Revisions suggested by Anonymous Referee #3 (Report #2):

More substantial points:

a) In general the writing (English language, punctuation…) needs to be improved (quite a few awkward formulations and wrong order of terms in sentences) and minor editing issues (such as for example, singular/plural, wrong spaces, brackets and commas around citations etc.) need to be eliminated by carefully checking and proof reading the manuscript in a further revision. As there were too many such issues I did not mark them all in the detailed comments below.

I have tried to rectify the errors to the best of my ability.

b) (p. 4 first paragraph): I struggle to follow the line of argument on line 3 and 4. On what basis the authors comes to the conclusion that why in a later stage thinning rate would in A become smaller than in glacier B and sentence. Is the reason due to the delayed response of B whereas A already is adjusted to the changed climate. I can very well see this conclusion from the later modelling but at this stage it seems not so obvious to me.
Should be clarified and better explained.

I have rewritten this paragraph following the suggestions by the reviewer.

c) Figure 1 c and d (and e and f): Figure 1 is very instructive, but unfortunately it is difficult to see the temporal evolution of thing rates or dF/dx which is however very crucial to understand what is going on. One should be able to see which lines are at which time step. A reader who is experienced with such model output can probably read it right but not the general reader.
Either label the different blue lines with the model years or maybe visually easier color them following a easy to read color code (rainbow colors that change with time).

I have made the changes in the figure as suggested by the reviewer.

d) If I understand right a crucial point in that the thinning rates from debris covered tongues get similar or higher than on debris-free tongues is the delay in dynamic response of the debris covered tongues. Or in other words the ice-free tongues have already adjusted when the debris covered parts are approaching their highest thinning rates (or do I get this wrong?). This point of delayed response should in my view be made more explicite in paragraph '3.1.2. time evolution of thinning rates' at it seems it is all about timing.

I have included the statement: "the emergence velocity profile in the lower ablation zone of the debris-covered glacier shows a delayed response (figure 1f) leading to a lower value of the glacier-averaged initial thinning rate"

e) More a note to further support this study: Often elevation change assessment are focussed on lower parts of glaciers (ablation areas, as not too steep), but the suggested dynamic effect on average thinning rates would probably be even more amplified and clearer if focussed only on for example the ablation area. This would further support the conclusions of this paper.

I did discuss that in section 3.1.2: "While we have considered the glacier-wide thinning rate, the same conclusions are obtained if one compares only the lower part of the two glaciers as they are identical in their upper parts". However, we prefer to compare the glacier-averaged thinning rate that is equivalent to the net specific blance – an well-accepted fundamental observable for glaciers.

Detailed minor comments and editing issues:

p. 1 line 12: I would say '…in its DYNAMIC response…' to flag more the DYNAMIC aspect.
p. 1 line 12: here only modelling studies are cited but surely there are 'other' studies that considered 'dynamic effects' before.
p.1 line 23: '…has emerged FROM the large…'
p. 1 line 25 and p 2 line 1: I would reformulate tis to '…of supraglacial debris-cover and may seem counterintuitive.'
p. 2 line 7: '…melting FROM thermokarst PROCESSES, namely'
p. 2 line 33: for clarification I would add a 'initially' before 'just the difference
p. 3 line one: something wrong in the sentence at end of line: '…over a time scale THAT is short COMPARED to the …'?
p. 3 line 7: singular 'glacier'
p. 3 line 10 'mass-balance' (double 'ss')
p. 3 line 13 : profile should be in plural: '…mass-balance profiles…'
p. 3 line 14: '…and only CHANGES only by the shift in ELA, and no reference needed here.

All of the above suggestions have been accepted.

p. 3 line 18: I am sure some readers will not agree with the point that changes in ice cliffs/ponds are NOT IMPORTANT. The point is that in this study it makes sense to explicitly exclude it as it wants to see what the 'dynamic' effect is. Thus, in my view there is no need to say the ice cliffs etc are not important or the effect is small.

I have rewritten the section emphasising that the ice-cliffs/ponds are being neglected only as a first approximation to focuss oon the effects of the flux dynamics.

p. 3 line 9: I think even without 'fast' advection this simple mass-balance profile is justified.

I agree with the reviewer. However, this discussion was included in the previous draft in response to a reviewer's comments and is left unchanged here to clarify that the mass-balance profile used affords a reasonable description of debris-covered glaciers .

p. 3 line 21: I would add 'initially' again between '..responds' and 'with a…'
p. 4 line 15, 16: YEARS should be in plural on both lines
p.4 line 17: i assume these decadal rates refer to the first (few) decade and later decline.
p. 4 line 25: I assume these is the '…initial AVERAGE thinning rate (averaged along glacier)
p. 5 line 3: '… profile of THE thinning rate gets …'
Fig 1, caption: make clear that this figure refers to experiment 1.

All of the above suggestions have been accepted in this version.

Brief Communication: Thinning of debris-covered and debris-free glaciers in a warming climate

Argha Banerjee

Earth and Climate Science, Indian Institute of Science Education and Research Pune, Pune 411008, India

Correspondence to: Argha Banerjee (argha@iiserpune.ac.in)

Abstract. Recent geodetic ~~mass balance~~ mass-balance measurements reveal similar thinning rates ~~in~~ on glaciers with or without debris cover in the Himalaya-Karakoram region. This comes as a surprise as a thick debris cover reduces the surface melting significantly due to its insulating effects. Here we present arguments, supported by results from numerical flowline model simulations of idealised glaciers, that a competition between the changes in the surface ~~mass balance~~ mass-balance forcing and that of the emergence/submergence velocities can lead to similar thinning rates ~~with or without~~ on these two types of glaciers. As the climate starts warming, the ~~debris. The~~ thinning rate on a debris-covered glacier is initially smaller than that ~~of~~ on a similar debris-free glacier. Subsequently the ~~thinning~~ rate ~~in~~ on the debris-covered ~~glaciers~~ glacier becomes comparable to and then larger than that ~~in~~ on the debris-free ~~glacier.~~ one. The time evolution of ~~the glacier averaged~~ glacier-averaged thinning rates after an initial warming is strongly controlled by the time-variation of the corresponding emergence velocity profile.

1 Introduction

A knowledge-gap related to debris-covered glacier dynamics affects our understanding of the past and future of Himalayan glaciers in a changing climate (**?**). ~~A~~ The supra-glacial debris cover present over the ablation zone of ~~any~~ a glacier induces qualitative changes in its dynamic response (**??**

banerjee.shankar2013**??**) due to a suppressed melt-rate under a thick debris layer (**??**). ~~Where as~~ Whereas a thin debris cover is expected to accelerate ~~melt,~~ melt due to its low albedo. While responding to a warming climate, debris-covered glaciers exhibit a larger climate sensitivity, a longer response time (**?**), a decoupling of volume and length ~~change,~~ change and the formation of a slow-flowing stagnant downwasting tongue (**??**). Despite several efforts to model and understand the dynamics of debris-covered glaciers with various degrees of sophistication (**?????**), challenges still remain. This task is made more difficult by our limited understanding of the time-evolution of the debris extent (**?**), the variability of debris thickness, and common occurrences of highly dynamic supraglacial ponds and ice-cliffs that cause intense localised melting (**???**).

A curious fact that has emerged ~~in the~~ from large scale remote sensing measurements of glaciers in the Himalaya and Karakoram during the first decade of 21st century is ~~the~~ a similar magnitude of thinning of glacial ice irrespective of the presence of supraglacial ~~debris-cover. This seems~~ debris-cover (**????**) and this may seem counter-intuitive. A thick debris cover, due to its insulating properties, significantly inhibits the melt of the underlying ice - so much so that in the debris-covered part of the glacier, the specific melt-rate does not increase with decreasing elevation. Rather, it ~~reaches a saturation~~

~~value~~ saturates to some lower bound or even decreases ~~on~~ downglacier (**?**). On the ~~lower reaches of~~ other hand, on a debris-free glacier the ~~glacier.~~ melt rate typically increases monotonically as elevation decreases. Why then should both the glacier-types experience similar ~~rate~~ rates of thinning as climate warms up?

Heuristic arguments were offered by various authors to reconcile with this apparent paradox. **?** suggested that the insulating effect of the debris cover might be compensated for at the scale of the whole ablation ~~zone,~~ zone due to an enhanced melting ~~at~~ from the thermoskarst ~~features, namely,~~ processes, namely supra-glacial ponds and ice-cliffs that are often present ~~in debris covered~~ on the debris-covered glaciers. These features, due to ~~the~~ an associated discontinuous debris cover, experience large localised melting. Given that these features typically contribute $\sim 10-20\%$ of the total melt (Sakai et al, (2000); Reid and Brock, ~~(2014)) ,~~ (2014)), it is unlikely that they can lower the ~~glacier wide~~ glacier-wide mean melt rate ~~in the~~ on debris-covered glaciers sufficiently so ~~as to match~~ that ~~of~~ it matches that on the debris-free glaciers. Field measurements by **?** ~~seems~~ seem to confirm this. It was also conjectured that a reduction ~~of ice flux~~ in ice-flux from upstream areas to ~~a~~ the stagnant tongue may be behind ~~this~~ the larger-than-expected thinning of debris-covered glacial ice (**??**). **?** too ~~mentioned~~ pointed out the possible role of reduced flux ~~at~~ into the low-slope slow-moving stagnant ~~tongue~~ tongues of large debris-covered ~~glaciers, but~~ glaciers. However, a quantification of this flux-effect is missing as yet.

On the other hand, **?** showed that a reduced melt-rate ~~in the~~ on a debris-covered ~~tongue~~ glacier does not affect the ~~nature of~~ volume response of the glacier qualitatively, in stark contrast with its drastic effect on the length ~~response.~~ response of the glacier. However, their model results (figure 3d of **?**) show a relatively larger thinning rate ~~in~~ on the debris-free ~~glaciers. Further,~~ glaciers in response to a rapid warming. Also, it was reported that in the Pamir-Karakoram-Himalaya, depending on the region chosen, geodetic measurement ~~gives~~ yielded decadal thinning ~~rate~~ rates of debris-covered ice ~~under a debris cover~~ that ~~are~~ were either larger or smaller than, or similar to that of debris-free ice (**?**). The present scenario is summed up neatly by **?**, "This question of area-averaged melting rates over debris-covered or clean glacier ablation areas remains unanswered".

In this contribution, we analyse the rate of thinning ~~in~~ on debris-covered and debris-free glaciers in a warming ~~climate,~~ climate using a ~~simplified~~ one-dimensional flowline model of idealised glaciers (**??**). We conduct ~~a few~~ simple numerical experiments to investigate the role of the magnitude of warming rate, the ice dynamics (i.e. the changes in ~~flux gradients~~ the flux-gradient profiles or equivalently ~~the changes~~ that in emergence/submergence ~~velocities)~~ velocities), and that of the surface mass ~~balance,~~ balance forcing, in controlling the thinning rates ~~in~~ on these two glacier types.

2 Glacier response to instantaneous warming

An easy-to-analyse piece of this problem is the behaviour of a steady-state debris-covered or debris-free glacier immediately after an instantaneous rise of temperature (or equivalently that of the equilibrium line altitude (ELA)). In a steady state, the ice-thickness profile ~~is kept steady~~ remains constant due to a stable balance between the surface ablation (accumulation) rate and the emergence (submergence) velocities. Dictated by mass conservation of incompressible ice, the emergence or submergence rate equals the negative gradient of the flux, $F(x)$. After an instantaneous change in ELA, the surface mass balance values change, but the viscous ice flow takes a characteristic longer time to relax. Therefore, the ~~initial~~ local thinning rate is initially just the difference in specific mass balance, $B(x)$, before and after the change in temperature. However this is valid only over a time scale that is short compared to the above flow-relaxation time.

Let us consider two idealised model glaciers. Glacier A is without debris and has a linear mass-balance profile. Glacier B has a supraglacial debris cover and on its lower ablation zone where the ablation rate saturates to a value of -2 m/yr in the debris-covered region (figure 1b). This idealised mass-balance profile for the debris covered glacier is motivated by data from Himalayan glaciers glacier (?). Similar simplified mass-balance profiles have been used to analyse the response of the debris-covered Himalayan glaciers (??). In a real glaciers, glacier, possible variability of the debris thickness and ephemeral thermokarst features (ponds and ice-cliffs) cause significant spatial variation of the melt-rate in the debris covered debris-covered parts of the glacier. However, a relatively fast advection of these surface features would imply that a long-term mean melt-rate at a specific location is a well defined quantity. This justifies the simplified mas-balance mass-balance profile employed here. Further, the observed thinning rate values in the Himalaya are obtained for a large set of glaciers. So glaciers so that the possible effects of specific details of mass-balance profile of individual glaciers would be averaged out.

In figure 1a, 1b we show mass-balance profile profiles for the idealised model glaciers before and after an instantaneous rise of ELA, ΔE =50 m. It is assumed here that the mass-balance shape remains the same and changes only change is through that by a shift of ELA . ELA. In practice, the debris layer may thicken and debris-covered area may grow in a warming climate, affecting the shape of the melt-rate profile. However, it is known that above a debris thickness of $\sim$ 10 cm, the decrease in melt-rate with a thickening debris layer is small (?). Therefore such changes can safely be neglected as a first approximation. The possible changes in supraglacial ponds/ice-cliffs are not important neglected at this level of approximation due to a relatively smaller contribution of these features to the total melt, as argued in discussed before. This assumption of an invariant shape allows for possible increase in debris extent with warming as the upper boundary of the region with saturated melt-rate moves up with the ELA. Overall these simplifications allow us to focus on the role of ice-flow dynamics in the downwasting of glaciers in a warming climate.

As is clear from figure 1a, glacier A responds initially with a uniform glacier-wide thinning rate, $\langle \frac{dh}{dt} \rangle_A = \beta \Delta E$, right after the ELA change. Here β is the mass-balance gradient. For glacier B, a uniform thinning operates only in on the debris-free upper part of the glacier and the lower part has not thinned at all (figure 1b). Thus, glacier B has a lower mean thinning rate to start with, with that is given by $\langle \frac{dh}{dt} \rangle_B = (1 - f_d)\beta \Delta E$, where f_d is the debris-covered fraction. Remarkably these expressions should work independent of do not involve the length of the glaciers. Also, the initial lack of thinning in on the debris-covered glacier is independent of the actual value of the melt-rate under the thick debris layer (assumed to be 2 m/yr here) under the thick debris layer and depends only on the general shape of the melt-curve (figure 1b).

A more general mass-balance profile for a debris-covered glacier than the one considered above, above would involve a smaller or inverted mass-balance gradient in the debris-covered parts (?). Even then, the mean initial thinning rate of this on such a glacier would be less compared to its than that of a corresponding debris-free counterpart. one. This delayed thinning of the debris-covered terminus is consistent with the formation of a slow-flowing stagnant tongue with very little retreat as observed on debris-covered glaciers in the Himalaya-Karakoram (?). This raises confidence in the minimal description of such glaciers that is being used here. In case of an inverted mass-balance, a transient thickening of the lower ablation zone is

~~obtained,~~ observed, though this is likely to be an artifact of the assumed fixed shape of mass-balance curve. ~~Above delayed thinning of the debris-covered terminus is consistent with the formation of a slow-flowing stagnant tongue with a steady length commonly seen in the debris-covered glaciers in the Himalaya-Karakoram , which raises confidence in our minimal description of these glaciers.~~

Thus, a debris-covered glacier starts with a lower value of mean thinning rate compared to a debris-free one (as $\langle \frac{dh}{dt} \rangle_A > \langle \frac{dh}{dt} \rangle_B$). The ice fluxes then respond to the mass-balance change and ~~the~~ subsequent evolution of ~~flux gradient (or~~ the flux-gradient profile or equivalently that of the emergence ~~velocity)~~ velocity profile alters the distribution and magnitude of the thinning ~~rate distribution.~~ rate. Though the detailed spatial and temporal pattern of ~~the subsequent~~ such changes ~~in thinning rate is~~ are difficult to predict, at some later stage the thinning rate ~~would decrease in~~ on glacier ~~A and may~~ B is likely to become ~~smaller~~ larger than that ~~in~~ on glacier A. This is beacuse, 1) the debris covered glacier B ~~which~~ has ~~to shed more mass due to~~ a larger climate sensitivity ~~. If that is~~ (**?**) as compared to glacier A and thus loses more mass for a same change in the ~~case, then there~~ ELA; 2) On glacier B, the lower ablation zone responds to the perturbation with a delay. There must be an intermediate crossover period ~~during which~~ as well, where the thinning rates ~~in~~ on both the glaciers ~~are~~ have similar magnitude within measurement errors. ~~This hypotheses is to be tested against numerical simulation of synthetic glaciers.~~

3 Numerical investigations

To verify above claims on the nature of the evolution of ~~mean~~ thinning ~~rates in~~ rate on glacier A and B, we perform a set of numerical experiments with 1-d flowline models of glacier A and B. The model glaciers have bedrock slope of ~~0.1,~~ 0.1 and mass balance gradient $\beta = 0.007$ yr^{-1}. See **?** for further details of the flowline model used. Note that these glaciers are identical above the debris-covered ~~region.~~ region (figure 1a, 1b). The initial steady-states are prepared by running the models with ~~an initial~~ a fixed value of ELA for 500 (900) years for glacier A (B). The ~~steady~~ steady-state length of the simulated glaciers ~~studied~~ are in the range 6–14 km. Subsequently, the following ELA perturbations are switched on at $t = 0$:

1. An instantaneous rise by 50 m.
2. A total rise of 50 m in steps of 5 m every five ~~year.~~ years.
3. A total rise of 30 m in steps of 1 m every five ~~year.~~ years.

In all the three experiments the net warming is similar, but the rates ~~are~~ and durations of the ELA perturbations different ~~(infinite,~~ (1. an instantaneous warming; 2. a rate of 10 ~~m/decade, and~~ m/decade for 50 years, 3. a rate of 2 m/decade ~~respectively).~~ for 150 years). In experiment (3), we ~~limit~~ restrict the total ELA rise to 30 m so as to limit the duration of the experiment to 150 years ~~for the sake of easy~~ to facilitate comparison with the other two experiments.

3.1 Results and discussions

3.1.1 Initial thinning rates

Just as argued in section 2, ~~the~~ mean thinning rate profiles obtained after a year in experiment (1) show uniform thinning ~~rate~~ all over glacier A and in the upper part of glacier B (figure ~~1c, 1d).~~ 1e, 1f). In ~~contrast~~ contrast, the debris-covered parts of glacier B ~~shows zero~~ show no thinning. At this point, the flux gradient profile (same as the negative of emergence velocity), $\frac{dF}{dx}$, has not changed significantly from the initial steady mass balance profile $B(x)$ (figure ~~1e, 1f).~~ 1c, 1d). Further, the initial thinning ~~rate~~ rates for glaciers A and B in experiment (1) are quite accurately given by $\beta\Delta E$ (0.35 m/yr) and $(1 - f_d)\beta\Delta E$ (0.22 m/yr) respectively. All these results are consistent with our arguments as outlined in section 2. The thinning rate trends for finite warming rates follow a similar pattern, with the difference between two ~~thinning~~ rates during the initial phase growing ~~with~~ for larger value of the warming rate ~~value~~ (figure 2; experiments (2) and (3)).

3.1.2 Time evolution of the thinning rates

~~The~~ A thinning of ice ~~results from a difference between~~ in the ablation zone takes place when the local melt-rate ~~and~~ overcomes the ~~corresponding~~ local emergence velocity. Data from experiment (1) ~~shows~~ show that the initial profile of the thinning rate gets modified at later times largely due to ~~the changes in the~~ a changing profile of $\frac{dF}{dx}$ (figure 1e, 1f). After the initial ~~applied~~ rapid change, the competing term of mass balance rate varies weakly with time - ~~only~~ due to a feedback from a changing ~~thickness.~~ ice-thickness. Therefore, the evolution of the spatial distribution and the mean value of the thinning rate ~~is~~ are mostly dynamically ~~controlled, due to~~ controlled by a changing emergence velocity profile. ~~This~~ While this is in general true for both the glaciers ~~types.~~ types, emergence velocity profile on the lower ablation zone of the debris-covered glacier shows a delayed response (figure 1f) which leads to a low glacier-averaged initial thinning rate for these glaciers.

Consistent with arguments given in section 2, ~~initial low values of glacier-averaged~~ the mean thinning rate ~~in~~ on glacier ~~B,~~ B has a lower magnitude initially. Subsequwntly the thinning rate matches and then overtakes that ~~of~~ on glacier ~~B~~ A (figure ~~2) with time. That is,~~ 2). This illustrates that depending on the stage of response, a debris-covered glacier can ~~show~~ have a smaller, larger or similar mean thinning rate as compared to that ~~of~~ on a similar debris-free glacier. As expected, similar trends are obtained in experiments with finite warming ~~rates as well.~~ rates. However, at the limit of a very low rate of warming, the ~~thinning rate~~ differences between the thinning rates on the two glaciers are small (figure 2; experiment(3)). The cross-over time ~~seem~~ seems to be controlled by the rate of warming.

While we have considered the ~~glacier wide~~ glacier-wide thinning rate, the same conclusions are obtained if one compares only the lower part of the two glaciers as they are identical in their upper parts. The thinning ~~rates~~ rate when measured on a regional ~~scale~~ scale, is an average over glaciers ~~with differences in~~ having different size, shape, bedrock-profile, and even history of ~~warming as well.~~ warming. Clearly, in the light of the above discussion, this may lead to larger, smaller or similar mean thinning rates in the ~~two glacier types~~ the debris-covered glaciers as compared to the debris-free glaciers from the same region, in agreement with observations by **?**.

4 Conclusions

We provide very general arguments that debris-covered ~~glaciers~~ glaciers, while responding to a warming climate, can have smaller, larger or similar thinning rates ~~responding to a warming climate~~ as compared to the corresponding debris-free glaciers. ~~The thinning rate~~ Thinning of glaciers is controlled by a competition between a changing mass-balance and the emergence velocity ~~profiles.~~ profile. A debris-covered glacier starts with a smaller ~~glacier averaged~~ glacier-averaged thinning rate, but overtakes that of a debris-free glacier at later ~~stages.~~ stages of evolution. The initial difference in the corresponding ~~warming~~ thinning rates depend on the balance gradient and the debris-covered fraction. ~~Our arguments are validated against results from flowline model simulations of idealised glaciers.~~ The ~~numerical analysis show that the change~~ changes in local melt-rates controls the thinning of glacial ice immediately after an instantaneous warming, whereas a stronger variation of the corresponding ~~emergence velocity~~ emergence-velocity profile dictates the evolution of the thinning ~~rate~~ of ice at subsequent stages. Our arguments are validated against results from flowline model simulations of idealised glaciers.

Acknowledgements. This work is supported by DST-SERB grant no ~~SB.DGH-71.2013.~~ SB.DGH-71.2013 and DST-INSPIRE Faculty award (IFA-12-EAS-04).

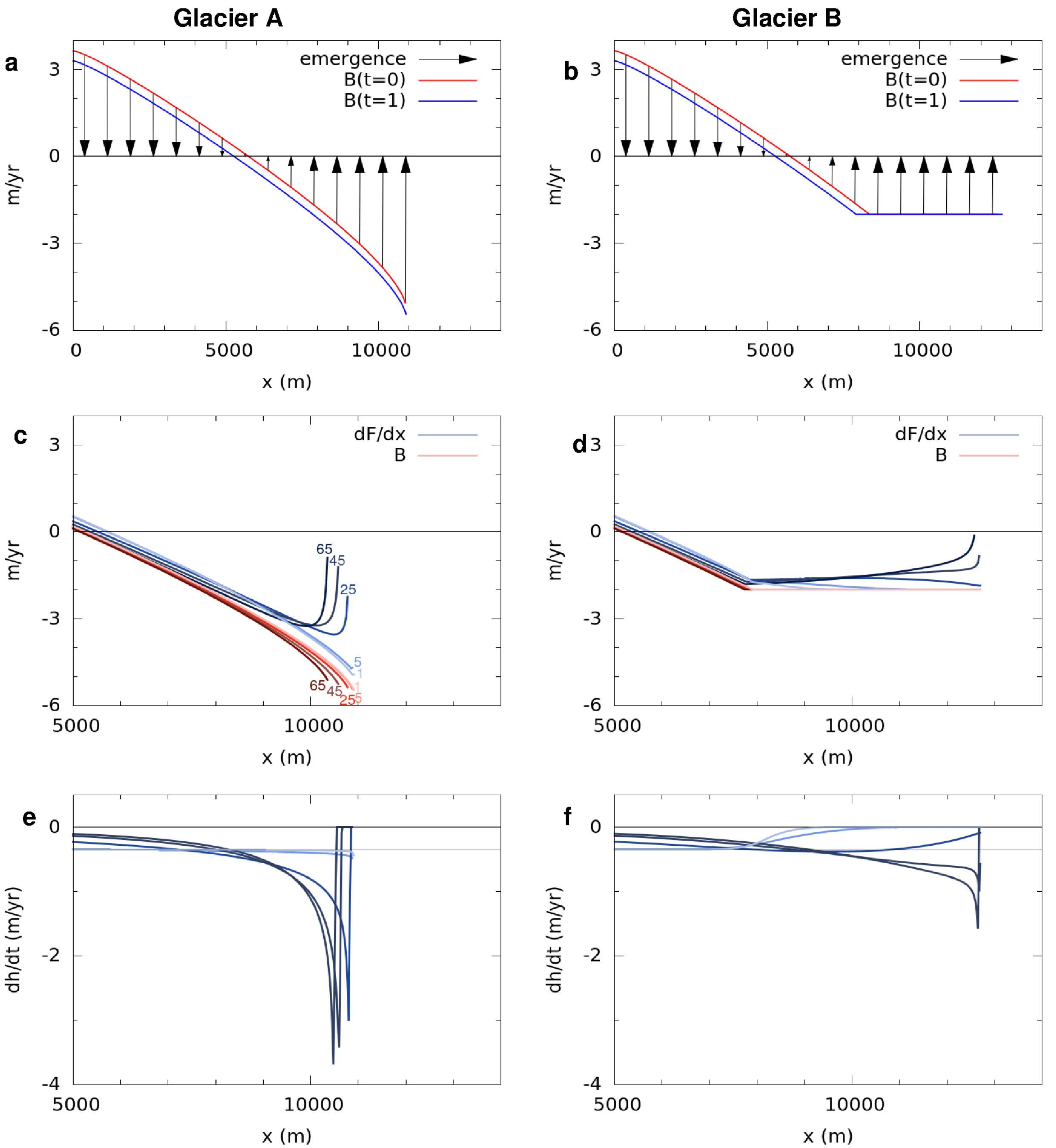

Figure 1. (a, b) The specific mass-balance as a function of position for the initial steady-states of ~~the~~ glacier A and B (red ~~lines), with black~~ lines). Black arrows ~~showing~~ denote the emergence velocities that balances the surface mass balance at ~~$t = 0$ year.~~ $t = 0$. The blue lines are the surface mass-balance profiles a year after a step change in ELA by ~~50m. (c,d)~~ 50m (Experiment (1)). (c, d) The specific mass-balance (red lines) and flux-gradient (blue lines) profiles after 1 , 5, 25, 45, and 65 years. In (c) the curves are labeled with the corresponding year. (e, f) The thinning rate profiles after 1 ~~(thick line),~~ , 5, 25, 45, and 65 ~~years (thin lines).~~ years. Note the ~~different vertical scales and~~ horizontal black thin lines at $\beta \Delta E = 0.35$ m/yr (see text for ~~details). (e,f) Specific mass-balance (red) and flux gradient (blue) profiles after 1 (thick line), 5, 25, 45, and 65 years (thin lines).~~ details).

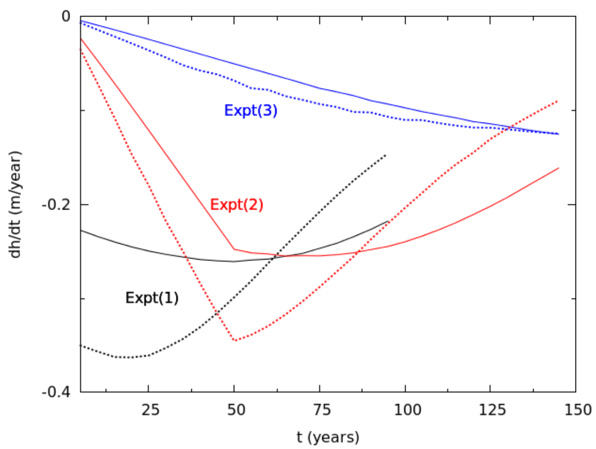

Figure 2. Evolution of thinning ~~rate~~ rates after ELA perturbations are applied to a model debris-covered glacier (solid line) and a debris-free glacier (dotted line). The warming rate ~~profile~~ profiles for each of the ~~experiment is~~ experiments are described in section 3.