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.

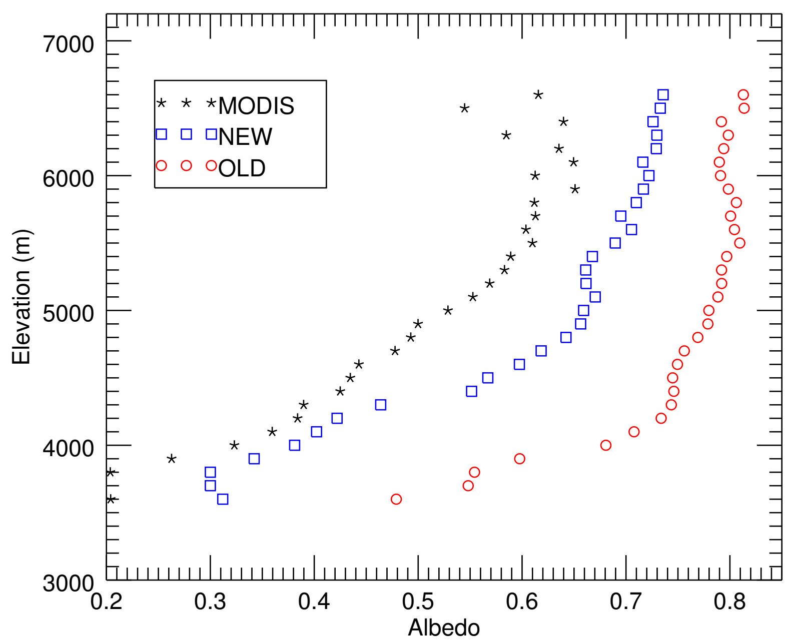

Figure R1: Elevational profiles of snow albedo in MODIS MOD10A1/MYD10A1 (black marker), the CLN simulation in the discussion paper, and the CLN simulation in the revised manuscript, averaged over glacierised grid cells in WRF D3 and the months of July and August. Valid MODIS data with the highest quality 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>

1) 2263 L24-26 Please provide the reason more specifically. Why significantly sloped levels make problem? Is it possible to show the reference (e.g. developers forum)?

Horizontal diffusion in WRF, when used, can be computed along model levels (namelist option diff_opt=1) or in physical space (diff_opt=2). When the first option is used and the coordinate surfaces are steeply sloped, as they are in complex terrain, then the computed horizontal diffusion (1) includes an implicit vertical component and (2) can result in along-slope transport and thus reduced uplift, condensation and surface precipitation. When the second option is employed, diffusion acts along horizontal gradients computed in physical space using a vertical correction term.

Unfortunately, there is no clear reference for our choice. We read about this option in some WRF-physics tutorials:
http://cires.colorado.edu/files/8214/3292/4862/at730-2006-schumacher.pdf
http://www2.mmm.ucar.edu/wrf/users/tutorial/201201/Physics_Dudhia.ppt.pdf
(last retrieved 16.07.2015).

As such, we removed the emphasis from the manuscript about this option being recommended by the WRF developers for complex terrain. However, we can demonstrate an improvement in simulated precipitation when diffusion is computed in physical space (diff_opt = 2) through two case studies:

1) Figure R2b shows accumulated precipitation during a four-day period (1 July to 5 July 2012) in the monsoon season in the Langtang catchment of the Nepalese Himalayas for two

simulations with 1-km grid spacing, one using diff_opt =1 and one using diff_opt = 2. These simulations are described in a paper under revision at *JGR Atmospheres* and the observational data are described in *Immerzeel et al.*, [2014]. Diffusion computed in physical space provides a clear improvement in the simulated magnitude and along-valley distribution of precipitation (cf. map of station locations in Fig. R2a).

2) In *Collier et al.*, [2013], we compared our simulations with meteorological data from the Urdukas AWS on the Baltoro glacier (specifically, in Fig. 3 of that paper). In Fig. R3, we repeat the evaluation and compare our earlier work with this study. We see that while the magnitude of daily total precipitation in early August is now slightly over-estimated, there is a clear improvement in the number of events captured by the model. However, we note that differences are also attributable to the different land surface models (the AWS is located next to the glacier, in a non-glacierised pixel) and to the use of slightly finer grid spacing (2.2-km grid spacing in D3 in *Collier et al.*, [2013] compared with 2 km in this study).

Thus, we changed the relevant statement about this option to, *"Horizontal diffusion was also changed to be computed in physical space rather than along model levels, whereby diffusion acts on horizontal gradients computed using a vertical correction term rather than on the gradients on coordinate surfaces. We adopt this approach because it may be more accurate in complex terrain where the vertical levels are significantly sloped and because it provided a clear improvement in simulated precipitation in recent applications of WRF-CMB."*

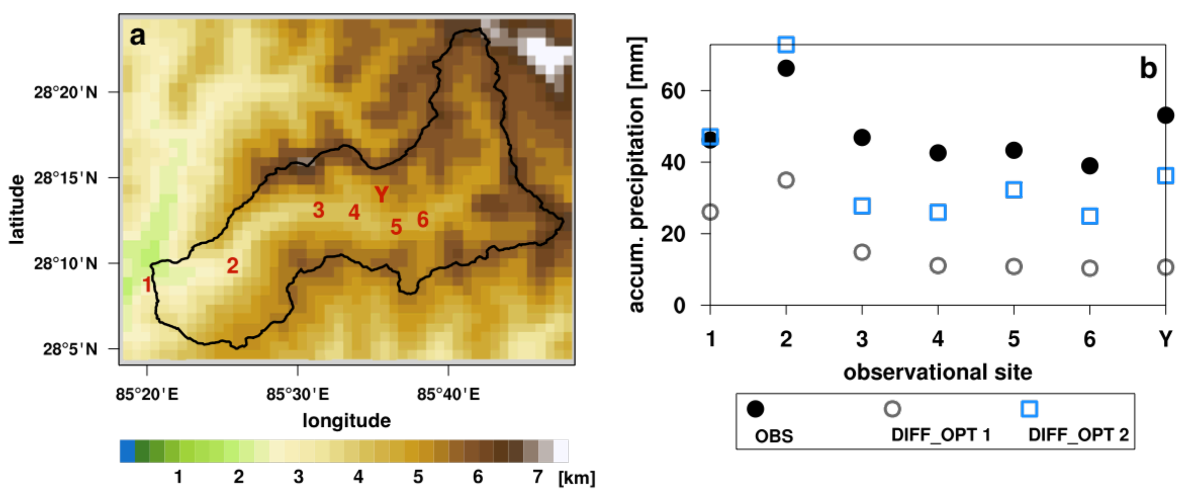

Figure R2: (a) Topographic height shaded in [km] in a 1-km grid spacing WRF domain centered over the Langtang catchment, whose extent is delineated by the black contour. The locations of seven observational sites used for evaluation are indicated in red. **(b)** Accumulated precipitation [mm w.e.] during the monsoon season between 1—5 July 2012 at each location site (black circle marker) and for the WRF simulations with diff_opt = 1 (grey circles) and with diff_opt = 2 (blue squares).

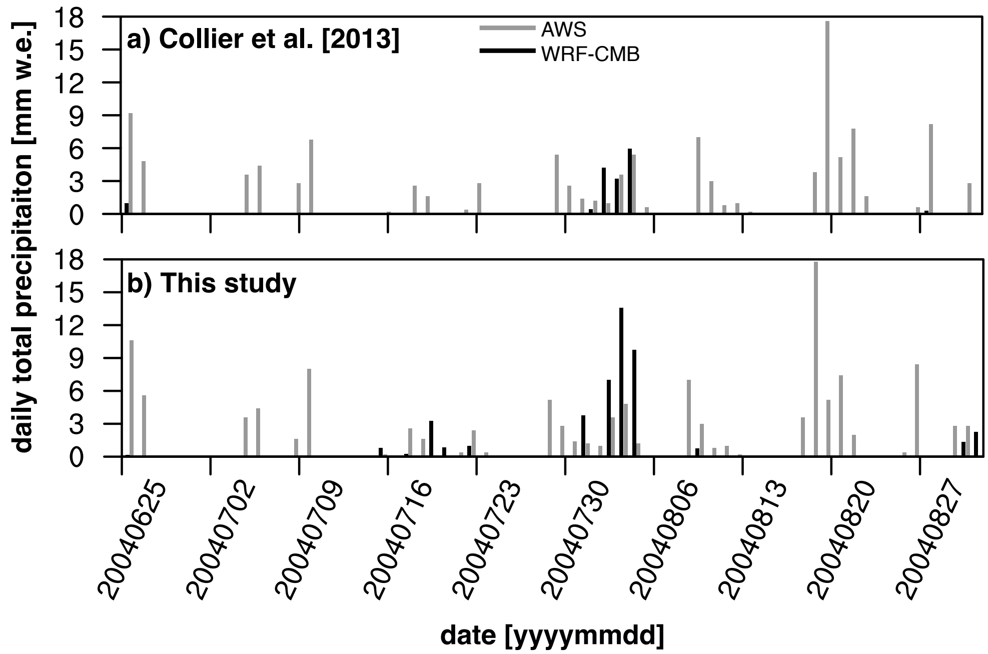

Figure R3: Daily total precipitation [mm w.e.] at the Urdukas weather station (grey bars) between 25 June and 1 September 2004, compared with **(a)** a previous case study in Karakoram of debris-free glaciers (*Collier et al.*, [2013]; see this reference for details about the station) and **(b)** this study (black bars).

2) Figure 2: Is X axis title in Fig. 2c correct? Is it debris thickness values? You explain the color in Fig. 2b and 2d are the distance down-glacier over debris-covered areas. Why all of debris-covered glaciers, where located outside of red line, are orange color (8-10 km in color scale) ? You did not mentioned constant distance of 10 km but mentioned constant thickness 10 cm. Please clarify.

We corrected the x-axis label of Fig. 2c to read "debris thickness [cm]," since the box plot shows debris thickness values obtained by assuming a gradient of 0.75 cm km^{-1}. We also changed Fig. 2d to shade debris-covered pixels where no centerlines were available as a missing value rather than a particular distance down-glacier.

3) Figure 5: Grey-square markers is a little confusing because the shape is same with 1-5 cm debris thickness of DEB. I recommend to change the shape to other shape. For example solid grey circle, which is slightly larger than solid black circle, might be better.

We changed the markers for CLN in Fig. 5 to slightly larger filled-grey circles and added the CLN marker to the legend.

4) Figures 8&9: I suggest to overlay boundary line of the region where centerline information available from Rankl et al. (2014). I would be helpful to judge effect of constant debris thickness assumption.

We contoured the boundary in Figs. 8 and 9.

Additional references

Immerzeel, W. W., L. Petersen, S. Ragettli, and F. Pellicciotti (2014), The importance of observed gradients of air temperature and precipitation for modeling runoff from a glacierized watershed in the Nepalese Himalayas, *Water Resour. Res.*, *50*(3), 2212–2226.