Review of Compagno et al, Modelling supraglacial debris-cover evolution from the single glacier to the regional scale: an application to High Mountain Asia

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Overview

This is an interesting study that simulates the expansion and thickening of debris and its affect on the response of debris-covered glaciers to climate change in HMA. There are new, simple parameterizations presented to represent the expansion and thickening of debris for application on both the individual and regional scales. It is shown that based on these parameterizations of debris thickness change and the *assumptions held within* that debris cover plays a minor role in glacier-wide mass balance evolution for simulations of HMA glaciers run out to 2100.

I applaud the immense effort put into this work and the novel contributions made. There are a number of exciting inferences and conclusions. But there are some major issues that need to be addressed before it is ready for publication.

Major comments

Correct citing of Equation 1
Some important citations are omitted. Some of which need to be cited or (I hate to have to say it) plagiarism is occurring. I am directly referring to Eq. (1) which was derived in its exact form by Anderson and Anderson (2016). This model is also presented in detail in the debris cover melt model intercomparison project manuscript (Pellicotti et al., in prep). This form of Østrem's curve is also referred to as the *hyper-fit model* by (Anderson et al., 2021a, b). I am personally glad it is useful it but *please* cite it appropriately.

Neglected role of surface velocity in thickening and expanding debris
The mass conservation equation for surface debris thickness change in time on a glacier surface includes debris melt out and dynamic re-distribution of debris:

$$\frac{\partial h_{debris}}{\partial t} = \frac{C\dot{b}}{(1-\phi)\rho_r} - \frac{\partial u h_{debris}}{\partial x} - \frac{\partial v h_{debris}}{\partial y} \qquad (3)$$

where C is near-surface englacial debris concentration, φ is the porosity of the debris, ρ_r is the density of the rock composing the debris, and u is surface velocity in the x-direction and v is surface

Debris melt out is represented by the first term on the right and dynamic re-distribution of debris is represented by the second two terms on the right. This form is taken form Anderson et al. (2021b).

The parameterizations for debris thickness change presented here (Eqs. 4 and 6) do not include the effect of ice dynamics in changing debris extent or thickness. Equation 6 in this paper really only takes into account the debris melt out term in that debris thickness change is directly related to the melt rate as it varies in time by a factor (Eq. 4 is very similar):

$$h_{z,t} = h_{z,t-1} + abs(b_{z,t}) \cdot \overline{B_{(t-9,t)}} \cdot (-1) \cdot \overline{h_0} \cdot c_{thickening}, \quad \text{if } \gamma_{z,t-1} = 0 \tag{6}$$

where $h_{z,t}$ is the debris thickness for elevation z and time t. $c_{thickening}$ is a calibration parameter for the debris-cover thickness evolution, constrained based on observations (see section 4.2). As for lateral debris expansion, the local mass balance $b_{z,t}$ relates linearly to debris thickness change. Higher melt rates will lead to faster debris thickening, thus implicitly assuming that debris concentrations within the ice are homogeneous. The long-term glacier-wide mass balance $\overline{B_{(t-9,t)}}$ mimics ice-dynamical processes. It leads to constant debris thickness for steady-state conditions ($\overline{B_{(t-9,t)}} = 0$), and to decreasing local debris thickness for consistent mass balances, thus mimicking the evacuation of debris with enhanced flow. This is in line with the few direct observations that are available (e.g. Gibson et al., 2017; Verhaegen et al., 2020). $\overline{h_0}$ is the mean debris thickness of the glacier at the inventory year. It parametrizes the effect that glaciers with a low mean debris thickness will thicken slower compared to glaciers with a high mean debris thickness. This is motivated by the assumption that glaciers with thick debris are likely to have a higher englacial debris concentration, indicative for high debris supplies from the surroundings.

Anderson and Anderson (2018) notes, using a theoretical analysis, that debris thickness patterns are strongly controlled by the inevitable decline of surface velocity down glacier. This is also basically outlined by Kirkbride (2000) and further supported by the modeling presented in Ferguson and Vieli (2021). I have not seen a compelling a reason in this manuscript why surface velocities should be neglected when considering the evolution of debris covers.

Furthermore, Anderson et al. (2021b) presents evidence that the dynamic effects of debris thickening (debris advection and debris compression) are unavoidably important for the thickening of debris in response to climate change. The dynamic affects on debris thickness are especially important where surface velocities are low and debris already tends to be thick. Meaning that debris might thicken substantially right where the model/parameterizations presented here is not accounting for it. This is because the thickening parameter is tuned with debris thickness estimates from the upglacier end of debris covers.

Anderson et al. (2021b) also shows how changes in flow patterns can change debris extent (I do believe this is mentioned breifly). I recognize that Anderson et al. (2021b) was published as this paper was coming out in TCD, but the work has direct implications for the parameterizations presented in this study.

I don't think the neglect of the role of ice dynamics makes this work invalid, rather the fact that the dynamical terms in the debris conservation equation are neglected should really *be discussed* and *stated very clearly in this paper*. Right now half of the continuity equation for debris change is assumed to be negligible in this manuscript, but the affect of surface velocities on debris thickness is not negligible even where surface velocities are low.

It is difficult to evaluate this work without reading McCarthy et al., submitted and understanding how the debris thicknesses across HMA were estimated. I am not sure where to access that manuscript. How many validation data points are used to evaluate the debris thickness estimates in that study? What do the debris thickness patterns look like? In some way this pre-requisite work needs to be made available be thorough description here or elsewhere.

Minor comments

There are places in the manuscript where the modelling results seem to be presented as reality but are really still just modeling results that rely on all of the assumptions inherent to the model design. More care should be taken to avoid overstatements.

I also wonder: How do the debris change evaluations change if the evaluating datasets are not used in the tuning process?

Line-by-line comments

Line 3: You could remove 'potential' here

Line 5-8: The sentence should be split in two as it is hard to follow as written.

Line 10: 'previous projections' would maybe be better here.

Line 15: no need for a '-' between debris and cover.

Line 48-51 see the inversion for debris thickness change by Anderson et al. (2021b) as an example of debris thickening. This paper also highlights how the change in direction in flow can lead to debris expansion.

Line 86. remove plural from 'glaciers'

Line 97. What do the variables represent beyond free parameters? I am surprised that Anderson and Anderson (2016) are not cited here. As that work originally derived this form of Østrem curve and discussed what these free parameters represent in detail. The model is called 'Hyper-fit' in Anderson et al., (2021a) and Anderson et al. (2021b). I hate to have to say this by as the text is written this is plagiarism. Please cite this appropriately.

Figure 3. The text in the figure is not legible in places.

Line 205. not sure what 'from the surroundings' means here.

Line 207. Deline (2005) is a valuable citation here.

Section 3.2.2 this is an interesting parameterization but it should be stated that you *assume* that debris expansion is directly related to ELA change. As far as I am aware there are no datasets that show this as a direct relationship. Snowline change on glaciers is instantaneous but debris melt out does not need to be. This relationship is dependent on where englacial debris is present within the glacier.

Line 221. "As for the lateral expansion of debris, the evolution of debris thickness is linked to internal debris concentration and glacier mass balance (e.g. Gibson et al., 2017; Mölg et al., 2019; Verhaegen et al., 2020)."

Please see Anderson et al. (2021b) for a detailed process-based simulation of debris thickening that shows the importance of debris advection and compression (both highly dependent on surface velocities) as well as debris melt out.

Line 221. Also the change in surface velocity of the glacier: see Anderson et al (2021b)

252. 'w.e.a −1' add a space.

270. At this point I had forgotten what S1 was. Might be helpful for readers to remind them here?

Section 4.2.2 This is a clever approach but again this is emphasizing the role of debris melt out as the only process that causes debris thickening. It is again hard to know though the validity of the McCarthy dataset without access to the errors from in situ debris thickness measurements.

Section 5.2 It would be helpful to remind the reader where the pre-2000s climate forcings are coming from for the evaluation of the debris change. Maybe just re-state it or reference the section.

313. So you evaluate the lateral expansion parameretrization against the data that you used to tune it? I wonder how the parameterization works on glaciers that are independent of the tuning dataset?

344-346. This is an overstatement. Being off by 10 cm or ~20 cm of debris thickness, using the h_star values (same as (k_debris) in Equation 1) (the debris thickness change needed to reduce sub-debris melt rates by 50%) from A and A (2106) mean sub-debris melt rates are off by 50 to 100% or 200 to 400%. This uses h_star values = 5 cm and 10 cm. These percentages will be even bigger with melt amplification effects included. Since the evaluation of the debris thickness change estimates are coming from the upglacier end of debris covers the errors are actually quite large.

Figure 7. It would be helpful for the reader if the x axis was extended beyond +-200 m

358. In the ablation zone or across the whole glacier?

439-440. "In fact, accounting for the debris cover explicitly enables the model to correctly represent the driving processes, rather than compensating the lack of model capabilities through a suitable parameter choice."

I suggest that this be re-written as it is a significant overstatement from my reading. The explicit model presented here neglects the role of debris advection and compression and is evaluated with highly uncertain modelled debris thickness estimates. I would replace 'correctly' throughout this paragraph.

446. Citations would be helpful here.

Section 7.2 Nice to have this clear statement of the sensitivity!

457. Also from the assumptions held within each parameterization.

Section 7.3 Interesting analysis/results.

519. when only debris melt out is included.

528. typo

References

Anderson, L. S. and Anderson, R. S.: Modeling debris-covered glaciers: response to steady debris deposition, 10, 1105–1124, https://doi.org/10.5194/tc-10-1105-2016, 2016.

Anderson, L. S., Armstrong, W. H., Anderson, R. S., and Buri, P.: Debris cover and the thinning of Kennicott Glacier, Alaska: in situ measurements, automated ice cliff delineation and distributed melt estimates, The Cryosphere, 15, 265–282, https://doi.org/10.5194/tc-15-265-2021, 2021a.

Anderson, L. S., Armstrong, W. H., Anderson, R. S., Scherler, D., and Petersen, E.: The Causes of Debris-Covered Glacier Thinning: Evidence for the Importance of Ice Dynamics From Kennicott Glacier, Alaska, 9, 19, 2021b.

Deline, P.: Change in surface debris cover on Mont Blanc massif glaciers after the‘Little Ice Age’ termination, 15, 302–309, https://doi.org/10.1191/0959683605hl809rr, 2005.

Kirkbride, M. P.: Ice-marginal geomorphology and Holocene expansion of debris-covered Tasman Glacier, New Zealand, in: Debris-Covered Glaciers, Proceedings of a workshop at Seattle, Washington, USA September 2000, 211–217, 2000.