Dear Colleague,

Thank you for your helpful comments and feedback on our manuscript.

Please note that in the revised version of the manuscript we have corrected an important issue with the glacier albedo scheme, wherein the surface albedo was being reset to the value of fresh snow after only very small amounts of precipitation. Specifically, when we updated the coupled model to WRF v. 3.6.1 and the land-surface parameterization to the Noah-MP scheme, we inadvertently retained the criteria of the Noah scheme for resetting the surface albedo to the value of fresh snow, which is a frozen fraction of precipitation of 50%.

Since submitting the manuscript, we applied the model in a study of the Nepalese Himalayas, where in situ measurements revealed that a threshold based on the depth of solid precipitation, of ~1 cm, greatly improves the simulation of glacier surface albedo. This threshold is in agreement with both the default option in the Noah-MP LSM and in the latest version of the CMB model. Therefore, we adopted a 1-cm threshold and repeated the DEB and CLN simulations with an otherwise identical model configuration.

In Fig. R1, we compare altitudinal profiles of the basin-mean snow albedo in July and August 2004 from the MODIS Aqua/Terra (MOD10A1/MYD10A1; 500-m resolution) datasets with (i) the CLN simulation we showed in the discussion paper ("old") and (ii) the CLN simulation we have incorporated into the revised manuscript ("new"). The old simulations have a high glacier surface albedo (> 0.7) down to ~ 4000 m, which explains a significant part of the cold bias we struggled with in the discussion paper. Conversely, the new simulations provide a basin-mean profile that is in much closer agreement with MODIS.

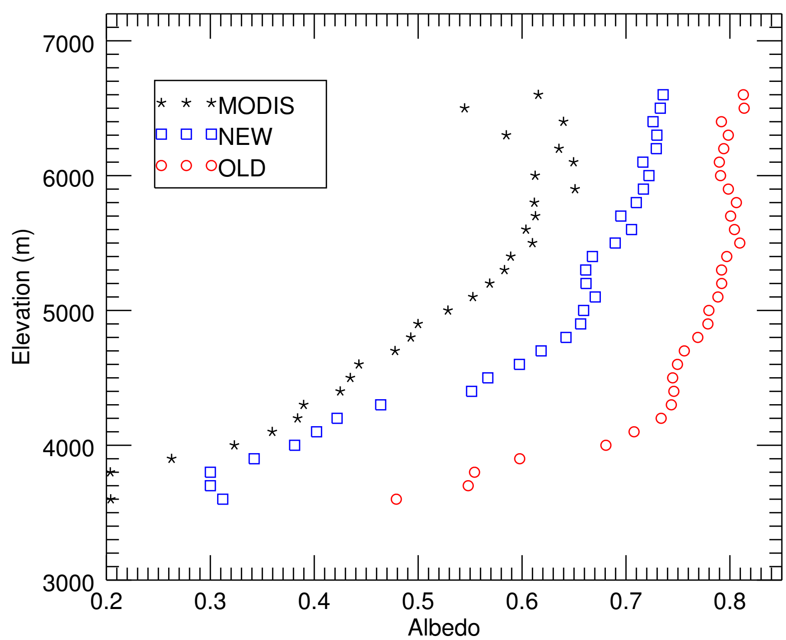

Figure R1: Elevational profiles of snow albedo in MODIS MOD10A1/MYD10A1 (black marker), the CLN simulation in the discussion paper, and the CLN simulation in the revised manuscript, averaged over glacierised grid cells in WRF D3 and the months of July and August. Valid MODIS data with the highest quality flag were used and WRF-CMB data were taken from the corresponding grid cells and time periods for comparison.

The alteration does not change any of the conclusions of the paper; however, it reduces some issues and inconsistencies that were present in the discussion paper, including:

- the maximum number of snow-free debris-covered grid cells exposed over the simulation has increased from ~ 60% in the discussion paper to more than 90% in the revised manuscript, which is more plausible.
- simulated ablation in the debris-free study of Collier et al. (2013) and the CLN simulation in this study are now in much closer agreement.

With the improved simulation of glacier surface albedo, more than 35% percent of debris-covered pixels are exposed between 1 July and 15 September 2004, giving a reduction in mass loss below the zero-balance altitude of 18% (compared with 10% in the discussion paper). Finally, considering the whole simulation period, the reduction in basin-mean ablation by 1 October 2004 in DEB compared with CLN is 14% (compared with 7% previously).

Please find our replies to your comments (**bold**) below, including modifications to the manuscript text (*italics*).

Best regards,
Dr. Emily Collier

<u>**Specific comments**</u>
Section 2.3.
The parameterisation as debris thickness, d, as a function of length with a gradient of 0.75 cm km-1 generates 'thick' debris, but only on extremely long glaciers, e.g. the maximum thickness on a 20 km glacier would be just 15 cm. I think this value is unrealistically low as there is evidence from Himalaya, e.g. Rounce and McKinney, 2014; TC 8, 1317-1329, and elsewhere, e.g. Mihalcea et al., 2008, Cold Regions Science and Technology, 52, 341-354 of 30 cm + thickness debris being extensive on much shorter glaciers. Hence, the debris thickness gradient is probably steeper on shorter glaciers leading to an underestimate of d on many glaciers in the study. However, the authors are probably correct that most of the 'energy balance impact' of debris occurs in the first 20 cm or so in addition to acknowledging this likely underestimation, this point is really a consideration for future work.
We created a new paragraph in the discussion section to address this point and other potential issues with our approach:

"The alterations to the glacier energy and mass fluxes and to atmosphere-glacier interactions presented in this study are based on the ablation season of 2004 only and are sensitive to the debris thickness field, with small adjustments to the thickness gradient resulting in large changes in basin-mean glacier CMB. The gradient was consistent with ASTER-derived thickness data on the Baltoro glacier (Mihalcea et al. 2008a) except close to the terminus. <u>However, our approach results in peak thicknesses of less than ~15 cm on glaciers less than 20 km in length, while other studies in the Himalaya and elsewhere have reported much higher depths on glaciers of similar lengths (e.g., Mihalcea et al. 2008b;</u>

Rounce and McKinney 2014). Thus, the impact on glacier ablation that we reported likely represents an underestimate, due to non-linear effects near termini and the likely presence of steeper thickness gradients on shorter glaciers. Additional sources of uncertainty in our results include (i) the temporal discrepancy between our study period and the clean snow/ice mask of Kääb et al. (2012) used to delineate debris-covered areas, which was generated using Landsat data from the year 2000; and, (ii) our binary assignment of surface types as "debris-covered" or "debris-free" using a 40% threshold."

Section 3.3

2273, 4-5, the presence of debris results in >800 additional melt hours compared with bare ice. On p 2275 you discuss a very interesting feedback via energy emission to the lower layers of the atmosphere from sun-warmed debris resulting in higher air temperatures and hence increased melt rates. Is an additional explanation the fact that debris surface temperature can exceed 0 deg. C, resulting in conduction of energy to the ice, even when air temperature is <0.

Figure R2 shows the simulated hourly melt rates [cm w.e. hr^{-1}] in DEB at snow-free debris-covered grid cells when the near-surface air temperature is below 0°C and the debris surface temperature exceeds 0°C. Non-zero melt rates are simulated in 11683 out of a total of 17553 total hours at all grid-points that satisfy these conditions. Thus, we agree that this additional explanation likely also contributes to sub-debris melt rates. Thank you for your suggestion.

We amended the relevant sentence in the discussion/conclusion to, *"The interactive nature of the simulation may permit a positive feedback mechanism, in which higher surface temperatures over thicker debris transfer energy to the atmosphere, in turn promoting higher air temperatures and further melt. Even when the air temperature is below 0°C, energy conduction when the debris surface temperature exceeds this threshold likely also contributes to sub-debris ice melt, which is supported by our simulations."*

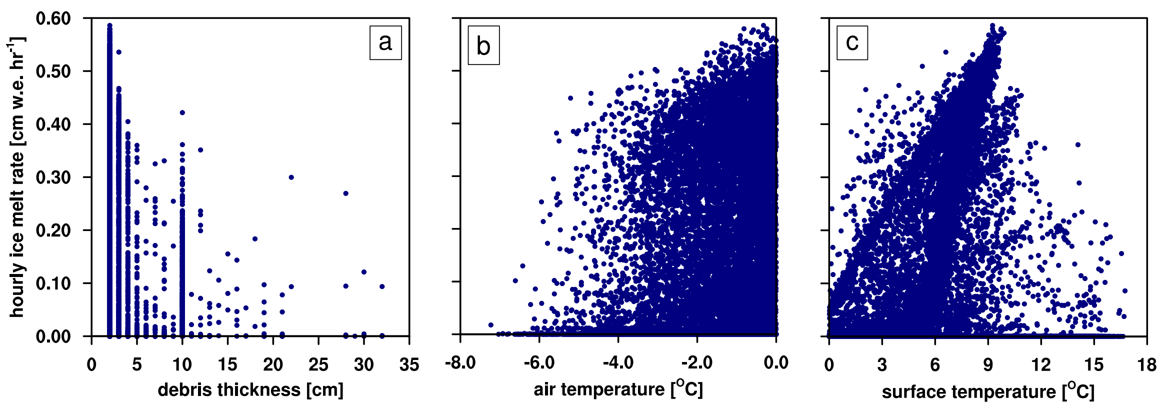

Figure R2: Hourly sub-debris ice ablation rates [cm w.e. hr^{-1}] in DEB at snow-free debris-covered grid cells between 1 July and 15 September 2004, compared with (a) debris thickness, (b) air temperature in the (from the lowest model level; [°C]); and debris surface temperature [°C].

2273, 5-7. Surely, it isn't only during 'melt hours' that DEB Qs flux to the atmosphere is greater than CLN as implied here. Debris could still be a lot warmer than the air and supply heat to the atmosphere when temperatures are below zero.
We rephrased the sentence to clarify that the difference in energy transfer by QS that we calculated included all time periods, not only hours with surface temperatures above 273.15: *"The presence of debris results in up to 700 additional hours with surface temperatures above 273.15 K in DEB compared with CLN (Fig.9b), which provide a strong heat flux to the atmosphere. Considering all hours between 1 July and 15 September, an extra* $3.5x10^7 W$ *of energy is transferred to the atmosphere in DEB between by the sensible heat flux."*

There isn't much discussion of latent heat flux in Section 3.3. An interesting observation in figure 10b is the slightly increased precipitation for the DEB runs at highest elevations, particularly >7 km. Why? Is this due to additional moisture input from debris, or from enhanced convection?
We chose not to focus on alterations to the latent heat flux, since the parameterization was developed using eddy-covariance measurements on the Miage glacier in the Italian Alps (Collier et al. 2014) and has not been evaluated specifically for the Karakoram region. Please also see our replies to your comments on Sect. 4 and the discussion section for more details.

The difference in accumulated precipitation is small, especially in the new simulations (Fig. R3, which shows the updated version of Fig. 10 in the revised manuscript). In addition, there are only 9 glacierised grid cells above 7 km, which means that the difference between DEB and CLN above this elevation is not a robust spatial pattern. We think the general pattern (slight decrease in DEB at the lowest elevations and slight increase at the highest elevations) is consistent with alterations to orographic precipitation by the presence of debris, namely that higher near-surface temperatures and thus lower relative humidities over exposed debris contribute to slower cooling and saturation of air moving upslope and, as a result, to a slight up-glacier shift in surface precipitation.

We added a final paragraph to Sect. 2.3: *"In the following section, we evaluate and compare the DEB and CLN simulations, often focusing on altitudinal profiles where variables are averaged in 250-m elevational bins. Note that in these profiles there are only 3 (9) glacierised grid cells present below 3250 m a.s.l. (above 7000 m), compared with at least 17 grid cells and up to 1100 in between these elevations. In addition, when computing basin-averaged quantities, we excluded the bordering 10 grid points in WRF D3 (5 of which are specified at the boundaries)."*

We changed the relevant sentence in Sect. 3.3 about Fig. 10b to, *"Basin-mean accumulated precipitation ranges from 50—175 mm w.e. below 5000 m and increases approximately linearly with elevation above this level. The area-averaged differences between CLN and DEB are very small, with a slight decrease (increase) at the lowest (highest) elevations in DEB, consistent with warmer and thus less humid conditions contributing to slower cooling and saturation of air moving upslope and a shift of surface precipitation up-glacier.*

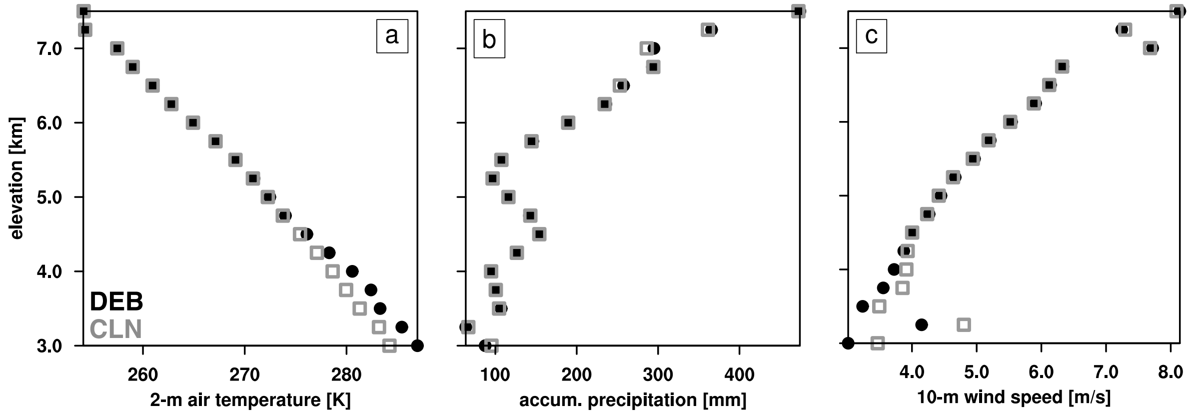

Figure R3 (updated version of Figure 10 from the manuscript): Elevational profiles of near-surface (a) air temperature [K] and (b) accumulated precipitation mm and (c) wind speed at a height of 10 m, from the DEB (black-circle markers) and CLN (grey-square) simulations between 1 July and 15 September 2004.

Section 4

2274, 23-27. "Accounting for vapour fluxes increases the net loss by 3.7% compared with CLN and comprises 8.7% of the total negative mass flux in DEB" How can net loss (assuming this means mass loss) be greater than for CLN when earlier in the paragraph the opposite conclusion is drawn (i.e. debris cover reduces glacier mass loss by 7% over the whole basin and by >2.5 m w.e. at lowest elevations). Is the mass loss from ice which melts and subsequently evaporates counted twice?: once in the melting of ice and second when it evaporates. This ignores the fact that most meltwater from clean ice melt runs off so it isn't a consistent comparison between DEB and CLN.

We agree that this sentence was confusing. We were referring to the net loss by the vapor fluxes. We updated and clarified this sentence to, *"In the DEB simulation, the latent heat flux over exposed debris was non-negligible and primarily negative; furthermore, it contributed to a vapor loss that comprised 5.5% of the total considering all glacierised grid cells."*

Ice mass loss is not counted twice in most timesteps, because:

- the calculation of the vapor fluxes over exposed debris considers water and ice stored in the debris but changes in the moisture content are not included in the cumulative CMB calculation (since they are approximately zero; see Collier et al. 2014).
- vapor fluxes in the debris are not computed unless the overlying snow-cover is zero. (thus, snow melt is not counted twice as vapor lost from the debris).

However, we note that snowmelt may be counted again as a loss by a negative vapor flux in the timesteps immediately after the overlying snowcover has been removed before this water runs off. We estimate that this double-accounting impacts ~0.1% of all hourly periods at all grid points in WRF D3 between 1 May and 1 October 2004.

We removed the comparison with CLN from the aforementioned sentence and will fix this calculated in future applications of the model.

Discussion

The model results are highly dependent upon assumptions of: a) debris thickness and other debris thermal properties distributions and b) moisture conditions within debris layers and their distribution. In a) a small adjustment to the parameterised gradient of debris thickness change along glaciers has a dramatic impact on debris mass balance and presumably QS to the atmosphere. In b) the finding that debris cover results in a minor increase in QL compared to clean ice could be dependent on necessary assumptions about moisture distribution within debris. As the authors note in their previous paper (Collier et al., 2014) the simple reservoir parameterization applied in the CMB model underestimates the surface-atmosphere vapour pressure gradient. In addition to the conclusion regarding the importance of determining debris thickness fields in the final paragraph of the paper, the authors should also emphasize the need to improve understanding of moisture fluxes between debris and the atmosphere.
We added a paragraph to the discussion/conclusion about the representation of QL and the debris moisture content:
"In surface energy balance studies of supraglacial debris cover, the latent heat flux is often neglected where measurements of surface humidity are unavailable, due to the complexity of treating the moist physics of debris. In the DEB simulation, the latent heat flux over exposed debris was non-negligible and primarily negative; furthermore, it contributed to a vapor loss that comprised 5.5% of the total considering all glacierised grid cells. Thus, our study suggests that neglecting QL and surface vapor exchange may be inappropriate assumptions, even for basin-scale studies. We further note that the simple parameterization developed for QL tended to underestimate the vapor-pressure gradient in the surface layer (Collier et al. 2014), suggesting that the importance of QL is underestimated in this study. However, the treatments of QL and the debris moisture content represent key sources of uncertainty in our simulations, since (i) they were developed in a different region and (ii) these fields impact sub-debris ice melt rates (Collier et al. 2014) but are not well measured or studied."

To address your comment, we also:

- created a paragraph in the discussion focusing on the approach to specifying thickness/extent that begins with, *"The alterations to the glacier energy and mass fluxes and to atmosphere-glacier interactions presented in this study are based on the ablation season of 2004 only and <u>are sensitive to the debris thickness field, with small adjustments to the thickness gradient resulting in significant changes in basin-mean glacier CMB.</u>"* (see our reply to your comment on Sect. 2.3).
- amended the second-last sentence in the conclusions to, *"Thus, important future steps for glacier CMB studies in the Karakoram include increasing the accuracy and spatial detail of the debris thickness field and <u>its physical properties; improving our understanding of moisture fluxes between the debris and the atmosphere;</u> and accounting for subgrid-scale surface heterogeneity (e.g., by introducing a treatment of ice cliffs; Reid et al. 2014)."*

<u>Minor corrections</u>
2270, 18-20, why are only 55% of debris-covered pixels exposed. I would have thought this would be close to 100% during the summer ablation period. Later in the same paragraph, a minimum figure of 15% is given for the Karakoram as a whole. Again, why so low? The fact that 2004 was probably a particularly snowy year becomes apparent later, but it would be helpful to point this out here.

As we stated earlier, we discovered an issue with the albedo routine in our simulations whereby the glacier surface albedo was being reset to the fresh-snow value for only small amounts of solid precipitation. After increasing the threshold for resetting the albedo to 1 cm, upwards of 90% of debris pixels are exposed during this ablation season. For the revised results, we focus on the period of 1 July to 15 September 2004, when more than 35% of debris-covered grid cells are now snow-free.

2275, 1, 'thicker' than what?
We revised to "under thicker debris ~(O(10 cm))."

Figure 2 (c) does not show debris thickness as stated in the caption, but it could do so if the x-axis label was changed from km to cm.
We corrected the x-axis label of Fig. 2c to read "debris thickness [cm]," since the box plot now shows the debris thickness values obtained by assuming a gradient of 0.75 cm km^{-1}.

Table 4 and Figure 6– Subsurface melt is 3 x greater (and half the surface melt value) for DEB compared with CLN. Does 'subsurface' in this case mean sub-debris? In which case, please use different terms to distinguish subsurface melt in ice due to penetrating shortwave and sub-debris (or debris-ice interface) melt. Otherwise, explain the physical process leading to so much sub-ice-surface melt beneath a debris layer.
For Table 4, sub-surface melt included both sub-debris ice melt and sub-surface snow and ice melt due to, e.g., penetrating shortwave radiation. To clarify, we have now combined the melt fields in Table 4 as a "total-column melt" field.

Figure 7 compares sub-debris melt rates in snow-free debris-covered grid cells, specifically, with the total-column (surface and englacial) melt rate in the corresponding grid cells in CLN. The model does simulate higher melt rates in DEB where the thickness is less than ~ 5 cm and suppressed melt rates above this depth, consistent with many previous studies of the impacts of debris cover.