I thank the anonymous referees for their critical review of the discussion paper and useful suggestions. Below I list my resplies to the comments of Anonymous Referee #1 and #2. The red lines are referee's comments and the corresponding replies are in black. The relevant changes in the revised manuscript are listed by referring to the corresponding page/line numbers within parenthesis.

Authors response to review comments of Anonymous Referee #1:

* It is difficult to find the significance of the study. Glacier thinning occurs by a combination of the surface mass balance and the emergence velocity. Initial change in ice thickness is controlled by surface mass balance, and then affected by changes in glacier dynamics later. Response time of a debris-covered glacier is generally longer than that of debris-free glaciers. All these were frequently argued and well demonstrated in previous studies.Therefore, it is not surprising to see the results shown in Figure 2.

Undoubtedly glacier thinning is controlled by conservation of mass, a slow dynamics of ice and a fast changing mass-balance forcing. I do not claim to have introduced this ideas here in this paper for the first time. However, to the best of my knowledge, these basic principles were not applied in interpreting the recent large scale glacier thinning data from debris-covered and debris-free glaciers in the Himalaya (Kääb et al , 2012; Gardelle et al , 2012; Nuimura et al , 2012; Gardelle et al , 2013; Vincent et al, 2016), leading to the apparent and well-known puzzle that has been outlined in detail in the introduction section. Despite such a long list of well-known papers that have dealt with this issue, Vincent et al (2016) have recently stated: “This question of area-averaged melting rates over debris-covered or clean glacier ablation areas remains unanswered”. This shows that a clear understanding of this effect has been lacking in the present literature so far. This paper addresses the issue based on first principles.

If the effect has already been clearly explained in some reference that is not known to me, I am ready to accept that the present contribution is redundant.

* Moreover, the model and experimental conditions are very simple (1D flow line model, simple ice dynamics and mass balance). Among others, this study neglects important aspects of a debris-covered glacier, which are listed in the introduction of the paper (line 19-20); time-evolution of the debris extent, variability of debris thickness, and highly dynamic supraglacial ponds and ice cliffs.

I apologise to the reviewer and the readers for not providing a detailed justification of the simple model used in this paper. I thank the reviewer for pointing this weakness out. This is now discussed in the revised version (P2 L6, L9-13, L15-20).

The basic point here is that the relatively fast spatio-temporal variations of melt-rate due to the advecting ephemeral thermokarst features (ponds and cliffs) on the glacier surface and an inhomogeneous debris layer, in combination with a slow response of debris-covered glaciers, imply that long term avarage melt-rate is a rather well-defined quantity and that is what that controls the thinning dynamics at any given point, *x*, over deacal scale. Moreover, as pointed out in the article, the present data suggest, the theromokarst feature play a relatively weaker role in terms of the total melt - at the level of 10-20% (Sakai et al, (2000); Reid and Brock, (2014)).

In addition, since the quoted thinning data are from a large ensemble of glaciers, another level of averaging over such a large ensemble would get rid of the effects of specific details of the mass balance the individual glaciers.

Therefore, it is justified to use a simple (and thus tractable) average mass balance curve to investigate the question of large scale thinning rates in glaciers in the Himalaya. The specific melt-curve used here is motivated by data from Himalayan glaciers (Chhota Shigri, Hamtah, Dokriani and Chora Bari glaciers; eg Banerjee and Azam, 2015). A more complicated representative melt-curve would not change our basic results.

There is a possibility that climatic forcing may increase the average melt rate or may lead to higher abundance of ponds/cliffs (discussed later in the reply), and thus changing the mean melt-rates near the tongue. Given the lack of long term data, this effect is hard to quantify at present. The fact that there are number of debris-covered glaciers with large stagnant tongues in the Himalaya (Scherler et al , 2011), may be a pointer that this increase is not very significant in terms of its magnitude. The idealised mass balance used here, captures the formation of the stagnant tongue quite well.

The uppper elevation range of the thickly debris-covered region has been assumed to increase in our idealised debris-covered glacier model by the same amount as the ELA, to take care of the possible increase of debris covered area in a simple way.

* In any case, the paper is too short to report complex behavior of debris-covered glaciers.

As explained above, the aim here is to investigate the specific question of decadal scale data of thinning rates of a large collection of debris-covered vs debris-free glaciers. I have argued that the model/paper is adequate for this specific purpose.

I do not intend to explain all aspects of the complex behaviour of debris covered glaciers. The complexities alluded to above, would only be relevant in answering more detailed questions like the pattern of thinning in a specific glacier and can be safely ignored in the present context.

Besides, the existing detailed models may not be capable of simulating the large ensemble of glaciers considered here. Most of these models require very high resolution baseline data related to glacier and climate, which may not be available.

* I list below specific comments on the manuscript.
page 1, line19-20: These are very important aspects, but completely neglected in the study.

I have already explained my view on this issue in the response detailed above.

* page 2, line 28: "vertical ablation" is odd. Do you mean "surface ablation"?

It is corrected.

* page 3, line 3-4: "mass balance shape remains the same" » This is a very crude assumption because the debris layer thickens and lakes are formed.

A thickening debris layer would affect the mass balance values for sure. However, in the thickly debris covered parts of the glacier this effect would be relatively unimportant. This is evident from the known variation of melt rate under a debris layer (Ostrem curve) that shows smaller decrease in melt-rate in the thick debris limit (more than about ~10 cm). (eg Juen et al, The Cryosphere, 8, 377–386, 2014). And, the possible increase in debris-extent is included in an empirical manner by moving up the saturated portion of the melt-rate curve as ELA goes up (expected in case of melt-out debris).

On the other hand, supra glacial lakes, as pointed out before, only contribute ~10-20% of the total melt (Sakai et al, (2000); Reid and Brock, (2014)) for specific glaciers studied. Also large-scale studies (eg Gardelle et al, Global and Planetary Change, Elsevier, 2011, 75 (1-2), pp.47-55) reveal that the *supraglacial* lake area is typically only a fraction of a percent of the total glacierised area in the region, and that the total supraglacial lake area is growing at a rate of a few 10's of percent or less per decade (with large uncertainties in the estimates). So the net effective lowering of melt rates due these possibly increasing supraglacial lakes can be ignored in the first approximation.

These discussions is incorporated in the revised draft (P2 L15-20).

* page 3, line 13-14: The result is not "interesting" if "this is an artifact".
I agree with the reviewer and appropriate changes have been made.

* page 3, line 25: What is the unit of the mass balance gradient?
Unit is specified now.

* page 3, line 3: Why 30 m (not 50 m)?
A change of 50m at the rate of 1m every five year, requires a total of 250 years, stretching the time axis of the figure 2 – that is why we had truncated it at 150 years ie a total change of 30 years. This has been mentioned in possible revised draft (P4 L17-19).

* page 4, line 4-10: These results are easily expected before the experiments. The results are like that, simply because of the assumptions given to the mass balance.
In above replies I have hopefully justified why such a simple mass balance function is enough to investigate the important specific issue of the recent thinning rates in Himalayan glaciers with and without a supraglacial debris-cover.

Authors response to review comments of Anonymous Referee #2:

* I think that the way in which debris included creates a circular argument. Areas with ‘debris’ cannot thin below a threshold, but this threshold covers a large portion of the ablation area in the model glacier. The author then uses this result to show that the debris covered area has not thinned, whereas the ice free glacier, which does not have this limit, does not thin. To me, this does not tell us about debris cover, but uses an arbitrary threshold to stop thinning at a certain point on one glaciers, but not on another. This debris parameterisation is fundamental to the paper. If my understanding is correct, then it is fundamentally flawed and circular and does not give us any information about the impact of debris on glacier melt rates.

I believe the claim that the paper uses a circular argument is incorrect. Here are my arguments:

1) Our modeled thinning rates are in the range ~0.2-0.3 mwe/yr. The assumed threshold value and corresponding mean melt rate is much larger.

2) The mean melt-rate in principle does set an upper bound on thinning rate, but that bound is irrelevant here. Immediately after a step change of ELA, the debris covered parts do not thin. This is not becasue of a low melt rate there, but because the mass balance curve is *flat* there. The actual value of the threshold does not matter - The same effect would be seen if the treshold value was larger, as is clear from figure 1b (Though the time scale of stagnation may be smaller in that case).

3) As explained in the paper, the interplay of the changes in mass balance forcing and a slowly evolving flux-divergence profile controls the net thinning of any glacier, as opposed to the melt rate being the only controling factor. That is why one has higher/lower/similar mean thinning rate in

debris-covered glaciers as compared to their debris-free counterparts, depending on the stage of response and the rate of mass-balance change (eg, our numerical results clearly show that debris-covered glaciers thin at a faster rate during the later stages of the response (fig 2, expt 1,2)).

4) The "threshold" on melt rate in the thickly debris covered part is supported by glaciological mass balance data from Himalayan glaciers (eg Banerjee and Azam, 2015) and is not an arbitrary imaginary construct (as explained in the revised draft (P3 L5-7)). The threshold does exist and also its exact magnitude is not important for the effects described here (as explained in point 2).

5) That the model describes and explains the stagnant debris-covered glaciers commonly observed in the Himalaya that have formed in response to a warming climate (Scherler et al, 2011; Banerjee and Shankar, 2013) indicates that it describes debris covered glaciers reasonably well.

* Page 1 Line2: Where as thin debris cover is expected to accelerate melt, due to its low albedo
I prefer to leave it out of the abstract. The welknown albedo effect of a thin debris layer does not seem to be visible in the measured mass balance profile of Himalayan glaciers (Banerjee and Azam, 2015). It is likely that the thin debris extent is small compared to that of the thickly debris region. May be the accelerated melt in the thin debris region contributes a large melt-out debris flux, leading to quick thickening of the debris layer.
I have included this line in the introduciton (P1 L14)

* Line 5: in >on
Line 6: The sentence starting 'Subsequently. . ..' Is hard to follow.
Express more clearly.
Line 7: I find this sentence hard to understand (starting 'Time evolution. . ..')

Based on above suggestions, the abstract has been rewritten.

* Line 13: Outline the impacts of thin debris cover on ice loss.
Line 15: .. length change, and formation of..
Line 18: This task is made more difficult by our limited understanding of. . .
Page 2 Line 2: Why then should. . ..
Line 5: get compensated> be compensated for.
Line 8: Very briefly outline what these are.
Line 11: pointed out> highlighted. Pointed out is colloquial.
Line 12 debris-covered glaciers, but. Should be a comma not full stop.
Line 27: steady state THE ice thickness profile.

All above suggestions/corrections have been incorporated in the revised draft.

* Page 3 Line 1: If I have understood correctly, the debris cover is applied by simply saturating ablation at -2 ma-1 over part of the terminus. This therefore seems like a very circular argument, as the value for this section cannot become less than -2 ma-1. It therefore cannot thin and this is then used in an argument to say that debris cover means that the glacier does not thin. The only thing that can change is the upper section, which does thin. To be, this is circular parametrisation and not an appropriate way to evaluate the impact of debris cover. Perhaps I have misunderstood this, but it needs to be explained more clearly. Also, why a value of -2 ma-1?

We have have outlined our reply to this objection in the beginnning of the section.

* Line 17: I don't follow this argument.

We have added some clarifications to make the point clearer. (P3 L34-35, P4 L1-6)

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

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Abstract. Recent geodetic mass balance measurements reveal similar thinning rates in 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 forcing and that of the emergence/submergence velocities can lead to similar thinning rates with or without the debris. The thinning rate ~~in~~ on a debris-covered glacier is initially smaller than that of a similar debris-free glacier. Subsequently the ~~former~~ thinning rate in the debris-covered glaciers becomes comparable to and then larger than that in the debris-free glacier. The time evolution of the glacier averaged thinning ~~profile in both the type of glaciers are mainly~~ rates after an initial warming is strongly controlled by ~~a relatively stronger time variation~~ time-variation of the 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 (Scherler et al , 2011). A supra-glacial debris cover present over the ablation zone of any glacier induces qualitative changes in its response (Naito et al , 2000; Vacco et al , 2010; Banerjee and Shankar , 2013; Anderson and Anderson , 2015) due to a suppressed melt-rate under ~~the~~ a thick debris layer (Nakawo and Young , 1982; Mattson et al , 1993). Where as a thin debris cover is expected to accelerate melt, due to its low albedo. While responding to a warming climate, debris-covered glaciers exhibit a larger climate sensitivity, longer response time (Banerjee and Shankar , 2013), a decoupling of volume and length ~~changes,~~ change, and formation of a slow-flowing stagnant downwasting tongue (Scherler et al , 2011; Banerjee and Shankar , 2013). Despite several efforts to model and understand the dynamics of debris-covered glaciers with various degrees of sophistication (Naito et al , 2000; Vacco et al , 2010; Banerjee and Shankar , 2013; Anderson and Anderson , 2015; Rowan et al , 2015), challenges still remain. This task is made more difficult by ~~a not-so-well-understood~~ our limited understanding of the time-evolution of the debris extent (Anderson and Anderson , 2015), the variability of debris thickness, and common occurrences of highly dynamic supraglacial ponds and ice-cliffs that cause intense localised melting (Sakai et al , 2000; Miles et al , 2015; Steiner et al , 2015).

A curious fact that has emerged in the large scale remote sensing measurements of glaciers in the Himalaya and Karakoram during the first decade of 21st century (Kääb et al , 2012; Gardelle et al , 2012; Nuimura et al , 2012; Gardelle et al , 2013) is the similar magnitude of thinning of glacial ice irrespective of the presence of supraglacial debris-cover. This seems counter-intuitive. A thick debris cover, due to its insulating properties, significantly inhibits the melt of underlying ice - so much so that in the debris-covered part of the glacier, specific melt-rate does not increase with decreasing elevation. Rather, it reaches a saturation value or even decreases (Banerjee and Azam , 2015) ~~at~~ on the lower ~~altitude.~~ reaches of the glacier. Why then should both the glacier-types ~~should~~ experience similar rate of thinning as climate warms up?

Heuristic arguments were offered by various authors to reconcile with this apparent paradox. Kääb et al (2012) suggested that the insulating effect of the debris cover might ~~get~~ be compensated for at the scale of the whole ablation zone, due to enhanced melting at the thermoskarst features, namely, supra-glacial ponds and ~~ice-cliffs.~~ ice-cliffs that are often present in debris covered glaciers. These features, due to the 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)) , it is unlikely that they can lower the glacier wide mean melt rate in the debris-covered glaciers sufficiently so as to match that of the debris-free glaciers. Field measurements by Vincent et al (2016) seems to confirm this. It was also conjectured that a reduction of ice flux from upstream areas to a stagnant tongue may be behind this larger-than-expected thinning of debris-covered glacial ice (Kääb et al , 2012; Gardelle et al , 2012). Nuimura et al (2012) too ~~pointed out~~ mentioned the possible role of reduced flux at low-slope slow-moving stagnant tongue of large debris-covered ~~glaciers. But~~ glaciers, but a quantification of this flux-effect is missing as yet.

On the other hand, Banerjee and Shankar (2013) showed that a reduced melt-rate in the debris-covered tongue does not affect the nature of volume response of the glacier qualitatively, in stark contrast with its drastic effect on the length response. However, their model results (figure 3d of Banerjee and Shankar (2013)) show larger thinning rate in debris-free glaciers. Further, it was reported that in the Pamir-Karakoram-Himalaya, depending on the region chosen, geodetic measurement gives decadal thinning rate of ice under a debris cover that are either larger or smaller than, or similar to that of debris-free ice (Gardelle et al , 2013). The present scenario is summed up ~~well~~ neatly by Vincent et al (2016), "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 debris-covered and debris-free glaciers in a warming climate, using a simplified one-dimensional flowline model of idealised glaciers (Banerjee and Shankar , 2013; Banerjee and Azam , 2015). We conduct a few simple numerical experiments to investigate the role of the magnitude of warming rate, ice dynamics (i.e. the changes in flux gradients or equivalently the changes in emergence/submergence velocities) and that of the surface mass balance, in controlling the thinning rates in 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 ~~a step~~ an instantanepus rise of temperature (or equivalently of equilibrium line altitude (ELA)). In a steady state, the ice-thickness profile is kept steady due to a stable balance between the ~~vertical~~ 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 a an instantaneous change in ELA, the surface mass balance values change, but ice flow takes a characteristic longer time to relax. Therefore, the initial local thinning rate is just the change difference in specific mass balance, $B(x)$, before and after the change in temperature. However this is valid only over a time scale short compared to the above flow relaxation flow-relaxation time.

In figure 1a, 1b we show mass balance profile for

Let us consider two idealised model glaciers before and after an instantaneous rise of ELA, ΔE =50 m. glaciers. Glacier A is without debris and has a linear mass balance profile. Glacier B has supraglacial debris cover and 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 Himalyan glaciers (Banerjee and Azam , 2015). Similar simplified mass-balance profiles have been used to analyse the response of the debris-covered Himalayan glaciers (Banerjee and Shankar , 2013; Banerjee and Shankar , 2015).

In a real glaciers, possible variabitlity of the debris thickness and ephemeral thermokarst features (ponds and ice-cliffs) cause significant spatial variation of the melt-rate in the 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 profile employed here. Further, the observed thinning rates in the Himalaya are obtained for a large set of glaciers. So 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 for the idealised model glaciers before and after an instantaneous rise of ELA, ΔE =50 m. It is assumed here that the mass balance mass-balance shape remains the same and only change is through that of ELA (Banerjee and Shankar , 2013). Similar simplified mass balance profiles have been used 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 thickenning debris layer is small (Juen et al , 2014). Therefore such changes can safely be neglected as a first approximation. The possible changes in supraglacial ponds/ice-cliffs are not important due to a relatively smaller contribution of these features to study the response total melt, as argued in the introduction. The assumption of an invariant shape allows for possible increase in debris extent with warming as the Himalayan glaciers . upper boundary of the region with saturated melt-rate moves up with the ELA.

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

A more general mass balance profile for a debris-covered glacier than the one considered above, would involve a smaller or inverted mass balance gradient in the debris-covered part parts (Banerjee and Azam , 2015). Even then, the mean thinning rate of this glacier would be less compared to its debris-free counterpart. Interestingly, in In case of an inverted mass balance, a transient thickening of the lower ablation zone is obtained, 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 slow-flowing stagnant tongue with a steady length seen in the debris-covered glaciers in the Himalaya-Karakoram . (Scherler et al , 2011), 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. one (as $\langle \frac{dh}{dt} \rangle_A > \langle \frac{dh}{dt} \rangle_B$). The ice fluxes subsequently adjust then respond to the mass balance mass-balance change and the subsequent evolution of flux gradient (or equivalently the emergence velocity) profile alters the thinning rate distribution. Though the detailed pattern of the subsequent changes in thinning rate would be difficult to predict, at some later stage, stage the thinning rate decreases would decrease in glacier A and may become smaller than that in glacier B. This is because glacier B which has to shed more mass due to a larger climate sensitivity (Banerjee and Shankar , 2013). There If that is the case, then there must be an intermediate crossover period during which the thinning rates in both the glaciers are similar within measurement errors. This hypotheses is to be tested against numerical simulation of synthetic glaciers as described below.

3 Numerical investigations

To verify above claims on the evolution of mean thinning rates in glacier A and B, we perform a set of numerical experiments with 1-d flowline model models of glacier A and B. The model glaciers have bedrock slope of 0.1, mass balance gradient $\beta =$ 0.007. 0.007 yr^{-1}. See Banerjee and Shankar (2013) for further details of the flowline model used. Note that these glaciers are identical above the debris-covered region. The initial steady states are prepared by running the models with an initial fixed value of ELA for 500 (900) years for glacier A (B). The steady length of 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 50m.
2. A total rise of 50 m in steps of 5m every five year .
3. A total rise of 30m in steps of 1m every five year .

In all the three experiments the net warming is similar, but the rates are different. different (infinite , 10m/decade and 2m/decade respectively). In experiment (3), we limit the total ELA rise to 30m so as to limit the duration of the exeriment to 150 years for the sake of easy 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). In contrast the debris-covered parts of glacier B shows zero 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). Further, the initial thinning rate 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 outlined in section 2. The thinning rate trends for finite warming rates follow similar pattern, with the difference between two thinning rates during the initial phase growing with the warming rate value (figure ~~2).~~ 2; experiments (2) and (3)).

3.1.2 Time evolution of thinning rates

The thinning ~~rate~~ of ice results from a difference between local melt-rate and the corresponding emergence velocity. Data from experiment (1) shows that the initial profile of thinning rate gets modified at later times largely due to the changes in the profile of $\frac{dF}{dx}$ (figure 1e, 1f). After the initial applied change, the competing term of mass balance rate varies ~~quite~~ weakly with time - only due to a feedback from changing thickness. Therefore, the evolution of the spatial distribution and the mean value of thinning rate is mostly dynamically controlled, due to a changing emergence velocity profile. This is true for both the glaciers types.

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

While we have considered the glacier wide thinning rate, the same conclusions are obtained if one compares the lower part of the two glaciers as they are identical in their upper parts. The thinning rates measured on a regional scale is an average over glaciers with differences in size, bedrock-profile, and history of warming as well. Clearly, this may lead to larger, smaller or similar mean thinning rates in the two glacier types from the same region, in agreement with observations by Gardelle et al (2013).

4 Conclusions

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

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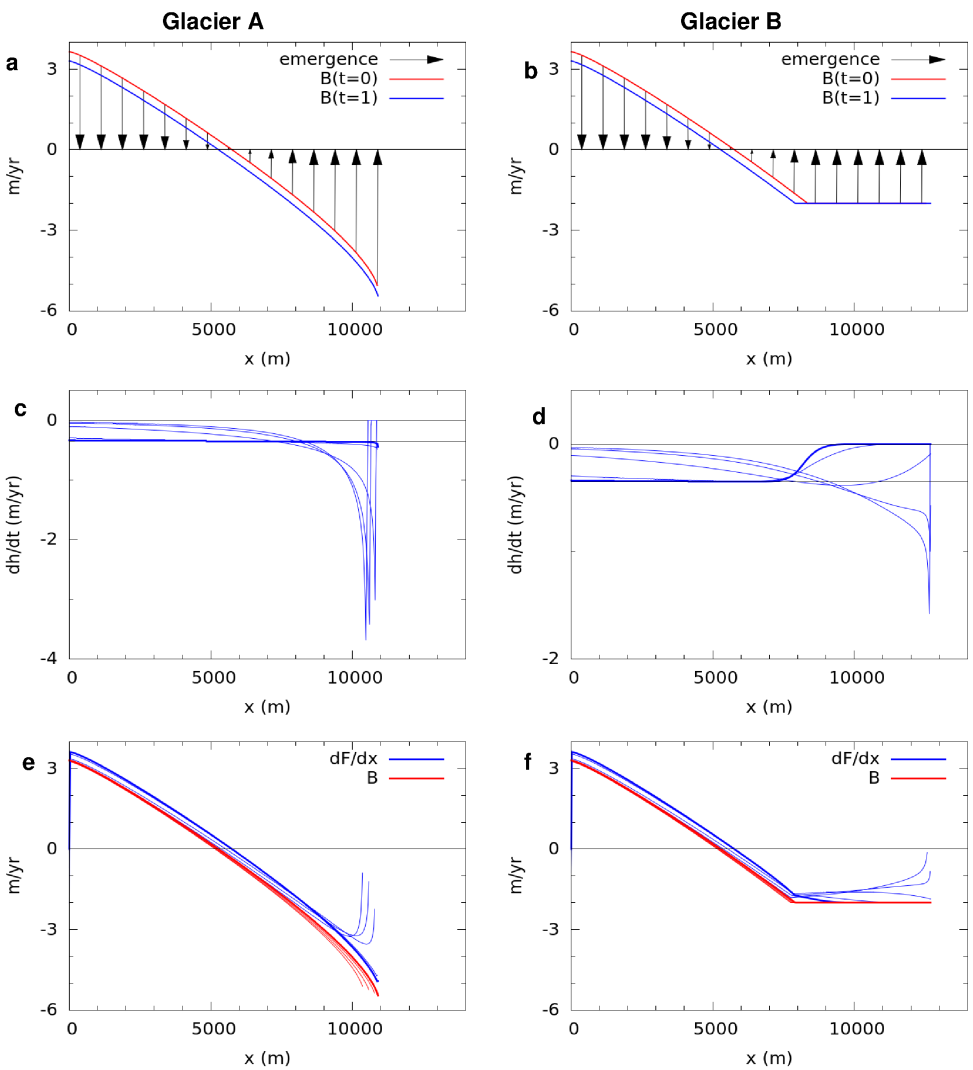

Figure 1. (a,b) The specific mass-balance as a function of position for the initial steady-states of the glacier A and B (red lines), with black arrows showing emergence velocities that balances surface mass balance at $t = 0$ year. The blue lines are the surface mass-balance profiles a year after a step change in ELA by 50m. (c,d) The thinning rate profiles after 1 (thick line), 5, 25, 45, and 65 years (thin lines). 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).

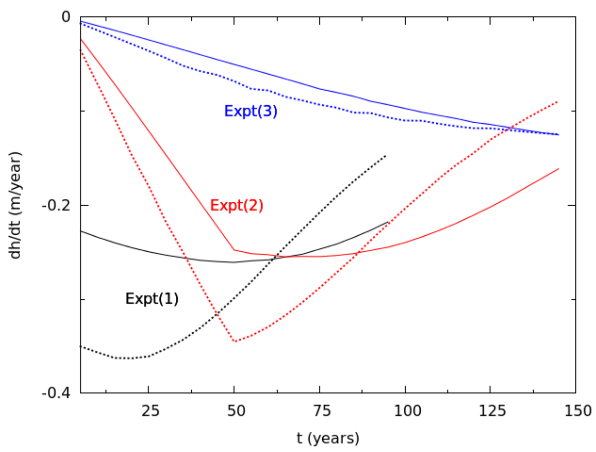

Figure 2. Evolution of thinning rate after ELA perturbations are applied to a model debris-covered glacier (solid line) and a debris-free glacier (dotted line). The warming rate profile for each of the experiment is described in section 3.