Reply to Hendrik Wulf Referee #2

We thank Hendrik Wulf for his extensive comments and positive feedback. All the suggested typographical revisions will be adjusted for the revised manuscript. Below we summarize the comments given by the reviewer and our replies (italic)

Dear Editor, author and co-authors.
This paper presents an illuminating analysis in the spatial (and temporal) distribution of SWE in the Langtang Valley, Nepal, and the findings are useful to anyone investigating the hydroclimatic phenomena and variability from the Hindu Kush to the Eastern Himalaya. Unique to this study is the use of actual field observation (a rarity in the Himalayas) and their incorporation in a modeling approach for SWE. The explication could be improved, and I have marked up the manuscript. But although my comments are extensive, they are straightforward, so I do not feel I need to see the paper again.
I look forward to reading the published version.
Kind regards, Hendrik Wulf

p1 l20 Why only in the Himalayas? Isn't this of general interest in complex snowy terrain?

It is a new approach for the Himalayas and therefore of main interest for the Himalayas. However, it is indeed of general interest for complex terrain. We will stress this in the revised manuscript.

p1 l22 Why do you assume an increase in precipitation at high elevation in the future? Is that true for all your four scenarios or which one do you focus on here? I find this a little bit confusion. A suggestion. Pick the most likely out of your four scenarios and provide the impact of the change with some numbers. So, what is the change in temperature and what would be the impact on SWE.

Immerzeel et al. (2013) analysed all available CMIP5 simulations for the emission scenario RCP4.5 for the Langtang catchment. They selected the four extremes from the RCP4.5 ensemble members ranging from dry to wet and from cold to warm. We used their projected changes in precipitation and temperature (Table 3). Their projected changes show both a decrease and increase in precipitation. We want to emphasize that we do not intend to perform a climate change impact study but merely a sensitivity study (see also the reply to reviewer #3). We describe the patterns that result from the climate sensitivity tests (including increase and decrease in precipitation). There is not per definition a climate sensitivity test that is most likely. Therefore a description is given of the most interesting results from the sensitivity tests, i.e. patterns that occur as result of changes in temperature and precipitation.

p1 l25 Some kind of closing sentence is missing with regard to the opening. For example, snow as important water storage in the Langtang Valley is projected to decrease by X% assuming a temperature increase of X°C, which has implications on ...

No numbers are presented here to prevent the thought that we actually performed a climate impact study. We rather performed climate sensitivity tests and we intend to mainly describe qualitative results.

p2 l11 "No information" is not quite correct. Using the "inverse melt" approach by Molotch et al. (2009) you can gain information on SWE. I used this simple approach in the western Himalaa and it worked quite well (Wulf et al. 2016)

MolotchNP,NorteD.ReconstructingsnowwaterequivalentintheRioGrandeheadwatersusingremotelysensedsnowcoverdataandaspatiallydis-tributedsnowmeltmodel.HydrolProcess2009;1089:1076–89.http://dx.doi.org/10.1002/hyp.7206.

It will be changed into 'limited information'. The given references will be added. We appreciate the suggestion.

p2 l12 Do you refer to currently recorded data or available data? I am aware of continuos data records in the Indian Himalaya, which are not publicly available. Further efforts existed in the central Himalaya. There are publications on snowfall and SWE in the Himalaya. See Putkonen et al.(2004) and Wulf et al. (2016).

Putkonen, J.K.
Continuous snow and rain data at 500 to 4400 m altitude near Annapurna, Nepal, 1999-2001
(2004) Arctic, Antarctic, and Alpine Research, 36 (2), pp. 244-248. Cited 38 times.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-9944234078&partnerID=40&md5=c770cdf50445a4762d9b9757e46f56de

Wulf, H., Bookhagen, B., Scherler, D.
Differentiating between rain, snow, and glacier contributions to river discharge in the western Himalaya using remote-sensing data and distributed hydrological modeling
(2016) Advances in Water Resources, 88, pp. 152-169. Cited 1 time.
https://www.scopus.com/inward/record.uri?eid=2-s2.0-84954410375&doi=10.1016%2fj.advwatres.2015.12.004&partnerID=40&md5=a48d65ad590068da9a363c979cd7b15b

This sentence will be rephrased: 'Currently there is limited information of SWE for the Himalayas'.
We were referring to available data sets. Thank you for making us aware of this interesting literature. The references will be added to the revised manuscript.

p2 l30 You highlight the differences between low-elevation and high-elevation precipitation at the southern slopes. Is there also a north south gradient in precipitation?
See the work of Ana Barros.

We will rephrase this as follows:
There is a strong interaction between the orography and precipitation patterns. During the monsoon, at the synoptic scale, there is a decreasing trend from south to north during the monsoon, but at smaller scales there are more local orographic effects associated to the aspect of the main valley ridges (Barros et al, 2004) that determine the precipitation distribution. During the monsoon precipitation mainly accumulates at the south western slopes near the catchment outlet at low elevation. Winter westerly events can also provide significant snowfall. Snow cover has strong seasonality with extensive, but sometimes erratic, winter snow cover and retreat of the snowline to higher elevations during spring and summer and less snow cover. During the winter precipitation mainly accumulates along high-elevation southern-eastern slopes (Collier and Immerzeel, 2015).

p3 l25 I would recommend to use the more general formulation: NDSI (Green-SWIR1) / (Green+SWIR1). This way you could reuse the equation for L8, too.

The formula for the NDSI will be changed into a more general formula using green and SWIR.

p4 l2 How many cloud free scenes out of how many total scenes did you use in the end? How well did they cover the snow melt period?

10 out of 34 available Landsat 8 images were used for validation of the snow model. The coverage can be seen in Figure 3.

p4 l14 What did you use the surface temperature for?

We used the surface temperature measurements for distinguishing between snow covered and no-snow covered periods at a point-scale. These point measurements are used to validate the remotely sensed snow cover. This is described in the results and discussion section.

p4 l16 Surface or air temperature?

Surface temperature. This will be revised.

p4 l25 What are the lapse rate values? How good do they describe the variation between the temperature stations? Do these values vary during the year?

The temperature lapse rates agree with values presented in the study of Immerzeel et al. (2014). There is seasonal variation in the lapse rates similar to Immerzeel et al. (2014).

p4 l29 How uncertain are these temperature measurements?

We do not refer to the uncertainty in the temperature measurements, but to the uncertainty of the derived temperature lapse rate. We will clarify this in the revised manuscript.

p5 l9 How did you incorporate the 500m MODIS pixel in your model? Simple upscaling?

The 500m MODIS pixels were resampled to 100m to fit the spatial resolution of the model.

p6 l10 Do you have any idea by which degree your snow depth measurements are affected by snow redistribution?

The snow depth measurements are not influenced by avalanching, though there might be some influence from wind transport. However, when assimilating the snow depth measurements, an uncertainty was added to the snow depth measurement to account for the uncertainty that results from wind-induced snow deposition and erosion. See also the reply to reviewer 1.

p7 l29 I assumed you use a distributed modelling approach. Do I rightly assume that snowmelt is generated per elevation band not per model pixel? Please clarify.

Snowmelt is generated per pixel. This will be clarified.

p7 l30 Landsat snow cover data is not used in your model only the validation?

Yes, it is used as an independent validation of the simulated snow cover.

p7 l31 Why did you not choose equal area breakpoints to ease the direct comparison?

We want to characterize the snow cover per elevation zone. Equal area breakpoints resulted in unevenly distributed elevation zones given the catchment's hypsometry. Therefore, unequal area breakpoints were chosen to have approximate equal elevation intervals.

p8 l24 What does this mean?

Immerzeel et al. (2013) analysed all available CMIP5 simulations for the emission scenario RCP4.5 and extracted precipitation and temperature trends. They selected 4 models that ranged from dry to wet and from cold to warm for the Langtang catchment. The changes in in temperature (°C) and precipitation (%) are extracted from the 4 models. The projected annual change is for 2021-2050 relative to 1961-1990. This will be clarified in the manuscript.

p8 l25 What about the dry to dryer scenario is the summer monsoon and/or westerlies weaken?

It is assumed that both occur. However, precipitation is much more substantial during monsoon and therefore the dry to dryer climate sensitivity tests mainly influence the monsoon precipitation.

p8 l26 I recommend to clearly distinguish between your results and the discussion. This is common scientific practice.

We believe that combining these sections improves the readability in our case. It is nowadays also not uncommon to combine the results and discussion, so we propose to keep it as it is..

p9 l12 The other studies compared MOD10A1 data. The simplification of MOD10A2 surely introduces additional errors. Larger uncertainties also stem from large viewing angles, which can increase the observation area by a factor of 10 for MODIS. See Dozier et al. 2008.

Both notes will be added to the manuscript.

p9 l17 I would assume that the snow observation on the ground differs, too. I honestly doubt that relief introduces such a big error if the satellite data is geocoded correctly. USGS does a good job here for their TOA products.

In situ snow observations indeed result in additional uncertainty. This is already described in the manuscript (p9 l17-22). The relief is causing high spatial variability in snow cover. It is believed that the spatial resolution of MOD10A2 snow cover does not capture this spatial variability. We do not refer to correct geocoding. This will be clarified.

p10 l6 Any values (before and after calibration) would be much appreciated.

These values can be found in Table 6. We already refer to this table in the manuscript (p10 l2).

p15 l4 Do you mean: "increased melt due to higher temperatures"?

Yes, this will be revised.

p18 l14 Nice figure. However, the map is missing coordinated and an inset to locate it in the Himalayas.

The figure will be revised so it addresses these comments (See Figure 1 *below).*

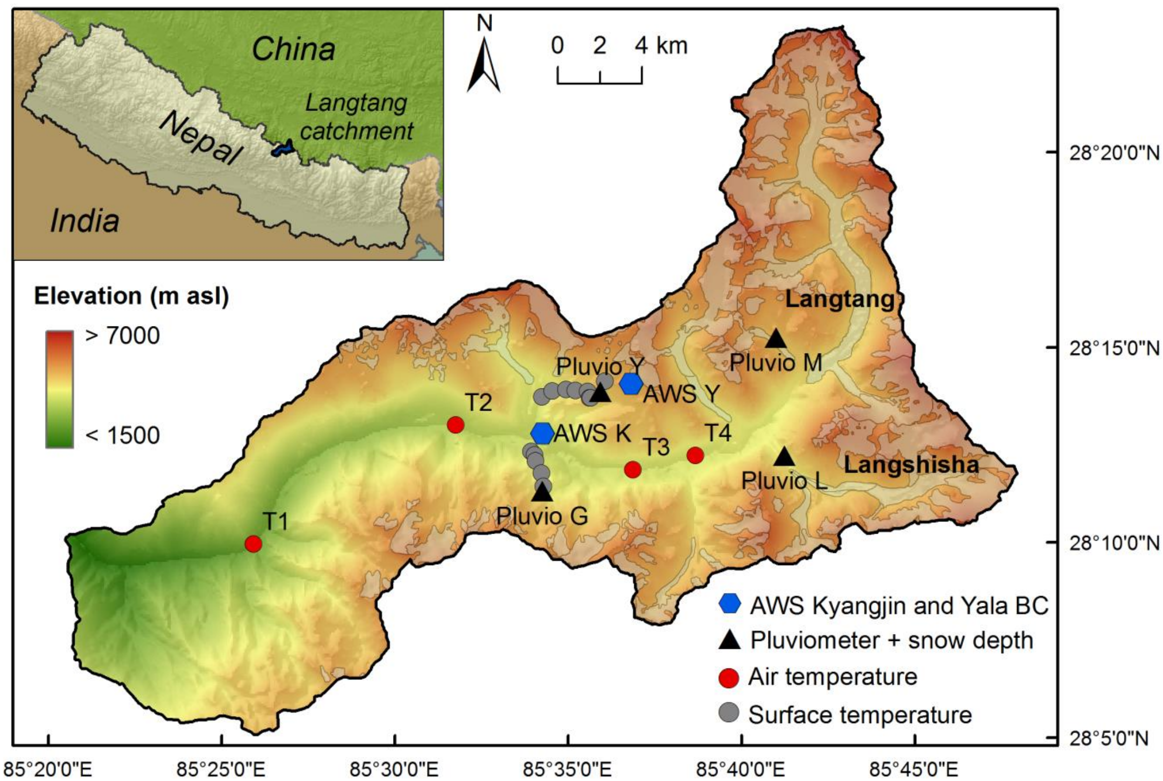

Figure 1 Study area with the locations of the in situ observations. Langtang and Langshisha refer to two main glaciers in upper Langtang Valley.

p19 l1 Which are these locations and what is their respective elevation? Why is the surface temperature above zero for some snow cover periods? How certain are you about the snow free periods during sprng the upper example (Yala 5)? Are late snowfall events more common in spring as compared to the winter period?

The locations and elevation are given in Table 1. The table number will be added to the figure description.
The above zero temperature results from the uncertainty of the surface temperature measurements. The short snow free periods during spring for Yala 5 are associated with the uncertainty of the temperature measurements. During winter precipitation events are rare, whereas during spring late snowfall events are common.

In Figure 3 there seems to be quite a mismatch between Landsat and MODIS. How do you explain this difference?

The coarse resolution of MODIS does not allow observing the high spatial variability in snow cover. MODIS snow cover shows full snow cover, whereas Landsat shows higher spatial variability (also some no-snow cover) at higher elevations. This results in a mismatch between MODIS and Landsat.
In addition the Landsat 8 derived snow maps are influenced by shading. Shaded snow covered area is erroneously mapped as no-snow areas and therefore also results in underestimation of snow cover by landsat compared to MODIS.

p21 l5 Could you indicate these locations in your Fig. 1? I would opt for dashed and solid lines to improve the distinction in b/w printouts.

These locations are already indicated in Table 1 and Figure 1.
The figure will be updated and will contain more lines (see reply to reviewer 1). Therefore we believe that dashed and solid lines will not enhance distinguishing between different lines.

Do the values in Figure 7 match the glacier snow accumulation rate at high elevations? What is the maximum SWE value you got?

We do not know the snow accumulation rate at high elevations as there is only yearly mass balance data available that also includes ablation.
The maximum SWE will be given in an additional figure showing box plots of SWE values per elevation zone (see reply to reviewer 1).

In Figure 8 you have (white) space enough to write the different scenarios directly into the figure (as a subfigure headline. Please also state here what wet, dry, cold and warm refer to.

This will be adjusted. Reference will be made to Table 3 to clarify the different climate sensitivity tests mentioned in this figure.

p24 l1 How was runoff measured? Which method? Does melt also include glacier melt? If not, it is better to refer to snow melt.

Runoff was not reliably measured in the field and is therefore not included in this study. In the model it is assumed that all runoff, for each pixel, collects at the catchment outlet for each time step without applying routing.
Melt includes only snowmelt, although it includes snowmelt on glaciers. The legend will be adapted to snowmelt.

References:
Barros, A. P., Kim, G., Williams, E. and Nesbitt, S. W.: Probing orographic controls in the Himalayas during the monsoon using satellite imagery, Nat. Hazards Earth Syst. Sci., 4(1), 29–51, doi:10.5194/nhess-4-29-2004, 2004.