Responses to Anonymous Referee #1 Comments

We would like to thank the reviewers for their valuable time in reviewing the manuscript and providing suggestions for improvement. We appreciate their feedback and constructive criticism. We would also like to thank the editor for giving us the opportunity to improve the manuscript.

Responses to the reviewer comments are specified below. Reviewer's comments are stated in black whereas the response is in blue color.

Reviewer#1

Abstract:

In your abstract you had mentioned and put a link to access the data that you produced (MOYDGL06*) with a reference. You should remove it from here and you better put it in the data analysis section or in any other appropriate sections.

Response: A link to access the data with a reference in the abstract is given following the journal format/recommendations. We are just following the journal format.

Introduction:

In your introduction please try to include the objective of the study and how your study will contribute in filling the existing gaps. The paper miss this point.

Response: The third paragraph of the Introduction highlights the issues/uncertainties in MODIS snow which are reduced in this study. In the second last sentence of the Introduction sentence which is now modified to make it more clearly, we have described the aim/objective of the study. It is now stated that "The aim of this study is to reduce uncertainty in MODIS snow data caused either by cloud cover or sensor's limitations, using a multi-step approach to removes cloud persistence causing underestimation and reduces an enormous amount of overestimation in snow cover mainly by the larger SZA of MODIS".

I think you can also merge Section 3.6 and Section 5 together and you can remove section 5.

Response: We agree and thank the reviewer for the suggestion. Sections 3.6 and section 5 are now combined.

General Comments and Questions:

1. Please define variables and symbols in your equations.

Response: We thank the reviewer for identifying this. All the variables and symbols in the equations are now defined and added to the revised manuscript. On page 4: line 7 we added "where S represents matrix, c denotes cloud, x and y are row and column index of S, t is time index."

2. To what extent were your original MODIS Terra and Aqua data were disturbed by cloud cover?

Response: Cloud cover affected TERRA and AQUA data by 5.31% and 6.52% on average. This is now added to the text in the manuscript (Page 6: Line 5-6).

3. Can you show us the comparison map of pixels affected by cloud and the improved map after you are applying the three filtering techniques on mapping the snow cover? Your manuscript miss this important aspect.

Response: We are thankful for the reviewer suggestion to make a new map and show the cloudy pixels in raw data converted to snow and no snow. We have added Figure 4 showing improved map with cloudy pixels converted to snow and no snow by temporal and spatial filters.

4. How do you separate the debris-covered and debris-free glacier ice?

Response: Debris-cover and debris-free glacier ice are available at RGI database (as mentioned on Page 4: line 37-38. We included/merged the available glacier data (debris cover and debris free) to our snow product as described on Page 5: Line 1-5. "*In the regions where snow and glaciers both exist, it is challenging to differentiate particularly in the accumulation period. Also, the glacier ice mainly in the late ablation season is difficult to map using the MODIS algorithm for snow detection when the albedo of the glacier surface is comparatively low. MODIS is incapable of mapping ice under the debris. Therefore, we used the latest Randolph Glacier Inventory version 6.0 (RGI6.0) (RGI Consortium, 2017), partly developed by Mölg et al., (2018) and supraglacial debris cover for RGI 6.0 by Scherler et al. (2018), resampled into the MODIS pixel size and merged it into the combined MODIS data. A combined snow and glacier cover (debris-covered and debris-free) product was developed which will be useful mainly for glacio-hydrological applications*". This kind of dataset is very demanding for cryospheric research in particular glacio-hydrological modelling. We believe that our dataset will add significant role in hydrological modelling.

5. Do you have any reason why you choose Landsat 8 data for validation only in 2018? Why not in any other years of the study period? 6. Why the minimum and maximum snow periods are selected in 2018 only?

Response: We selected 2018 randomly to compare our results with the latest observation period. The study area is quite large, therefore, we selected 10 locations as a representative of the whole region and validation of snow data. We divided the year into winter and summer and validated the snow to make the validation seasonally well distributed. We have selected 20 Landsat images for validation which is quite extensive for validation. Our validation captures the variability and uncertainty quite well.

7. Have you tried to improve the existing snow detection algorithms to avoid overestimation of the MODIS snow cover data or you simply used the one developed by others from the literatures? Please try to discuss everything clearly.

Response: As the snow overestimation is not because of the snow detection algorithms (Page 2: Line 11-14). The reason behind snow overestimation is " Larger Sensor Zenith Angle (SZA) (Li et al., 2016) and low spatial resolution (Hou et al., 2019; Huang et al., 2017) mainly causes overestimation of snow. The overestimation is also significantly influenced by the broad swath of MODIS that amplifies the edge-pixels more than four times compared to the pixels at the image centre (Zeng et al., 2011; Zhang et al., 2017)". "We used 8-day maximum snow extent product version 6 of the MODIS onboard Terra (MOD10A2.006*) and Aqua (MYD10A2.006*) available from February 2000 and July 2002, respectively with 500 m spatial resolution for the Hindukush, Karakoram, and Himalaya (HKH) and surroundings. This version minimises the error of omission and commission compared to version 5 primarily in clear sky conditions as described by Riggs et al., (2016). In collection 6, band 6 of AQUA is restored instead of the previously used band 7 in calculating NDSI making the algorithm similar to that used for TERRA (Riggs et al., 2016) which helps to reduce an additional uncertainty in AQUA snow cover." Page 2: Line 35-41.

8. Which snow detection threshold method have used in this study? Please mention it clearly.

Response: We used Terra (MOD10A2.006*) and Aqua (MYD10A2.006*) products. These are level 2 products and give snow data represented as (200) as mentioned in Page 3 Line 2. We didn't derive snow from images but the data is already available as snow. We processed the available product and improved the final snow with a significant improvement of reducing underestimation of 3.66% on average because of cloud cover and 46% of overestimation because of MODIS sensor larger zenith angle.

9. "The seasonal filter removed approximately 44.66 % and 31.29 %, temporal filter removed 54.08 % and 65.48 %, spatial filter removed 99.91 % and 99.84 % of the total cloud cover existing mainly outside the snow cover extent in Terra and Aqua products." Line 32- 38. So, why temporal filter is the most effective step in cloud removal than the others? It is not clear for me.

Response: The temporal filter basically considers any pixels which are cloud-free in any of the consecutive 40 days rather than seasonal (consecutive cloud cover for the six months), and majority spatial filter (considering only surrounding 8 pixels). However, it is important to mention that all the filters including temporal filter only improve cloudy pixels (3.66% of the total snow) to snow or no snow.

10. Why the overall snow extent is showing significantly decreasing trend since 2013 as compared to the whole observation period between 2002 and 2018? Please elaborate this.

Response: Thank you for pointing out this question. Our aim and scope of the paper is to improve the snow data only and we do not work on the trend analysis. For trend analysis and the possible reasons of dynamics in snow cover dynamics, we are carrying out another study to analyze the snow cover in detail for different regions (Karakoram, Himalaya, Hindukush, and Tibetan Plateau).

On Figure 6 caption please change the word “now” to “snow”.

Response: Thanks to the reviewer for pointing out the typo, “now” is corrected as “snow” in the Figure 6 caption.

On Figure 7, the unit for SCA is not mentioned.

Response: The unit (%) is now added to Figure 7, thanks to the reviewer for the comment. The caption is also slightly revised by removing second sentence as “Correlation of the snow cover area (SCA) from raw, improved Terra/Aqua, and combined Terra/Aqua snow data with the Landsat 8 (L8) data”.

From Figure 9, generally we can say that the number of pixels changed from snow to no snow are much more higher than the pixels changed from no snow to snow which shows that the uncertainty in snow cover underestimation due to cloud cover is less than that of the MODIS large swath width and poor spatial resolution. It also shows to use better spatial resolution snow cover product than the one you proposed. Please try to elaborate and discuss this point in your discussion part.

Response: We completely agree to the reviewer comment and have therefore highlighted the overestimation by MODIS in this study. We have added some explanation on Page 6 in the Discussion section (as described in italic font below). The method of combining Terra and Aqua is also an inter-verification of the snow derived by both the satellites. Our results indicate that on average approximately 46% of the total snow on average is overestimated by MODIS. This significant difference in the snow data is mainly due to the large swath and low spatial resolution of MODIS which makes it challenging to map snow cover accurately, particularly at the edges of each image. Similarly, the off-nadir view makes the sensor zenith angle larger causing it to replicate the edge pixels. Whereas, the underestimation is mainly caused by the cloud cover but is insignificant, i.e. 3.66% of the snow on average. *These results suggest that the uncertainty of underestimation in the snow cover due to cloud cover is quite low (approximately 7% of the overall uncertainty), in contrast to the overestimation uncertainty contribution of about 93%. It is to be noted that this cloud cover is significantly reduced in the 8-day composite as the cloud cover is the least possible in consequent eight days.* We are more confident about the MODIS snow cover derived from our method. Combining the snow with the glacier cover (debris-covered and debris-free) makes it more comprehensive and usable for various hydro-glaciological applications. The glacier ice captured by MODIS as snow is represented as 200 (snow). We combined glaciers uncaptured as snow by MODIS in the combined product representing debris-covered and debris-free ice as 240 and 250, respectively. These values (240 and 250) may be ignored or converted to no snow if the user of the data is interested only in the MODIS snow product. In this case, the values 200 and 210 can be considered as the final snow.

Comparison of the snow cover area estimated by Landsat and MODIS Aqua/Terra raw/final and combined product shows that our methodology improved the accuracy by 10% from 77% to 87% on average reducing the inevitable overestimation for twenty well-distributed (in space and time) Landsat scenes. The remaining overestimation ~~may either require improvement in snow detection algorithm or be~~is constrained by low spatial resolution and large swath. *Therefore, for very small scale studies, low spatial resolution data, including our improved snow product is not recommended.*