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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 a debris-covered glacier is initially smaller than that of a similar debris-free glacier. Subsequently the former rate becomes comparable to and then larger than that in the debris-free glacier. The time evolution of the thinning profile in both the type of glaciers are mainly controlled by a relatively stronger 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 debris layer (Nakawo and Young , 1982; Mattson et al , 1993). 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, 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 difficult by a not-so-well-understood 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 lower altitude. Why then 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 compensated at the scale of the whole ablation zone, due to enhanced melting at the thermoskarst features, namely, supra-glacial ponds and ice-cliffs. 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 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 well 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 rise of temperature (or equivalently of equilibrium line altitude (ELA)). In a steady state, ice-thickness profile is kept steady due to a stable balance between the vertical 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 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 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.

In figure 1a, 1b we show mass balance profile for two idealised model glaciers before and after an instantaneous rise of ELA, $\Delta E = 50$ m. Glacier A is without debris and has a linear mass balance profile. Glacier B has supraglacial debris cover and ablation rate saturates to a value of -2 m/yr in the debris-covered region (figure 1b). It is assumed here that the 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 to study the response of the Himalayan glaciers (Banerjee and Shankar , 2013; Banerjee and Azam , 2015).

As is clear from figures, 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 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. 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.

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 (Banerjee and Azam , 2015). Even then, the mean thinning rate of this glacier would be less compared to its debris-free counterpart. Interestingly, 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).

Thus, a debris-covered glacier starts with a lower value of mean thinning rate compared to a debris-free one. The ice fluxes subsequently adjust to the mass balance change and the 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, the thinning rate decreases in glacier A and may become smaller than that in glacier B. This is because glacier B has to shed more mass due to a larger climate sensitivity (Banerjee and Shankar , 2013). There must be an intermediate crossover period during which the thinning rates in both the glaciers are similar within measurement errors.

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 of glacier A and B. The model glaciers have bedrock slope of 0.1, mass balance gradient $\beta = 0.007$. 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.

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).

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 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. 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 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 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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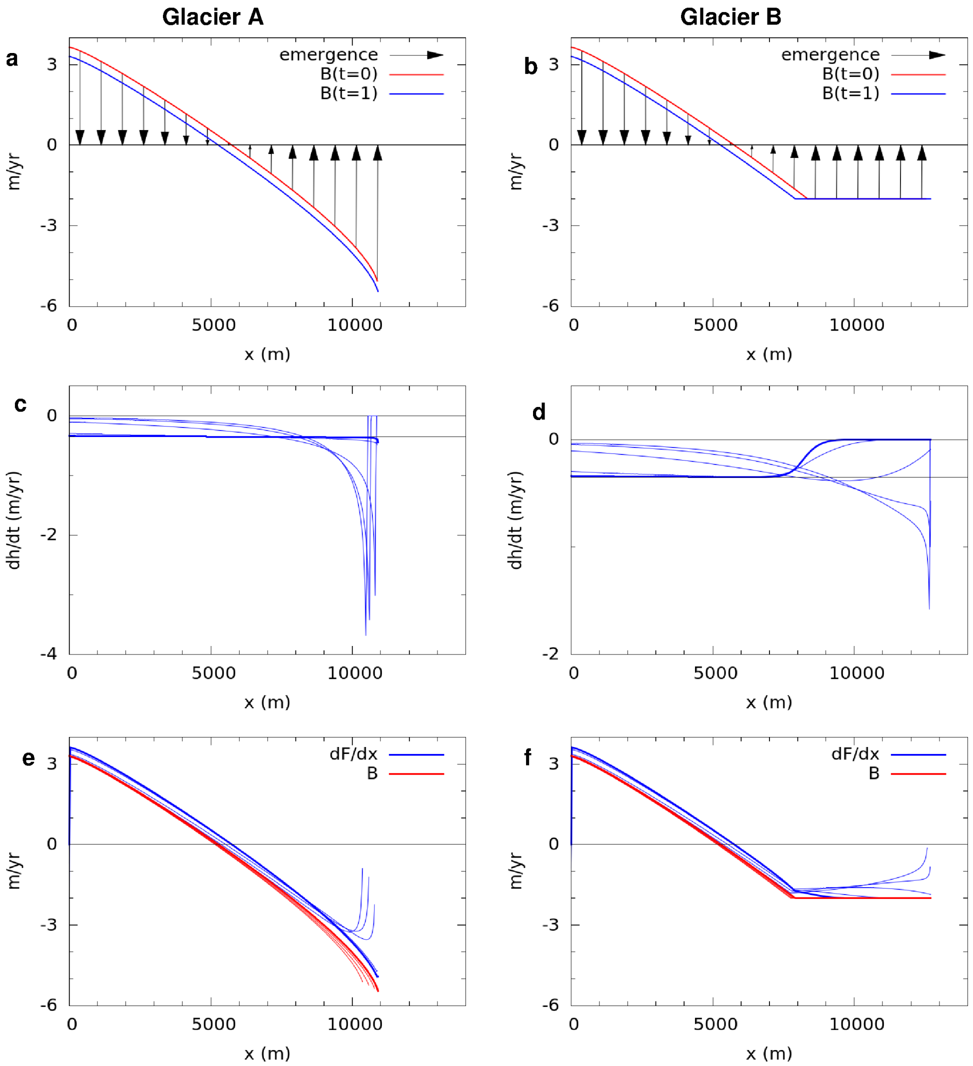

Figure 1. (a,b) The specific mass-balance as a function of position for the initial steady-states of the glacier A and B (red lines), with black arrows showing emergence velocities that balances surface mass balance at $t = 0$ year. The blue lines are the surface mass-balance profiles a year after a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

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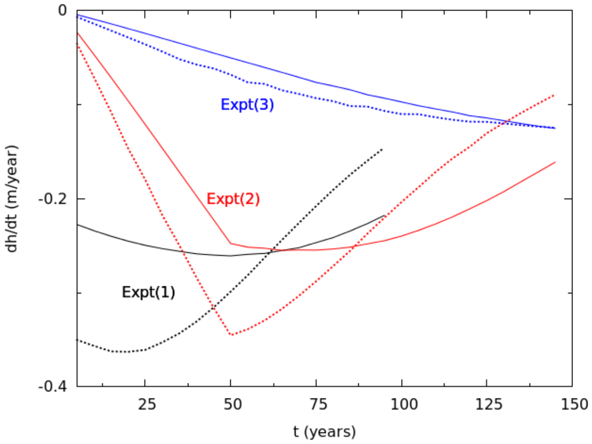

Figure 2. Evolution of thinning rate after ELA perturbations are applied to a model debris-covered glacier (solid line) and a debris-free glacier (dotted line). The warming rate profile for each of the experiment is described in section 3.