# Author response to reviewer comments

In the following we respond to the reviewers comments on our document. Since they raise similar points we reply to both reviewers in one document. C. Kinnard (Reviewer 2) stated some specific comments in his reply which we respond to (R2.x) before we reply to the all comments in the manuscript of L. Arenson(reviewer 1) (M1.x) and C. Kinnard (M2.x) posted directly into the manuscript.

Note for notation in our response below: In blue our response to the reviewers comments and italics marks the text as it has been changed to in the revised paper.

1 Specific comments Reviewer C Kinnard (Reviewer 2)

R2.1	Terminology - rock glacier VS rockglacier: I believe the former is correct. We would like to hold on to the term rockglacier On the one hand, this study follows the periglacial reasoning, and in order to emphasize the autonomy of the phenomenon, the term 'rockglacier' is written in one word, following Barsch (1988). Thus, rockglaciers are significant indicators of past and present permafrost distribution and related climatological changes. On the other (and the more pragmatic) hand, the first author has used the term 'rockglacier' in all his previous publications and it would introduce a break of consistency in his work and dissertation of which this publication is the final part of.
R2.2	P.5 L20: "The limitations concerning processing, uncertainties and application are presented in Kääb and Vollmer (2000), Roer et al. (2005c), Roer and Nyenhuis (2007) and Müller et al. (2014b), and applied in this assessment."
R2.3	-My first question when looking at the DEM difference field in Figure 2 is what is the error on dZ/dt? In other words what is the detection limit? If this information has indeed been produced before you should at least state it, in the text or in the figure caption, for the benefit of the reader. We corrected the systematic error/trueness (Mentitto et al. 2007) of the remote sensing data using the terrestrial survey points (TS, tachymeter) as reference for the TLS and the TS and ALS data as reference for the photogrammetric DEM data. Therefore we were able to set a detection limit of 20 cm for the ALS and a slope dependent detection limit derived from the assessment presented in Mueller et al. 2014b. The slope dependent error for the photogrammetric error ranges from 0.5m to 0.9m. Since we use multiple independent datasets with different precisions, we are confident that we can use them to detect even such small topographical changes. Winsvold et al. (2016) have shown that by 'stacking and investigating larger time series for individual pixels, … (they are) able to reduce noise and the chance for bias, compared to using single observations.' We applied a similar approach where we checked the annual subsidence rates between all individual

timesteps of all sensor systems (ALS vs Tachymeter vs Photogrammetry)to the longest timespan (which has the clearest signal) and ended up with very similar annual subsidence rates which we used for our analysis.

To clearify we changed in the manuscript:

The systematic error/trueness (Menditto et al. 2007) of the remote sensing data was corrected using the terrestrial geodetic survey points (tachymeter) as reference for the ALS and the ALS data as reference for the photogrammetric DEM data as presented in Müller et al. (2014b). The spatial coverage of each reference dataset allowed to establish a slope dependent detection limit derived from the assessment ranging from 0.5 m to 0.9 m (see also Mueller et al. 2014b). The availability of numerous multisensoral datasets enabled stacking, investigating dense time steps and crosschecking products with different precisions (terrestrial survey, ALS, photogrammetry) which led to a high reliability of the derived annual subsidence rates.

And added the following references:

Menditto, A., Patriarca, M., and Magnusson, B.: Understanding the meaning of accuracy, trueness and precision, Accred Qual Assur, 12, 45–47, doi:10.1007/s00769-006-0191-z, 2007.

Winsvold, S. H., Kaab, A., and Nuth, C.: Regional Glacier Mapping Using Optical Satellite Data Time Series, IEEE J. Sel. Top. Appl. Earth Observations Remote Sensing, 1–14, doi:10.1109/JSTARS.2016.2527063, 2016.

R2.4	- My other question is why not presenting the average dZ/dT for the whole rock glacier surface as well? This should give you the total (or average) rock glacier mass-balance, assuming that the data is precise enough: if it is negative then internal ice melting has been larger than mass influx (sediments + ice). You present contrasting results (p6, L10) on the 'main lobes' where DEM differences and survey data do not give consistent results. The difference may be due to sampling errors in the survey data (22 points if I recall), or else DEM errors which are not presented.

After further consideration, we decided to omit the subsidence analysis derived from the terrestrial survey. Since these surveying points were originally installed for the monitoring of rockglacier movement, they are mounted on selected boulders which are exceptionally stable and deeply embedded in the rock-ice matrix and might therefore not be useful for the analysis of surface subsidence. To reduce confusion we therefore deleted the corresponding paragraph.

A closer look at the annual subsidence over the entire rockglacier area shows a general thinning of the entire landform (0.02 ma-1 for the Murtèl rockglacier and -0.09 ma-1 for the Huhh1 rockglacier (see Fig.1 in this document for the corresponding histograms) derived from the multisensoral analysis. The magnitude of subsidence in the deposition area is is almost almost twice as high as the overall average annual subsidence of the landforms and already just the visual inspection of the DEM differencing (Fig. 2 in the manuscript) shows the thinning signal. Therefore we think that the focus of the subsidence analysis should remain on the deposition area (and therefore Fig 3) due to its strong signal and previous mentioning in the literature. |
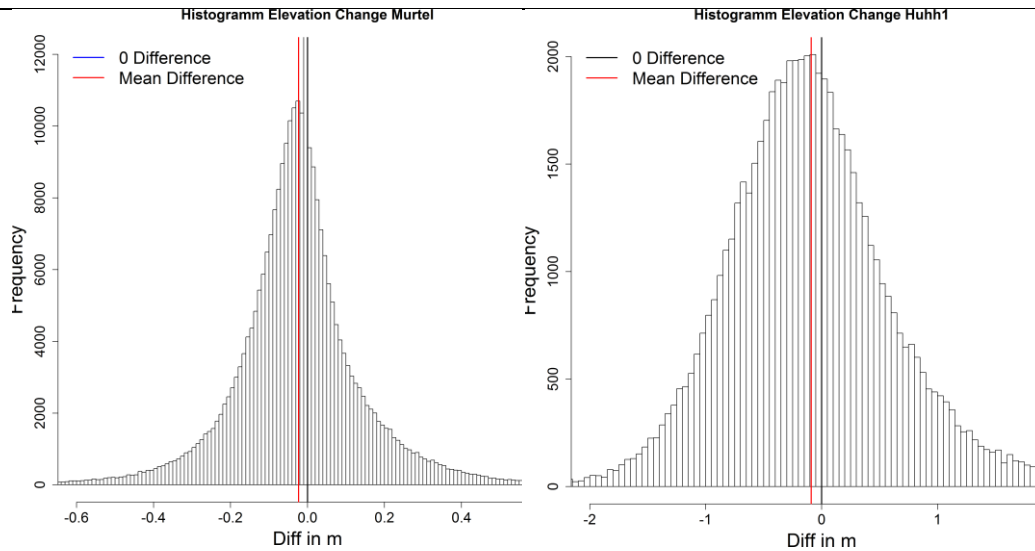
Fig. 1: The frequency distribution of annual vertical surface change (ma^{-1}) from DEM-differencing over the entire rockglacier systems. Both systems show negative mean values (red lines). The black line refers to 0 ma^{-1} difference.

We included the subsidence values for the entire landforms in the manuscript with the corresponding paragraph reading as:

This analysis (over decadal time periods) showed distinct subsidence features of different magnitudes on the entire rockglacier, most pronounced in the deposition area (outline with green in Fig. 2) of the rockglacier. A more detailed assessment of the subsidence shows a general lowering of the entire surface of the rockglacier system of 0.02 ma^{-1} for the Murtèl rockglacier and -0.09 ma^{-1} for the Huhh1 rockglacier. The spatial analysis of the subsidence phenomenon depicts the strongest signal of annual lowering in the deposition area (talus slope/sedimentation area, see Fig. 3) with an overall average of annual subsidence of -0.04 ma^{-1} for the Murtèl rockglacier and -0.16 ma^{-1} for the Huhh1 rockglacier. Such subsidence features, especially in the deposition area, have been described as signs of permafrost degradation (Roer et al., 2008a, Springman et al., 2013, Bodin et al., 2015) and are assessed by the rockglacier evolution model in Sect. 6.2.4.

R2.5	- The viscosity (or the softness parameter A) depends on temperature, but also on fabric, and moisture content. The later is particularly true for 'warm' rock glaciers , i.e. close to their melting point. For 'warm' ice increasing debris concentration may in fact decrease the viscosity by favouring higher moisture content at ice-debris interfaces, up to a critical debris concentration past which inter-particle frictional strength increases the viscosity (see reference below and other works cited in them). I do not expect that you include the sensitivity to moisture in your model, but that this aspect be included in the literature review on rock glacier rheology, and discussed with respect to its implication for the sensitivity of the softness parameter to temperature as climate warms. An excellent review of the rheology of debris-ice mixture is also given by Moore

(2014), which you should refer to in your introduction and discussion.

We agree with the reviewer that moisture content is influencing the rheology and the rate factor specifically. We do not explicitly include changing in moisture content in our rheology model but this is implicitly included over the temperature. We added some explanation to this and the two suggested references, with the text now reading as:

The rate factor A is estimated from observed surface flow speeds by inverting Eq. (3) for A but is known to be influenced by the material temperature but also by other factors such as the moisture and debris content (Cuffey and Peterson, 2010). Moisture content is known to vary with time and temperature (see Moore, 2014 and Monnier and Kinnard, 2016) but we do not explicitly include this in our model as such changes are poorly constrained. The temperature related effect from moisture is however implicitly included by writing the rate factor of the rockglacier material as a product of the temperature dependent part $A^*(T)$ and a scaling factor f_A accounting for the influence of the debris:

$$A = A^*(T) \cdot f_A \qquad\qquad\qquad (6)$$

This approach is in agreement with known rheological investigations (Paterson and Budd, 1982, Arenson and Springman, 2005) and allows including a temperature forcing in our modelling experiments.

R2.6	(p.8 L25): The rock glacier density is kept constant in space and time in your model, you should state it clearly in the model definition. This means that (i) no internal ice melting can take place, and (ii) that variations in active-layer thickness, which in rock glacier is often blocky and dry, are not considered. Hence in your model experiment the rock glacier is allowed to grow downslope indefinitely over time. In reality as the rock glacier front flows downslope/down-valley warmer temperature there should increase internal ice melting, i.e. the active layer should deepen, which could have a stabilizing effect on flow by increasing the frictional resistance. This is in my opinion the most important oversimplification of the model: you consider mass influx (debris+ice with a fixed fraction) but mass outflux is not permitted. See Konrad and Humphrey (2000) for example of prescribed mass balance profile on rock glaciers (debris-covered glacier in their case). The active layer will isolate the internal ice from the atmosphere but climate warming on decadal to centennial scales will change the active-layer thickness. This point should be emphasized and the implications discussed. Including mass loss could be a nice addition for follow-up work. Konrad, S. K., & Humphrey, N. F. (2000). Steady-state low model of debris-covered glaciers (rock glaciers). IAHS PUBLICATION, 255-266. *We used a constant rock glacier material density and clarified this in the text.* *We further agree with the reviewer that internal ice melt may occur but its relationship to external temperature forcing is very poorly constrained by data and models and elevation differences between the tongue and the upper part of the rock glacier in our case very small. We therefore purposely excluded this process in our modelling experiments in this paper (out of*

scope). We are actually already are working on some further research in this direction.

To clarify these point we added this in the text in section 4.2 Rockglacier creep modelling approach:

For simplification we assume the rockglacier material to be a homogenous mixture of ice and sediment, meaning the rheological parameters such as the rate factor A, flow exponent n and rock glacier material density ρ_r do not change within the rockglacier body. This means that we exclude any internal ice melting and consider the active layer rheologically in the same way as the rock glacier material.

…and at the of the discussion section 6.2.4 (geometry change and subsidence)

…and therefore we did not include this process in our flow modelling. In future work, ice melt (as a function of temperature) could technically be easily included through a negative accumulation term in the surface evolution equation (8) and an adjustment of the mean density.

R2.7	P.10 L8: you use the shallow ice approximation which implies a slab of infinite width, i.e. without friction effects, yet you parameterise the rock glacier bed with a parabolic cross-valley profile of finite width. Consider using a side drag parameterisation (shape factor, see e.g. Cuffey and Paterson, 2010, and use in Monnier and Kinnard, 2016). If you do not include it, discuss why not and possible effects of ignoring side friction: the driving dress can be reduced by 10-25% depending on the cross-profile shape (this if the shape factor approach is valid).
	Our across glacier parabolic shape is actually included to account for an adjustment in width with varying thickness (in particularly at front). It has no impact on the flow speed. Yes we could of course include a shape factor but this would not change our modelling results at all our channel shape is constant along flow and the shape factor would implicitly be included in the scaling factor f_A for the rate factor (eqn 6) and thus make no difference. We added a sentence to explain this:
	This allows the width of the rock glacier to vary with changing thickness, but the effect of side drag is not explicitly included, but implicitly is contained in the scaling factor f_A of the rate factor.
R2.8	(p15 L7 and Figure 10): Why did you choose to present the model run with a decrease of material input to 40% of the original value? I may have missed it: is it because this particular combination fits the observation better in some way? It is not clear and could be better presented. Do you have a basis to assume that there has been a 60% decrease in mass influx to the rock glacier in the past?
	We introduce a 60% reduction in material influx because we assume that an expected climate warming will most strongly influence the aggradation and incorporation of subsurface ice. We agree that the studies on rockwall dynamic and their future activity hint towards an increase in

sediment production on the short but the long-term prediction is rather uncertain. Krautblatter et al. 2013 show that the warming and subsequent thawing permafrost will increase instabilities in the rockwalls but 'dry' and ''warm' rockwalls will become more stable again on the long term. Therefore we assume for the combined experiment that the material input from the rockwall will remain the same but the ice input will change significantly. A 60% reduction of ice due to a 1°C warming is of course extreme but it exemplifies the impact of such potential environmental changes.

This argumentation is indeed not very clear in the manuscript therefore we added the following text and reference:

We assume that warming and subsequent thawing of permafrost in rockwalls will lead on the short-term to an increase in sediment production but is expected to extenuate on the long-term (Krautblatter et al., 2013). Therefore we keep the material input from the rockwall constant but reduce the overall material influx by the amount of ice.

Krautblatter, M., Funk, D., and Günzel, F. K.: Why permafrost rocks become unstable: a rock–ice-mechanical model in time and space, Earth Surf. Process. Landforms, 38, 876–887, doi:10.1002/esp.3374, 2013.

R2.9	I found this section somewhat confusing, especially with regards to the analogy with glacier response times definitions (p20 L21), and the section deserves some clarification.
	i) Your adjustment time scale is based on the kinematic wave speed (cf equation 12). This is the time taken for the topographic perturbation to travel to the front, and is faster than the ice velocity.
	ii) Your diffusion timescale (cf equation 14) is the time taken for the topographic perturbation to diffuse over the whole landform, and is longer than the adjustment time. My impression is that your adjustment time (kinematic wave) is more akin to the reaction time that you mentioned for glaciers, i.e. the time it takes for the front to respond to a mass-balance perturbation, while your diffusion time scale is in turn more akin to the volumetric time scale, i.e. the time taken for (most of) the landform to adjust to a new mass-balance state. You say the reverse. I may get this

wrong, but you may want to clarify better theses concepts and the analogies to glaciers. The fact that the terminology of response times in the glaciology literature is somewhat confused certainly does not help... See discussion in Hooke (Principles of Glacier Mechanics, 2005, p.375) for example for the different definitions.

We agree that this section was probably slightly confusing, in particular together with the reference to the 'response time' of glaciers. Because we have no surface ice melt in our model, our adjustment time is very different to the classic Johannesson Volume response time scale for glaciers (which requires the ablation at the tongue). As the proposed adjustment time scale is easy to estimate from flow speed we think this measure may be very useful for dynamic assessments of rock glaciers but requires a proper explanation.

We therefore rewrote and restructured this section completely and consistent with Hooke (2010), and made much clearer that the proposed 'adjustment time' scale is NOT related to the glacier response time. The whole paragraph no reads as:

The modeling shows that the adjustment times in thickness and advance rates are for the faster and steeper Huhh1 rockglacier with 100 a, an order of magnitude faster than the 1000 a of Murtèl rockglacier (Fig. 6d and 7d). While in the literature such differences in adjustment timescales have qualitatively been linked to the general rheology and mass turnover, the controlling factors remain unquantified. A comparison to theoretical considerations based on the kinematic wave theory developed by Nye (1963) can be made for the material supply experiment. Besides the change in material supply rate, the thickness adjustment depends mainly on the travelling wave speed of the thickness perturbation and on its diffusion. According to Nye (1963; and see also Hooke 2005, p. 371-381) the travelling wave speed v_0 is given by a multiple of the the rock glacier flow speed and specifically

$$v_0 = (n+2) \cdot u_s \qquad\qquad (11)$$

The diffusion of the thickness perturbation is proportional to the diffusivity which is given by

$$D_0 = \frac{n \cdot q}{\alpha} = \frac{n \cdot \bar{u} h}{\alpha} \qquad\qquad (12)$$

where q is the ice flux and α the surface slope. For Murtèl and Huhh1 this results in diffusivities of 30 m^2a^{-1} and 53 m^2a^{-1}, which are as a result of very small creep velocities and low thicknesses much lower compared to diffusivities of pure-ice glaciers.

Following Johannesson et al. (1989; see also Hooke, 2010, p. 376) the related 'adjustment time-scales' of thickness changes to expand over the whole rock glacier lobe then depend on a propagation time-scale T_p and a diffusion time-scale T_d. The propagation time-scale is given by

$$T_p = \frac{L_0}{v_0} = \frac{L_0}{(n+2) \cdot u_s} \qquad\qquad (13)$$

where L_0 is the length-scale of the rockglacier lobe. This timescale is inversely proportional to the horizontal velocity and consistent with the modeling results, that a factor 10 difference in creep velocity between Huhh1 and Murtèl rockglacier translates into a factor 10 difference in adjustment time. For n=3, lengths of 300 m and 250 m and creep velocities of 0.07 ma^{-1} and 0.6 ma^{-1} for Murtèl and Huhh1, we obtain adjustment timescales of 860 a and 83 a respectively. These theoretical values agree in absolute and relative magnitude well with our modeled estimates.

	The diffusion timescale is given by
	$$T_d = \frac{L_0{}^2}{D_0}. \qquad\qquad (14)$$
	which results in 3000 a and 1200 a for Murtèl and Huhh1, respectively, for the thickness perturbation to spread over the entire landform and is substantially longer than the timescales derived above for the kinematic wave propagation. These diffusion timescales are also much longer compared to pure-ice glaciers and are consistent with the existence of the characteristic morphological features of ridges and furrows on the surface of rockglaciers.
	To conclude, the propagation timescale, and therefore the, horizontal velocity, is a simple and meaningful measure for rockglacier 'adjustment times'. The very similar adjustment times obtained for the different types of perturbation experiments support the notion that this propagation timescale T_p can be used as a general measure of adjustment in creep dynamics to a step change in external forcing. Note that the introduced adjustment timescale is not the same as the 'volume response time' for pure-ice glaciers for adjusting to a new climate (Johannesson, 1989) and should not be confused with a 'reaction time' (time taken for a rockglacier to show a detectable reaction on an external forcing).
R2.10	P.7 L6: "Surface features (e.g. slope, substrate) as well as velocity fields are further used to delimit the different subsystems." - Which velocity fields? If you refer to previously published data insert the proper reference.
	We calculated velocity fields for both rockglaciers from feature tracking in TLS and photogrammetric data but refrained from showing it in another figure since it would introduce another figure and the benefit from said figure would be marginal.
	Similar but older and less comprehensive data have been shown in Roer et al., 2005 and Kääb et al., 1998.
	In order to clarify we now reference
	Roer, I., Kääb, A., and Dikau, R.: Rockglacier kinematics derived from small-scale aerial photography and digital airborne pushbroom imagery, Zeitschrift für Geomorphologie, 49, 73–87, 2005.
	Kääb, A., Gudmundsson, G. H., and Hoelzle, M.: Surface deformation of creeping mountain permafrost. Photogrammetric investigations on rock glacier Murtel, Swiss Alps., in: 7th International Permafrost Conference Proceedings, Yellowknife, USA, 531–537, 1998.

2   Response to Comments in Manuscript L. Arenson (Reviewer 1)

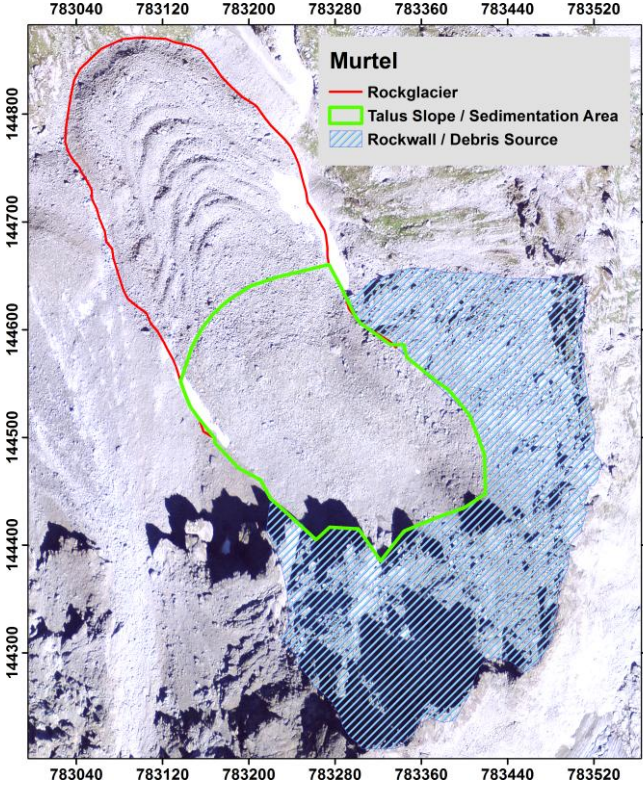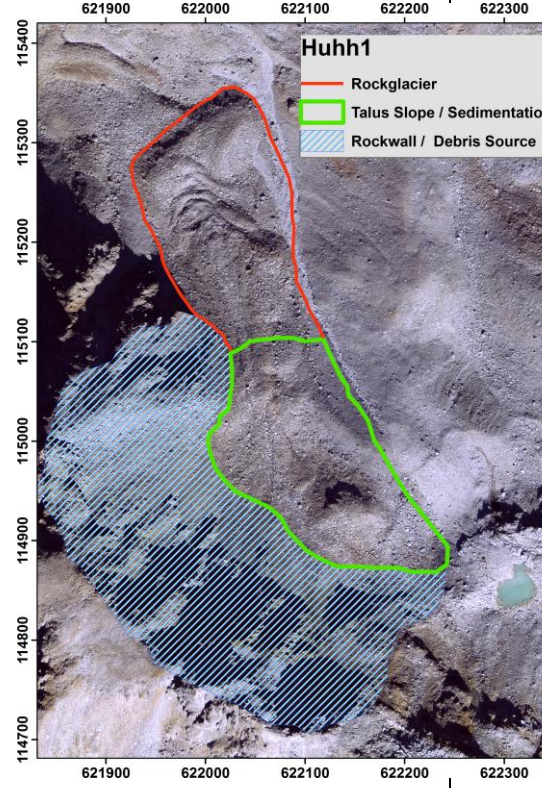|	
M1.1	Page: 1 Text: I would prefer to use "rock glacier" in 2 words instead of 1 word. I do understand the motivation behind using a single term, but this is a fight against windmills in my view. Using

	the two word version makes the paper easier to be found during general search by most people. See R2.1
M1.2	Page: 1 Highlight: Indicative of permafrost creep Text: I'd say they are geoforms that form as a result of permafrost (actually excess ground ice, since permafrost is only define by temperature and time) creep and not indicators Changed to *Rockglaciers are landforms that form as a result of creeping mountain permafrost which have received considerable attention concerning their dynamical and thermal changes.*
M1.4	Page: 2 **Insert:** (rock wall retreat) Changed
M1.5	Page: 2 Highlight: crevasse Text: I understand that others have used the term crevasse for rock glaciers, but I suggest to use tension cracks, similar to what is used in landslide literature. Since you are using rockglacier to clearly differentiate the fact that a rock glacier is not a special glacier Io think it would also be appropriate to use a from the landslide / mass movement community to describe the cracks. Changed
M1.6	Page: 2 Text: what about effect of water. Changed to *These potential factors are most likely connected to the complex combination of the local topography, the thermal state of the permafrost (climate-induced response), the existence and intrusion of liquid water and/or to variations in the sedimentation regime affecting the sediment load during long-term landform evolution.*
M1.7	Page: 2 Highlight: constraint Text: really "constraints" Changed to *foundation*
M1.8	Page: 3 Delete: coarse Changed
M1.9	Page: 3 Delete: permafrost Changed

M1.10	Page: 3 Delete: ing
M1.11	Page: 3 Text: and presence of moisture Changed
M1.12	Page: 4 Highlight: rockglacier Huhh1 in the Turtmann valley and the well studied Murtèl rockglacier in the Engadine Text: change order so that it is similar to the order you have in the paper Changed
M1.13	Page: 4 Text: WGS84? Changed
M1.14	Page: 4 Insert: Changed
M1.15	Page: 4 Highlight: mm Text: add space between different units, please check the whole document. changed
M1.16	Page: 4 Text: Arenson et al., 2002 changed
M1.17	Page: 4 Highlight: l Text: please check the format of all your citations, e.g. et al., 20-- changed
M1.18	Page: 4 Delete: a changed
M1.19	Page: 4 Insert: an changed
M1.20	Page: 5 Text: projection? changed
M1.21	Page: 6 Highlight: a negative subsidence or settlement would actually be heave. I recommend to

	not use negative values if the noun you are using has a direction. it would be different if you were to use vertical deformations only and define positive deformations as upward. changed
M1.22	Page: 8 Text: and temperatures the warmest changed
M1.23	Page: 9 Text: What is the difference between the surface flow speed and the averaged horizontal flow speed? would the latter be the average of all the surface flow speeds? They are not the same, one is the velocity at the surface and the other is actually the depth or vertically averaged velocity. For making this clearer we changed this to: …depth averaged horizontal flow …
M1.24	Page: 9 Highlight: Text: roh changed
M1.25	Page: 9 Text: You may also indicate that in a glacier A is only temperature dependent (Arrhenius equation) with B being constant, whereas in a rock glacier this parameter may also vary with depth in response to changing ice contents We agree with the reviewer but explained the varying shearing with depth further above. However, we added a sentences on the point of the reviewer, the text reads now as: Although this equation is in its form identical to the case of glacier ice (Cuffey and Paterson, 2010), for rock glaciers the flow exponent n and the rate factor A (referring to the material softness) are, due to the presence of debris and water within the ice, not necessarily the same (Moore 2016) and may in reality also vary with depth.
M1.26	Page: 10 Highlight: 50m Text: space between number and unit changed
M1.27	Page: 13 Highlight: over what time? Within the next 50 a See Marmy, A., Rajczak, J., Delaloye, R., Hilbich, C., Hoelzle, M., Kotlarski, S., Lambiel, C., Noetzli, J., Phillips, M., Salzmann, N., Staub, B., and Hauck, C.: Semi-automated calibration method for modelling of mountain permafrost evolution in Switzerland, The Cryosphere Discuss., 9, 4787–4843, doi:10.5194/tcd-9-4787-2015, 2015.

M1.28	Page: 13 Delete: °
	changed
M1.29	Page: 13 Insert: ,
	changed
M1.30	Page: 13 Delete: two roughly
	changed
M1.31	Page: 13 Insert: about two
	changed
M1.32	Page: 17 Text: add Arenson et al., 2002
	changed
M1.33	Page: 18 Delete: of
	changed
M1.34	Page: 18 Text: how are these changes in relative terms, i.e. percentage? are the relative changes similar for the two rock glaciers?
	Yes the relative changes are similar between rock glaciers which we already state just in the sentence above. We do not give relative % numbers because for different quantities they are not the same, but it can be well seen in fig 10 which is already referenced. We rephrased the sentences here slightly to make this point clearer:
	Relative to the initial quantities however (pre-perturbation velocity, thickness or advance rates), the dynamic changes are for both rockglaciers very similar (Fig. 10). This means that we should expect dynamic changes of rockglaciers to be scalable by their geometric (thickness) and kinematic characteristics (flow speed).
M1.35	Page: 18 Insert: thermal
	changed
M1.36	Page: 19 Highlight: this is speculative w/o any calculation. Based on my experience it is likely more in the order of daces. Ground temperatures change slowly.
	Marmy et al. show that general permafrost degradation with thawing at 10 m, even partially reaching 20 m depths until the end of the century, but with different timing among the sites.
	So its rather decades than centuries!

	Marmy, A., Rajczak, J., Delaloye, R., Hilbich, C., Hoelzle, M., Kotlarski, S., Lambiel, C., Noetzli, J., Phillips, M., Salzmann, N., Staub, B., and Hauck, C.: Semi-automated calibration method for modelling of mountain permafrost evolution in Switzerland, The Cryosphere Discuss., 9, 4787–4843, doi:10.5194/tcd-9-4787-2015, 2015.
M1.37	Page: 19 Highlight: to centuries See M1.36 but the thickness of Murtel might still result in longer warming time scales.
M1.38	Page: 19 Highlight: unclear, check wording Rewritten to: *The modeling shows that the adjustment times in thickness and advance rates are for the faster and steeper Huhh1 rockglacier with 100 a, an order of magnitude faster than the 1000 a of Murtèl rockglacier (Fig. 6d and 7d).*
M1.39	Page: 22 Highlight: instead Text: how about: "in addition to" so that these monitoring systems complement each other? changed
M1.40	Page: 22 Text: The model has one key limitation that must be discussed here, which is that it cannot generate tension cracks. You can only model a continuum and the tension cracks that you are describing at the beginning and that may change rock glacier morphology cannot be reproduced. I do not believe that takes anything away from your conclusions, but it should be explained. Yes we agree with the reviewer, and clarified this point by adding a sentence in the conclusions that also picks up the issue of internal ice melt from reviewer 2. Otherwise we made it clear that we cannot reproduce individual and small scale features in the model description. *Note that effects of internal ice melt or non-continuous deformations such as the formation of tension cracks are not included in the current version of the model.*
M1.41	Page: 22 Highlight: alpin Text: can be deleted, as it may also be applicable for rock glaciers in other regions Changed
M1.42	Page: 22 Highlight: immediately Text: you may have to be careful in saying "immediately". In your model, you are shocking the system, whereas in reality, ground temperatures do not chance so quickly, in particular at depth where the majority of the deformation seem to occur We agree with the reviewer. It is still feasible to assume that a warming is influences the entire landform faster than a change in material input. Nevertheless, we still deleted the 'immediately'

M1.43	Page: 22 Highlight: sustenance Text: or sustainability? Changed to endurance
M1.44	Page: 28 **Insert:** "data from sources cited in the text" or did you measure these values by yourself? We did measure most of the parameters ourselves. But ages and Rockwall properties are published elsewhere for Murtel. *The data sources are cited in the text.*
M1.45	Page: 31 Highlight: use subscript changed
M1.46	Page: 32 Text: can you make the elevation change layer transparent so that one can see through and identify some of the structures? If we make the elevation change more transparent you don't see any of the small scale features. For a more detailed look at the landforms we included the same figure without the elevation change in the supplement Figure S1 Figure S1: Orthophotos oft he two selected rockglaciers.
M1.47	Page: 34 Text: the axis implies that the rock glacier has a single temperature, but this is not

	correct and the axis is actually referring to the temperature of the frozen soil, i.e. the rock glacier material. Changed
M1.48	Page: 35 Text: why is the bedrock above the DEM surface? See R2.29
M1.49	Page: 36 Text: Murtèl, be sure you use correct spelling all the time. Changed
M1.50	Page: 37 Text: for these plots, would there be value in adding change in velocity as well? We actually looked at this but it does not add that much and in our view would give too much repetition. We also think reading the absolute velocities is easier and provides the general flow speed of the rock glacier as well. So we did not add such figures.
M1.51	Page: 40 Text: maybe add a note that the change in temperature is immediate, i.e. the system is shocked. We clarified this in the caption: *… immediately after a 1°C temperature step increase*

3 Response to Comments in Manuscript C. Kinnard (Reviewer 2)

M2.1	Page 1 rockglacier or rock glacier? check correct terminology See R2.1
M2.2	Page 4 fix coordinates. If in UTM projection then it should be in meters. If in lat/long then use the degree symbol Changed to *401 555, 5 115 642 (zone 32T) for Huhh1 and 563 131, 5 142 001 (zone 32T) for Murtel*
M2.3	that is rather dense :) g m-3 But I think the S.I. is indeed kg m^-3 so values should read 2650-2750 kg m^-3

	Corrected
M2.4	are theses ages B.P.? 5000 to 6000 years Indeed B.P. Corrected
M2.5	Page 5: The vertical elevation change is obtained by subtracting the surface-parallel component of the vertical displacement from the total measured vertical displacement.
M2.6	Page 6: I don't see why the ridge and furrow topography is a problem if your are concerned about average topographic changes. Clearly, from your Fig.2 there is advection of topographic features which cause alternating zones of subsidence and rising of the surface, but these will cancel out when averaging. I think, since changes are small, that differences between DEM differencing and the points survey is a results of differences in spatial sampling (density and pattern), i.e. 20 points for fields surveys VS XX gridpoints in DEM differencing. You would need a complete error assessment to be able to truly compare these two measures (measurement error + sampling error). The extraction of vertical changes from the 3D measurements can also be affected by the slope calculations which you used to remove the surface-parallel component of vertical movement. It would be useful to expand on the reasons why these two dataset give different results, even if you don't do a complete error analysis. See R2.4
M2.7	Page 8: why the change in symbology? This is the 'driving stress.? check for consistency We rephrased it consistently with the shear stress before integrating it. It now reads as: The shear stress τ_{xz} is then given by the local surface slope $\frac{\partial s}{\partial x}$ and ice depth d_z $$\tau_{xz} = \rho_r g \frac{\partial s}{\partial x} d_z \qquad\qquad (3)$$ where $\frac{\partial s}{\partial x}$ is the surface slope.
M2.8	Page 8: here you also make the assumption that density is constant over depth. You should state it clearly. We state this now more clearly at top of page 8: *…rockglacier material to be a homogenous mixture of ice and sediment, meaning the rheological parameters such as the rate factor A, flow exponent n and rock glacier material density ρ_r do not change within the rockglacier body.*
M2.9	Page 9 I strongly suggest your consult Monnier and Kinnard (accepted 2016) and Moore (2014) for an expanded discussion of the effect of ice, debris and water content on the rheology of ice-debrismixtures. Indeed with •>60% ice inter-particle frictional strength will not dominate the strength of the debris-ice mixture and the mixture will mostly behave as ice according to Glen's law. The 'softness' parameter (A) will the depend on ice temperature water content, fabric, etc. Monnier and Kinnard, accepted 2016: Interrogating the time and processes of development

	of the Las Liebres rock glacier, central Chilean Andes, using a numerical flow model. Earth Surface processes and Landforms
	Moore PL. 2014. Deformation of debris–ice mixtures. Review of Geophysics 52: 435-467
	See general response to R2.5: we now mention the effect of moisture on deformation and added the two references
M2.10	Page 9: and other factors, see Hooke (2005) or Cuffey and Paterson (2010) for a discussion for ice, and Monnier and Kinnard for the influence of moisture and its interactions with the debris-ice fraction.
	See general response to R2.5: we now mention the effect of moisture on deformation and added the two references:
M2.11	Page 10: can it be negative due to melting of internal ice?
	That is correct but we assume the state of an 'intact' rockglacier which is constantly receiving sediment and ice and therefore has a positive accumulation in the deposition zone. Negative accumulation would result subsidence in the upper part of the rockglacier which we interpret as degradation and address later in the .
M2.12	Page 10: Here you should discuss the implication of side drag, because your SIA formulation assumes an infinite width yet you apply it to a finite width of size w and having parabolic cross-profile.
	One manner to deal with this is to include of side drag effect using a shape factor (Monnier and Kinnard 2016 and references cited in their paper)
	This has been addressed, see response R2.7 above.
M2.13	Page 10: could you not have melting and runoff of internal ice?
	We explicitly excluded internal ice melt and clarified this in the model description (see response . Yes in nature this could be possible which is also what we conclude at the end.
	We therefore added at the of the discussion section 6.2.4 (geometry change and subsidence)
	…and therefore we did not include this process in our flow modelling. In future work, ice melt (as a function of temperature) could technically easily included through a negative accumulation term in the surface evolution equation (8) and an adjustment of the mean density.
M2.14	Page 10: Or gained (?)
	Correct. Changed to
	Is lost or gained
M2.15	Page 11: Here you should mention that is stays constant in space and time
	Changed to
	We estimate the density of the rockglacier material ρ_r from the percentage ice content c_i and from the respective densities of ice $\rho_i = 910$ kg m^{-3} and the debris material $\rho_d = 2700$ kg m^{-3} which we assume to stay constant in space and time

M2.16	Page 11: also see Monnier and Kinnard and Moore (2014) : increasing debris concentration can increase moisture content, which decreases the viscosity, up to the limiting debris fraction fromwhich frictional strength increase. Has been addressed, see response R2.5
M2.17	Page 12: Is this explained somewhere? Your flow equation does not include threshold for thickness, is the 'critical' thickness only a results of the nonlinear flow law? Please explain better. There is not a fixed critical thickness but the transition is rather smooth. We therefore changed it to: *... once it is thick enough and the shear stress high enough,…*
M2.18	Page 13: You don't take into account that as the rock glacier expands downslope/down valley temperatures are warmer there which will feedback on internal ice melting and rheology. Your figure 6 suggest that under a constant accumulation rate the rock glacier keeps increasing in length over time. Is this realistic? Would you not expect increased melting of internal ice as the front expands downslope, and a parallel increase in frictional strength? Theses aspects should at least presented in the discussion Yes, as we exclude melting of ice in our modelling experiments, the rock glacier would keep advancing. For the time scales and related rock glacier length considered here the elevation at the tongue does however not change significantly and therefore unlikely affects melt rates. We added a sentence in section 5.1 (Rock glacier build up) clarifying thjs point: *This continuing advance is a direct result of constantly adding mass at the top while no mass is remobved through melting.*
M2.19	Page 15: Why did you choose to present this particular scenario? Is it because it is the one that best fit the observations? Is there any theoretical and observational evidence for decreased material input? Is climate warming not causing increased rockfall in the Alps? My impression is that the rockfall rate would increase, at least initially, but that the ice content (%) would decreases if snowfall rates decrease as climate warms... Hence the assumption off a constant ice content for the accumulation rate, ac, may be simplistic. That being said it is ok to simplify as long as these simplifications and their potential effects are presented and discussed. See R2.8
M2.20	Page 17: but see recent review by Moore (2014) Moore (2014) gives a very comprehensive overview the physical properties and mechanical interactions between ice and rock debris. His summary concerning rockglaciers and their special characteristics relies on almost the same studies as we used in our experiment (such as Arenson, 2002, Arenson & Springman, 2005 and Ikeda). He interestingly stresses the point of the role of unfrozen water influencing the mechanical properties of rock-ice mélanges and presents water concentration of several frozen homogeneous materials and elaborates on its impact on rheology. This is surely the right direction for further research but his recommendations are hardly applicable to our rockglacier rheology since the main source of unfrozen water in rockglacier is precipitation and snow melt and there we is to our knowledge no field based data yet how rain- or melt-fed subsurface hydrology develops in rockglaciers. In our further research on RG rheology we will definitely look more detailed into this paper but we still believe that 'there is very limited quantitative, field-based information available

| | to constrain more complex constitutive relationships' concerning the description of the flow law. To elaborate on that we changed the following in the text:

A more complex rheology of ice-debris mixtures could in theory and should in the future be included in rockglacier creep models, but currently there is very limited quantitative, field-based information available to constrain more complex constitutive relationships. Especially the role of unfrozen water appears to have a strong impact on the properties ice-debris mixtures as temperature nears the melting point and need to be further addressed (Moore, 2014) in establishing an adapted flow-law for rockglaciers.

Moore, P. L.: Deformation of debris-ice mixtures, Rev. Geophys., 52, 435–467, doi:10.1002/2014RG000453, 2014. |
|---|---|
| M2.21 | Page 18: very different for the two rock glaciers

Change accordingly |
| M2.22 | Page 18: the sentences does not read well I suggest rephrasing

This sentence has been rephrased to:

The modeling shows that the adjustment times in thickness and advance rates are for the faster and steeper Huhh1 rockglacier with 100 a, an order of magnitude faster than the 1000 a of Murtèl rockglacier (Fig. 6d and 7d). |
| M2.23 | Page 19: Could you explain better the difference between these two quantities?

Changed the sentence to:

…which results in 3000 a and 1200 a for Murtèl and Huhh1, respectively, for the thickness perturbation to spread over the entire landform and which is substantially longer than the timescales derived above for the kinematic wave propagation. |
| M2.24 | Page 20: Why? explain.

We changed this sentence for clarifying:

These diffusion timescales are also much longer compared to pure-ice glaciers and are consistent with the persistent occurrence of morphological features of ridges and furrows on the surface of rockglaciers. |
| M2.25 | Page 20: I am confused.

Would the kinematic adjustment time, Tk, not be rather similar to the reaction time for glaciers, i.e. the time it takes for the geometry to respond to a change in mass flux, while the diffusion time, Td, the time taken for the perturbation to spread over the whole landform, i.e. the volumetric response time, which is longer than the reaction time?

I may get this wrong but I suggest you clarify and differentiate these two concepts clearly in the text for the reader

Has been addressed, see response R2.9 |
| M2.26 | Page 21: The DEM differencing over the WHOLE rock glacier should give you the variation in mass no? (geodetic balance). This assuming that they are precise enough. By integrating topographic changes over the whole RG area mass transfers cancel out and the volume change will be the mass-balance, which for a rock glacier is m = material (rock+ice) accumulation - internal ice melting. If m is negative then internal ice melting was more than the accumulation rate. If m is positive you can compared it with the theoretical value you |

	used for accumulation... but of course you cannot isolate internal melting.
	See 2.4
M2.27	Page 22: rephrase.
	Do you mean: rock glacier show spatially contrasted response to changes in environmental factors.
	We mean that the rockglacier adapts to changes in environmental factors in different ways at different places. Not contrasting but temporally and spatially variable.
	Rockglaciers react spatially and temporally variable to changes in environmental factors.
M2.28	Page 22: Consult Moore (2014) for a more up to date review of debris-ice mixture rheology models, and Monnier and Kinnard (2016) for an application. One intervening factor ignored in your analysis is the moisture content. There is not necessarily an easy way to include it, but this aspect should be mentioned and discussed briefly, see Monnier and Kinnard for a discussion of the topic and related key references
	We addressed this issue in the main text (R2.5) but do not want to bring this up in the conclusions.
M2.29	Page 23: the modelled front does not connect with bedrock, why? Does the modelled rock glacier extend further downslope?
	For the modelling application we introduced strong limitations according the bedrock topography which are responsible for the deviation between observed and modeled rockglacier topographies. We simplified the talus slope and rockglacier bedrock topography as planes with two constant inclinations. The talus slope bedrock inclined with the angle of repose for such material as stated in Carson, 1977 and the rockglacier bedrock derived from field-based geomorphometry at the two sites. The real bedrock topography is most likely more complex than this assumption which results in the deviating model results. In particular the lower part of Murtel rockglacier is believed to have a less inclined bedrock topography and even convex formation at the snout of the rockglacier which is hindering its advance. In the case of the talus slope of Huhh1 where the observed topography lies lower than the modeled surface, we introduced an idealized upper talus slope (first 150 m) in the modelling which deviates from the observed surface. We believe the upper part of the rockglacier to be already disconnected from its source area, therefore 'draining' the talus slope of material and the rockglacier body 'creeping away' which would explain the deviation between model and observation.
	The point we are trying to make with this figure is that the model produces a good agreement concerning length and thickness in the assumed timespan of rockglacier development.
	In order to clarify we added the following in the text:
	Note that the bedrock topography of the talus slope and rockglacier are assumed to be of constant inclination. We defined the first 150 m of slope as an idealized talus slope with an inclination of 37° which we assumed to be the angle of repose for such unsorted and unconsolidated blocky material (Carson, 1977). The general inclination of the bedrock topographies (see Table 1) underneath the rockglaciers are derived from digital elevation models where we assume the bedrock to be parallel to the rockglacier surface (see Table 1). Figure 5 depicts the observed rockglacier front shapes and positions slightly differently from the modeled ones as the real bedrock geometries of the rockglaciers are more complex than

	the assumed uniform mountain slopes. Also, the idealized talus slopes differ from the observed geometries due to above mentioned simplification. And in the caption of fig 5: *Note that the model cannot replicate the exact geomoetry of the landform due to tis various simplifications but shows good agreement in length and thickness of the rockglacier main body.*
M2.30	Page 23: why is the bedrock surface above the DEM? See M2.29
M2.31	Page 36: the assumption of mass conservation ignores spatial variations in internal ice melting rates. The active-layer thickness is likely to increase downslope as air temperatures become warmer: this will reduce the overall rock glacier density (if ice is replaced by air...) and eventually increase the frictional strength as the ice content decreases. Addressed, see response in R2.6
M2.32	Page 37: to be consistent with Figure 6 you should move panel d (length) to the left and panel e (volume) to the right Changed

Rockglaciers on the run – Understanding rockglacier landform evolution and recent changes from numerical flow modeling

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Abstract. Rockglaciers are landforms ~~indicative~~ that form as a result of creeping mountain permafrost ~~creep and~~ which have received considerable attention concerning their dynamical and thermal changes. Observed changes in rockglacier motion on seasonal to decadal timescales have been linked to ground temperature variations and related changes in landform geometries interpreted as signs of degradation due to climate warming. Despite the extensive kinematic and thermal
10   monitoring of these creeping permafrost landforms, our understanding of the controlling factors remains limited and lacks robust quantitative models ~~for~~ of rockglacier evolution in relation to their environmental setting.

Here, we use a holistic approach to analyze the current and long-term dynamical development of two rockglaciers in the Swiss Alps. Site-specific sedimentation and ice generation rates are linked with an adapted numerical flow model for rockglaciers that couples the process chain from material deposition to rockglacier flow in order to reproduce observed
15   rockglacier geometries and their general dynamics. Modelling experiments exploring the impact of variations in rockglacier temperature and sediment/ice supply show that these forcing processes are not sufficient ~~for explaining~~ to explain the currently observed short-term geometrical changes derived from multitemporal digital terrain models at the two different rockglacier~~s~~. The modelling also shows that rockglacier thickness is dominantly controlled by slope and rheology while the advance rates are mostly constrained by rates of sediment/ice supply. Furthermore, timescales of dynamical adjustment are
20   found to be strongly linked to creep velocity. Overall, we provide a useful modelling framework for a better understanding of the dynamical response and morphological changes of rockglaciers to changes in external forcing.

1 Introduction

Rockglaciers and their dynamics have received much attention in permafrost research and beyond, most prominently by the International Panel on Climate Change (IPCC) in context of impacts of a warming climate on high mountain permafrost
25   (IPCC, 2014). Time series of rockglacier movement in the European Alps indicate acceleration in permafrost creep in recent decades is related to an increase in ground temperatures (Delaloye et al., 2010b, PERMOS, 2013, Bodin et al., 2015). Furthermore, multitemporal geomorphometric analysis have shown subsidence features and structural disintegration of alpine rockglaciers which are indicative of landform degradation and destabilization (Kääb et al., 2007, Roer et al., 2008b, Bodin et al., 2010, Springman et al., 2013, Micheletti et al., 2015). Many studies have addressed the connection between
30   mean annual air temperatures (MAAT) and rockglacier dynamics from a descriptive point of view (Ikeda and Matsuoka,

2002~~a~~, Roer et al., 2005a, Delaloye et al., 2010b, Springman et al., 2012) or have used modeling approaches to assess rockglacier dynamics (Jansen and Hergarten, 2006, Kääb et al., 2007, Springman et al., 2012). Most of these studies focus on the impact of air or ground temperature on rockglacier creep. Other authors stressed that rockglacier dynamics cannot solely be explained by temperature variations and should integrate flow and controlling environmental factors such as sediment

5   supply dynamics and landform characteristics (Roer et al., 2005a, French, 2007, Frauenfelder et al., 2008). Rockglaciers have been defined as 'lobate or tongue-shaped bodies of perennially frozen unconsolidated material supersaturated with interstitial ice and ice lenses that move down slope ~~or down valley~~ by creep as a consequence of the deformation of ice contained in them and which are, thus, features of cohesive flow' (Barsch, 1992, p. 176). Such a definition includes information on form, material and process and therefore, the observable rockglacier characteristics are influenced by

10   sediment and ice input, permafrost conditions and the geomorphological setting which in turn control rheology and landform geometry (Barsch, 1996). Very few studies have addressed rockglacier dynamics in such a holistic approach including ~~backweathering rates~~rockwall retreat, sediment and ice dynamics, and climate variations to gain insight into the long-term evolution of rockglaciers (Olyphant, 1983, Frauenfelder et al., 2008) and model validation was hampered by restricted observational data~~and were limited regarding validation by observational data~~.

15   Recent observations show signs of rockglacier destabilization such as acceleration, subsidence features and structural disintegration (forming of ~~crevasses~~tension cracks) at several rockglacier landforms in the Swiss Alps (Kääb et al., 2007, Roer et al., 2008b, Delaloye et al., 2011, Lambiel, 2011, Springman et al., 2013, PERMOS, 2013, Kenner et al., 2014, Bodin et al., 2015). These studies indicate that various factors can lead to such degradation but a common triggering for all the cases has not been identified. These potential factors are most likely connected to the complex combination of the local

20   topography, the thermal state of the permafrost (climate-induced response), the existence and intrusion of liquid water and/or to variations in the sedimentation regime affecting the sediment load during long-term landform evolution.

Numerous remote sensing techniques are available for acquiring data on permafrost creep (see Haeberli et al., 2006 and Kääb, 2008 for an extensive summary), high mountain geomorphometry (Bishop et al., 2003) and high mountain sediment dynamics (Gärtner-Roer, 2012, Heckmann and Schwanghart, 2013, Müller et al., 2014a). This provides the necessary

25   ~~constraints~~foundation for a holistic assessment strategy that includes the coupling of relevant landforms and processes and in which sediment supply rates can be quantified, ice volumes estimated and rockglacier rheologies derived (Frauenfelder et al., 2008, Gärtner-Roer and Nyenhuis, 2010).

Here we present such a holistic analysis approach to assess long-term rockglacier evolution and the impacts of variations in temperature, sediment and ice supply on rockglacier geometry and movement. We apply a numerical flow model to two

30   rockglaciers in the Swiss Alps with different topographic, morphometric and rheological characteristics. The modeling is motivated by observations of topographic and kinematic changes for the two rockglaciers revealing signs of degradation as presented in this study. The aim of the modeling approach is to relate these changes to the long-term evolution and short-term adaptation of rockglacier systems to changing environmental factors and ultimately to a better understanding of the

currently observed dominant controls of geomorphological changes. We thereby consider rockglaciers as an integral part of a coarse-debris cascading system in periglacial environments.

2 ~~Conceptional~~ Conceptual approach to high mountain periglacial systems

The topographic evolution of the rockglacier landform relies on the production, ~~transportation~~ transport and deposition of
5   ~~coarse~~ debris in the periglacial system and the generation and integration of subsurface ice (Wahrhaftig & Cox 1959, Barsch, 1996). The development of rockglaciers is therefore dependent upon the supply of debris from the source headwall(s) and the long-term preservation of an ice matrix or ice core inducing creep (Morris, 1981). Rockglaciers are also dynamic landforms that are influenced by the warming and melting of ice and changes in sediment input. The variations in environmental factors translate into observable changes in geometry and kinematics which can be interpreted as a sign for
10   degradation and/or destabilisation of these ~~permafrost~~ periglacial landforms (Roer et al., 2008b, Springman et al., 2013).
Figure 1 shows the theoretical concept of an idealized periglacial mountain slope with a corresponding rockglacier system and builds the conceptual basis for this study. Two main subsystems contribute to the temporal and topographical development of the rockglacier landforms: The upper headwall and talus slope system generate the sediments that are transported into the lower rockglacier system. Besides the sediment input, the rockglacier system is also controlled by the
15   existence, generation and state of subsurface ice and permafrost creep (see Fig. 1). The two subsystems differ on the basis of several characteristics: topographic features, typical landform(s) and the dominating mass transport~~ing~~ processes. Backweathering of the exposed rockwall and resulting rockfall are the most effective mass wasting processes (e.g. Krautblatter et al., 2012, Müller et al., 2014a) and supply the entire system with sediment. Backweathering rates and rockwall dynamics are strongly influenced by the geological structures, lithological conditions, the presence of moisture as
20   well as by the characteristics and dynamics of cleft ice which are in turn thermally controlled (Hasler et al., 2012). The progressive accumulation of sediments and ice on an inclined surface at the foot of the rockwall under permafrost conditions, leads to permafrost creep and ~~develops~~ the development of ~~into~~ a rockglacier (Barsch, 1992, Haeberli et al., 2006). The existence of ice and its properties within the sediment obviously plays an important role in controlling the rheology of the rockglacier~~as a process agent in these systems~~ and environmental changes influence erosion and transport processes that
25   result in topographical and kinematic changes (White, 1973, Arenson et al., 2004, Haeberli et al., 2006).

→ Insert Figure 1

We transfer this conceptual approach into a numerical flow model that integrates the whole debris process chain and couples
30   the different subsystems and related mass fluxes. It assumes a uniform sediment and ice input from the rockwall to an inclined surface, builds up a talus slope that is supersaturated with ice and then starts to creep as a viscous non-linear media similar to ice. This rheological assumption has repeatedly been used to assess rockglacier kinematics (Wahrhaftig and Cox,

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1959, Olyphant, 1983, Whalley and Martin, 1992, Barsch, 1996, Kääb et al., 2007, Frauenfelder et al., 2008). A few studies (e.g. Olyphant (1983), Wagner (1992), Leysinger-Vieli and Gudmundsson (2003) and Frehner et al. (2015)) have demonstrated that such a rheology can in principal be used in a numerical flow model for rockglaciers.

3 Recent observations of rockglacier change

5 The modeling work in this study is motivated by detailed observations of geometric changes of two rockglacier systems, both in Switzerland. We present in this section comprehensive new datasets of the two landforms, the well studied Murtèl rockglacier in the Engadine and the rockglacier Huhh1 in the Turtmann valley ~~and the well studied Murtèl rockglacier in the Engadine~~. Both show changes in surface geometry and kinematic behaviour but have distinctly different landform characteristics (see Table 1 for an overview). In order to assess the controlling mechanisms of rockglacier evolution and

10 potential degradation we use a "backward" approach: w~~W~~e quantify and discuss distinct observed changes in surface geometry and kinematics of the two rockglaciers, propose potential controlling forcing factors (sediment and ice input as well as ground temperature) and then assess these observations and related forcings with a numerical creep model.

➔ Insert Table 1

15

3.1   Murtèl rockglacier, upper Engadine

The first rockglacier site is the well-studied Murtèl (Hoelzle et al. 2002, Haeberli et al. 2006, Springman et al. 2012) situated below the northern face of Piz Corvatsch (3300 m a.s.l.) in the upper Engadine, in the south-eastern part of Switzerland (UTM~~-~~, 563 131, 5 142 001~~N563'112, E5'142'07~~; zone 32T). The lithology mainly consists of granite and granodiorite. The

20 density of the in-situ rock types are based on values given in the literature with a density of 2.65~~0~~-2.75~~0~~ kg ~~e~~m^{-3} for granite and 2.70~~0~~-2.8~~00~~ kg ~~e~~m^{-3} for granodiorite (Tarbuck et al.~~,~~ 2011), and studies on backweathering at this site have shown backweathering rates of 2 ~~mma~~mm a^{-1} (Müller et al., 2014a). Murtèl is one of the best investigated rockglaciers and observations from this permafrost site have been discussed in great detail (see summary in Haeberli et al., 1998). As part of the PERMOS network (Permafrost Monitoring Switzerland), parameters such as borehole temperatures, ground surface

25 temperatures and horizontal velocity have been monitored since 1987 (Vonder Mühll et al., 2008). The borehole data has revealed a layered internal structure with a shear horizon ~~in~~ at 32 m depth where almost all of the deformation takes place (Arenson et al., 2002, Springman et al., 2012). Attempts to determine the age of this rockglacier (Haeberli et al. 1999, Laustela et al. 2003) obtained an age of 5000 to 6000 a B.P. as a minimum value (Haeberli et al., 2003). These values were calculated from present day surface velocity fields assuming constant environmental conditions over the rockglacier

30 development (Kääb ~~und~~ and Vollmer 2000, Frauenfelder and Kääb, 2000, Haeberli et al., 2003). The rockglacier is

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characterized by rather slow creep velocity (0.06-0.13 m_a^{-1}) and is considered a thick and ice rich landform with ~~a~~ an average volumetric ice content of 60% (Haeberli et al., 1998, Arenson et al., 2002).

3.2   Huhh1 rockglacier, Turtmann Valley, Valais

The second rockglacier is located in one of the hanging valleys of the Turtmann Valley, a tributary of the Rhone valley in southern Switzerland (UTM 401 555, 5 115 642T~~UTM N401'580, E5'116'471~~; zone 32T). The valley's lithology mainly consists of Palaeozoic gneisses and schists and based on this lithology rather constant backweathering rates of 2 ~~mma~~mm a^{-1} are expected (Glade, 2005, Krautblatter et al., 2012, Müller et al., 2014a). The valley stretches from 2400 m a.s.l. to 3278 m a.s.l and is characterized by steep rockwalls, talus cones, a glacier, several moraines of different ages and multiple active and inactive rockglaciers (Roer and Nyenhuis, 2007). The focus within this study lies on the rockglacier Huhh1, which can be considered a thin, moderately fast moving rockglacier (see Tab. 1). This site is also part of the PERMOS network and has undergone several scientific assessments (Rasemann 2003, Roer, 2005, Nyenhuis et al. 2005). There is no direct subsurface information available but Gärtner-Roer (2012) used a semi-quantitative approach to derive the rockglacier thickness and sediment storage assuming an ice volume of 50%-70%. The age of the landform is estimated at 500-600 a using the same approach as Haeberli et al. (2003) and Kääb and Vollmer (2000), where the current velocity fields are assumed to be constant over the rockglacier evolution time. Therefore the age estimates can be seen as minimum ages.

3.3   Observations of rockglacier dynamics

Complementary to the PERMOS related kinematic monitoring, we used a combination of remote sensing and terrestrial surveying methods ~~for~~ to deriv~~eing~~ multitemporal elevation and displacement data in order to assess changes in geometry and creep.

Multitemporal ~~stereophotogrammetric~~ digital elevation models (DEMs) derived from stereophotogrammetry and airborne laserscanning (ALS) are available for the analysis between the years 1996 and 2007 for the Murtèl rockglacier. Five high resolutions DEMs (also stereophotogrammetry and ALS) have been generated in this study for the Turtmann valley between the years 2001 and 2010; the technical details ~~on~~ of these DEMs ~~are~~is given in Tab. 2. New elevation change maps are derived from differencing of the DEMs over the periods 1996 and 2007 for Murtèl and 2001 and 2012 for Huhh1. The limitations concerning processing, uncertainties and application of the different sensor systems are presented in Kääb and Vollmer (2000), Roer et al. (2005c), Roer and Nyenhuis (2007) and Müller et al. (2014b). The systematic error/trueness (Menditto et al. 2007) of the remote sensing data was corrected using the terrestrial geodetic survey points (tachymeter) as reference for the ALS and the ALS data as reference for the photogrammetric DEM data as presented in Müller et al. (2014b). The spatial coverage of each reference dataset allowed to establish a slope dependent detection limit derived from the assessment ranging from 0.5 m to 0.9 m (see also Mueller et al. 2014b). The availability of numerous multisensoral datasets enabled stacking, investigating dense time steps and crosschecking products with different precisions (terrestrial

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survey, ALS, photogrammetry) which led to a high reliability of the DEM differencing and derived annual subsidence rates (Winsvold et al., 2016).

~~, and applied in this assessment.~~

Additionally, kinematic data is available for both rockglaciers from yearly terrestrial geodetic surveys of approximately 20 points as described in PERMOS (2013) and Roer (2005). Horizontal and vertical changes are quantified annually with an accuracy of 1–2 cm. The vertical elevation change is obtained by subtracting the surface-parallel component of the vertical displacement from the total measured vertical displacement.

~~The extracted vertical elevation change from these 3 dimensional displacement vectors is obtained from subtracting the surface-parallel component of the vertical displacement component.~~

➔ Insert Table 2

Based on the above DEMs, new elevation change maps have been derived for both rockglaciers and the subsystem units of the main rockglacier body and contributing talus slope have been identified (Fig. 2). This analysis (over decadal time periods) showed distinct subsidence features of different magnitudes on the entire rockglacier, most pronounced in the deposition area (outline with green in Fig. 2) of the rockglacier ~~systems~~. A more detailed assessment of the subsidence shows a general lowering of the entire surface of the rockglacier system of 0.02 ma^{-1} for the Murtèl rockglacier and -0.09 m a $^{-1}$ for the Huhh1 rockglacier. The spatial analysis of the subsidence phenomenon depicts the strongest signal of annual lowering ~~is shown in Fig. 3 where the histograms of the yearly subsidence~~ in the deposition area (talus slope/sedimentation area, see Fig. 3) ~~shows~~ with an overall ~~negative~~ average ~~of~~ annual subsidence of -0.04 ~~ma~~m a $^{-1}$ for the Murtèl rockglacier and -0.16 ~~ma~~m a $^{-1}$ for the Huhh1 rockglacier. Such subsidence features, especially in the deposition area, have been ~~described~~ interpreted as signs of permafrost degradation (Roer et al., 2008a, Springman et al., 2013, Bodin et al., 2015) and are assessed by the rockglacier evolution model in Sect. 6.2.4. These observed subsidence rates are calculated considering the uncertainties resulting from the DEM differencing (see Müller et al., 2014b). Additional vertical displacement data from terrestrial surveys conducted from 2001/2009 – 2015 corrected for slope parallel movement agree with the results from the DEM-differencing.

~~The main lobes of the rockglacier landforms (outlined red in Fig. 2) have also been analysed for subsidence, but the typical 'furrow and ridge structure' of the rockglacier and the topographic dynamics introduced by the creep process complicate the subsidence quantification. Depending on the methodology, annual average surface elevation change in the terminus area of the rockglaciers range from -0.03 ma~~m a $^{-1}$ ~~(derived from terrestrial point surveys corrected for slope-parallel movement) to +0.01 ma~~m a $^{-1}$ ~~(digital photogrammetry) at Murtèl and -0.2 ma~~m a $^{-1}$ ~~(terrestrial point surveys corrected for slope) to +0.06 ma~~m a $^{-1}$ ~~(digital photogrammetry) at Huhh1. At the front of both rockglaciers, the elevation change signal is close to the measurement uncertainty and thus, no clear subsidence seems apparent.~~

Theoretically, subsidence features can result from surface lowering by ice melt (Phillips et al., 2009), reduced ice and sediment input, acceleration of the entire landform (potentially thermally induced, leading to a 'creeping away' and thinning of the rockglacier from its feeding area) or, and most likely, a combination of the above (Roer et al., 2005a).

Our elevation change data also shows the continuing advance of the rockglacier front and the "furrow and ridge" structure. This shows that the rockglacier continues to be active although it is probably no longer fully connected to its sediment source and therefore not in an equilibrium state with the current sedimentation and/or thermal state of the system.

➔   Insert Figure 2

➔   Insert Figure 3

4   Rockglacier evolution- modeling approach

We present here a quantitative rockglacier evolution modeling approach that is based on the conservation of mass and includes the entire debris process chain in high mountain environments (see Fig. 1).

4.1   Geomorphological Setting

In order to initialize and evaluate the numerical model, it is necessary to derive geometric information about the headwall, talus slope and rockglacier. Therefore, the two rockglacier sites have been analyzed according to the concept introduced in Sect. 2 for their along flow geometry and the quantification of sediment input and sediment deposition. Geomorphological mapping in the field as well as by interpretation of DEMs and orthophotos are used to identify the contributing headwall areas, deposition areas and rockglacier landforms (see Fig. 2). Surface features (e.g. slope, substrate) as well as velocity fields are further used to delimit the different subsystems (Kääb et al., 1998, Roer et al., 2005).

The DEMs served as basis for the geomorphometric analyses to determine spatial dimensions, slope and surface geometry of the periglacial high mountain systems.

4.2   Rockglacier creep modeling approach

A 1-dimensional time-dependent numerical flow model is used to simulate the evolution of the rockglacier surface, length and creep velocity along the centre flowline based on a given sediment/ice input and rockglacier rheology. In this study we are not aiming to reproduce the exact evolution or small scale geometric features of the two chosen real-world rockglaciers, but rather use the model to simulate the basic behaviour of a rockglacier body creeping down a slope and investigate the first order dynamic response of the geometry on changing external factors such as temperature and sediment supply. Specifically,

7

we will investigate potential causes for the observed surface geometry changes (subsidence, front advance and velocity variations) as set out above (Sect. 3.3).

Rockglacier creep

5 For our study we therefore reduce the rheology of the rockglacier to a body of ice-bonded sediment that deforms and creeps like a non-linear viscous material under the influence of gravity, as proposed already in 1959 by Wahrhaftig and Cox (1959) and applied similarly by Olyphant (1983) and Frauenfelder et al. (2008). This rheology can be described by a Glen-type flow law (Glen, 1955) as typically used for glacier ice (Cuffey and Paterson, 2010) which relates the strain rate $\dot{\varepsilon}$ non-linearly to the stress τ

10

$$\dot{\varepsilon} \propto A\tau^n \tag{1}$$

where n is a flow law exponent that is typically between 2 and 3 for frozen material (Paterson, 2010) and A the rate factor describing the softness of the rockglacier material. Such a constitutive relationship has been applied and discussed in other

15 studies on rockglacier creep (Olyphant, 1983, Whalley ~~und~~ and Martin, 1992, Whalley ~~und~~ and Azizi, 1994, Barsch 1996, Azizi ~~und~~ and Whalley, 1996, Kääb et al., 2007, Frauenfelder et al., 2008), and is further supported by results from borehole measurements on real world rockglaciers and shear experiments in the laboratory on rockglacier material (including Murtèl rockglacier; Arenson et al., 2002, Kääb and Weber, 2004, Arenson and Springman, 2005, Frehner et al., 2015). For simplification we assume the rockglacier material to be a homogenous mixture of ice and sediment, meaning the

20 rheological parameters such as the rate factor A, ~~and~~ flow exponent n and rock glacier material density ρ_r do not change within the rockglacier body. This means that we exclude any internal ice melting and consider the active layer rheologically in the same way as the rock glacier material. However, from boreholes we know that the rheology within rockglaciers is variable with depth (Haeberli et al., 1998) and typically enhanced deformation in ice rich shearing zones are observed, for example, in the case of the Murtèl rockglacier. Such shearing zones are typically near the bottom of the moving body of the

25 rockglacier, where shear stresses are highest and temperatures the warmest, and thus they dominate creep process. Consequently, potential variations in rheology in the material above are not substantially changing the non-linear viscous creep behaviour. The modeled flow is calibrated with observed surface velocities (see Sect. 4.3) and is dominated by the rheology of the material near the base and thus our modeling implicitly includes the shear zone in its vertically averaged rheology. In addition, the rheology within rockglaciers is generally poorly known and the assumption of a uniform rheology

30 is therefore justified for studying the first order controls of geometric changes. We further simplify the problem to the case of an infinite sheet of uniform thickness that creeps down an inclined plane (Cuffey ~~und~~ and Paterson, 2010, also known as the shallow ice approximation in glaciology (SIA)) and thereby neglect longitudinal stress gradients. As our focus is the evolution of the surface and not the detailed stress field within the landform, according to Leysinger Vieli and Gudmundsson (2004) this approximation is justified even for relatively high length to

thickness ratios such as occurring for rockglaciers. For this 2-dimensional case along a centre flowline the vertical strain rate $\dot{\varepsilon}_{xz}$ is directly related to the shear stress τ_{xz} through

$$\dot{\varepsilon}_{xz} = A \cdot \tau_{xz}{}^{n} \tag{2}$$

5

where x is the horizontal coordinate along the centre flowline and z the vertical coordinate. The shear stress τ_{xz} ~~at the base~~ is then given by the local surface slope $\frac{\partial s}{\partial x}$ and ~~material thickness~~ice depth d_z~~h~~

$$\tau_{\cancel{d}xz} = \rho_r g \frac{\partial s}{\partial x} \cancel{h} d_z$$

10   (3)

where ~~ρ_r is the ρ_r density of the rockglacier material and~~ $\frac{\partial s}{\partial x}$ is the surface slope.

Integration of Eq. 2 over the rockglacier thickness results in a surface flow speed u_s from deformation of the rockglacier material of

15

$$u_s = \frac{2A}{n+1} \left(\rho_r g \frac{\partial s}{\partial x} \right)^{n} h^{n+1} \tag{4}$$

and accordingly a ~~vertically~~ depth averaged horizontal flow speed $\bar{u}$ of

20
$$\bar{u} = \frac{2A}{n+2} \cdot \left(\rho g \frac{\partial s}{\partial x} \right)^{n} h^{n+1} \tag{5}.$$

Although this equation is in its form identical to the case of glacier ice (Cuffey and Paterson, 2010), for rock glaciers the flow exponent n and the rate factor A (referring to the material softness) are, due to the presence of debris and water within the ice, not necessarily the same (Moore, 201~~4~~6) and may in reality thereby also vary with depth.~~.~~ From boreholes and
25   laboratory experiment flow law exponents of rockglaciers have been found between n=1.9 and 4.5 (mean n=2.72) and increase linearly with volumetric ice content c_{ice} of the sediment (Arenson and Springman, 2005). For our relatively high ice contents (60%) a value of n=3 equivalent to the case of ice seems justified and has been used in earlier studies of Leysinger Vieli and Gudmundsson (2003) and Frauenfelder et al. (2008).

The rate factor A is estimated from observed surface flow speeds by inverting Eq. (3) for A but is known to be influenced by
30   the material temperature but also by other factors such as the moisture and debris content (Cuffey and Peterson, 2010). Moisture content is known to vary with time and temperature (Moore, 2014 and Monnier and Kinnard, 2016) but we do not explicitly include this in our model as such changes are poorly constrained. The temperature related effect from moisture is

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however implicitly included by writing ~~Thus, for the purpose of our temperature forcing experiments and in agreement with known rheological investigations (Paterson and Budd, 1982, Arenson and Springman, 2005) we write~~ the rate factor of the rockglacier material as a product of the temperature dependent part $A^*(T)$ and a scaling factor f_A accounting for the influence of the debris:

5

$$A = A^*(T) \cdot f_A \qquad (6)$$

This approach is in agreement with known rheological investigations (Paterson and Budd, 1982, Arenson and Springman, 2005) and allows including a temperature forcing in our modelling experiments. For the temperature dependent part we use
10 two approaches. Firstly, as done in Kääb et al. (2007) we use the dependence on the temperature of pure ice, for which $A^*(T)$ increases exponentially with temperature (see Figure 4~~Figure 4~~; Paterson and Budd, 1982).

Secondly, and probably more realistic for rockglaciers, we follow the description based on shearing experiments of frozen debris material of Arenson (2005) which is given by

15
$$A^*(T) \propto \frac{2}{T+1} \qquad (7)$$

for temperatures between -1 and -4°C. Note that this second version is at warm temperatures above -2°C, as expected for our two cases, more sensitive to temperature warming (Figure 4~~Figure 4~~). For both approaches the temperature dependence is applied at a reference temperature which refers approximately to the real mean annual temperature within the rockglacier
20 body.

➜ Insert Figure 4

Thickness evolution

25 The evolution of rockglacier thickness h and rockglacier surface elevation s along the central flowline is calculated from the principle of mass conservation which takes for the 1-dimensional representation the following form (Oerlemans, 2001)

$$\frac{\partial h}{\partial t} = a_r - \frac{1}{w} \cdot \frac{\partial \bar{u} h w}{\partial x} \qquad (8)$$

30 where t is the time, a_r is the rate of rockglacier material accumulation or removal at the surface (>0 for accumulation; in ma^{-1}), w the rockglacier width and $\bar{u}$ the horizontal and vertically averaged flow speed. The geometry of the rockglacier bed transverse to flow is accounted for by assuming a parabolic shaped valley that is prescribed and here assumed to be uniform

along the flow. This allows the width of the rock glacier to vary with changing thickness, but the effect of side drag is not explicitly included, but implicitly is contained in the scaling factor f_A of the rate factor.

The evolution of the rockglacier thickness and surface is calculated numerically on a regular grid with 10 m spacing along the centre flowline. Using a standard implicit finite-difference scheme (Oerlemans, 2001) the surface evolution equation (8) is solved at each time step and for all grid points from the depth averaged material flux $\bar{q} = \bar{u} \cdot h \cdot w$ and the material input a_r at the rockglacier surface.

4.3 Model input and calibration

Model geometry

Approximate bedrock topographies are derived for both rockglaciers from the DEMs and geomorphic mapping (Sect. 4.1) and assumes the bedrock to be roughly parallel to the rockglacier surface. The shapes of the rockglacier beds are approximated to two sections of constant slope that are representative of the two respective rockglaciers. For both rockglaciers we mapped the first 150 m of the distance along flow as deposition area and apply there a spatially uniform material accumulation rate at the specified sedimentation rate and ice content whereas further downstream no mass is added or lost at the surface. In the talus slope, where the material is accumulated, we use a slope of 37° (which is slightly below the angle of repose for unconsolidated talus slope material (Carson, 1977)~~critical angle of talus slopes~~) and which is steeper than on the rockglacier part (12° for Murtèl and 27° for Huhh1, see Tab. 4). The respective dimensions and slopes for the two rockglaciers are presented in detail in Tab. 1 and visualized in Fig. 5.

Material input

The rockglacier material input rate a_r at the surface is assumed to be positive and uniform on the talus slope and, if not mentioned otherwise, set to zero on the surface of the main rockglacier body. The latter means that in general no sediment or ice is lost or gained at the surface of the main rockglacier. The rockglacier material input at the surface is estimated from the sediment input from the headwall to the talus slope and its respective ice content, which is assumed to be constant in time. The total amount of sediment produced at the headwall is calculated from backweathering rate and headwall area, and is distributed equally over the deposition area (talus slope/accumulation area). Based on in situ measurements (Müller et al., 2014a) and previous studies (Glade, 2005, Krautblatter, 2012), a backweathering rate of 2 ~~mma~~mm a^{-1} is used, resulting in an annual sediment input over the entire talus slope of 0.006 m^{3}m^{-2} for ~~Murtel~~Murtèl and 0.022 m^{3}m^{-2} for Huhh1. Together with the ice content of the material the accumulation rate of rockglacier material (sediment-ice mixture) is then calculated

$$a_r = \frac{a_s}{(1 - c_i)} \tag{9}$$

11

Based on field studies (Hoelzle et al. 2002) and previous approaches (Gaertner-Roer, 2012) we use an estimated ice content c_i of 60% for both rockglaciers which results in a rockglacier material input rate that is 2.5 times higher than the pure sediment input rate.

Rockglacier density

We estimate the density of the rockglacier material ρ_r from the percentage ice content c_i and from the respective densities of ice $\rho_i = 910$ kg m^{-3} and the debris material $\rho_d = 2700$ kg m^{-3} which we assume to stay constant in space and time

$$\rho_r = (1 - c_i) \cdot \rho_d - c_i \cdot \rho_i \tag{10}$$

Estimating the rate factor A

Solving the equation describing surface ice flow from creep of a viscous material (Eq. 4) for the rate factor *A*, we obtain

$$A = A^*(T) \cdot f_A = \frac{(n+1)u_s}{2h^n \tau_d} = \frac{(n+1)u_s}{2h^{n+1}\rho_r g \frac{\partial s}{\partial x}} \tag{11}$$

Using observed surface flow speed data (u_s) we can then estimate the corresponding rate factor *A* (respective f_A for a given reference temperature and temperature dependence model) for both rockglaciers. These rate factor values are both substantially lower than the values known for pure ice at similar temperatures (Paterson and Budd, 1982; -1.5^{o}C) which probably reflects enhanced mechanical resistance from the sediment within the ice (Arenson and Springman, 2005).

5   Model experiments

The model is applied to the two selected rockglacier systems using the landform specific input parameters in Table 3 and the simplified geometries described in Sect. 4.

→   Insert Table 3

5.1   Rock glacier build up

The build up experiment is documented for Murtèl in Fig. 6 (first 6000 a) and is qualitatively very similar for Huhh1 (shown in Supplementary Fig. S1~~43~~ to S2~~5~~4). The model starts with an 'empty' topography of bedrock (bedrock topographies in Fig. 5). Initially, it builds up a homogenous sediment-ice body in the talus slope which starts to creep and therefore advances once ~~it reaches a~~it is thick enough and the ~~critical thickness and~~ shear stress high enough, which occurs roughly after 600 a

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for Murtèl and 150 a for Huhh1. A rockglacier body is then generated to a characteristic thickness while the front keeps advancing at a roughly constant rate. This continuing advance is a direct result of constantly adding mass at the top while no mass is remobved through melting. Further, the growth and geometry change of the rockglacier landform mainly occurs through moving the rockglacier forward at the front. The modeled advance rate is slightly below the surface speed of the main rockglacier body. After a run time of 6000 a for the Murtèl rockglacier and 600 a for Huhh1 which correspond to the ages of the landforms estimated earlier, we obtain geometries (lengths and thicknesses) that are very close to ones currently observed (Fig. 5 and Tab. 4). The actual furrow-ridge structure of the landform cannot be replicated (Fig. 5) due to model design but the overall geometry is well reproduced.

The modeled surface velocities on the main rockglacier lobes range between 0.06 ~~ma~~ m a $^{-1}$ and 0.09 ~~ma~~ m a $^{-1}$ for Murtèl and between 0.63 ~~ma~~ m a $^{-1}$ and 0.79 ~~ma~~ m a $^{-1}$ at Huhh1 which is in good agreement with the observed values from long term kinematic monitoring (see Tab. 1).

➔ Insert Table 4

Note that the bedrock topography of the talus slope and rockglacier are assumed to be of constant inclination. We defined the first 150 m of slope as an idealized talus slope with an inclination of 37° which we assumed to be the angle of repose for such unsorted and unconsolidated blocky material (Carson, 1977). The general inclination of the bedrock topography (see Table 1) underneath the rockglacier are derived from digital elevation models where we assume the bedrock to be parallel to the rockglacier surface (see Table 1). Figure 5 depicts the observed rockglacier front shapes and positions slightly differently from the modeled ones as the real bedrock geometries of the rockglaciers are more complex than the assumed uniform mountain slopes. Also the idealized talus slopes differ from the observed geometries due to above mentioned simplification.

➔ Insert Figure 5

5.2 Perturbation modeling experiments

Starting with the rockglacier geometries from the build-up experiments (see Sect. 5.1), we investigate the impact of variations in temperature and material input on rockglacier dynamics. In a first phase we perform two distinctly different perturbation experiments in which we increase the temperature of the rockglacier body by 1°C (Sect. 5.2.1) and in a second independent experiment we completely switch off the material supply to the talus slope (Sect. 5.2.2). In a second step, we then combine these perturbations in temperature and sediment supply.

Atmospheric warming is expected to influence both rockglacier temperatures and consequently creep, as well as the production of sediment and incorporation of subsurface ice, but quantification of the latter is highly uncertain (Gruber, 2004,

Fischer et al., 2010, Ravanel and Deline, 2011, Schneider et al., 2012). We therefore run varying scenarios for the sediment and ice input with the zero sediment supply being at the extreme end of the spectrum.

For the temperature experiments the chosen step temperature increase of 1°C in the rockglacier depicts a potential warming scenario which roughly refers to a 2°C warming in ground surface temperature (GST) for a fixed position at the permafrost base. The 1°C subsurface warming is also consistent with current and expected future subsurface warming trends based on borehole observations (PERMOS, 2013) and modelling results in the next 50 a in the Swiss Alps (Marmy et al., 2015) (PERMOS, 2013).

→ Insert Table 5

Assuming relatively warm reference rockglacier temperatures between -1 and -2°C°, as observed in the European Alps, the Arenson and Springman (2005) temperature dependence gives an increase of the rate factor by a factor of 1.4 to 2.7 (Tab. 5) for a 1°C warming. The Paterson and Budd (1982) temperature relation, however shows almost no dependence on rockglacier temperature and increases only by factor 1.25 with a 1°C temperature increase. If not indicated otherwise, we therefore use the Arenson and Springman (2005) relation in the temperature warming experiments.

The results for the simple temperature and sediment experiments are presented in the following section only for Murtèl rockglacier but the results are qualitatively similar (although of higher absolute magnitude) for the Huhh1 rockglacier. The more complex and realistic experiments combining variations in temperature and sediment supply are presented for both rockglaciers later in Sect. 5.2.3.

5.2.1   Temperature experiment

In a first experiment, a step temperature increase of the entire rockglacier body of 1°C is applied after rockglacier build-up (at 6000 a), while the sediment supply is held constant. The reference temperature of the rockglacier is set at -1.5°C which results in a rate factor increase by a factor 1.7.

Figure 6 shows the modeled response of the surface geometry, landform thickness and horizontal surface velocity of the Murtèl rockglacier along the central flowline. For reference, the black line in Fig. 6 shows the state of the rockglacier just after build-up (6000 a), immediately before the temperature step change is introduced. The increase in the rate factor causes an immediate speed-up in horizontal flow of the entire landform by a factor of about two roughly (Fig. 6c, yellow lines), which then decays with time (orange to red lines). As a result of the enhanced mass transport, the landform also shows a distinct thinning of up to 0.02 ma m a^{-1} in the upper part of the rockglacier and on the talus slope (Fig. 6b). At the front the rockglacier continues to thicken and consequently advance, but at accelerated rates as a consequence of enhanced flow speeds (Fig. 6d). With time, both the creep velocity, advance rate and thinning reduce and approach stable values again after about 1000 a for Murtèl. We term in the following the time it takes for this readjustment as 'adjustment time'. This new state

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is, apart from the advancing front, stable and characterised by a slightly faster creep velocity and a thinner rockglacier body in order to transport the constant material supply from upstream. Consistent with the creep velocity, the advance rate is also slightly enhanced (Fig. 6d) whereas the volume grows at a constant rate throughout the simulation, reflecting again the constant material supply and mass conservation (Fig. 6e).

5

Additional model simulations for other reference temperatures of the rockglacier of -1°C and -2°C, show qualitatively very similar results but the absolute rates of change scale proportionally to the enhancement factors in the rate factor given in Tab. 5. The same experiments for the Huhh1 rockglacier show quantitatively similar responses which are of higher absolute magnitude and adjust within 100 a to a new quasi stable state also much faster.

10

➔ Insert Figure 6

5.2.2 Sediment experiment

In a second set of experiments, the influence of variations in sediment and ice supply is investigated by varying the material

15 input a_r but keeping the rockglacier temperature constant. Since there is no empirical data on the impact of temperature increase on sedimentation and ice accumulation rates, a range of changes in material supply rates has been explored.

➔ Insert Figure 7

20 Figure 7 shows the modeled response for an extreme example in which the ice and sediment input is completely switched-off after rockglacier build-up (at 6000 a). The results show that the rockglacier continues to creep downslope and advance but with reduced velocities that start to decrease from upstream. This slow-down is related to a thinning, reduced slope and driving stresses in the upper part of the rockglacier as the downstream flowing mass is no longer fully replaced by accumulation of material on the talus slope. The rockglacier body essentially creeps downstream without any mass added or

25 removed which is well reflected in the constant volume with time (dotted line in Fig. 7e). The advance rates thereby decrease at relatively low rates. The upper parts of the rockglacier react immediately to the change of material input as this is where the sedimentation is taking place. Note that the maximal thinning rates are only as high as the former material accumulation rate (in case of Murtèl 0.006 ~~ma~~ m a $^{-1}$, for Huhh1 0.022 ~~ma~~ m a $^{-1}$).

Experiments with different perturbations in material input rates show qualitatively similar changes but of reduced magnitude

30 (supplement Fig. S2~~1~~ to S13~~2~~) and are also evident in differing advance and volume growth rates (Fig. 7d and e).

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5.2.3 Combined experiment

As atmospheric warming is expected to influence both rockglacier temperatures as well as ice and sediment production, we thus perform a third set of experiments in which we combine the above perturbations.

12 scenarios were run for each rockglacier assuming three different initial thermal states of each rockglacier (see Tab. 5), a potential warming of 1°C and four different scenarios concerning the material input (see Tab. 6). The corresponding results are shown in the supplementary material.

➔ Insert Table 6

In Fig. 8 and 9 we show detailed results for both Murtèl and Huhh1 rockglacier for one representative perturbation experiment in which we used a reference rockglacier temperature of -1.5°C, an increase in temperature of 1°C (corresponding to a rate factor increase by factor 1.7, Tab. 5) and a decrease of material input to 40% of the original value. We assume that warming and subsequent thawing of permafrost in rockwalls will lead on the short-term to an increase in sediment production but is expected to extenuate on the long-term (Krautblatter et al., 2013). Therefore we keep the material input from the rockwall constant but reduce the overall material influx by the amount of ice.

➔ Insert Figure 8

Figure 8 and 9 illustrate the evolution of surface geometry and horizontal velocities along the central flow line of Murtèl and Huhh1 rockglacier, respectively. This combined experiment shows an upstream thinning of the "initial" landform in the subsequent years (Fig. 8a and 9a) and a substantial increase in horizontal velocities (Fig. 8b and 9b). The maximum thinning rates occur within the first few decades of the experiment and amount to 1.6 cm a^{-1} for Murtèl and 6 cm a^{-1} for Huhh1 (see Fig. 11). A new stable geometry with advancing front is successively approached, again within adjustment times of roughly 1000 a and 100 a for Murtèl and Huhh1, respectively. The final thickness and velocities of the main rockglacier body are, however, very close to the initial values.

Figure 10 shows the more detailed temporal evolution of geometry and creep velocity at three distinct positions on both rockglaciers. The rockglaciers keep advancing throughout the simulation, with initially slightly enhanced rates caused by the temperature increase and a successive slight slowing down caused by the reduced material accumulation rates. The adjustment time~~ss scales~~ of Murtèl rockglacier are much lower compared to Huhh1, which was also shown by the simple perturbation experiments.

➔ Insert Figure 9

➔ Insert Figure 10

The additional combined experiments with a 1°C temperature increase but variable reference temperatures and varying sediment supply rates show qualitatively similar geometric and kinematic responses (see Supplementary Figure S1-S24).

Subsidence

The sensitivity of the dynamic response to the initial temperature and to the temperature dependent model has been further analysed for the combined perturbation (1°C warming, 60% reduction in material input) in a sensitivity modeling study (for detailed results see Supplement). As subsidence is one of the observable quantities from repeated DEM-analysis on real rockglaciers, we summarized the results in terms of maximum thinning rates in Fig. 11.

For the Paterson and Budd (1982) temperature relation, thinning rates are almost independent of the reference rockglacier temperature, but increase with a reduction in material supply and reach maximum thinning rates of 1.8 cma^{-1} and 6.5 cma^{-1} for Murtèl and Huhh1, respectively. When using the Arenson and Springman (2005) temperature model, thinning rates strongly increase towards warmer rockglacier reference temperatures, reaching maximum values of 3.4 cma^{-1} and 12.5 cma^{-1} for Murtèl and Huhh1, respectively.

➔ Insert Figure 11

6   Discussion

6.1   Modeling approach and rockglacier build-up

Based on a continuum approach, our numerical model couples observed sediment input rates and the rockglacier creep process in order to simulate the evolution of creep velocities and surface geometry as well as their dynamic interactions. This quantitative approach of coupling the relevant subsystems (headwall, deposition area and rockglacier), although highly simplified, was successful in building-up the observed rockglacier geometries and related kinematics (horizontal velocities) within the expected timescales (Tab. 1). The basic dynamic behaviour of a continuously advancing rockglacier body is well reproduced, while the thickness of the main body remains roughly constant.

The modeling of rockglacier build-up shows that besides topographical factors such as slope, the long-term advance rates and horizontal velocity are predominantly controlled by the rates of material accumulation and rockglacier rheology, whereas the thickness of the main landform seems less sensitive to material supply rates.

The match of observed to modeled velocities and thicknesses should, by model construction, be expected (for similar surface slopes) given that the rate factor A and therefore the viscosity of the rockglacier material has been derived from such observed quantities (Eq. 11), but the agreement supports our modeling approach. More importantly, the material input rates

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and build-up times are fully independent estimates and it is therefore not necessarily obvious to get the right rockglacier geometry at the prescribed time.

Our modeled constant advance rates and consistency between modeled and previously estimated rockglacier build-up times further supports the method of back-calculating rockglacier age from current surface velocities (Frauenfelder and Kääb, 2000, Kääb ~~und~~ and Vollmer, 2000, Haeberli et al., 2003). Even for the case of temperature perturbations, advance rates of the front do not substantially change in the long-term and thus this 'dating' methods seem still appropriate for alpine rockglaciers. Advance rates are in the long-term however affected by changes in material supply rates. It remains to note that it is actually the vertically averaged velocity, and not the surface velocity, that should match the advance rates. Our modeled advance rates (derived from an assumed rheology with n=3 in Eq. (5)) corresponds in general to 4/5 of the surface velocity (e.g. modeled surface velocity on the main body of 0.065 ~~ma~~ m a $^{-1}$ and an advance rate of 0,054 ~~ma~~ m a $^{-1}$ for ~~Murtel~~Murtèl rockglacier). Consequently, using surface velocities in back-calculations of rockglacier age may overestimate the age. For many real-world rockglaciers (including Murtèl), rockglacier movement is dominated by deformation in a shear zone near the base and thus surface and vertically averaged creep are almost identical.

Strong simplifications have been made for our modeling approach such as using a homogenous sediment-ice body of uniform temperature and rheology and a spatially uniform and temporally constant material input. The successful rockglacier build-up therefore supports the idea that despite such simplifications rockglacier dynamics and evolution can be reduced to our simple model approach which is based on the historic concept of Wahrhaftig and Cox (1959) and confirms earlier numerical modeling approaches of Olyphant (1983) and Frauenfelder et al. (2008).

The non-linear viscous Glen-type flow-law used here is also supported by laboratory experiments (Arenson and Springman, 2005) and field observations from boreholes (Arenson et al., 2002). However, in reality the involved flow law parameters are, unlike the assumptions of our model, rarely constant in space and time. The flow-law exponent n has been found to increase with ice content (Arenson et al., 2002, Arenson and Springman, 2005) and relatively thin shear layers with strongly reduced viscosity often dominate rockglacier creep (Hoelzle et al., 2002, Haeberli et al., 2006, Buchli et al., 2013). A more complex rheology of ice-debris mixtures ~~rheology~~ could in theory and should in the future be included in rockglacier creep models, but currently there is very limited quantitative, field-based information available to constrain more complex constitutive relationships. Especially the role of unfrozen water appears to have a strong impact on the properties ice-debris mixtures as temperature nears the melting point and need to be further addressed (Moore, 2014) in establshing an adapted flow-law for rockglaciers. Due to the fact that the creep is also dominated near the base within our model and that we have calibrated our model parameters to observed geometry and velocities, we do not expect the general dynamical behaviour and involved time-scales to be substantially different for other rheological parameters choices. We see our highly reduced approach also as an advantage for identifying the most essential controls and processes in rockglacier evolution.

In our approach the geomorphological mapping of the different subsystems, the quantification of sediment input rates, the ice content and the horizontal velocities are the crucial observational constraints and sufficient to set up a model of

rockglacier evolution. However, the simplicity of the model design does not, by construction, allow reproduction of the exact small scale features such as ridges and furrows of the two chosen real-world rockglaciers (Frehner et al., 2015).

6.2 Dynamical adjustment to external forcing

The perturbation modeling experiments of applying a sudden change in sediment input, material temperature or a combination of the two provide useful insights into the dynamic and geometric adjustment of rockglaciers to changes in external forcing and therefore also into potential mechanisms that explain observed rockglacier degradation.

The two types of perturbation experiments show similarities but also clear differences in the dynamic response. Both, an increase in the rockglacier temperature as well as a reduction in material input lead to a thinning of the rockglacier and the talus slope whereas the front keeps advancing through thickening. Although the thinning is caused by different mechanisms (lack of material supply from the rockwall or a runaway of mass through creep acceleration), from an observational point of view the two forcing mechanisms are difficult to distinguish. Importantly, the modeling shows a pronounced thinning occurring in the upper parts of both rockglacier systems (deposition area/talus slope).

The response ~~of~~ in horizontal velocities are, for the two types of perturbations, distinctly different. A reduction in material supply results in a decrease of creep velocities from the top, whereas the temperature increase leads to an immediate acceleration of the entire landform, although in the long-term the velocities return to almost pre-perturbation conditions (see Fig. 6c and 7c). The temperature experiments show a brief increase in the advance rates ~~of~~ in the rockglaciers, ~~which also~~but subsequently~~-~~ return to similar rates as before the perturbation. This occurs in contrast with a continuous reduction of the advance rate ~~at~~ during the decreased sediment supply experiment. Therefore, temperature changes within the rockglacier show a strong impact on short term velocity variations whereas changes in the material input determine the long term advance rates and geometry. Similar experiments by Olyphant (1983) and Frauenfelder et al. (2008) focused only on combined experiments and could therefore not address the impact of the individual forcings.

6.2.1 Dependence on rockglacier properties

Irrespective of the type of experiments, the absolute magnitude in response (velocity change, thickness change or advance rate) is very different for the two rockglaciers ~~very different~~. ~~R~~Relative to the initial quantities however (pre-perturbation velocity, thickness or advance rates), the dynamic changes are ~~and temporal evolution~~ for both rockglaciers ~~are~~ very similar (Fig. 10). This means that we should expect dynamic changes of rockglaciers to be scalable by their geometric (thickness) and kinematic characteristics (flow speed and advance rate). This scalability is also in good agreement with the observational dataset of multiannual creep variations of rockglaciers in the Swiss Alps (PERMOS, 2013). These show very similar normalized horizontal velocity variations as a potential response to air temperature changes despite their distinctly different characteristics (Delaloye et al., 2010a and PERMOS, 2013). Recent continuous observations of creep velocities on rockglaciers in the Matter Valley in the Swiss Alps confirm this finding even for seasonal timescales (Wirz et al. 2015).

The modeled short-term increase in horizontal velocity for a 1°C warming in rockglacier body is also consistent with the observed speed-up in rockglacier creep of about 300% in the year 2003/2004 with exceptional snow conditions and a very warm summer (Delaloye 2010a).

6.2.2 Temperature dependence

Our temperature perturbation experiments assume an immediate warming of the entire rockglacier due to an increase in air temperature and consequently GST. This is, of course, an over-simplification because the vertical heat transfer depends on the energy balance at the surface and heat transport processes and thermal properties ~~within~~of the rockglacier material (Hanson and Hoelzle, 2004). Heat transfer processes should potentially be implemented in future studies (Kääb et al 2007, Scherler et al., 2014). Hence we consider our modeled warming rather as a simple way to investigate the sensitivity to temperature increase.

For relatively thin rockglaciers such as Huhh1, a climatic warming could affect the whole rockglacier thickness in time scales of a few years to decades (Marmy et al., 2015). For thicker rockglaciers such as Murtèl, it could take several decades to centuries for the temperature change to reach the base where most of the deformation actually occurs. This implies that thin, and consequently steep and fast rockglaciers should be more sensitive to warming from the surface.

The sensitivity to temperature warming is also enhanced for relatively warm rockglaciers (with temperatures only a few degrees below freezing), considering the most realistic model for temperature dependence of rockglacier rheology by Arenson and Springman (2005). At -1.0°C rockglacier temperature, a warming of 1°C results in a 2.7 times increase in the rate factor (and hence creep velocity) whereas the same warming at -2°C results only in a 1.4 times higher rate factor. Observed rockglacier temperatures in the Swiss Alps indicate already relatively 'warm' temperatures (close to zero degrees) and show a tendency for further warming (PERMOS, 2013). Such a warming would further amplify the response in acceleration. In contrast, when using a temperature dependence of pure ice (Paterson and Budd, 1982), as done in an earlier attempt of modeling the impact of temperature change on rockglacier creep (Kääb et al., 2007), the sensitivity of creep to temperature warming is smaller (a 1°C warming results in only a 1.25 times increase in rate factor) and does not additionally increase towards warmer rockglacier temperatures (Fig. 4). Thus, the impact of warming on creep acceleration could be bigger than previously expected.

6.2.3 Adjustment timescales

The modeling shows that the *adjustment times* in thickness and advance rates are for the faster and steeper Huhh1 rockglacier with ~~about~~ 100 a, an a *adjustment times* ~~of thickness and advance rates (Fig. 6d and 7d) that are an~~ order of magnitude faster than the 1000 a of Murtèl rockglacier (Fig. 6d and 7d). While in the literature such differences in adjustment timescales have qualitatively been linked to the general rheology and mass turnover, the controlling factors remain ~~rather~~ unquantified. A comparison to theoretical considerations based on the kinematic wave theory developed by

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Nye (1963) can be made ~~regarding~~ for the ~~sediment~~ material supply experiment. Besides the change in material supply rate, the thickness adjustment depends mainly on the travelling wave speed of the thickness perturbation and on its diffusion. According to Nye (1963; and see also Hooke 2005, p. 371-381) t~~T~~he travelling wave speed v_0 ~~of thickness changes~~ is ~~thereby~~ given by a multiple of the the rock glacier flow speed and specifically

$$v_0 = (n+2) \cdot u_s \tag{11}$$

The diffusion of the thickness perturbation is proportional to the diffusivity which is given by

$$D_0 = \frac{n \cdot q}{\alpha} = \frac{n \cdot \bar{u} h}{\alpha} \tag{12}$$

where q is the ice flux and α the surface slope. For Murtèl and Huhh1 this results in diffusivities of 30 m^{2}a^{-1} and 53 m^{2}a^{-1}, which are as a result of very small creep velocities and low thicknesses much lower compared to diffusivities of pure-ice glaciers.

Following Johannesson et al. (1989; see also Hooke, 2005~~10~~, p. 376) the related 'adjustment time-scales' of thickness changes to expand over the whole rock glacier lobe then depend on a propagation time-scale T_p and a diffusion time-scale T_d. The propagation time-scale is given by

~~which results in a typical adjustment timescale of this thickness change to reach the terminus of~~

$$T_{p\mathbf{k}} = \frac{L_0}{v_0} = \frac{L_0}{(n+2) \cdot u_s} \tag{1\underline{3}\sout{2}}$$

where L_0 is the length-scale of the rockglacier lobe. ~~Thus, the~~This timescale is inversely proportional to the horizontal velocity and consistent with our modeling results ~~means that~~means, that a factor 10 difference in creep velocity between Huhh1 and Murtèl rockglacier translates into a factor 10 difference in adjustment time. For n=3, lengths of 300 m and 250 m and creep velocities of 0.07 ~~ma~~ m a^{-1} and 0.6 ~~ma~~ m a^{-1} for Murtèl and Huhh1, we obtain adjustment timescales of 860 a and 83 a respectively. These theoretical values agree in absolute and relative magnitude well with our modeled estimates. ~~This implies that the kinematic wave speed, obtained from observed horizontal velocity, is a simple and meaningful measure for rockglacier adjustment times.~~

~~Based on the same theory (Nye, 1963), the~~The diffusion timescale is given by ~~of the thickness perturbation is proportional to the diffusivity which is given by~~

$$D_0 = \frac{n \cdot q}{\alpha} = \frac{n \cdot \bar{u} h}{\alpha} \tag{13}$$

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$$T_d = \frac{{L_0}^2}{D_0}. \tag{14}$$

~~This~~ which results in 3000 a and 1200 for Murtèl and Huhh1, respectively a, for the thickness perturbation to spread over the ~~whole~~ entire landform ~~for Murtèl and Huhh1, respectively, which~~ and which is substantially longer than the timescales

10 derived above for the kinematic wave propagation. These diffusion timescales are also much longer compared to pure-ice glaciers and are consistent with the persistent occurrence ~~existence~~ of ~~the characteristic~~ morphological features of ridges and furrows on the surface of rockglaciers.

~~This implies that~~To conclude, the ~~kinematic wave speed~~propagation timescale, and therefore the, ~~obtained from observed horizontal velocit~~y.~~y~~, is a simple and meaningful measure for rockglacier 'adjustment times'. The very similar adjustment

15 times~~cales~~ obtained for ~~all~~ the different types of perturbation experiments support the notion that ~~the kinematic wave~~this propagation timescale T_{pk} can be used as a general measure of adjustment in creep dynamics to a step change in external forcing. Note that the introduced adjustment timescale ~~is, as a concept, similar to~~is not the same as the 'volume response time' for pure-ice glaciers for adjusting to a new climate (Johannesson, 1989) and should not be confused with a 'reaction time' (time taken for a rockglacier to show a detectable reaction on an external forcing).

20 **6.2.4   Geometry change and subsidence**

Regarding geometry, the modeled rockglaciers respond to both warming and reduction in material input by a thinning of the landform that is fastest and most pronounced in the deposition area and in the upper parts of the rockglacier (Fig. 10). The front and therefore the landform as a whole ~~remains~~ continues to advance~~advancing~~, although at slightly differing speeds depending on the applied perturbations (see Fig. 7b and 10a); even if the material input is completely ~~stopped~~halted. The

25 perturbation experiments can also be compared with the observed subsidence data presented in Sect. 3, in order to investigate the potentially controlling mechanisms of such geometry change. The observations in Fig. 2 and 3 show a pronounced subsidence in the lower deposition area and upper parts of the rockglaciers of roughly -0.05 ~~ma~~ m a⁻¹ for the Murtèl rockglacier and -0.16 ~~ma~~ m a⁻¹ for Huhh1 rockglacier while the lower rockglacier lobe shows relatively small or unchanging thicknesses and an advancing front. Thus, the spatial patterns in modeled geometry changes agree well with the observations.

30 The absolute maximum rates of modeled subsidence are for both rockglaciers between 2 to 10 times smaller than the observed rates depending on the perturbation. These modeled rates result from an immediate warming of 1°C of the entire rockglacier body which is a rather extreme scenario. Further, the possible maximum rates of thinning from a total switch off

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in material input rates are limited to their pre-perturbation absolute values (0.006 ~~ma~~ m a $^{-1}$ for Murtèl and 0.022 ~~ma~~ m a $^{-1}$ for Huhh1), which are also almost an order of magnitude smaller than the observed subsidence rates.

Thus, we conclude that thinning due to thermally induced acceleration and a reduction in material input are not sufficient to explain observed subsidence patterns at Murtèl and Huhh1 rockglacier and that melt of subsurface ice is additionally required for the observed volume loss. The process of landform thinning, especially in the upper parts of the rockglacier, has been described as a sign of degradation by Ikeda and Matsuoka, (2002~~b~~), Roer et al. (2008b) and Springman et al. (2013). However, subsidence through melt of subsurface ice remains poorly constrained through observations and our process understanding and models linking them to external forcing are still limited (Scherler et al., 2014) and therefore we did not include this process in our flow modelling. In future work, internal ice melt (as a function of temperature) could technically easily be included through a negative accumulation term in the surface evolution equation (8) and an adjustment of the mean density.

7   Conclusions

This study uses a numerical flow model based on the conservation of mass within the cascading transport system of coarse debris to simulate the long-term and current evolution of rockglacier surface geometry and velocity. For a given sediment/ice input and rockglacier rheology, the model is able to generate observed rockglacier geometries and creep velocities in realistic timescales for two distinctly different rockglaciers. It is also capable of reproducing the continuing advancing front through creep which is often observed for rockglaciers (Barsch, 1996).

Climatic changes, especially increasing temperatures are expected to influence rockglacier dynamics in a profound way. Our modeling approach allows not only for ~~investigation~~ investigating~~of~~ the impact of a direct warming of the rockglacier material by adjusting the rheology (rate factor) but also for including the influence of changes in material input consisting of sediments and ice. Changes in geometry and related kinematics in response to such external perturbations can thereby be modeled and contribute towards a better understanding of the evolution of rockglaciers. Note that effects of internal ice melt or non-continuous deformations such as the formation of tension cracks are not included in the current version of the model. Our detailed analysis of such perturbation experiments and modeling sensitivity studies give the following insights on rockglacier dynamics:

- Short-term changes in velocities and advance rates result from temperature variations whereas long-term geometric adaptations (thickness and advance rates) are mainly influenced by material supply. We show that a 1°C temperature increase in rockglacier temperature can result in a 1.5-3 time ~~(150%-300%)~~ acceleration of horizontal velocity depending on the initial thermal state of the rockglacier.

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- Both rockglacier temperature increase and reduction in material supply lead to thinning, while for the latter the maximum thinning rates are limited by the pre-perturbation material supply rate.

- Irrespective of the perturbation, the rockglaciers keep advancing and remain active although the thermal and sediment input conditions are not favorable for their ~~sustenance~~ endurance which is consistent with field observations.

- Rockglaciers react spatially and temporally variably to changes in environmental factors.~~Rockglaciers react spatially diverse to changes in environmental factors~~. Changes in temperature affect the entire landform ~~immediately~~ but the impact of material input variations are most pronounced in the sedimentation area and upper parts of the rockglacier. Comparing the model scenarios for localized topographic adaptations (subsidence) introduced by warming and variations in sediment/ice supply to observed subsidence features shows that these controlling factors are not sufficient to explain the magnitudes observed for our two examples. This implies that other processes such as melting of subsurface ice are responsible for subsidence and need further investigation.

- Although the absolute magnitudes in thinning and creep acceleration differ between the two rockglaciers, the changes relative to the initial thickness and creep velocity respectively are very similar thus indicating that changes scale with their geometric and dynamic characteristics.

- Based on most recent models of rockglacier rheology (Arenson and Springman, 2005), rockglaciers close to 0°C likely show much stronger reactions to thermal forcing than colder ones.

- On the basis of our modeling and kinematic wave theory, we propose a typical *timescale of dynamic adjustment* to external perturbations that is given by the inverse of a few times the horizontal velocity of a rockglacier. This timescale explains the order of magnitude difference in dynamic adjustment of our two chosen rockglacier examples which amount to 1000 a for Murtèl and 100 a for Huhh1.

The modeling approach presented here might serve as a useful tool to determine the dynamic state of ~~alpine~~ rockglaciers, their potential state of degradation and related forcing mechanisms. The growing amount of observations on geometric changes and rockglacier movements may thereby serve as important constraints for such model assessments and serve as indicators for the recent changes affecting periglacial high mountain systems. Therefore, future monitoring strategies should specifically be designed to detect spatially heterogeneous geometry changes and aim at observing entire slope systems, ~~instead~~ in addition to~~of~~ focusing on single landforms.

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Tables to "Rockglacier on the move – Understanding rockglacier landform evolution and recent change from numerical flow modeling

Table 1: Characteristics of the two selected rockglaciers (excluding their talus slopes). The data sources are cited in the text.

	Murtèl rockglacier	Huhh1 rockglacier
Average thickness	30 m	12 m
Length	280 m	310 m
Slope	12°	27°
Age	~ 5000- 6000 a	~600 a
Hor. Velocity	0.06 -0.13ma^{-1}	0.75 - 1.55 m a^{-1}

Headwall area	74687.1 m^2	82781.6 m^2
Depositing area	45931 m^2	32356 m^2

Table 2: Airborne and terrestrial remote sensing data available at the rockglacier sites.

Data type	Murtèl	Huhh1
Airborne remote sensing (Photogrammetry and Airborne Laserscanning (ALS))	RC30 in 1996 (PERMOS) RC30 in 2002 (PERMOS) ALS in 2003 RC30 in 2007 (PERMOS)	HRSC-A in 2001 (Otto el al. 2007) RC 30 in 2005 (Roer 2005) ALS in 2007 (Müller et al. 2014a) ADS 40 in 2010 (Müller et al. 2014a) ADS 80 in 2012 (Müller et al. 2014a)
Geodetic Point Surveys	2009-2015 (annually)	2001-2015 (annually)

Table 3: Specific model input parameters for the rockglaciers. The sediment/ice input describes the volume of debris deposited on the accumulation area per year. The rate factor A is derived from Eq. 11 and the runtime of each rockglacier model is selected due to their approximated age (see Sect. 3).

Input Parameter	Murtèl	Huhh1
Material input rate	0.006 m^{3}m^{-2} a^1	0.022 m^{3}m^{-2} a^{-1}
Rate Factor A	4.5*10^{-18} Pa^{-3} a^{-1}	7*10^{-17} Pa^{-3} a^{-1}
Runtime	6000a	600a
Rockglacier Slope	12°	27°

Table 4: Comparison of the observed (obs.) and modeled (mod.) rockglacier thickness and velocity for Murtèl and Huhh1 after 6000 years and 600 years respectively.

	Murtèl obs.	Murtèl mod.	Huhh1 obs.	Huhh1 mod.
Length	280m	300m	310m	240m
Thickness	30m	28m	12m	16m
Horizontal velocity	0.06-0.13 ma^{-1}	0.06-0.09 ma^{-1}	0.75 - 1.55 ma^{-1}	0.63-0.79 ma^{-1}

Table 5: Multiplicative increase in rate factor A from a 1°C rockglacier warming for the different temperature relations of Arenson and Springman (2005) and Paterson and Budd (1982) and varying rockglacier reference temperatures

Rockglacier reference temperature	Change in rate factor A for Arenson and Springman (2005) for a 1°C warming	Change in rate factor A for Paterson (1982) for a 1°C warming
-2°C	1.396*A	1.254*A
-1.5°C	1.705*A	1.253*A
-1°C	2.718*A	1.252*A

Table 6: All combined Experiments. The creep rate change is implemetented by increasing the rate factor A (Eq. 6) and the change in material accumulation by varying the accumulation rate a_r (Eq. 9).

Model run	Creep rate change	Accumulation change
1.4*A and 0*Acc	1.4*A	$0*a_r$
1.4*A and 0.4*Acc	1.4*A	$0.4*a_r$
1.4*A and 1*Acc	1.4*A	$1*a_r$
1.4*A and 2*Acc	1.4*A	$2*a_r$
1.7*A and 0*Acc	1.7*A	$0*a_r$
1.7*A and 0.4*Acc	1.7*A	$0.4*a_r$
1.7*A and 1*Acc	1.7*A	$1*a_r$
1.7*A and 2*Acc	1.7*A	$2*a_r$
2.7*A and 0*Acc	2.7*A	$0*a_r$
2.7*A and 0.4*Acc	2.7*A	$0.4*a_r$
2.7*A and 1*Acc	2.7*A	$1*a_r$
2.7*A and 2*Acc	2.7*A	$2*a_r$
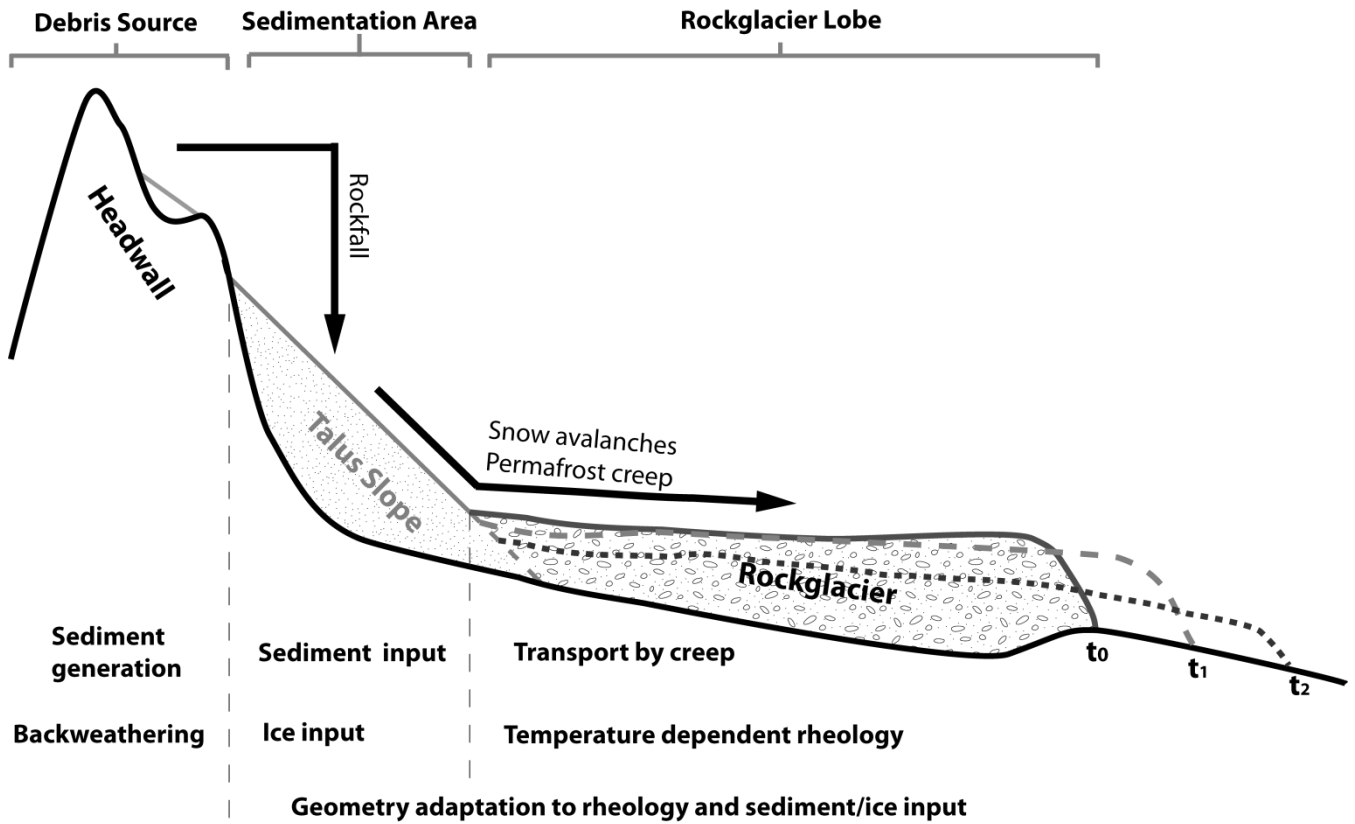
Figure 1: Conceptual model of the dynamic evolution of a rockglacier system (adapted from Fig. 1 in Müller et al., 2014a). Black arrows show the sediment transport. t_0, t_1 and t_2 show the rockglacier surface geometries at different time-steps resulting from variations in environmental factors such as warming and a decrease of sediment/ice input.
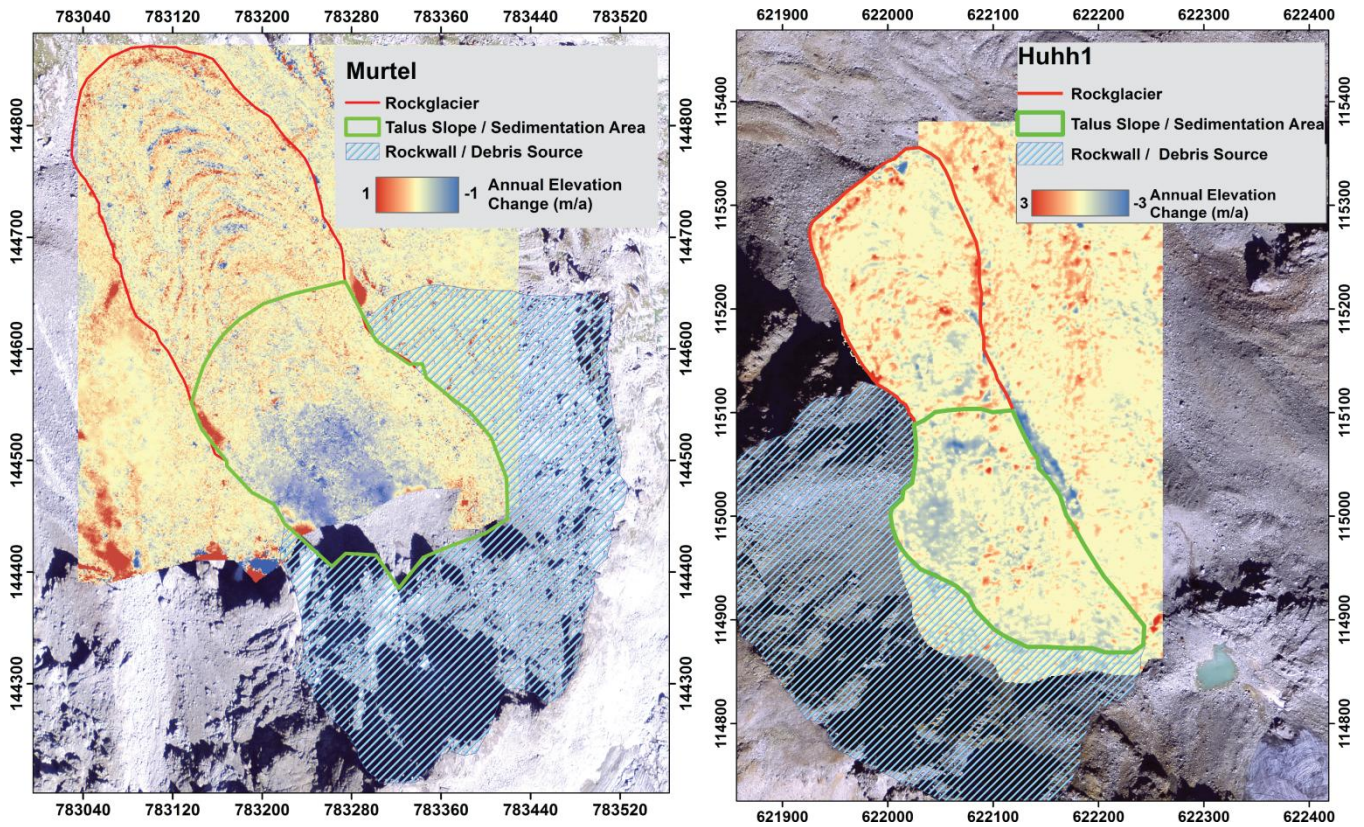
Figure 2: The annual elevation change of the two rockglacier systems for Murtèl (period 1996-2007) and Huhh1 (period 2001-2012). The annual rates are derived from multisensoral and multitemporal remote sensing products (Tab. 2). For a detailed depiction of the structure of the landforms see Supplement Figure S1 where the orthophoto is shown without the elevation change.
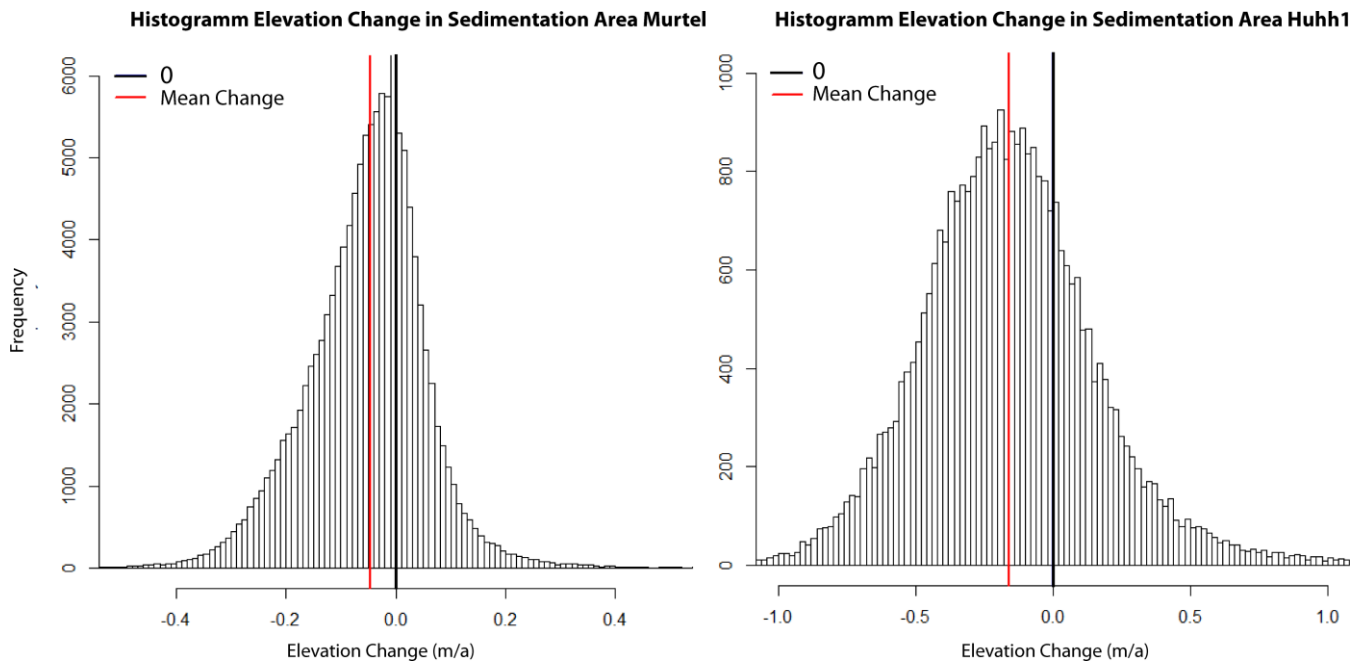
Figure 3: The frequency distribution of annual vertical surface change (ma[-1]) from DEM-differencing in the talus slope/ sedimentation area of the two rockglacier systems. Both systems show negative mean values (red lines). The black line refers to 0 ma[-1] difference.
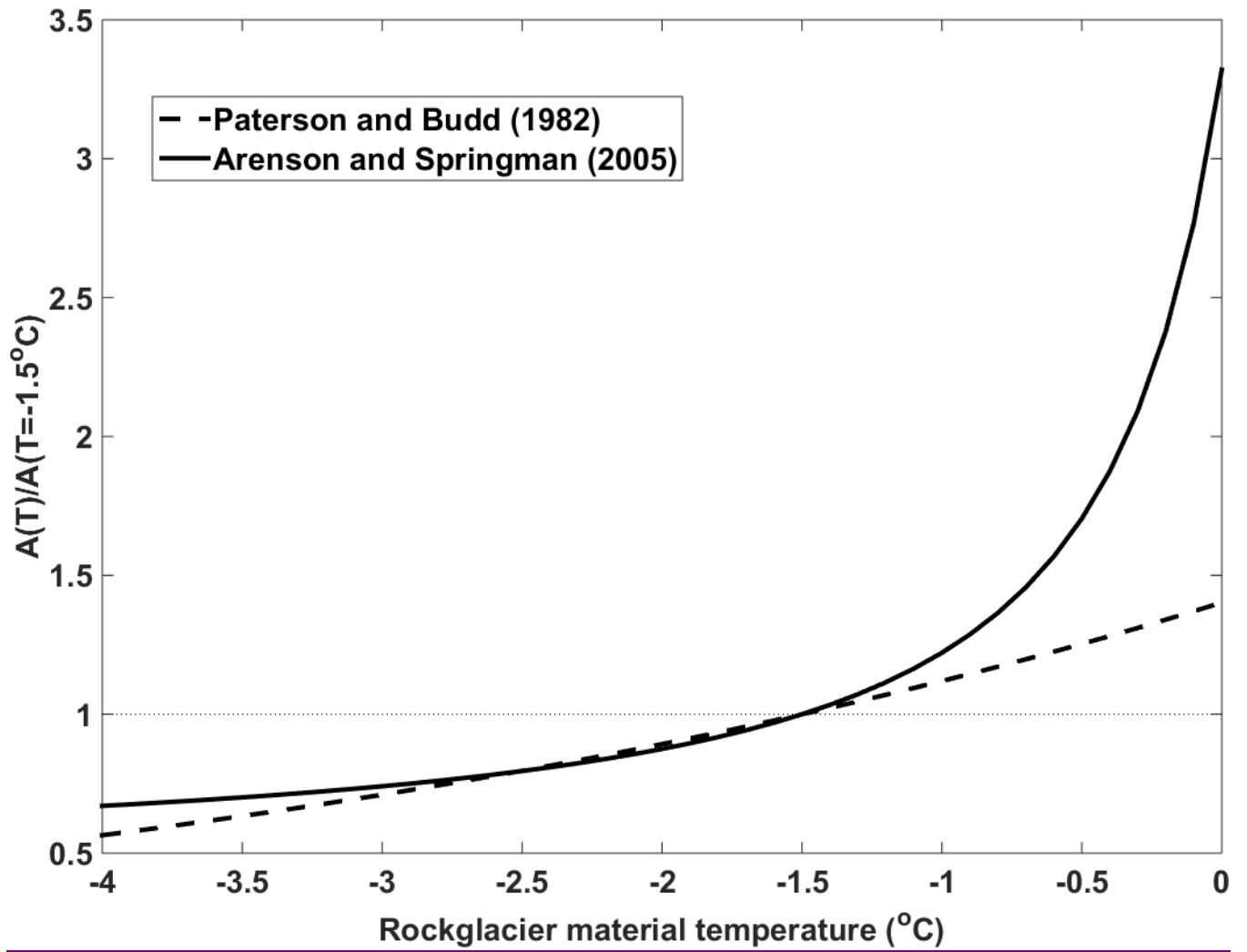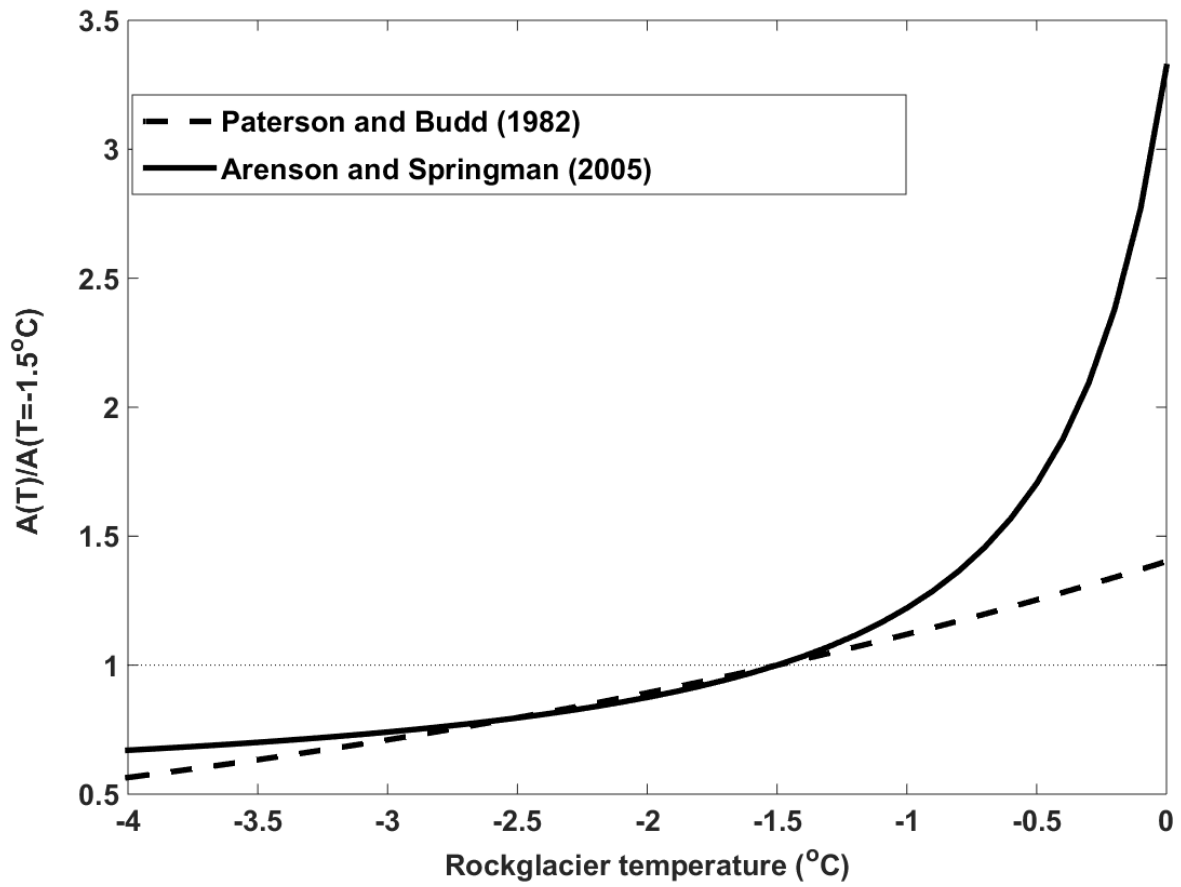
Figure 4: Temperature dependence of the rate factor relative to the rate factor at a reference temperature of -1.5°C as derived for pure ice (Paterson and Budd, 1982) and for rockglacier material (Arenson and Springman 2005).
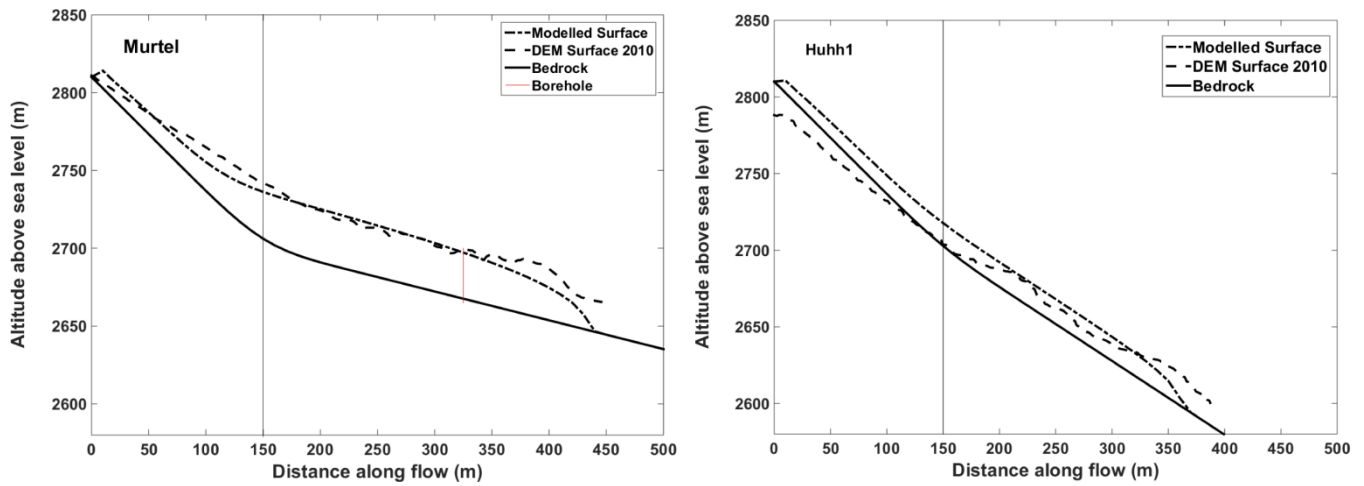
Figure 5: Observed and modeled rockglacier geometry after build-up. The along flow bed topography used in the model and the modeled and observed (from DEMs) rockglacier surfaces are shown. The vertical fine black lines mark the boundary between the deposition area (talus slope) and the main rockglacier lobe. Note that the model cannot replicate the exact geomoetry of the landform due to tis various simplifications but shows good agreement in length and thickness of the rockglacier main body.
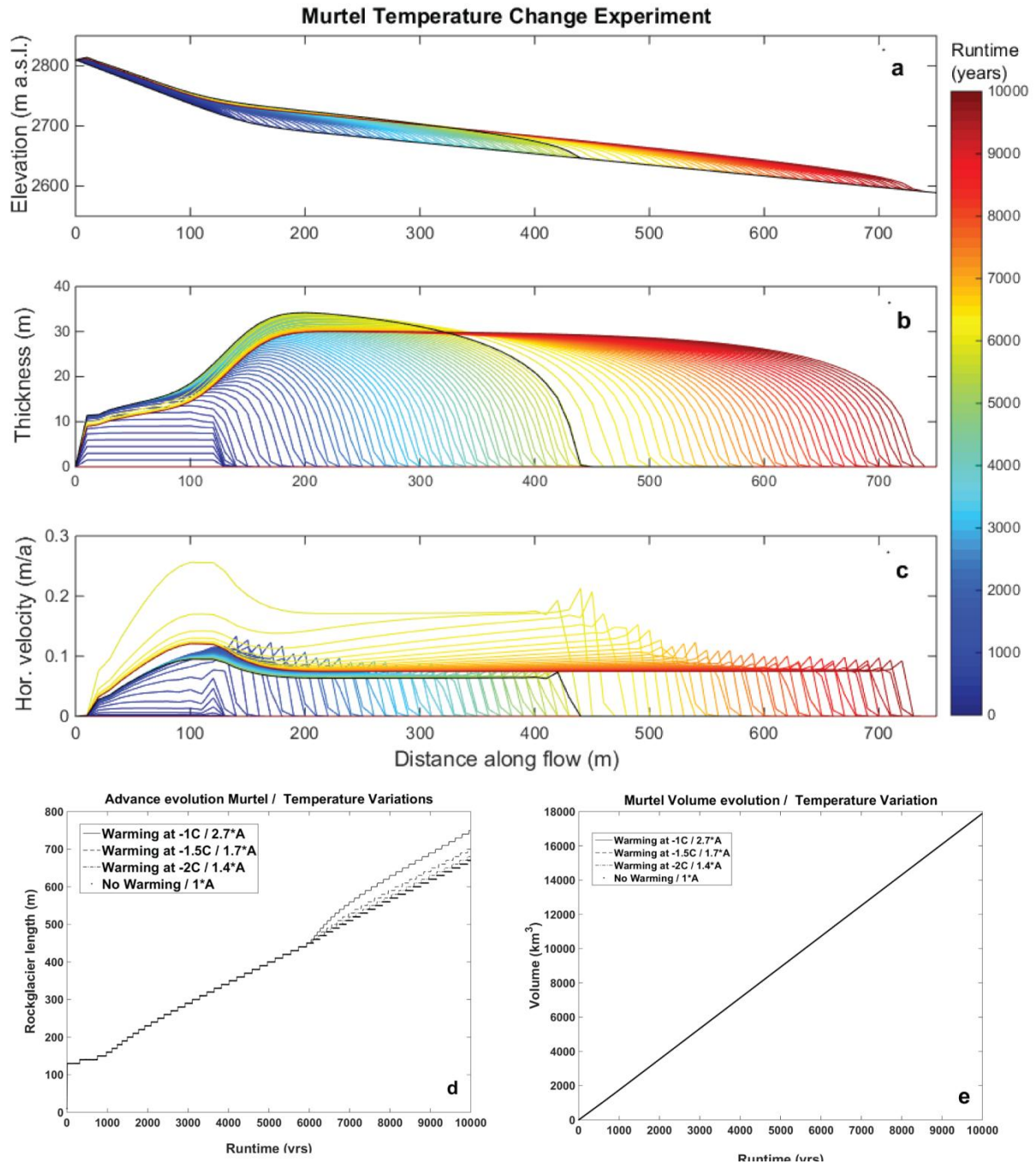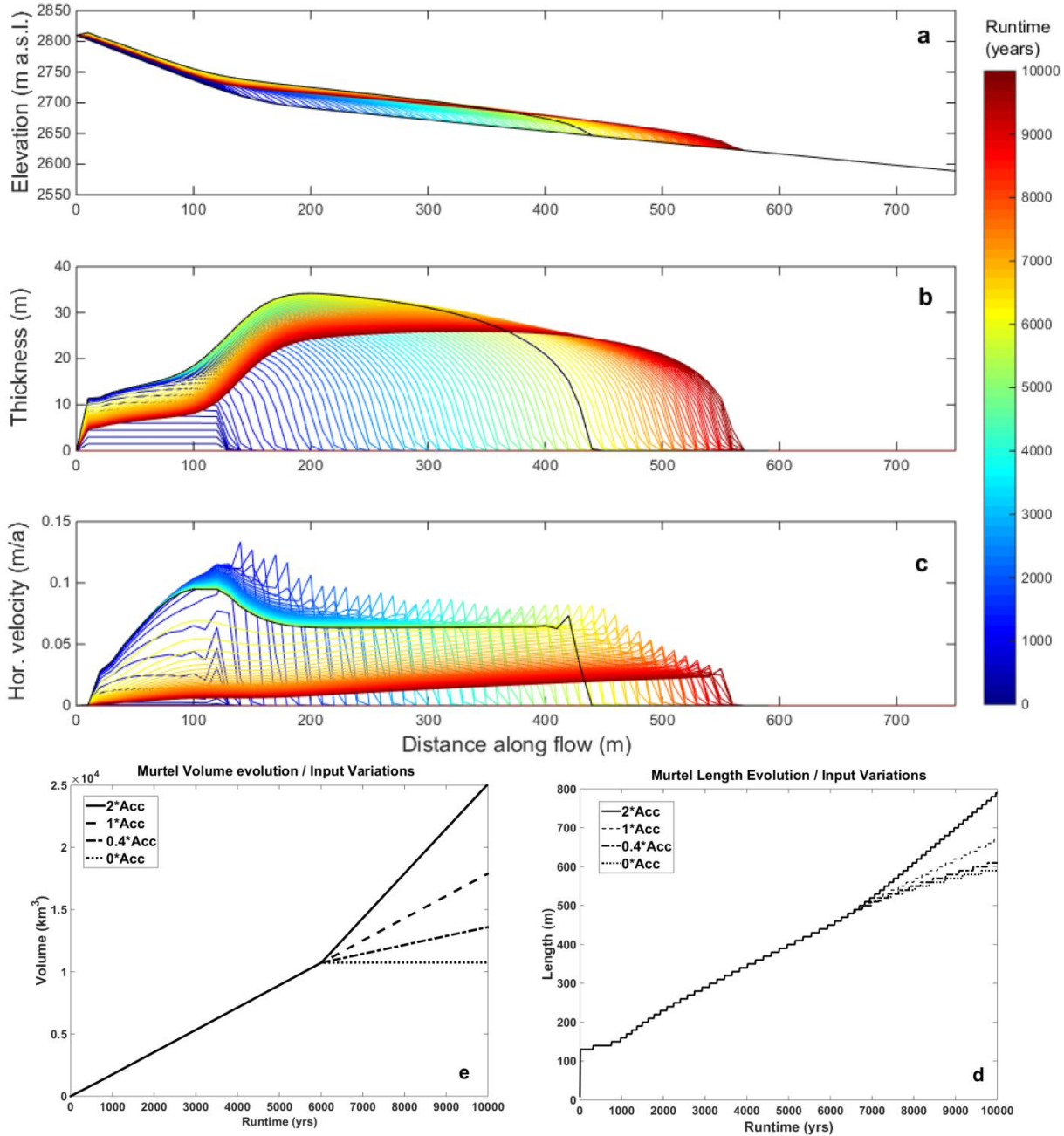
Figure 6: Modeled evolution of surface geometry (a), absolute thickness (b), horizontal velocity (c) along the central flow line, terminus advance (d) and volume evolution (e) for the rockglacier build-up (first 6000a runtime) and for the successive temperature perturbation experiment (temperature increase of 1°C, with -1.5°C reference temperature). The black line shows the state of the system before the temperature step-change at 6000a. The lines are plotted at 100a time intervals.

Murtel Material Input Change Experiment

Figure 7: Modeled evolution of surface geometry (a), absolute thickness (b), horizontal velocity (c) along the central flow line, terminus advance (d) and volume evolution (e) for Murtèl rockglacier when the material input is switched off at 6000a, after the rockglacier build-up (-1.5 C rockglacier temperature). The black line shows the state of the system before the switch-off of material supply at 6000years. The lines are plotted at 100yr time intervals.
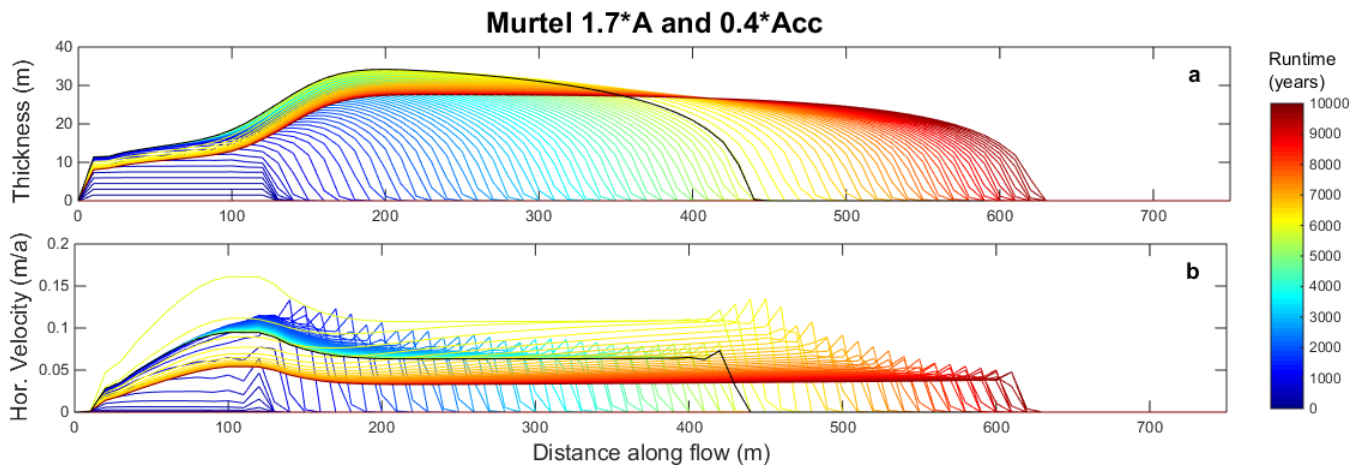
Figure 8: Modeled evolution of absolute thickness (a) and horizontal velocities (b) of the Murtèl rockglacier introducing a 1°C temperature increase (1.7 times increase in rate factor) and a reduction in material input to 40% after the rockglacier build-up (6000a, black line). The black lines in all plots depict the state of the rockglacier as shown in figure 5 before the perturbations were introduced The lines are plotted at 100a time steps.
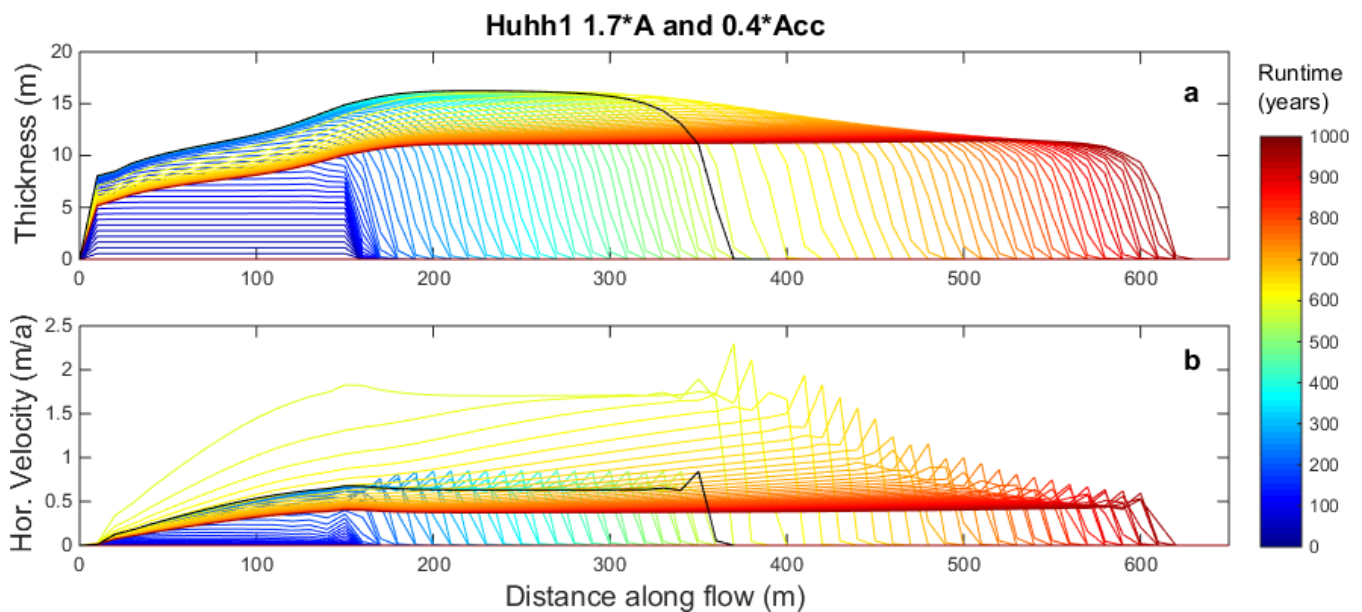
Figure 9: The evolution of absolute thickness (a) and horizontal velocities (b) of the Huhh1 rockglacier introducing a 1°C temperature increase (1.7 times increase in rate factor) and 40% of the initial material input after rockglacier build-up (600a, black line). The black lines in all plots depict the state of the rockglacier as shown in figure 6 before the perturbations were introduced. The lines are plotted in 10a steps.
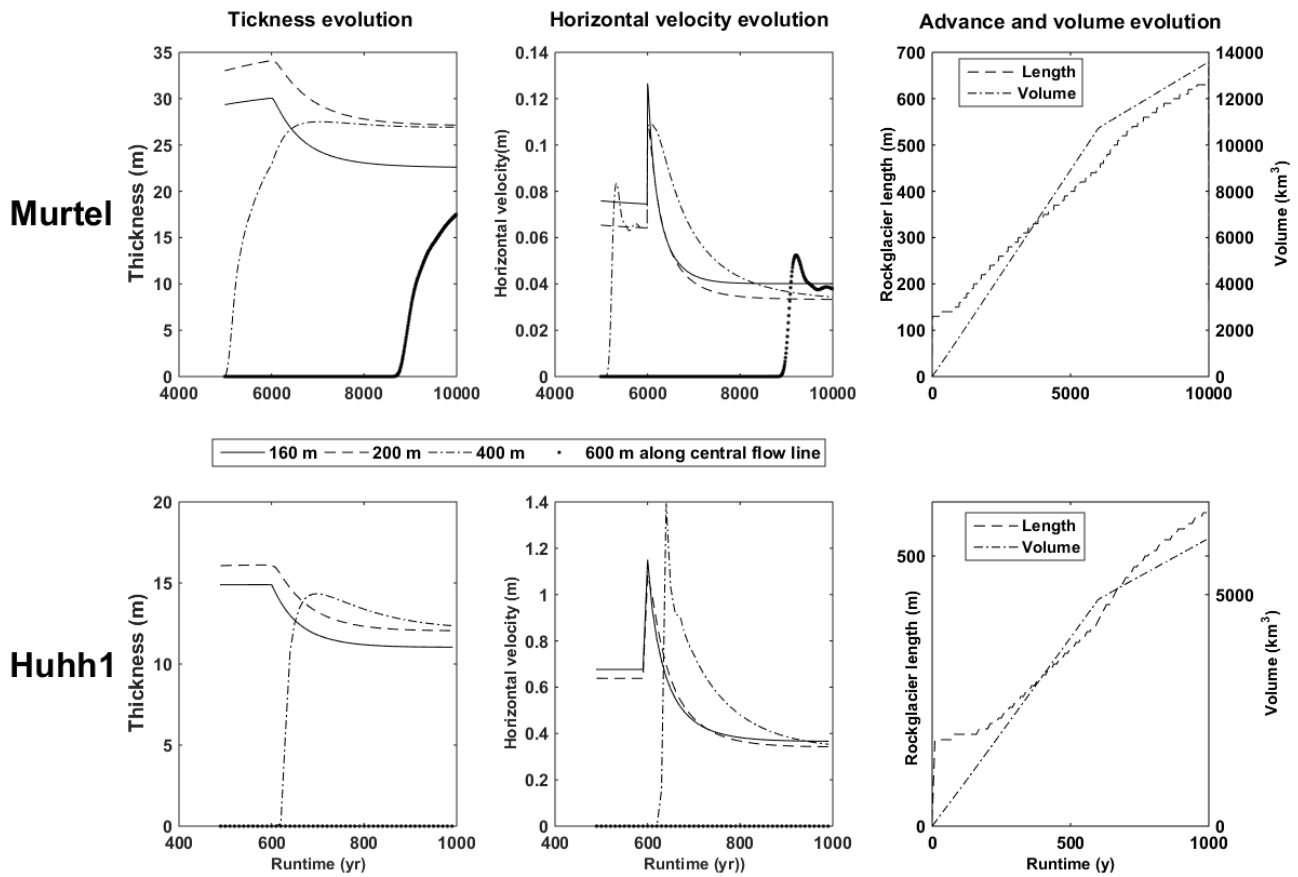
Figure 10: Rockglacier evolution of thickness, horizontal velocity, advance and velocity after a 1°C temperature increase and 40% decrease in material input after rockglacier build-up. The dynamic evolution is shown for three points along the central flow line at 160m, 200m and 400m. The rockglacier is assumed to have an initial temperature of -1.5°C
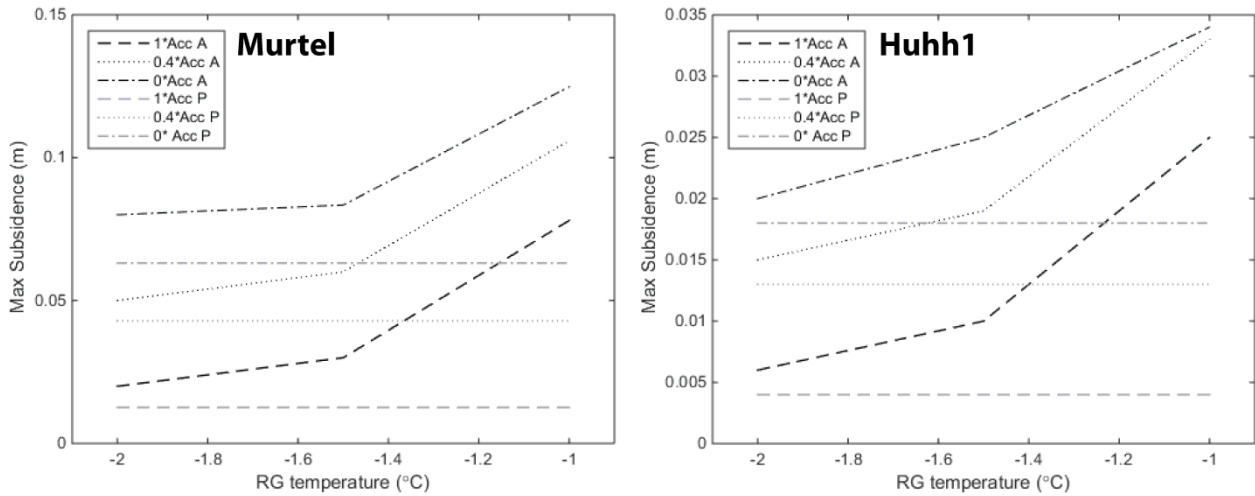
Figure 11: Modeled maximum annual subsidence rates in the deposition area of the rockglaciers in relation to the reference temperature and change in material input and for the two temperature models of Arenson and Springman (2005; black lines) and Paterson and Budd (1982; grey lines) immediately after a -1°C temperature step increase. Note the different scales for subsidence for the two rockglaciers.