# 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 on a debris-covered glacier is initially smaller than that of a similar debris-free glacier. Subsequently the 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 rates after an initial warming is strongly controlled by 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 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 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 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 counterintuitive. 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) on the lower reaches of the glacier. Why then should both the glacier-types 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 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 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 mentioned the possible role of reduced flux at low-slope slow-moving stagnant tongue of large debris-covered 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 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 an instantaneous 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 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 ice flow takes a characteristic longer time to relax. Therefore, the initial local thinning rate is 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 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 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 Himalayan 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 Azam , 2015). In a real glaciers, 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 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 rate values 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, $\Delta E$ =50 m. It is assumed here that the mass-balance shape remains the same and only change is through that of ELA (Banerjee and Shankar , 2013). 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 (Juene 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 the total melt, as argued in 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.

As is clear from 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 $\beta$ is the 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 (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 (figure 1b).

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 parts (Banerjee and Azam , 2015). Even then, the mean thinning rate of this glacier would be less compared to its debris-free counterpart. 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 a slow-flowing stagnant tongue with a steady length commonly 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 (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 equivalently the emergence velocity) profile alters the thinning rate distribution. Though the detailed pattern of the subsequent changes in thinning rate is difficult to predict, at some later stage the thinning rate would decrease in glacier A and may become smaller than that in glacier B which has to shed more mass due to a larger climate sensitivity (Banerjee and Shankar , 2013). 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.

## 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 models of glacier A and B. The model glaciers have bedrock slope of 0.1, mass balance gradient $\beta = 0.007$ 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 50 m.
2. A total rise of 50 m in steps of 5 m every five year.
3. A total rise of 30 m in steps of 1 m every five year.

In all the three experiments the net warming is similar, but the rates are different (infinite, 10 m/decade, and 2 m/decade respectively). In experiment (3), we limit the total ELA rise to 30 m so as to limit the duration of the experiment 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; experiments (2) and (3)).

### 3.1.2 Time evolution of thinning rates

The thinning 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 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 (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 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 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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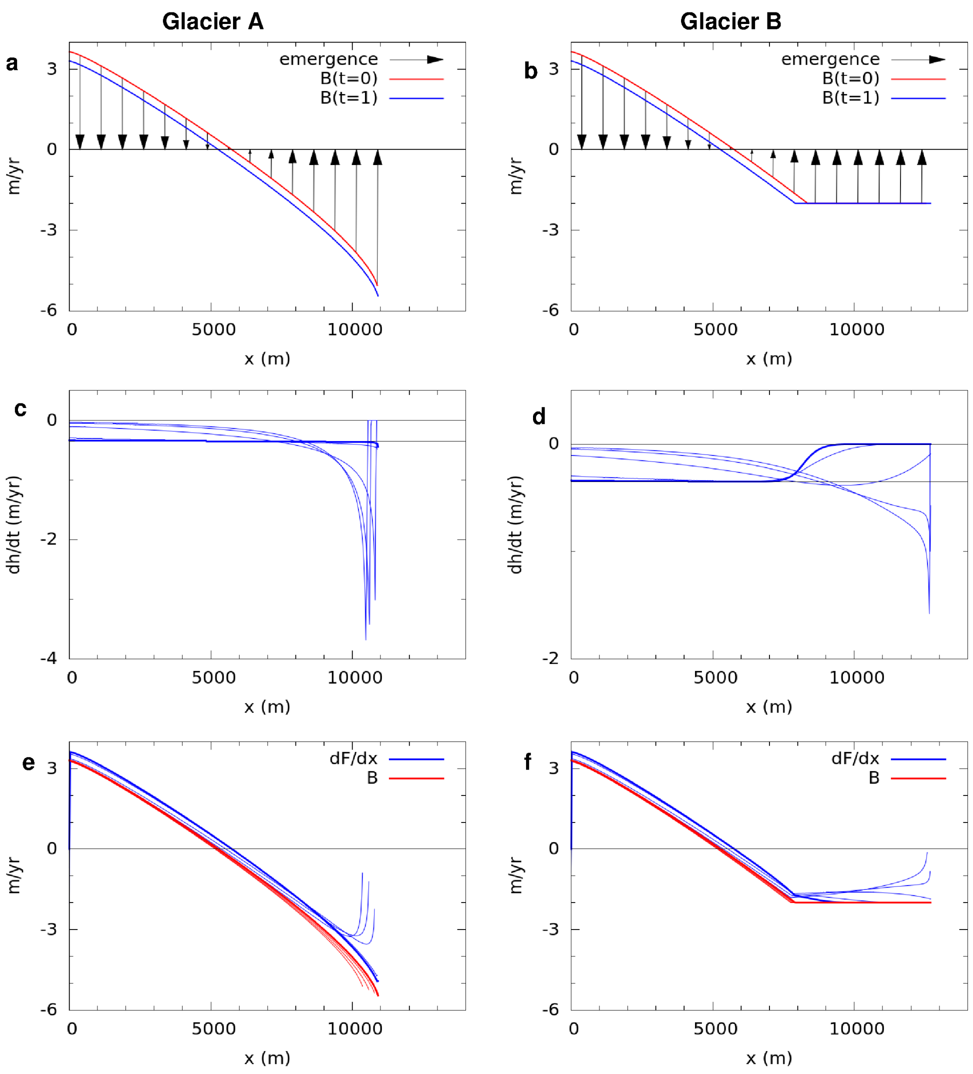


**Figure 1.** (a,b) The specific mass-balance as a function of position for the initial steady-states of the glacier A and B (red lines), with black arrows showing emergence velocities that balances surface mass balance at $t = 0$ year. The blue lines are the surface mass-balance profiles a year after 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).

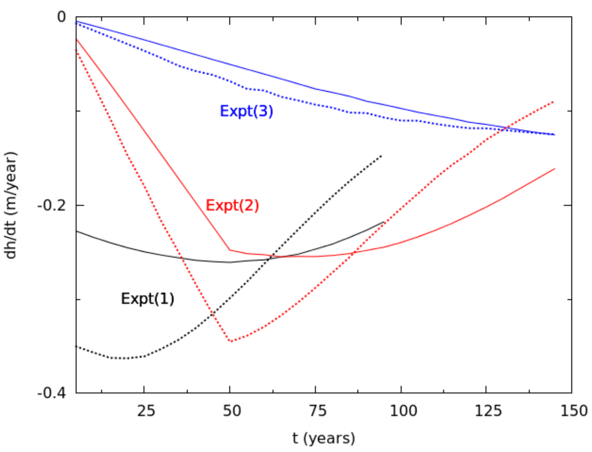


**Figure 2.** Evolution of thinning rate after ELA perturbations are applied to a model debris-covered glacier (solid line) and a debris-free glacier (dotted line). The warming rate profile for each of the experiment is described in section 3.