a reference, we estimate a sliding speed magnitude accuracy of 0.036 m day<sup>-1</sup> in the emergence-based inversion. Our additional validation test also indicates that using emergence velocities may provide for an improved constraint of the friction coefficient in accumulation areas. The reason for this is that the underlying data used in generating the emergence velocities (i.e. DEMs, modeled mass-balance) are often more spatially resolved and cover larger areas on small mountain glaciers, this as opposed to using measurements of horizontal displacements, which have for instance notorious problems over accumulation areas.

## 5.2. Frictional changes

Our results suggest that low friction below the Aru glaciers ~~is was~~ not linked to seasonal variability of water pressure ~~that~~, which is often observed on glaciers elsewhere (Bartholomaeus et al., 2008; Vincent and Moreau, 2016). Rather, it is likely associated with sustained change of the basal conditions caused by an accumulation of liquid water over several years prior to the collapse. Over a hard bed (Cuffey and Paterson, 2010), this would ~~mean~~ likely result in the existence of a subglacial lake which is very unlikely here because low friction on Aru-1 ~~reaches~~ extended to the tongue and the lake should have drained in such case. Furthermore, in temperate ice, high water pressure conditions are unstable over long time periods because they lead to channel formation that can efficiently ~~decreases~~ drain water and decrease the pressure (Schoof, 2010). High water pressure in a cavity network would be also difficult to maintain in the Aru cases since increasing sliding speeds tends to increase cavity size and decrease water pressure. These ~~results~~ arguments suggest that basal friction under the Aru glaciers was probably controlled by processes associated with soft bed properties (Cuffey and Paterson, 2010).

Comparison between sliding speed evolution and modeled basal steady-state temperature reveals a good correlation between ~~zone~~ the zones of sliding and temperate ice conditions and shows that the size of sliding areas remains similar during over time

(Figure 11). This confirms that friction reduction since 2011 mainly occurred within zones that were already temperate areas, and that friction reduction is therefore not linked to a simple change from cold to temperate to cold basal conditions. However, contrary to Aru-1, Aru-2 appears to have been affected by a high-friction zone under its lower tongue that, which the modeled basal temperatures do are not able to explain as it indicates that they indicate temperate conditions, not cold ones conditions (Figure 11). This zone of high friction explains the different behaviour behaviours observed between the two glaciers in terms of surface velocities and glacier advance. Indeed, a few months before the collapse, Aru-2 velocities were still very low compared to Aru-1 (Figure 7) and although Aru-1 advanced almost 200 m since July 2015, the front of Aru-2 remained unchanged until the collapse (Kääb et al., 2018). The Though, the high-friction zone may have delayed the collapse of Aru-2 but it did not prevent it. The possible origin of this high friction zone is discussed at the end of the following section 5.23.

### 5.3. Role of the bedrock lithology and glacier till

Field observations after collapse, and inspection of the detachment zones showed no presence of a hard-bed lithology beneath the glaciers, and no large boulders were observed in the forefields and avalanche deposits. Rather, extensive deposits of soft, unconsolidated and fine-grained lithologies were identified (see supplementary material, Figures S3S8 to S5S10). We collected till samples from the Aru-1 avalanche Aru-1 deposit and measured their grain-size distribution (Figure 12). Mean values over the four samples in the avalanche path (Fig. 12) give indicate till consisting of 14% clay, 24% silt, 44% sand and 18% gravel. These samples are representative of the material found in the deposit and are likely also representative of the glacier till on which the glacier rested. We also observed a rather smooth-surfaced failure interface (i.e. detachment plane) suggesting a low bedrock roughness at macro scale (>1m).

These findings confirms that the Aru glaciers flowed on a soft-bed, which may have likely played an important role in controlling the behaviour of the Aru glaciers from the surge initiation to the final-collapse. For such bed types, basal motion is not controlled by ice flow around bedrock bumps (Lliboutry, 1968; Weertman, 1964) but rather by deformation in the till (Truffer et al., 2001). The sustained very low basal drag under the Aru glaciers (<20kPa) may be similar to ice stream mechanisms whereby water-saturated till enables fast flow at low driving stresses ( $\approx 20$ kPa) (Cuffey and Paterson, 2010). It has been shown that glacier till behaves with a plastic rheology with a shear strength strongly dependent on the effective normal stress (Clarke, 2005; Iverson, 2010; Iverson et al., 1998). The use of a linear friction law in our inversion can be viewed as a parametrization where  $\beta$  includes these physics and is only valid at the time of the inversion. Therefore, the change in friction coefficient  $\beta$  can be interpreted in terms of a plastic till. Such behaviour was found to be well described by a Coulomb-type friction law (Boulton and Jones, 1979; Clarke, 2005; Tsai et al., 2015) as follows:

$$\tau_u = c + N \tan(\phi) \quad (7 \tau_{tt} = c + N \tan(\phi) \text{---} (4))$$

where  $\tau_u$  is the ultimate shear strength,  $c$  the cohesion parameter,  $N$  the normal effective stress and  $\phi$  the friction angle. This kind of law, where shear stress is independent of the sliding velocity, allows for unstable behaviour leading to failure. In a general case, glaciers remain stable because till and water pressure are not equally distributed at the basal interface, leading to sticky spots where stress concentrates to balance gravitational forces together with lateral drag at glacier margins (Cuffey and Paterson, 2010). The Aru collapses would thus be an example where ~~the till plastic rheology~~ basal shear stress becomes ~~the only source of~~ limited to till strength in such large zones that resisting forces ~~to~~ can no longer balance gravity, eventually leading to catastrophic failure. The latter would happen for a bedrock with low roughness, which is less able to provide vestigial resistance to constrain ice velocity in case of failure in the till. We propose that the change in effective normal stress due to increasing pore pressure in the till beneath the temperate areas/zones of the Aru glaciers quickly reduced the basal shear stress ~~to the~~ ultimate strength of glacier till, and limited the basal shear stress to a maximum value lower than driving stress. The glacier shape ~~did~~ could not adjust fast enough to reduce the driving stress due to strain-rate limitation in the cold-based areas producing zones, leading then to the accumulation of large stresses in the remaining sticky spots (**Figure 8**), until their sudden rupture. The sticky spots were likely remnants of stiff frozen till rather than solid rock irregularities, rendering them, rendering them susceptible to failure under high stress and vulnerable to thaw from water-saturated temperate surroundings and increasing deformational heat. The high clay and silt content measured in the till suggests is indicative of lithologies having unique low friction-angle properties (Iverson et al., 1998) and higher sensitivity of the shear strength to changes in water pressure.

~~As one~~ One likely scenario for the development of the now collapsed Aru glaciers probably is that they grew in the past (pre-industrial climate) in colder conditions with low melting rates in summer, allowing for rigidity in the basal till stiffness to support high driving stress (see section 4.3). The low water pressure meant that ~~actually~~ there was likely very little sliding and therefor very little production of till at that time. Upon commencement of some sliding, which may have occurred gradually over an increasing area of the bed over during the past century, till ~~was produced~~ production increased and the local glacier deformation regime tended to adapt to the distribution of till and liquid water reaching the bed. ~~However, to continue the above scenario~~ At this stage, the percolation into, and accumulation of meltwater beneath the glaciers increased so rapidly in recent years (Kääb et al., 2018) that ~~they~~ the glaciers could not keep balance with the changing conditions at the bed. Sliding may also have contributed to increase water pressure in a positive feedback by destroying any efficient drainage system (Clarke et al., 1984). The contributory role of a soft-bed lithology in the collapses is therefore likely threefold by (i) behaving with plastic rheology when shear strength is reached, (ii) ~~exhibiting~~ providing for low roughness at the ice-bed contact, and (iii) maintaining high water pressure while sliding speed increases; a known process that accounts for surge behaviour (Clarke et al., 1984; Fowler et al., 2001; Raymond, 1987). High content in clay and silt probably also leads to low hydraulic conductivity favourable to higher water pressure in the till (Fowler et al., 2001).

We ~~believes~~ suggest that the existence of a high friction area ~~in~~ under the Aru-2 tongue prior to collapse is due to both, higher basal normal stresses (see supplementary material, Figure S2) increasing S3 which increased the till strength, and higher lateral ~~drags~~ decreasing drag along the west side of the detachment which decreased the basal shear stresses compared to Aru-1 (Figure

9). In this way, and contrary to Aru-1, basal shear stress ~~is under~~ the tongue ~~area~~ of Aru-2 only approached the ultimate shear strength of the till just before the final collapse in response to both decreasing resistance ~~of~~ by the lateral margin (due to crevassing) and increasing driving stresses (due to bulging).

#### 5.4. Till-strength controlled glacier collapses

5 The Aru collapses (~~and in retrospective the Kolka Glacier collapse~~), define a newly recognized type of avalanching glaciers ~~that are underlain~~ characterized by an underlying failing substrate. Such “iceslides” could occur on glaciers with fairly low angle ~~glaciers~~, involving therefore potentially large volumes of material, and presenting serious consequences in terms of hazard potentials. The high sensitivity of the ultimate shear strength of the substrate to water pore pressure ~~associated~~, combined with low bed roughness, allows for a dramatic and ~~durablesustained~~ change of basal friction conditions capable of driving this kind of instability.

15 The Kolka event in 2002 in the Caucasus Mountains is probably another example of this type of instability in which ~~ultimate~~ the maximum shear strength of the till is ~~reached~~ exceeded by a sudden increase of basal shear stress at constant effective normal stresses. Indeed, during the few weeks before this collapse, a significant mass ~~had been~~ was added on top of the glacier by rock and ice-fall activity increasing basal shear and normal stresses (Evans et al., 2009; Huggel et al., 2005). If the till was saturated with water and had low hydraulic conductivity, increasing water pore pressure could have compensated for the rising normal stress keeping the normal effective stress constant. ~~The ultimate~~ However, once maximum shear strength ~~can be reached~~ triggering this exceeded, failure is triggered (Evans et al., 2009). This hypothesis is ~~realistic~~ plausible since Kolka ~~g~~ Glacier is known to be a surging glacier, able to store large amounts of liquid water, and high water content and pressure were observed before its 2002 collapse (e.g. unusual ponds observed on the glacier prior to collapse) (Kotlyakov et al., 2004).

20 However, changes in till-strength in response to changing in water pressure are likely also involved in the surge mechanisms of temperate glaciers— without the large majority of surges turning into gigantic collapses. This renders sudden changes in till strength as a necessary, but not a fully sufficient condition, for collapses controlled by till-strength ~~controlled collapses~~. The necessary ~~second condition would be to maintain~~ secondary conditions for catastrophic failure is a sustained high driving stress ~~even~~ with low bed roughness ~~while the~~, coincident with weakening till ~~weakens~~. This means that the glacier has to grow over time, atop of a more stable substrate capable of supporting higher driving stresses. In particular, freezing conditions allows for the development of ~~a~~ relatively thick glaciers on slopes that would ~~else not otherwise~~ be unable to support such high shear stress under the presence of liquid water. This makes the spatio-temporal interplay of soft-bed characteristics and the polythermal glacier regime a prerequisite of the Aru collapses, whereas for the Kolka Glacier the additional loading over a short time should have caused a fast increase in shear stress significantly exceeding the glacier’s normal conditions.

30 ~~On~~ In many of the world’s glacierized regions, on-going ~~climate change (i.e. atmospheric warming)~~ increases in many regions surface melt and the amount of water reaching glacier beds, thereby modifying the till shear strength, ~~and~~. This development is therefore ~~susceptible to drive~~ in theory capable of driving more till-strength controlled instabilities and collapses. The most impacted glaciers would be those flowing on soft and highly erodible bed lithologies at high driving stress, particularly those

with heterogeneous thermal structure (polythermal glaciers). Such glaciers are mostly localized in cold and dry climates where a small increase in temperature results in a relatively large change in melting conditions such that the amount of water reaching the glacier base can significantly increase instability. In reality, however, an array of factors and their specific (and to this point rare) interplay in space and time are necessary to catalyse glacier collapsing as observed for the Aru and Kolka glaciers.

## 5 6. Conclusion

In summer 2016, one of the most spectacular glacier ~~hazard events/disasters~~ ever observed ~~on glaciers~~ occurred in Western Tibet. The twin collapses of the Aru glaciers set a new reference in terms of size and mobility of glacier instabilities, and requires revisiting our knowledge required a reassessment of impacts/assumptions and conditions that more typically drive hazards and impacts linked to mountain glaciers in mountainous areas. Using 3D thermo-mechanical modelling together with  
10 satellite and field observations we conclude that the Aru twin collapses were driven by increasing melt water reaching the bed in the temperate area of the ~~glaciers~~ polythermal structure of the glaciers, leading to the weakening of the underlying till and sediment ~~underneath them~~.

Our steady-state simulation reveals that both glaciers ~~were~~ likely polythermal, with predominant temperate basal conditions over the detachment areas. Using satellite-observed elevation change and modeled surface mass balance, we reconstructed the  
15 frictional and shear stress regimes at the glacier base that occurred during the five years prior to collapse. We show that both glaciers experienced a stress transfer in their detachment area, transitioning from basal drag to lateral shearing at the detachment margin ~~that~~, likely beginning around 2012. However, the different spatial repartitions of basal drag in the two detachment zones led to visibly different behaviours. As early as 2015, basal drag in ~~the northern~~ Aru-1 was very low over the  
20 whole detachment zone with a few remnant sticky spots where stress was concentrated. In contrast, basal drag of the southern Aru-2 glacier was distributed between a low-friction area in the upper half of the detachment zone and a high-friction area in the lower half. These circumstances led to a progressive destabilization of Aru-1 with a significant acceleration in ice flow in the detachment zone over several years prior to collapse, whereas stresses accumulated in Aru-2 until a sudden break of the shear margin occurred only few days before the collapse.

We interpret that the change in friction was due to glacier till reaching its ultimate shear strength in response to increasing  
25 water pore pressure. This assumption is supported by field observations showing that revealed soft and erodible material with high clay/silt content underneath the glaciers. Plastic rheology of the till underlying the Aru glaciers ~~till~~ combined with low bedrock roughness and polythermal glacier structure seem to be the basis of the collapses. The polythermal structure enabled the glaciers to grow at high driving stress on a partially frozen substrate while temperate areas facilitated the water to reach the bed. Increasing water pressure in temperate areas led to failure in the till and thereby to increasing shear stresses on localized  
30 sticky spots and along the detachment margin. Due to the low bed roughness, the nature of these sticking spots seems purely thermal (cold patches). They are therefore mechanically breakable/susceptible to failure and can be affected by thermal effects such as intense deformational heat or latent heat release.

Under climatic changes and related increase in surface melt rates, polythermal glaciers underlain by soft and erodible substrate are likely to destabilize more readily than hard-bed glaciers ~~due to lower, Lower~~ bed roughness of the former, ~~till and~~ plastic rheology, ~~and of such till promotes instability, while~~ hydrological feedbacks with high till shear ~~rate in response of high water pressure and inefficient drainage system by~~ destroying efficient drainage components (canals) ~~leads to increasing water pore pressure and weakening substrate strength~~. The Aru cases highlight the most extreme of ~~the plausible~~ glacier behaviours when bedrock roughness ~~is and/or frozen zones are~~ unable to ~~achieve the~~ sustain global stability while ~~the~~ substrate is failing, leading ~~to~~ the catastrophic failure of large glacier sections.

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**Table 1 – Different DEMs used in this study produced from satellite imagery data**

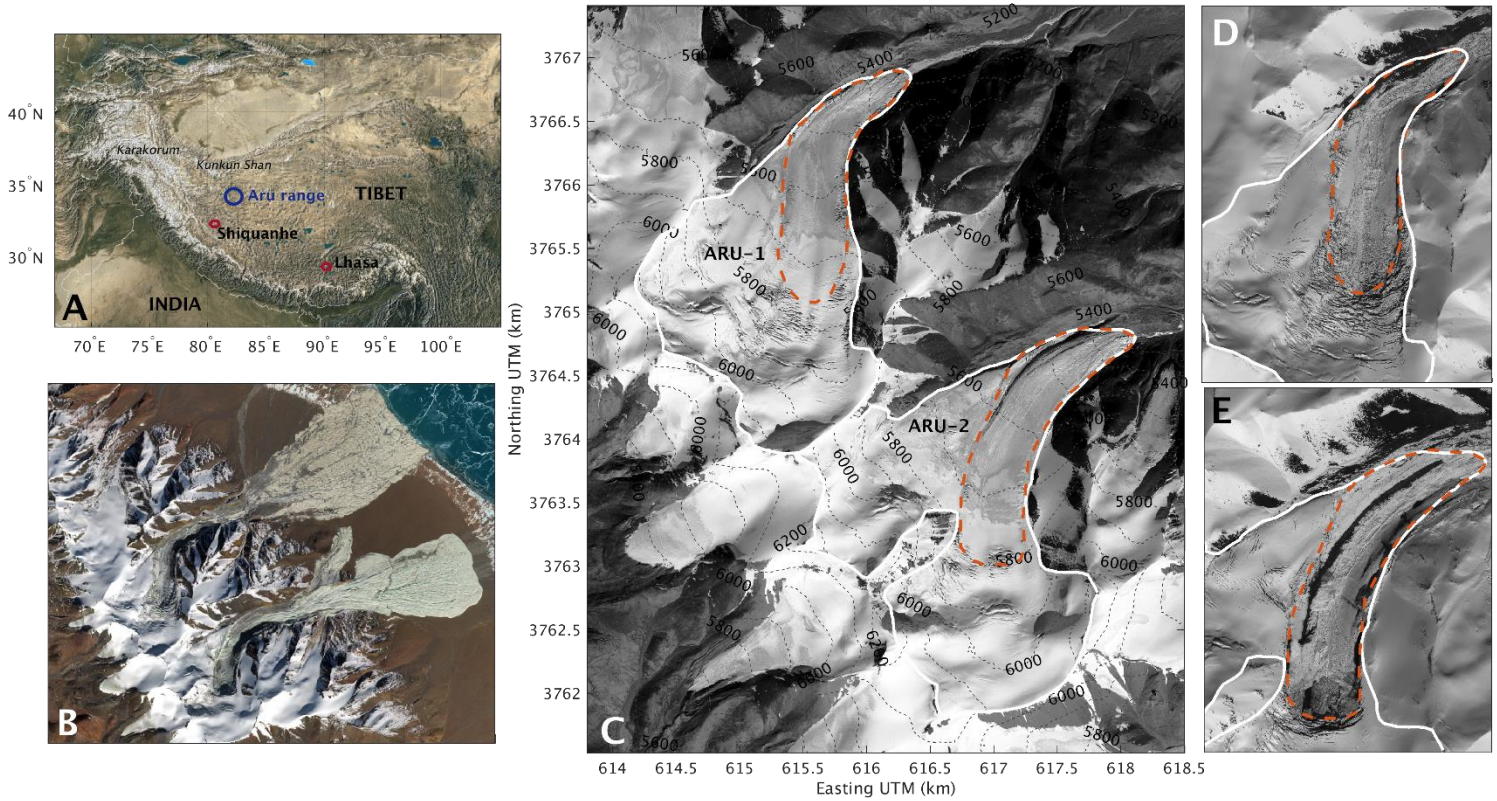
<b>Satellite /Sensor</b>	<b>Acquisition date</b>	<b>DEM resolution</b>	<b>Image type</b>
<b>SRTM C/X</b>	February 2000	30 m	Radar
<b>TanDEM-X</b>	6 June 2011	10 m	Radar
<b>TanDEM-X</b>	14 April 2013	10 m	Radar
<b>TanDEM-X</b>	01 April 2014	10 m	Radar
<b>Spot7</b>	06 September 2015	5 m	Optical
<b>WorldView</b>	25 November 2015	5 m	Optical
<b>Pléiades</b>	01 October 2016	5 m	Optical

**Table 2 – Variables and parameters of the thermo-mechanical model.**

<u>Name</u>	<u>Symbol</u>	<u>Value</u>	<u>Unit</u>
<u>Velocity</u>	<u><math>\underline{u}</math></u>	=	<u><math>\text{m yr}^{-1}</math></u>
<u>Stress tensor</u>	<u><math>\underline{\sigma}</math></u>	=	<u>MPa</u>
<u>Pressure</u>	<u><math>P</math></u>	=	<u>MPa</u>
<u>Enthalpy</u>	<u><math>H</math></u>	=	<u><math>\text{J kg}^{-1}</math></u>
<u>Temperature</u>	<u><math>T</math></u>	=	<u>K</u>
<u>Water Content</u>	<u><math>\omega</math></u>	=	=
<u>Density</u>	<u><math>\rho</math></u>	=	<u><math>\text{kg m}^{-3}</math></u>
<u>Firn thickness</u>	<u><math>H_{\text{firn}}</math></u>	=	<u>m</u>
<u>Friction coefficient</u>	<u><math>\beta</math></u>	=	<u><math>\text{MPa yr m}^{-1}</math></u>
<u>Flow Rate factor</u>	<u><math>A</math></u>	<u><math>f(T)^1</math></u>	<u><math>\text{MPa yr}^{-1}</math></u>
<u>Glenn law exponent</u>	<u><math>n</math></u>	<u>3</u>	=
<u>Basal heat flux</u>	<u><math>f_b</math></u>	<u>0.080</u>	<u><math>\text{W m}^{-2}</math></u>
<u>Thermal conductivity</u>	<u><math>k</math></u>	<u><math>f(\rho)^2</math></u>	<u><math>\text{W K}^{-1} \text{m}^{-1}</math></u>
<u>Heat Capacity</u>	<u><math>C_p</math></u>	<u><math>f(T)^1</math></u>	<u><math>\text{J kg}^{-1} \text{K}^{-1}</math></u>
<u>Maximum water content</u>	<u><math>\omega_{\text{max}}</math></u>	<u>0.03</u>	=
<u>Moisture diffusivity</u>	<u><math>\kappa_0</math></u>	<u><math>1.045 \cdot 10^{-4}</math></u>	<u><math>\text{kg m}^{-1} \text{s}^{-1}</math></u>
<u>Residual saturation in firn</u>	<u><math>S_r</math></u>	<u>0.01<sup>3</sup></u>	=
<u>Firn surface density</u>	<u><math>\rho_0</math></u>	<u>350</u>	<u><math>\text{kg m}^{-3}</math></u>

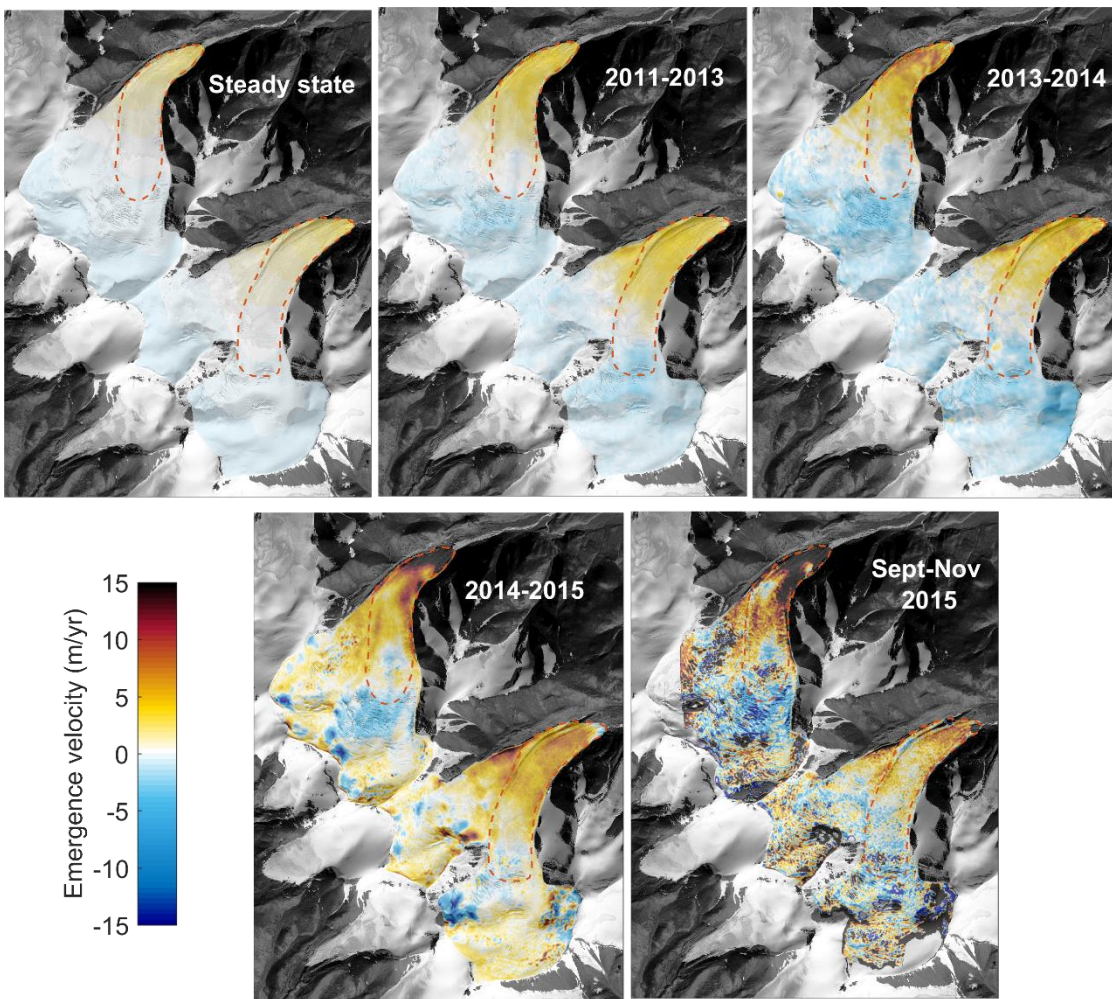
<sup>1</sup>(Cuffey and Paterson, 2010); <sup>2</sup>(Calonne N. et al., 2011); <sup>3</sup>(Gilbert et al., 2014)

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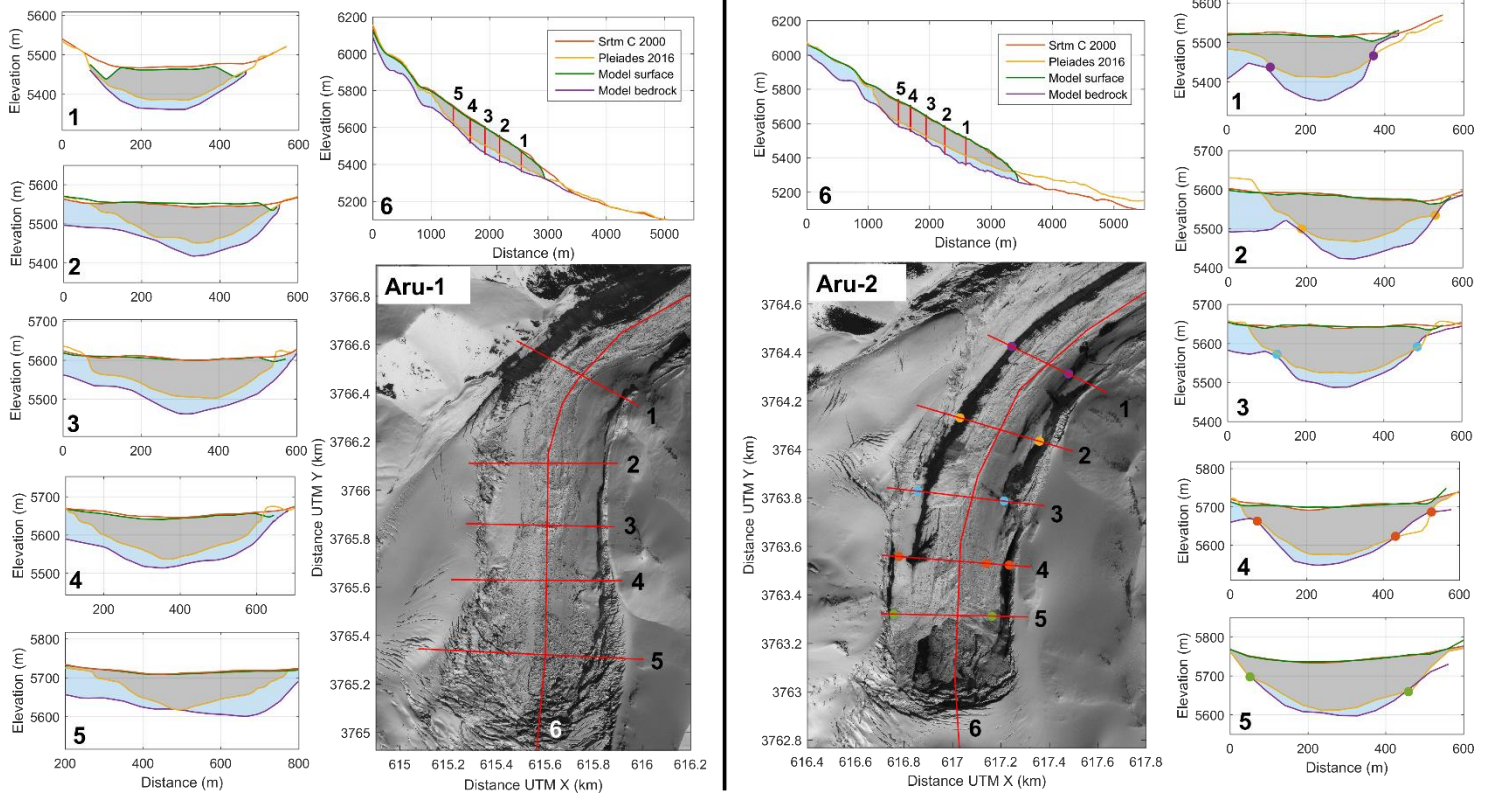


**Figure 1 – (A) Location of the Aru range in Tibet and (B) Sentinel-2 image from 2016, December 8 after the collapses. (C) Elevation contour lines of Aru-1 and Aru-2 glaciers (vertical datum WGS84) overlaid on an orthorectified Spot7 image from 2015 (Copyright Airbus D&S), September 21 as background used also in all other figures unless otherwise stated; orange dashed lines indicate the detachment outline, white lines are the glacier outline as of 2015. (D, E) Pléiades images from 2016, October 1 of the two glaciers Aru-1 (D) and Aru-2 (E) after the collapses (Copyright CNES 2016, Distribution Airbus D&S).**

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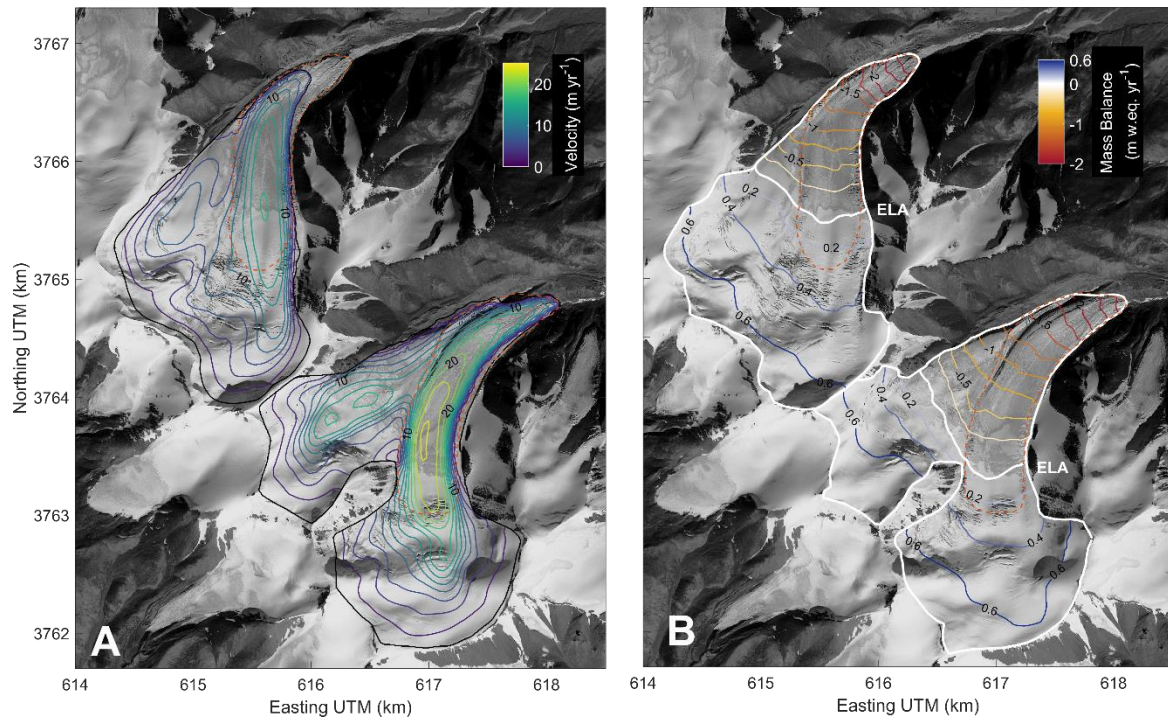
**Figure 2 – Mean vertical component of the emergence velocities obtained by differencing elevation changes from repeat DEMs and modeled mass balances during different periods prior to the collapses. Steady-state velocities in the first panel are modeled.**



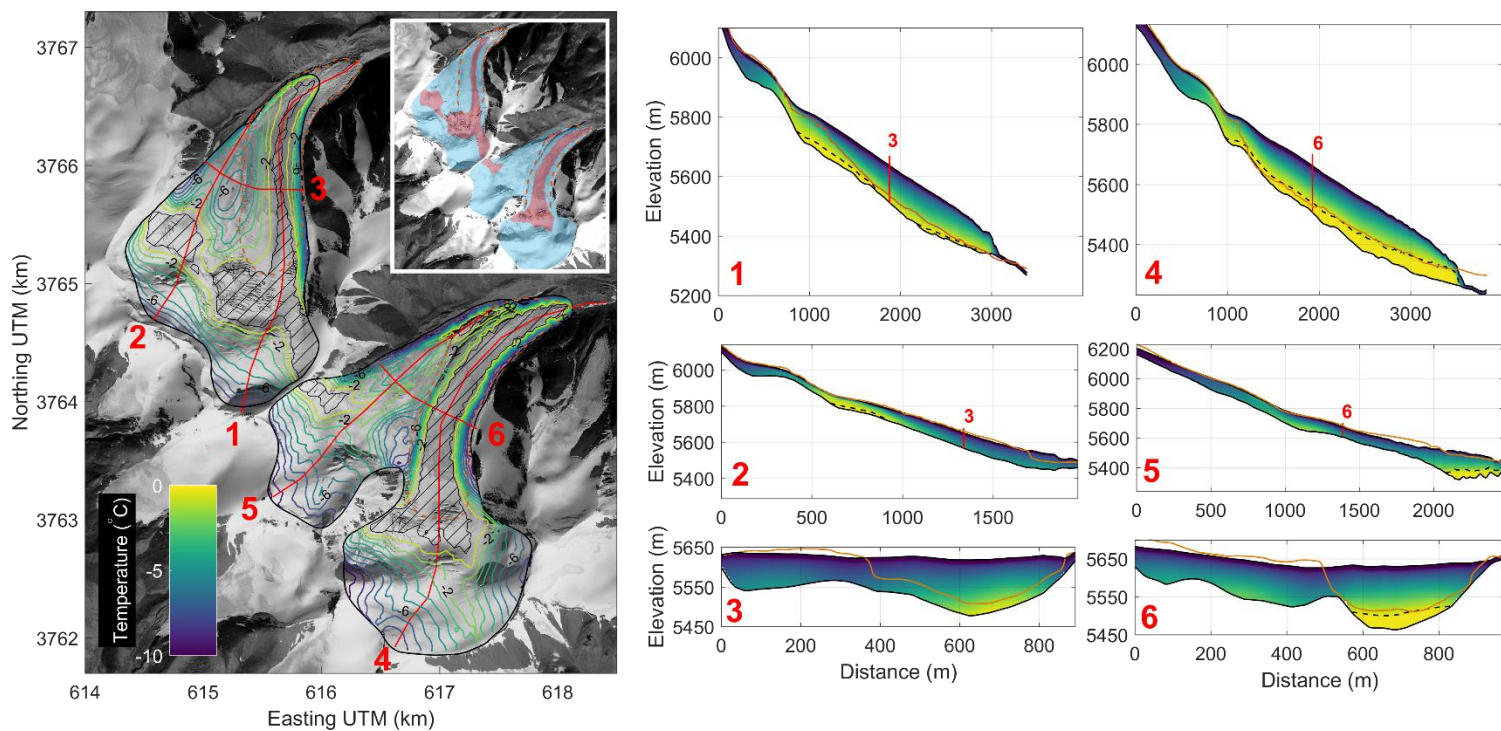
**Figure 3 – Pléiades image of Aru-1 glacier (left) and 2 (right) after collapse with topographic profiles 1 to 6 plotted for both glaciers (Copyright CNES 2016, Distribution Airbus D&S). The topographic profiles 1 to 6 show the measured surface topography in 2000 (SRTM, in red) and 2016 after the collapse (Pléiades, in yellow). These profiles are compared with the modeled bedrock (in purple) and surface (in green) topography. The colored dots on Aru 2 show the location of specific points of the profiles in the Pléiades image. Those points correspond to locations where our reconstruction matches the Pléiades DEM and where bedrock should thus be visible on the Pléiades image (no ice debris). Grey shading indicates the detached parts according to the Pléiades DEM compared to SRTM.**

5

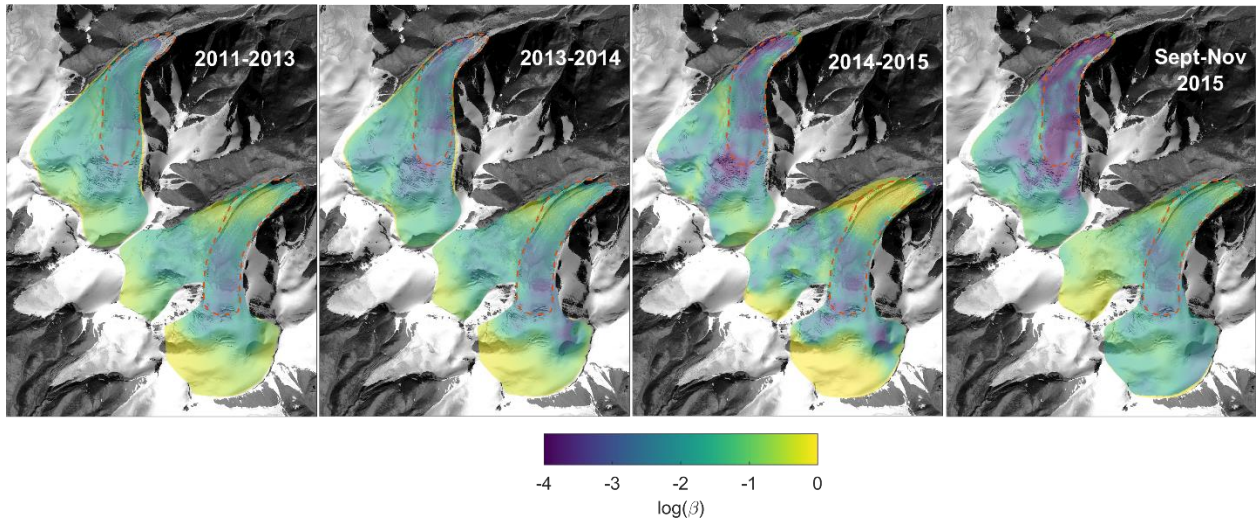
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**Figure 4 – Modeled steady-state horizontal surface velocities (A) and surface mass balance (B) for Aru-1 and Aru-2 glaciers. The black contours in (A) are modeled steady-state glacier outlines. The white contour in (B) is the glacier outline as mapped from 2015 images.**



**Figure 5 - Modeled steady state temperature on Aru-1 and Aru-2 glaciers. Left panel shows basal temperature where black hatched lines are temperate areas with an inset figure highlighting temperate-based (red) and cold-based (blue) areas. Right panels show 2D temperature profiles 1 to 6 as indicated in the left panel (red lines). Profiles include Pleiades 2016 elevation profiles (orange lines). The dashed black lines indicate the cold-temperate transition surface. Note that vertical scale is exaggerated in profiles 1 and 4.**



**Figure 6 - Friction coefficient  $\beta$  inferred from emergence velocity during different periods prior to the collapse.**



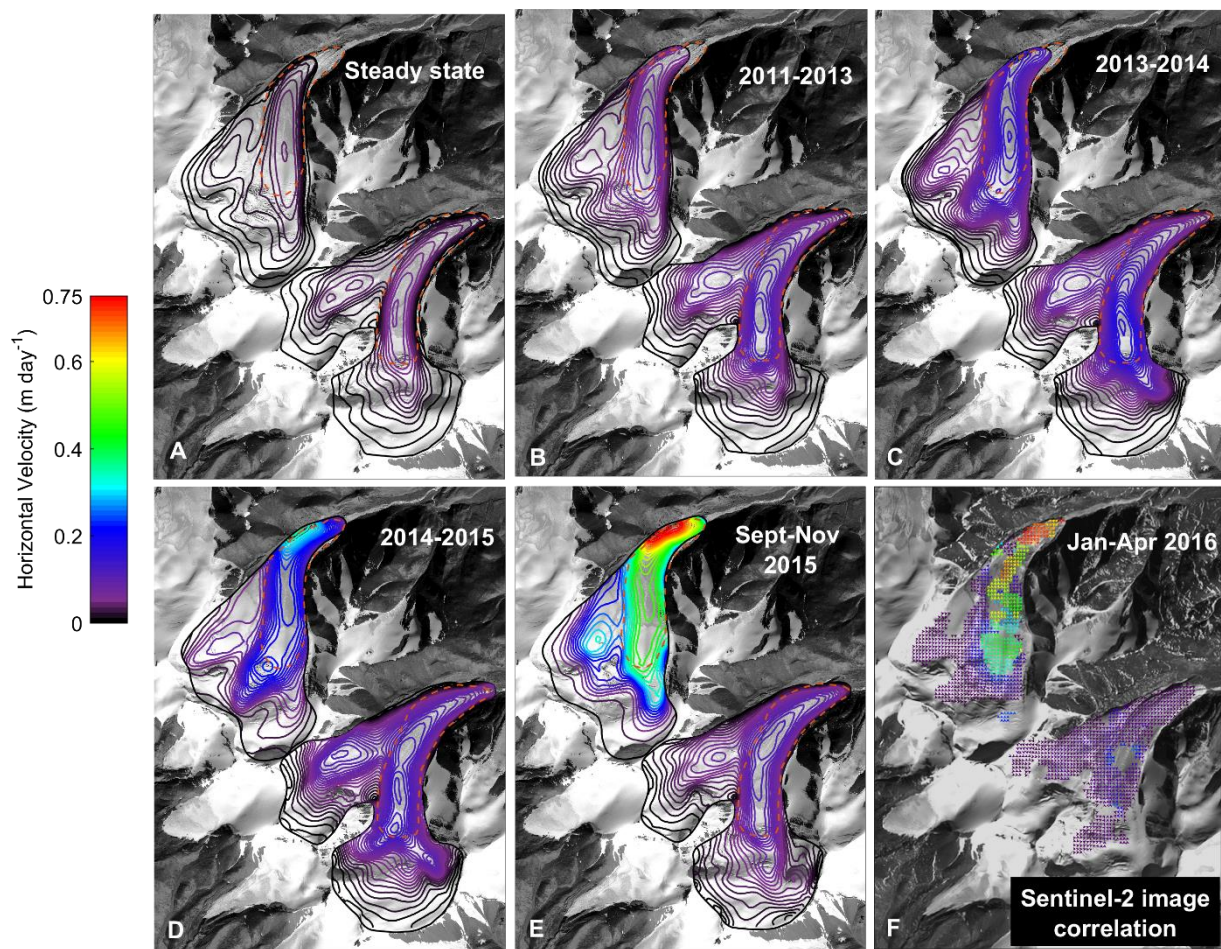


Figure 7 – (A-E) Modeled mean horizontal velocities for the two glaciers at steady state and for the period 2011-2013, 2013-2014, 2014-2015 and September to November 2015. (F) Measured horizontal velocities from Sentinel-2 image correlation between January and April 2016

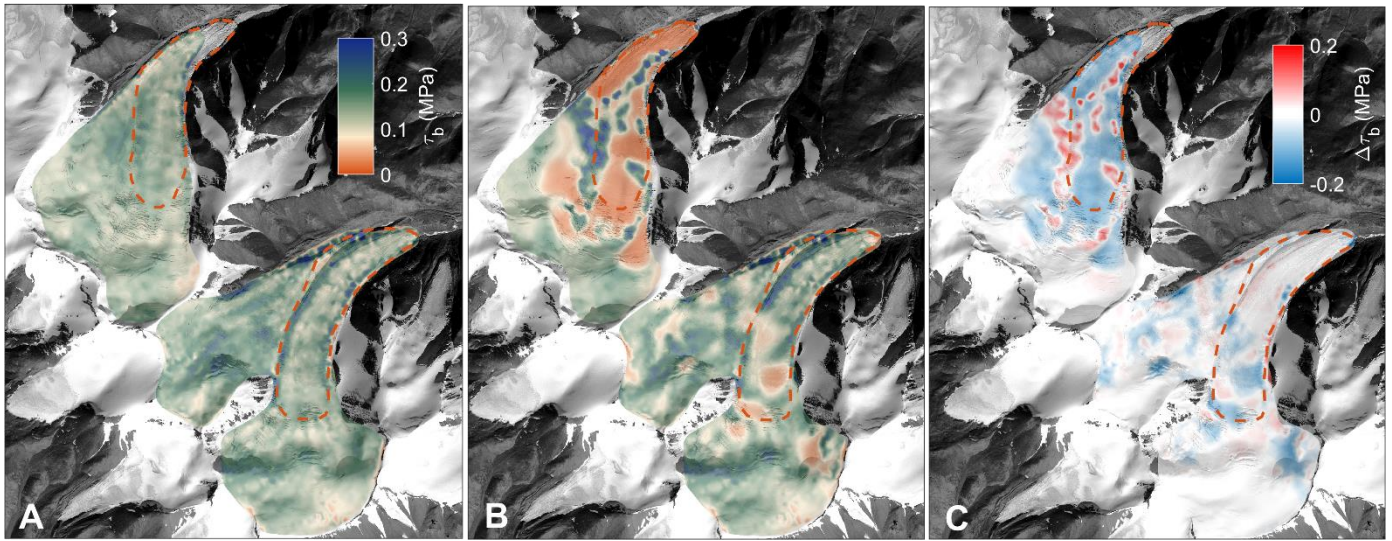


Figure 8 – Modeled basal shear stress at steady state (A) and in November 2015 (B). (C) is the difference between (B) and (A).

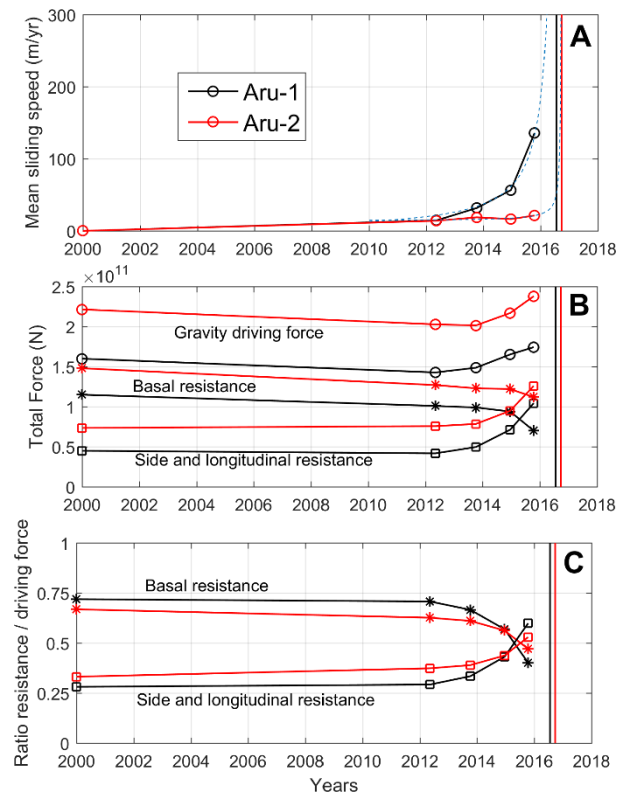


Figure 9 – (A) Mean sliding speed of the detachment zone for Aru-1 (black) and Aru-2 glaciers (red). The dashed blue lines show predicted speed following an empirical law of slope failure [Voight, 1990]. (B) Force balance of the detachment along the glacier bed direction. (C) Ratio of resisting force over driving force. Vertical lines show collapse dates in the three panels.

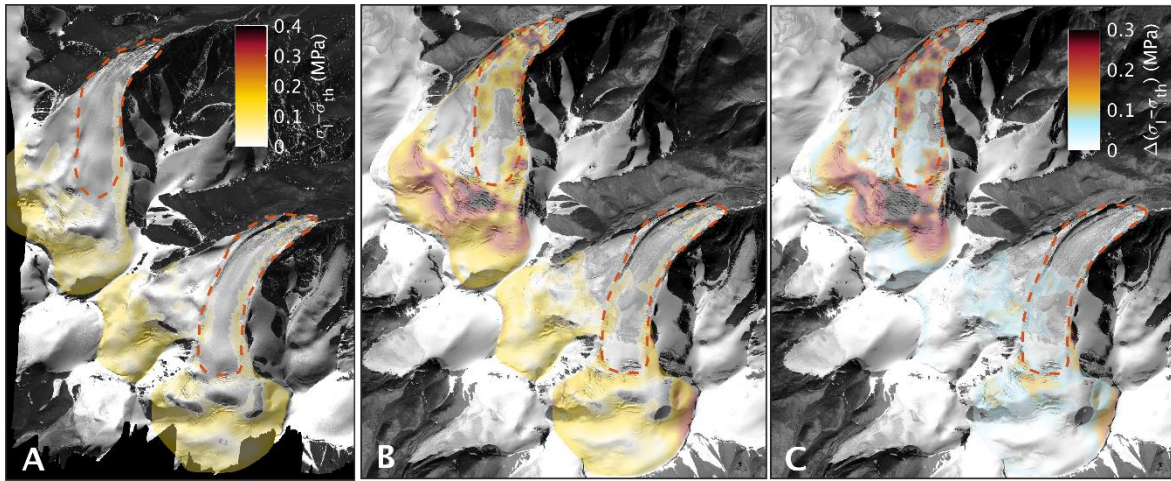


Figure 10 – Maximum principal Cauchy stress excess above damage initiation threshold at steady state (A) and prior to collapse (B) at the glacier surface. (C) shows the difference between (A) and (B). Background image in (A) is a WorldView image from 2011, December 2 when the instability just started. Background image in (B) and (C) is a Spot 7 image from 2015 September 21, one year before collapse (copyright Airbus D&S). These results show a good match between predicted and observed crevasse formation in response to frictional changes.

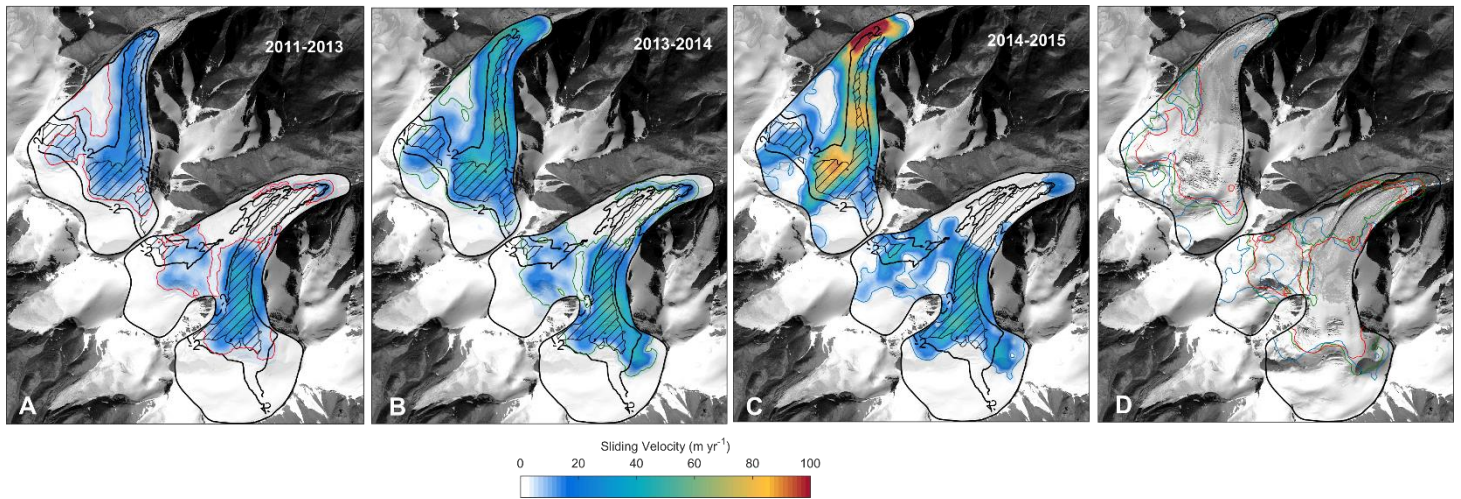
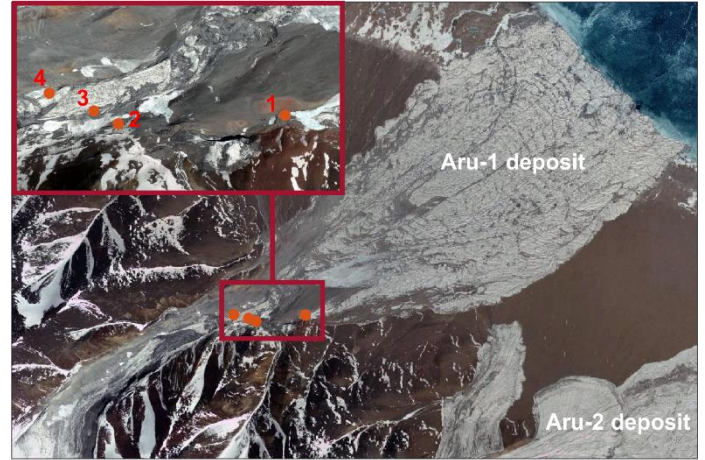
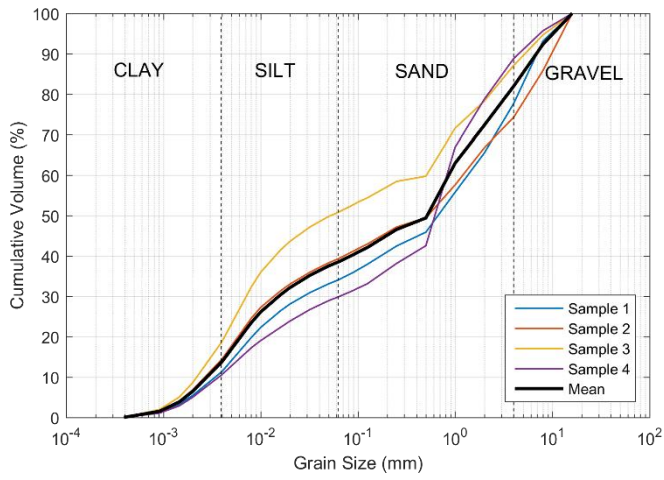


Figure 11 – (A, B, C) Modeled temperate area (hatched zones) and  $-2^{\circ}\text{C}$  isotherm at steady state compared with sliding speeds over different periods (background colormap). (D) Comparison of sliding location for the different periods.



**Figure 12 – Grain-size distribution measured in four glacier till samples collected in the Aru-1 deposit area (numbers 1 to 4 in the right panel). Background image Google Earth.**