

Interactive comment on “Modeling debris-covered glaciers: extension due to steady debris input” by L. S. Anderson and R. S. Anderson

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Thank you for your comments. We addressed your critiques by (1) clarifying the purpose of our study; (2) simplifying overly-complicated writing and figures; and (3) emphasizing that this study models hypothetical glaciers and simply reproduces the ‘general patterns’ from real debris-covered glaciers.

>The model is suggested to be representative of glaciers in the Himalaya, relying on data presented by Scherler et al. 2011, but only weakly represents these glaciers using a few measured parameters from this region.

It was not our intention to suggest that our simulations are representative of glaciers in the Himalaya. While we do use parameters derived from glaciers in the Himalaya

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(because these glaciers are extensively studied) we also use a linear bed, fixed glacier width, and steady state which implies that our simulations are hypothetical in nature. No real glacier has a linear bed or fixed width.

Furthermore, this manuscript does not rely on the ‘general trends’ documented by Scherler et al., 2011. Rather our simulations and conclusions are completely independent of Scherler’s inferences. The similarities of the ‘general trends’ brought up by Scherler et al., 2011 and our simulations are strong evidence of debris’ influence on glacier response. We go through an extensive sensitivity test to show how different parameters in the debris-glacier system effect glacier response. Scherler’s ‘general trends’ are supported by our simulations, independent of our parameter choices. So the fact that some of our base parameters loosely represent glaciers in the Khumbu region does not invalidate our study.

To alleviate this confusion, we have explicitly stated in numerous locations that our simulations are hypothetical in nature and are not meant to represent Himalayan glaciers. We also highlight that our simulations reproduce the ‘general trends’ documented by Scherler et al., 2011 and are not meant to represent the many Himalayan debris-covered glaciers. Please see the comments below.

>The model design is not sufficient to represent the behaviour of specific glaciers in a region with highly negative mass balance and instead would be more convincing as a theoretical case.

The model design is sufficient to address the goal of this manuscript: to isolate the effect of debris on glacier response. We think that this manuscript does represent theoretical glaciers. It was not our intent to model the behavior of specific glaciers in High Asia as you suggest.

Please see the comments below to see how we have worked to make this more clear.

>In particular, the model only operates with steady state simulations, whereas the mass

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balance of present-day glaciers in the Himalaya is clearly far from equilibrium.

The model is fully-transient but we largely present steady-state results from hypothetical, theoretical glaciers. We provide the first means to evaluate the effect of parameter choice on debris covered glacier response through a detailed definition of debris-covered glacier steady state. Scherler et al., 2011 highlight 'general trends' in their dataset and show that the trends hold independent of glaciers with stagnant ice (see below). We merely show that our simulations match these 'general trends' independent of parameter choice (like bed slope, erosion rate, debris deposition location, etc).

>Relevance of the study to present-day glaciers. The introduction section almost exclusively considers glaciers with negative mass balances where mass loss has been ongoing for several centuries.

Most of the literature has focused on debris-covered glacier response to climate change; thus it is reasonable that most of the introduction would focus on this research. However, even though nearly all studied debris-covered glaciers are experiencing periods of negative mass balance, the presence of debris cover has also perturbed each of the glaciers mentioned in the introduction. Our model highlights the urgent need to isolate debris as an essential driver of glacier response. To clarify this point, we have overhauled the introduction to precisely introduce our study and the problem we address.

>However, the work presented here does not address glaciers in this condition, but rather those that are slowly advancing without a climatic driver.

The paper is theoretical in nature and seeks to highlight the effect of debris on glacier response. The parameters are loosely based on glaciers from the Khumbu region. We also vary the parameters to explore their effect. The results are still representative of Scherler's 'general trends.' We use a hypothetical, linear bed and a uniform width, and a steady piecewise linear mass balance profile. Our intent is not to limit studies that have addressed the effect of climate change on glacier response but rather to

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understand the effect of debris on glacier length so that we can then more clearly diagnose the effect of climate change of debris-covered glaciers. On page 6427 line 17-19 we note:

"This study lays the foundation for future modeling efforts exploring the response of debris-covered glaciers to climate change."

We have changed this line to better represent our intentions.

"By only assessing the effect of debris on glaciers, this study lays the theoretical foundation for efforts exploring the response of debris-covered glaciers to climate change."

>The comment on P6425 at line 15 is misleading; whilst a minority of Himalayan debris-covered glaciers are advancing (which may be due to distinctive surge-type behavior, although it is not clear here which glaciers the authors refer to), the majority lose mass by surface lowering rather than terminus recession (e.g. Bolch et al. 2011, TC), so comparison of their terminus positions over time is a poor metric by which to explore glacier change.

The citations at the end of the sentence to which the reviewer refers highlight the variable response of debris-covered glacier termini. We agree that mentioning that these debris-covered glaciers are losing mass by surface lowering is important. Thank you.

This paragraph now reads:

"Debris-covered glacier termini exhibit a wide range of responses to climate change (Scherler et al., 2011a). While almost all Himalayan debris-free glaciers are retreating, Himalayan debris-covered glacier termini are not responding coherently to climate change despite a strong trend toward negative mass balance (e.g., Bolch et al., 2011; Benn et al., 2012). Some Himalayan debris-covered glacier termini are advancing, others are stationary, and yet others are retreating (e.g., Raper and Braithwaite, 2006; Scherler et al., 2011a; Benn et al., 2012; Banerjee and Shankar, 2013). This discrepancy between debris-covered glacier mass balance and terminal response highlights

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the pressing need to understand the sometimes counterintuitive effects of debris on glacier response.”

Instead of dismissing debris-covered terminus positions over time as a poor metric for glacier change, we would argue that they are a metric of debris-covered glacier response that is poorly understood. Why would a debris-covered glacier terminus keep advancing even when it is responding to a period of negative mass balance and experiencing surface lowering? The modeling framework we present allows us to address this question (though not in the present study).

This paper goes through an extensive sensitivity analysis, with detailed methods and justification (see the appendices) to show how we can use debris-covered glacier length for comparison between glaciers. The terminus parameterization is novel and also highlights how the processes of debris removal at the toe can have important implications for the time evolution of debris-covered glaciers.

>Implications/impact of the modelling. The authors could revise the manuscript to instead consider hypothetical glacier change rather than by attempting to match observational data, still by using mass balance/flow parameters that are representative of real glaciers.

This modeling effort does in fact address hypothetical glaciers, though we did not explicitly state that they are hypothetical in the original manuscript. Of course no real glaciers have a linear bed or uniform width. We simply compare our theoretical results to the dataset of Scherler et al., 2011 in order to reinforce the 'general trends' they highlight. See our reference to text from the Scherler et al., 2011 paper below. In order to avoid this sort of misunderstanding we now more clearly state that we model hypothetical glaciers where we match the general observations of Scherler et al, 2011b.

We find it compelling that our theoretical, hypothetical model nonetheless, reproduces the general trend between AARs and debris cover and the general trend between relative glacier surface velocities and debris cover in Scherler's dataset. It is noteworthy

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that the simulations were run with no attempt to 'tune to' or 'match' Scherler's observations. Rather the comparison arose after the simulations were completed.

>The interest in this study for me is in exploring how debris-covered glaciers can advance in the absence of climatic change, transform into rock glaciers, and how these processes are observed in the geological record. Under what conditions will an advancing glacier retain sufficient supraglacial debris to significantly affect its mass balance? The authors state that these results have important implications for palaeoclimate reconstructions from glacial geology, which would be a valuable outcome from this study.

The aim of this study is to determine the effect of debris input on glacier response. This paper therefore has implications for both glaciers in the geologic record as well as implications for modern debris-covered glaciers (simply because there is debris present in and on them). The vast majority of extant glaciers are undoubtedly undergoing periods of negative mass balance. That said, it is valuable to highlight the effect of debris cover on glaciers so we can better understand the initial conditions for our numerical debris-covered glacier models and better model the response of debris-covered glaciers to climate change.

>Assumption of steady state. The main model output is change in glacier length, which is not a suitable variable for observation of debris-covered glacier mass loss when considering present-day glaciers with a generally negative mass balance, such as those in the Himalaya.

No glaciers have a linear bed or constant width so it is implied that these are hypothetical glaciers. We are not aware of a metric (besides length) for comparing the cumulative effects of debris on glaciers. We go through great effort to define and justify our steady state definition which in turn justifies our comparison of glacier lengths. We do also present AARs and the half-width velocities as model output.

We thought that the hypothetical nature of our simulations was implied because we

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were using a linear bed, constant width glacier with a steady climate forcing. We have emphasized why we make these choices to avoid confusion. We now highlight the hypothetical nature of our model in the abstract, introduction, and numerics/implementation section.

>Moreover, the authors should emphasize the usefulness of their steady-state simulations to this study; for example, P6426 line 24, clarify if/why one would expect debris-covered glaciers to ever reach equilibrium.

The steady-state assumption is widely used in debris-covered and debris-free glacier modeling. It is a useful concept to establish a baseline or initial condition from which to explore a system that then responds to a climate change scenario. Konrad and Humphrey, 2000 use a steady-state debris-covered glacier model. Banerjee and Shankar, 2013 model steady-state debris-covered glaciers and their response to climate change. Rowan et al., 2015 also use a steady-state glacier to simulate a late-Holocene extent of the Khumbu glacier.

Konrad and Humphrey, 2000 highlighted the importance of terminal debris transport and terminal ablation as a key process that could limit rock glacier/debris-covered glacier extent. Our manuscript expands on this notion and has a clear theoretical foundation from several debris-covered glacier modeling studies. Our definition of steady state goes beyond previous debris-covered glacier modeling studies by explicitly defining that steady state requires steady debris, steady geometry, and steady mass balance. It is important that this model conserves debris; as far as we know, other models have not dealt with this vital issue.

Our intent is/was not to reproduce 'real' debris-covered glaciers rather the steady state we define is a metric by which we can compare model simulations.

> The dataset presented by Scherler et al. 2011 captures glaciers where surface lowering is sustained and is therefore difficult to relate directly to the model results.

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It is important to note that we do state this in the manuscript before revisions P6441lines 23-28:

"The Scherler dataset was collected from glaciers responding to periods of negative mass balance. Reduced surface velocities under debris cover (not necessarily stagnant) – resulting from debris-covered glacier response to climate change – could account for the data with low debris cover percentages and low ratios of half length mean ice surface velocities (Fig. 11b)."

We are not trying to model or represent all debris-covered glaciers in High Asia or the Himalaya or 'relate directly' our results to Scherler's data. Rather, our intent is to reproduce a 'general trend' based on a suggestion that debris input perturbs AARs and shifts peak velocities up glacier. We only compare our hypothetical results to glaciers from the Scherler et al., 2011 dataset. Scherler et al., 2011 makes a compelling case for a 'general trend' in debris-covered glacier AARs and surface velocity patterns. Our analysis also shows extensively how changing h_{star} , bed slope, debris deposition location, and debris flux would effect the model results in the context of the Scherler et al., 2011 dataset. Despite our inability to model the specifics of all debris-covered glaciers in High Asia, we believe that our analysis quantifies the 'general trends' laid out by Scherler et al., 2011.

We are now quoting from Scherler et al., 2011 paragraph [47]:

"[47] When hillslope-derived debris is deposited in the accumulation zone of a glacier, it first becomes englacial during its transport downstream and, at higher concentrations, may reduce the amount of ice deformation [Russell, 1895; Paterson, 1994] and influence basal sliding [Iverson et al., 2003]. On the glacier surface, however, its main effect is modulating melt rates and thus mass balances. Because debris thicknesses on Himalayan glaciers are usually greater than a few centimeters [e.g., Shroder et al., 2000; Owen et al., 2003; Heimsath and McGlynn, 2008], the insulating effect dominates so that melt rates are lower compared to clean ice [Mattson et al.,

C3104

1993; Kayastha et al., 2000; Mihalcea et al., 2006]. Lower melt rates allow debris-covered glaciers to grow longer for a given accumulation area, hence decreasing the accumulation area ratio (AAR; Figure 3). Because only the ablation zone grows larger, the position of the maximum velocity along a glacier's length, usually located near the ELA or the climatic snow line (Figure 6), should shift upstream as debris cover increases. This inference is supported by our velocity data (Figure 12) and results from a simple numerical model of a debris-covered glacier [Konrad and Humphrey, 2000]."

Scherler et al.'s 2011 data on AARs is presented in figure 11 A and B. Our model hypothetical/ theoretical model simply reproduces the 'general trend' laid out by Scherler et al., 2010.

and paragraph [49] from Scherler et al., 2011:

"We note that many Himalayan glaciers have been retreating and/or thinning during the past few decades [e.g., Berthier et al., 2007; Bolch et al., 2008a; Raina, 2009], and may have been doing so since ~1850 AD [Mayewski and Jeschke, 1979]. This has potential effects on the observed velocity distribution. In particular, heavily debris covered glaciers that are thinning [Bolch et al., 2008a], but not necessarily retreating [Scherler et al., 2011], could result in a gradual shift of maximum velocities upstream and exaggerate the trend we observe. However, the upstream shift of peak velocities with increasing debris cover (Figure 12a) is also observed when excluding stagnating glaciers, suggesting that this is a general trend."

This "general trend" is presented in the Scherler et al., 2011 data in figure 11 B and D. Our model hypothetical/ theoretical model simply reproduces this trend. The fact that our simulations in steady state can reproduce the 'general trend's documented by Scherler et al., 2011 makes the effect of debris on glacier response even more compelling. I emphasize again that our results and conclusions are independent of the comparison to Scherler's observations. We compare the results to lend support to our

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conclusions and make our study more compelling.

>The impact of climatic change on debris-covered glaciers could be discussed by reference to transient simulations by Rowan et al. 2015, EPSL.

We have added reference to the Rowan et al., 2015 paper in both the introduction and discussion with reference to both the paper's transient and steady-state simulations. We only found the Rowan et al., 2015 paper after the paper was submitted. We apologize for any frustration on your part. We did not cite it because we were not aware of it before we submitted the paper.

>Relevance to Himalayan glaciers. The simulations presented here cannot be considered to represent 'real' glaciers as the model design is too simplistic to capture the key factors controlling the behavior of these glaciers, such as high relief, variable bed topography, highly variable flow velocities, and highly negative mass balances.

We do use a simplified model design because we want to understand a specific portion of debris-covered glacier complexity: the effect of debris delivery on glacier length/dynamics, which we consider a pre-requisite to understanding glacier response to climate change. The model set up allows for a wide range of complexity without considering 'high relief, variable bed topography, highly variable flow velocities, and highly negative mass balances.' By including all of these complexities we argue that it would be more difficult to isolate the effect of debris on glacier response. As a result we chose the 'simplified, hypothetical' model framework.

The linear bed is necessary for this study because it allows us to isolate the effect of debris on glaciers. Without the linear bed our results would conflate the effects of a non-linear bed with the effects of debris on glacier response.

The introduction has been greatly modified to highlight our intent to isolate the effect of debris on glaciers. We have also added notes in the 'Implementation and numerics' section that explain why we use a linear bed.

C3106

>While the model parameterization may be more representative of Himalayan glaciers at some point in the geological past, the assumption of steady state undermines the relevance of the study to a complex set of glaciers in a variable climatic regime.

This study does use a hypothetical framework and it is not intended to represent any single glacier or 'real' glacier in the Himalaya or High Asia. Our intent in plotting the data from Scherler et al., 2011 with our model results is to show that the model reproduces the 'general trend' that Scherler et al., 2011 highlights. Along these lines we have better highlighted in the text that we only intend to match the broad observations laid out by Scherler et al., 2011 and emphasized that that Scherler data stems from glaciers responding to negative mass balance.

>The comparison to glaciers in the Himalaya or indeed elsewhere, does not add value to the paper as there is no clear indication that mountain glaciers ever approach steady state over decadal–centennial timescales.

While it is true that mountain glaciers do not likely reach steady state (at any timescale) due to the effect of interannual climate variability, transience in glacier dynamics, or stochastic debris input, modeling glaciers in steady-state allows us to compare the effect of parameters on glacier response in a quantitative fashion. And it is compelling none-the-less that our steady-state simulations reproduce the broad observations of the Scherler et al., 2011. This suggests that debris has an important effect on basic glacier properties. Our manuscript quantifies that effect.

>This could be addressed by considering longer-term change over glacial cycles where small climatic fluctuations could be “averaged out” by much larger glaciers.

This is an interesting suggestion but it is well outside the scope of the current study.

>Manuscript style. The manuscript is mostly well written, but would benefit from being more accessible to a glaciological and geological audience.

We agree that the paper could be more accessible. We have revised the introduction,

C3107

clarified where necessary, and removed jargon. We have improved the legibility of figures 8 and 9. We also clarified the Appendices and added an new explanatory figure in Appendix A. We have also used prose instead of variable names where appropriate to make the text more legible.

> The introduction does not really describe the specific problem considered in the study.

We have revised the introduction to address the specific problem we pose as you imply. This should improve the accessibility of the manuscript to a broader audience. Thank you for pushing us to look at the introduction again.

>Even with similar interests to the topic of this manuscript, I found the detail of text and figures somewhat dense and difficult to follow in places.

Our manuscript presents a significant number of new quantitative approaches to modeling debris-covered glaciers. Because of the sheer number of parameters and the complexity with which they interact the text will inherently be technical. Also because of the wide range of parameters explored and the number of simulations we ran our figures contain a lot of data. We feel that the number of simulations we present supports the robustness of our conclusions and is a strength of the paper.

With that said we have streamlined the text throughout. We also improved the legibility of several figures and captions. It would have been helpful if you listed the figures you struggled with and specifically listed what you found difficult.

>In particular, the relevance of different parameters noted to impact on and be affected by glacier behaviour (debris cover, AAR, glacier velocities, etc.) should be discussed quantitatively in light of the outcomes from the modelling experiments.

We are not sure how making our results more quantitative will improve the legibility of the figures and text. Because we explore a wide parameter space adding more numbers that are dependent on the specific parameter choice will only make the manuscript less legible especially as we would then have to list all of the parameter choices that

C3108

the results depended on. We have made efforts to improve and streamline this section just the same.

>Minor points Title: would better describe the study and read more readily without the colon. Suggest: “Modelling the extension of debris-covered glaciers due to steady debris input” or similar, as the model presented in this manuscript simulates this rather than all aspects of glacier change.

We feel that your suggested title is purely a style choice. Thank you for the suggestion but we are happy with the title as it reads.

>Abstract: should include more clearly quantitative results, for example, the conditions of the experiment described by “Our model and parameter selections produce two-fold increases in glacier length.” is not clear.

Because we explore a wide parameter space and use a hypothetical glacier geometry adding quantitative results that are dependent on the specific parameter choice/model set will only make the abstract less legible especially as we would then have to list all of the parameter choices that the results depended on. While “Our model and parameter selections produce two-fold increases in glacier length.” is general it is representative of the strong length enhancing effect of debris-cover.

>P6425, line 2: Scherler et al. 2011b is cited before 2011a.

This was corrected. We cite Konrad and Humphrey, 2000 Instead.

>P6425, l 5: “ablation” rather than “melt”

This is changed in the manuscript. We removed ‘melt rate’ and replaced it with ‘ablation’

>P6425, l 14: what is meant by “almost coherently”?

“almost coherently” was removed and replaced with ‘almost all’

C3109

>P6427, l 4–5: please phrase the problem more precisely, e.g. “how does the location/timing/frequency/magnitude of debris delivery and the description of the relationship between debris thickness and ablation affect change in glacier length/rate of advance/mass balance, relative to glacier morphology (e.g. size, shape, etc.)”.

We rewrote this paragraph to make the purpose of this study more clear. Because we address a number of issues linking debris and glaciers we prefer to highlight the problem in a paragraph as opposed to a sentence:

“Here we attempt to improve our understanding of the debris-glacier-climate system (and subsequently better project future glacier change) by isolating how each component (debris, glacier, and climate) in the system affects all others. While significant effort has focused on glacier-climate interaction, less research has focused on isolating the effect of debris on glacier dynamics, glacier length (e.g., Konrad and Humphrey, 2000), or glacier response to climate change. We address debris-glacier interactions by isolating the role of debris in governing basic glacier dynamics and glacier length.

We use a simple glacier model to simulate hypothetical debris-covered glaciers. This new framework allows us to isolate the effects of debris on glacier response by controlling the potentially conflating effects of a variable bed, variable glacier width, or a temporally variable climate. To isolate the effect of debris on glacier response, we start each simulation with a steady state debris-free (ssdf) glacier and impose a step change increase in debris deposition rate while holding climate steady. In many debris-covered glacier systems, debris is deposited in the accumulation zone, advected through the glacier, and emerges in the ablation zone (e.g., Boulton and Eyles, 1979; Owen and Derbyshire, 1989; Benn and Owen, 2002; Benn et al., 2012). Our new transient 2-D numerical model (x, z) links debris deposition, englacial debris advection, debris emergence, surface debris advection, debris-melt coupling, debris removal from the glacier terminus, and shallow-ice-approximation dynamics (Figs.~1 and 2). We provide a new terminus parameterization which allows for the use of glacier length as a metric for comparison between simulated debris-covered glaciers. This new framework allows

C3110

us to explore the sensitivity of hypothetical debris-covered glaciers to debris thickness-melt formulations or changes in debris-input related variables like debris flux, debris deposition location, and debris deposition zone width. We compare our theory-based results to the 'general trends' documented by Scherler et al. (2011b). By only assessing the effect of debris on glaciers, this study lays the theoretical foundation for efforts exploring the more complex response of debris-covered glaciers to climate change."

>P6428, I4: are these simulations run over thousands of years?

Yes. We are running a fully-transient model from a debris-free steady state to a debris-covered steady state, which takes thousands of years in most cases. Please see Figure 4, and Figure 12.

>P6436, I23: for Khumbu Glacier debris-covered ice mass balance, see also Benn and Lehmkuhl, 2000, Quaternary International, and references therein.

Thank you for the reference.

We make no change here because we use the Wagnon paper to guide our parameter selection.

>P6443, I24–26: this is not a helpful conclusion for those investigating palaeoclimate indicators in high mountain environments! Could your model results be used to reduce these uncertainties?

We are not sure why this is not a helpful suggestion. Debris cover can have a considerable effect (at least a two fold effect for the on glacier lengths for the parameter space we explore). So in addition to changes in precipitation and summer temperature the input of debris therefore becomes an important parameter for paleoglacier modeling. Knowing the detailed history of debris input to a specific paleo-glacier seems very difficult. From our perspective the best way to estimate paleoclimate from former glacier extents is to avoid catchments that were strongly perturbed by debris or to explore the full uncertainty associated with debris input rates and locations.

C3111

The sentence has been modified:

"The effect of debris on paleoclimate estimates can be mitigated by avoiding deglaciated catchments with high-relief headwalls, supraglacially sourced moraine sediments, or by using a debris-glacier-climate model to estimate the effect of debris on glacier extent."

>P6446: The "Future Work" section would be more usefully presented as "Limitation of the current study" or similar, to help the reader evaluate the strengths and weaknesses of the approach and results presented. The authors are then free to investigate these in future without asking the reader to wait to discover the value of the present study.

While we do not believe that readers will be confused by the title of this section, we do agree that it could be improved. It has been changed to:

"Potential model improvements and future research"

>P6447, I7: what is meant by "memory in the system"?

"memory in the system" refers to the fact debris-covered glaciers respond to mass wasting events that occurred in the past. So the system (the debris-covered glacier) is responding to depositional events in the past (the memory).

The sentence now reads: "Debris advection through and on a glacier can take hundreds of years, leading to memory in the system (i.e., the glacier responds to debris input from the past)."

>P6447: Some of the points presented in the conclusions could be drawn from previous work rather than the current study and can be removed to the introduction.

We state in the conclusion that that our 'simulations show that:' These conclusions can be directly drawn from our results and we are therefore comfortable keeping the conclusions as they stand. It would have been helpful if you included which conclusions should be moved to the introduction.

C3112

>Quantitative outcomes of the present study are needed in the conclusions (and the abstract) to demonstrate where the most important sensitivities of debris-covered glaciers are.

Because of the considerable parameter search we are not sure how to present quantitative results that would be meaningful. This manuscript is meant to help improve our theoretical understanding of how glaciers respond to debris input. We therefore do not include quantitative results in the conclusion as we would also have to include the parameters used to define these results.

>Finally, the conclusions would preferably be written as continuous prose rather than bullet points.

We prefer the bulleted style because of the diversity of conclusions. It is also easier to see each of the conclusions when a reader takes a quick glance.

We did change the leading sentences in the conclusion: “Before modeling the response of debris-covered glaciers to a warming climate, it is helpful to constrain how debris effects glaciers – independent of climate change.”

to

“It is necessary to constrain the effect of debris on glaciers so we can better predict and model the response of debris-covered glaciers to climate change.”

Interactive comment on The Cryosphere Discuss., 9, 6423, 2015.