<u>Response to the comments of reviewer 2 (RC3)</u>

The authors sincerely thank reviewer-2 for his valuable efforts in reviewing our manuscript titled "Passive Microwave Remote Sensing based High Resolution Snow Depth Mapping for Western Himalayan Zones using Multifactor Modelling Approach". The suggestions and feedback shared by the reviewer are highly helpful in enhancing the manuscript. The response to the queries and suggestions provided by the reviewer are attached in the response document below in the point-by-point manner. Kindly note that reviewer comments are in black colour font, response from the author is in blue colour font, whereas the changes made in the manuscript are highlighted in blue colour italic font.

Reviewer feedback: The authors present a novel technique for modelling snow depths using passive microwave observations in the Western Himalayan region. Their multiparameter approach is compelling and appropriate for the study area and remote sensing datasets utilized. The created multifactor model provides spatially distributed estimates of snow depth at a 500 m resolution, which are necessary for hydrologic modelling and understanding natural hazard risk in the region. While the author's model shows promising results for the Western Himalayan region, the following points may be addressed to improve the clarity and strength of the analysis.

Author response: The authors would like to sincerely thank the reviewer for his generous feedback about the manuscript.

Notes:

Reviewer comment 1: I recommend additional proofreading for the manuscript. Articles are used incorrectly or missing in places, and at times grammatical mistakes interfere with the meaning of the text.

Author response: The authors sincerely acknowledge the feedback and suggestions given by the reviewer. Additional proofreading of the manuscript is now carried out with help of Grammarly tool. The authors have verified and corrected grammatical mistakes as observed while proofreading, and those pointed by the Grammarly tool. Several sentences are rephrased to ensure that the information is conveyed clearly to the reader.

Reviewer comment 2: Acronym use is high in the manuscript and can lead to confusion while reading. Removing some of the lesser-used acronyms would improve.

Author response: The authors do agree that many acronyms are present in the manuscript. However, the authors opine that the acronyms present in the manuscript are necessary and used accordingly. Therefore, authors would like to proceed without removing the acronyms.

Reviewer comment 3: Repetition is an issue in the manuscript. Some sections of the Results and Discussion start by repeating methods or goals (e.g., lines 338, 354-356, 374-376, etc.). Please reduce repetition to improve the clarity of the text.

Author response: Thanks for pointing this out. The authors have done the proofreading of the entire manuscript. The following lines in the reviewed (original) version of the manuscript are removed to reduce the repetition.

Removed lines: L:338-339, L:354-356, L:374-376, L498-502

Reviewer comment 4: The Discussion section would be strengthened if the created multifactor model was discussed in more detail. This could include why the authors' model outperformed existing models, transferability to other mountain ranges, and model error. Summaries of the methods and results are overemphasized in this section.

Author response: The authors thank the reviewer for providing this valuable suggestion. The discussion section is now revised as suggested by the reviewer by including the details about – model error, why the model has outperformed existing models, and model's transferability to other regions. Following information is added for improving the discussion section.

"The regression modelling approach attempts to find a better fit by optimizing the loss function i.e., mean error. Over WH region, majority of the observations have SD > 25 cm. Therefore, understandably the model estimates are better in higher SD regions as compared to shallow SD regions."

"The topographical parameters in WH play a vital role in affecting the local climate as well as snow distribution. The inherent weakness of PMW TB in capturing deeper snowpack thickness is overcome to certain extent by considering SCD into model development. Thus, the overall improved performance of multifactor model over the previously developed other models and AMSR2 product can be attributed to the consideration of topographical parameters and SCD into the model development. Further, combination of multiple lower and higher frequency TB is considered into the model for capturing both deeper and shallower snowpack thickness. Different factors affecting the performance of the multifactor SD model are discussed in detail in the following section, 5.2."

"The developed model has shown improved performance as compared to other tested approaches in the WH region. However, the transferability of the multifactor model to the other regions specifically mountainous regions is uncertain. This is due to the fact that the relationship of SD with topographical conditions and SCD can potentially change in the other regions. The proposed multifactor model coefficients attempt to improve SD estimates as per prevailing snow conditions in WH. Understanding the influence of topographical conditions, and snow persistency, and snow pack dynamics is essential for using the model outside the WH."

Specific Comments

1: Line 155: The area of the study region should read “360,866 km^2.”

Author response: The numbering format is adjusted as suggested by the reviewer. Now the revised line is as follows.

“WH extends between longitudes from 73° 15' E to 79° 45' E, latitudes from 30° 00' N to 39° N and covers an area of 360,866 km^2.”

2. Line 193: How is the AMSR2 snow depth product created? A citation would be helpful.

Author response: Thanks for suggesting this. Reviewer #3 also suggested the same. The details regarding the AMSR2 SD product development along with the citation are now added into a new section 2.4 in the revised manuscript.

“In this study, the AMSR2 SD products have been downloaded from the website (https://gportal.jaxa.jp) during the snow season (October to March) from 2012 to 2019. The SD products corresponding to ascending (13:30 ± 15 min) and descending (01:30 ± 15 min) pass have been used for comparison with the multifactor model SD estimates. The standard AMSR2 SD algorithm primarily uses the daily 10, 18, 23, 36, and 89 GHz frequencies brightness temperature data and the surface physical temperature (T) data. In the development of the AMSR2 SD algorithm (Kelly 2009), the following steps and conditions have been considered.

Step 1- Isolate wet and dry snow/no-snow-covered regions: If dry snow is present in any region, it will satisfy the conditions (1) and (2)(move to step 2); otherwise, there is no snow-covered region, or only wet snow is present

$$Tb_{36H} < 245K \quad (1)$$

$$Tb_{36V} < 255K \quad (2)$$

Step 2- Isolate moderate/deep and shallow snow-covered areas: If moderate/deep snow is present, it will satisfy the conditions (3) and (4) (move to step 4) (Derksen 2008); otherwise, shallow snow is present or no snow-covered area (move to step 3)

$$Tb_{10H} - Tb_{36H} > 0K \quad (3)$$

$$Tb_{10V} - Tb_{36V} > 0K \quad (4)$$

Step 3- Identify a shallow snow-covered area. If it satisfies conditions in (5), then shallow snow is present, and a flag of 5.0 cm is set for the SD; otherwise, no snow is present

$$Tb_{89V} < 255K,\ Tb_{89H} < 265K, Tb_{23V} > Tb_{89V,}\ Tb_{23H} > Tb_{89H}\ and\ T < 267K \quad (5)$$

Step 4: Estimation of moderate to deep SD using Equation (6)

$$SD = \left[\frac{1}{log_{10}(Tb_{36V} - Tb_{36H})X(Tb_{10V} - Tb_{36V})}\right] + \left[\frac{1}{log_{10}(Tb_{18V} - Tb_{18H})X(Tb_{10V} - Tb_{18V})}\right] \quad (6)$$

The developed SD algorithm by Kelly, 2009 was tested using World Meterological Organization (WMO) collected SD measurements from 242 and 254 sites around world during the 2002-2003 and 2003-2004 winter season, respectively. In this only non-mountain stations with at least 30 days of measured snow were used in the comparison. In the recent study conduct over the mountainous terrain of Northern Xinjiang Region, China by the Zhang et al. (2017) the AMSR2 SD products were compared with ground collected SD data. They observed RMSE of 18.5 cm (in AMSR2_A) and 23.4 cm (in AMSR2_D) up to 30 cm of ground SD. However, AMSR2 SD products have not been evaluated for Indian Western Himalayan regions till date."

3. Line 194: The link did not work for me.

Author response: The working link of the JAXA data archive portal i.e., https://gportal.jaxa.jp is updated in the revised manuscript.

4. Line 210: "SCD" is not defined in the main body of the manuscript.

Author response: Thanks for pointing this out. Reviewer #3 (RC4) suggested some changes with regard to SCD. The revised manuscript defines the SCD at its first instance.

"Snow cover duration (SCD) depicts the number of consecutive days snow cover is present for a given pixel."

5. Line 214: More connection is needed to the studies from Sharma et al. (2014) and Singh et al. (2018). Were methods from these publications followed to estimate snow cover days?

Author response: The authors thank the reviewers for suggesting this. The studies by Sharma et al. (2014) and Singh et al. (2018) have calculated SCD, however their research interest is different. Their prime focus is on understanding the spatiotemporal variation of the snow cover, and SCD trends over the WH region. It is important to note that the exact methodology used by Sharma et al. (2014) is not described in the publication. Authors have independently calculated the SCD from the MODIS cloud free snow cover product for each water year. The details regarding how the SCD is calculated are added. Reviewer #3 (RC4) also made some suggestions with regard to SCD. Therefore, the connection with regard to Sharma et al. (2014) and Singh et al. (2018), and suggestions from reviewer 3 are now updated in the revised manuscript.

*"In WH, snow cover area (SCA)/snow cover pixels vary during different months of the year due to change in snowfall and snow ablation pattern. Least SCA has been observed during the month of August/September and maximum SCA was observed during the month of February/March. Snow cover duration (SCD) depicts the number of consecutive days snow cover is present for a given pixel. It provides information regarding the persistence of snowpack and is useful in improving PMW SD estimates (Singh et al., 2016; Wang et al., 2019; Dai et al., 2018). In this study, daily could-free MODIS snow cover product (i.e., M*D10A1GL06) generated for high-mountain Asia (Muhammad and Thapa, 2020) at 500 m spatial resolution (https://doi.org/10.1594/PANGAEA.918198) has been used to generate SCD product for the study area during the data period. Previously, Sharma et al. (2014) and Singh et al. (2018) have generated and evaluated the SCD maps for snow-covered Indian WH. These studies (Sharma et al., 2014, Singh et al., 2018) revealed a higher average monthly SCD (>80%) in high-altitude regions. These studies' results further emphasize a strong longitudinal and altitudinal dependence on SCD, snow cover accumulation and ablation in WH. Therefore, SCD information can provide valuable insights to improve the SD model. Daily binary snow cover maps prepared from M*D10A1GL06 are used to identify the snow cover presence for a given pixel. These binary snow cover maps are used for computing the SCD information for each day from October 1st of each year to September 30th of the following year during the study period."*

6. Line 222: Was land cover different in the study period (i.e., 2012-2018) from the 2019 composite? How might this impact results?

Author response: There is no change in the land cover classes over the selected stations during the study period. Therefore, it will not impact the results. However, authors agree that landcover changes elsewhere in the WH region during the study period. Therefore, while generating the daily snow depth products recently available landcover dataset for that time shall be used.

7. Line 235: What was the impact of resampling the AMSR2 brightness temperature observations? How do results change if the spatial resolution is increased or decreased?

Author response: The reviewer concern about the spatial resolution is duly noted by the authors. It is an interesting idea to test with different resolutions. The change in resolution may have an impact on the snow depth estimation results, however it is beyond the scope of what authors have proposed in this work. However, the authors would like to point that, the brightness temperature data used in this work are actually resampled instead of downscaling. Further, the main motivation behind this work is to develop the snow depth at high resolution i.e., 500 m. The ideas suggested by the reviewer however are already under consideration by the authors. Downscaling the brightness temperature to different resolutions then resampling the other datasets can be tested in the future works for investigating if it can improve the model estimates. Considering the amount of work involved in implementing this is considered as future scope for improvement. This information is now included into the manuscript as potential scope for improving this research work.

"The brightness temperature datasets used in this work are resampled to 500 m. Instead of resampling, downscaling the TB can be tested for further improvement of model. It is also worthwhile to investigate how downscaling the TB to different resolutions will impact the model performance."

8. Line 236: What software was used to resample images, reproject images, and calculate brightness temperature difference? Does any other processing need to be done to AMSR2 brightness temperature data or is it done already?

Author response: The reprojection of images is carried out using format conversion tool. Resampling is performed with help of ArcGIS software. Python programming is used for retrieval of TB and calculation of BTD. No additional processing is carried out. The detailed information is incorporated into the revised manuscript.

"*The brightness temperature and SD datasets downloaded from JAXA portal have northern hemisphere polar stereographic coordinate system and are present in the HDF5 format. These are reprojected to WGS 1984 coordinate system and are converted to tiff format with help of format conversion tool developed by the JAXA. Following that ArcGIS software is used for resampling the BT imagery to 500 m. No additional processing is carried out in the current work as the brightness temperature dataset acquired from JAXA are level-3 product. However, the brightness temperature is corrected for forest cover fraction in locations where vegetation is present as per the foster model. The brightness temperature from each image for all stations is then retrieved programmatically using python. The extracted TB data is used for calculating the BTD."*

9. Line 380: Was bias in the modelled estimates considered? I am curious if the models consistently over or underestimated snow depths.

Author response: Thank you for suggesting this. The bias is estimated by the authors in this work is now included in the discussion section of the revised manuscript.

"The proposed model has an overall positive bias with overestimated SD values for lesser SD, and underestimation in the case of higher SD observations. The bias for LHZ, MHZ and UHZ for the proposed model is 4.5 cm, 2 cm and 6.3 cm respectively. Whereas the bias for legacy model, and other regional model is considerably higher with substantial overestimates in the lower depth values and underestimates in higher depth regions. Further, it must be emphasized that these models have very poor correlation with the in-situ snow depth and the

SD estimates mainly confined in a range irrespective of the magnitude of the ground snow depth observation values."

10. Line 402: It is unclear to me why results from the MHZ refer to Figure 6 when the caption for Figure 6 states the reported regions are in the LHZ.

Author response: Thanks for pointing this, it is a typographical mistake. The figure caption is revised.

11. Line 410: It is unclear to me why results from the UHZ refer to Figure 6 when the caption for Figure 6 states the reported regions are in the LHZ.

Author response: Thanks for pointing this, it is a typographical mistake. The figure caption is revised.

12. Line 492: Figure 10(d) does not exist.

Author response: Thanks for pointing this, this is typographical mistake. It shall be Figure 8(d). Now it is corrected in the revised manuscript.

13. Line 532: Correlations of less than 0.5 are generally considered weak or moderate.

Author response: The authors agree with the reviewer. The statement is revised to include the word moderate in the place of strong.

14. Line 534: How did local incidence angles impact the accuracy of snow depth estimates?

Author response: PMW brightness temperature can be affected when nominal incidence angle is above 50° and the terrain slope exceeds 20° (Che et al., 2011). Considerable amount of area in WH exhibits a slope of above 20°. However, this effect on snow depth model can be minimized when Brightness Temperature Difference (BTD) is used for the model development. Further, the study (Che et al., 2011) demonstrated that local incidence angle has lesser sensitivity on SD retrievals. Therefore, this will have very less impact on the SD retrievals of multifactor model as BTD are used instead of single channel brightness temperature.

Che, T., Dai, L., Wang, J., Zhao, K., & Liu, Q. (2012). Estimation of snow depth and snow water equivalent distribution using airborne microwave radiometry in the Binggou Watershed, the upper reaches of the Heihe River basin. *International Journal of Applied Earth Observation and Geoinformation*, *17*, 23-32

15. Figure 1, Figure 4: The acronyms “J&K” and “HP” are not defined in the figure caption.

Author response: The acronyms are now defined in the captions of figure1, and figure4.

16. Figure 5: Units for standard deviation are missing. Standardizing the standard deviation may improve the interpretability of the figure.

Author response: The units for standard deviation are now updated in the revised figure 5. The standardization of standard deviation is not very common in many of the papers that are published as authors have observed. The origin plotting tool which authors have employed for making the taylor diagram natively does not allow to standardize the standard deviation. Though there are some other python packages and tools available for doing this, the authors have taken feedback from few other members. After consultation, the authors opined that the figure with the standardized standard deviation can also be equally difficult to interpret for some of the community unlike what the reviewer has mentioned. Therefore, authors suggest that it would be simpler to proceed with the same figure 5.

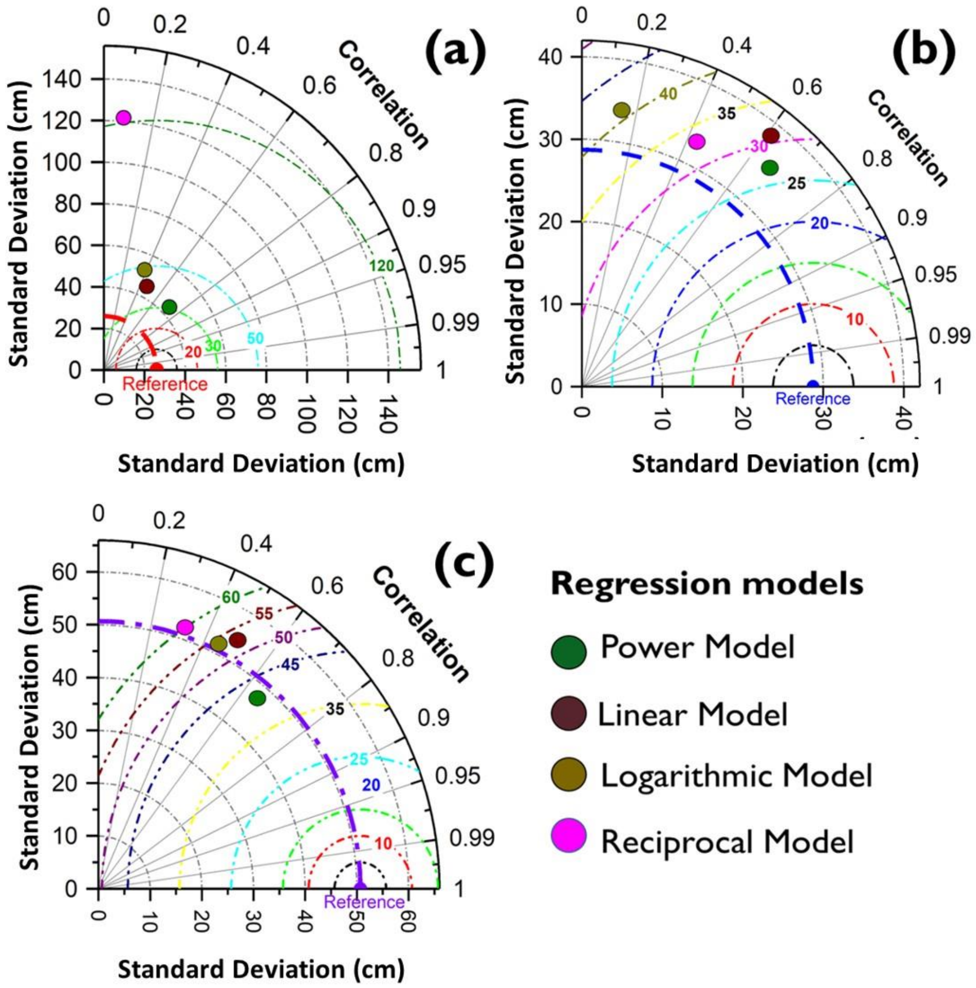

Figure. 5. Taylor diagram for the evaluation of multifactor SD models during 2017-2019 for (a) the LHZ, (b) the MHZ, and (c) the UHZ.

17. Figure 6: Where are the Pir-Panjal, Greater Himalayan, and Karakoram regions? Perhaps these regions could be marked in Figure 1.

Author response: The figure 1 is updated to include the information pointed by the reviewer.

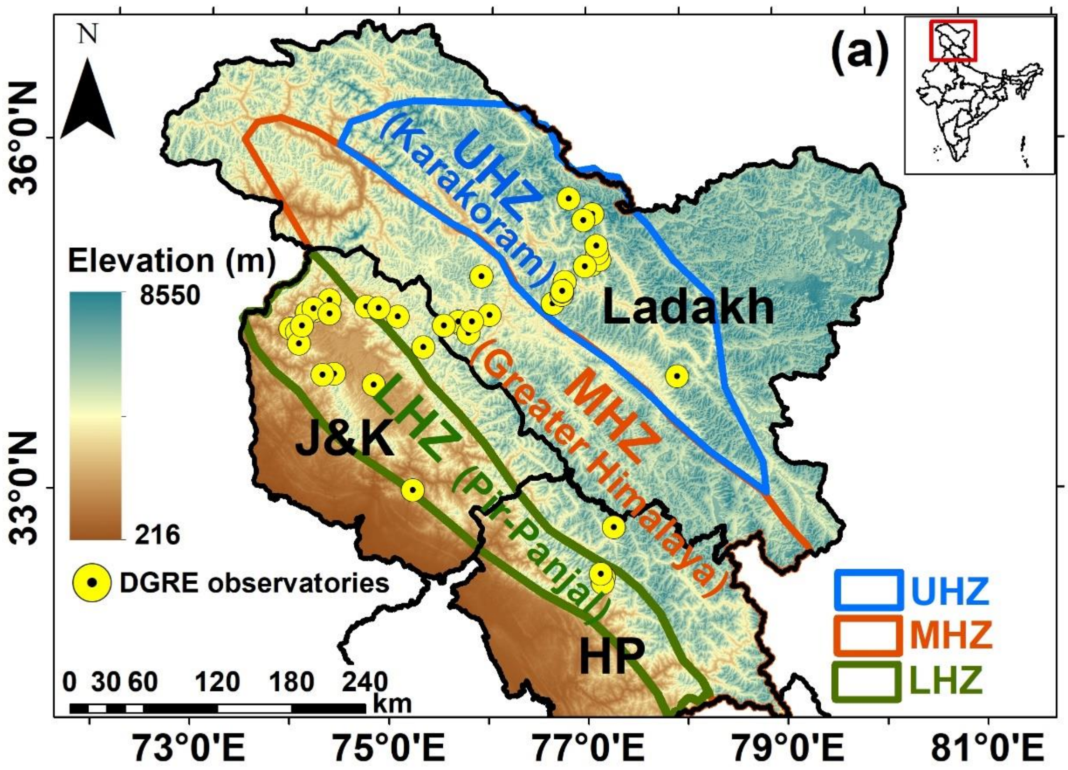

Figure. 1. (a) Elevation variability of WH zones (i.e., LHZ: Lower Himalayan Zone; MHZ: Middle Himalayan Zone; UHZ: Upper Himalayan Zone) and DGRE observatories distribution. (Note: J&K, H.P. are Jammu and Kashmir, Himachal Pradesh respectively)

18. Figure 7: The scale for subplots b, c, and d should be the same for comparison, especially at depths of 0 cm and for regions with missing data.

Author response: Thanks for suggesting this. The figure 7 is revised to ensure that that scale is consistent for all the subplots.

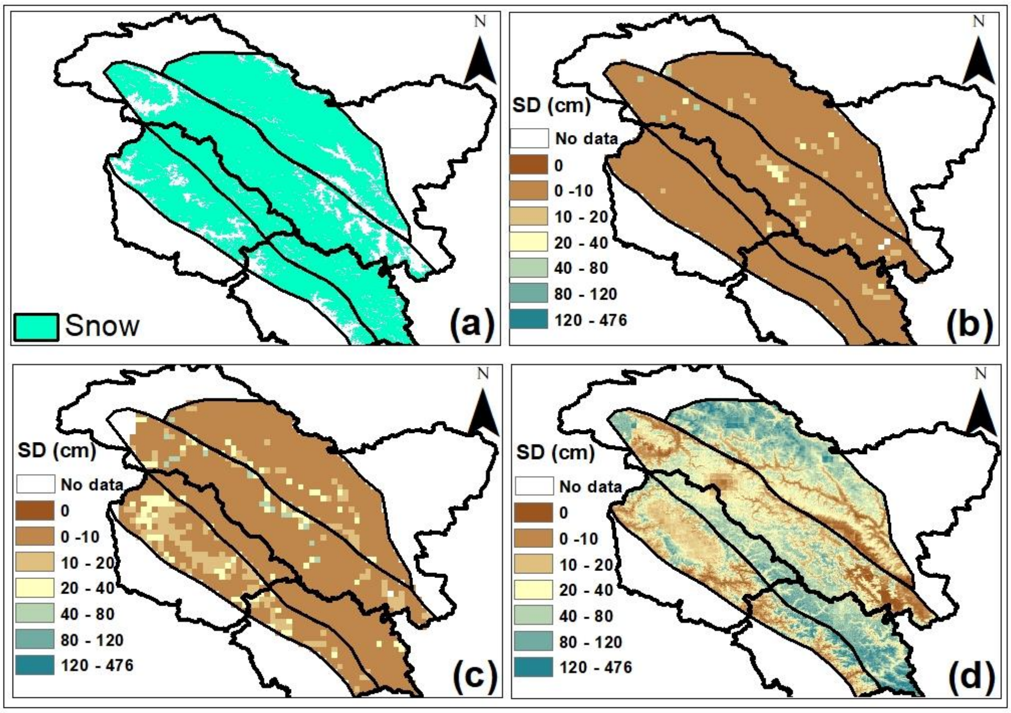

Figure. 7: Spatial map of SD variation on 3rd Feb 2019. (a) MODIS SCA, (b) AMSR2_A SD product map at 10 km, (c) AMSR2_D SD product map at 10 km, and (d) multifactor models SD map at 500 m.

19. Figure 8: RMSE may be better shown as scatter plots so variations in error between elevation, slope, land cover types, and snow cover days are more apparent. As depicted, these patterns are hard to assess visually considering the large study area, scale, and overlap between the stations. Further, this figure is discussed in terms of the lower, middle, and upper Himalayan zones (lines 465-470); however, only state borders are drawn on the map (rather than zone boundaries).

Author response: Figure 8 is updated with boundaries of zones. Additionally figure. 9 (i.e., scatter plots) is prepared as suggested by the reviewer. However, the authors believe that it would be difficult to discern any strong pattern even from the scatter plots. This is primarily due to the lesser number of stations and large variation in the error for stations at given elevations. Furthermore, the some of the stations in lower, middle and upper Himalaya have similar elevations despite having different climate and snow conditions. This would add to the complexity in interpreting the accuracy through scatter plots. Further, when it comes to slope, landcover there is not clear pattern in the scatter plot. With regard to SCDs, though no trend is observed it can be seen higher RMSE is present for stations having higher SCD.

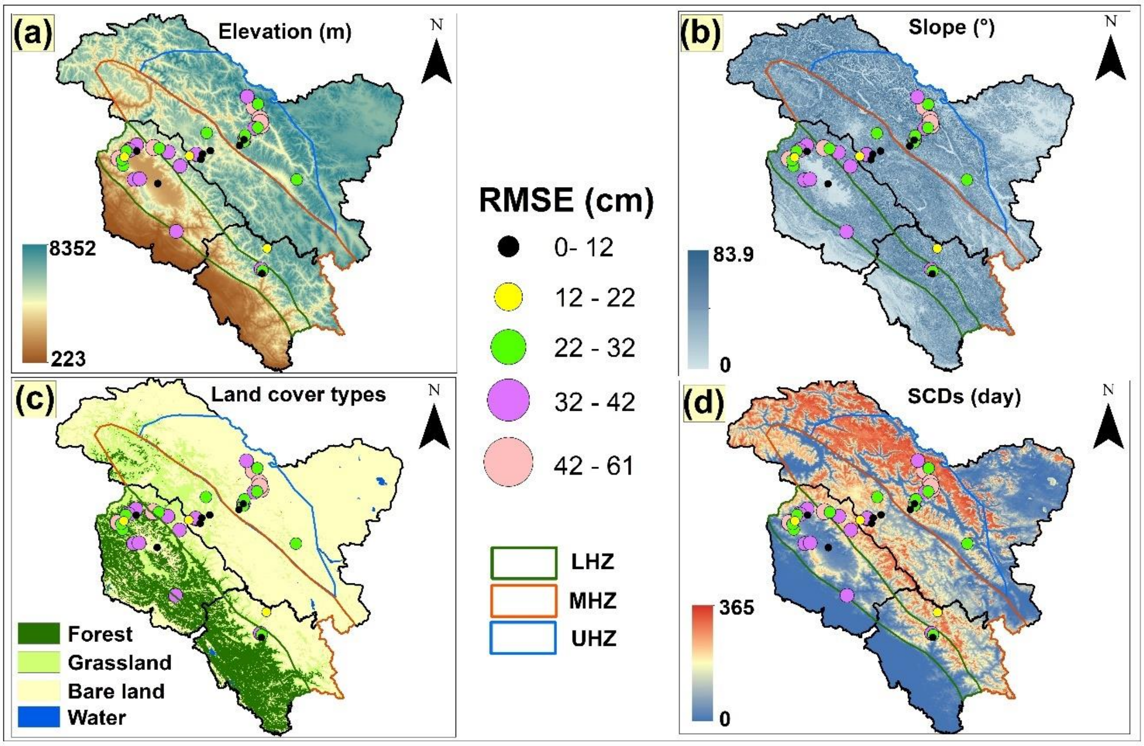

Figure 8. Spatial distribution of RMSE of multifactor SD model for varying (a) elevation, (b) slope, (c) land cover types, and SCDs along the 43 ground stations

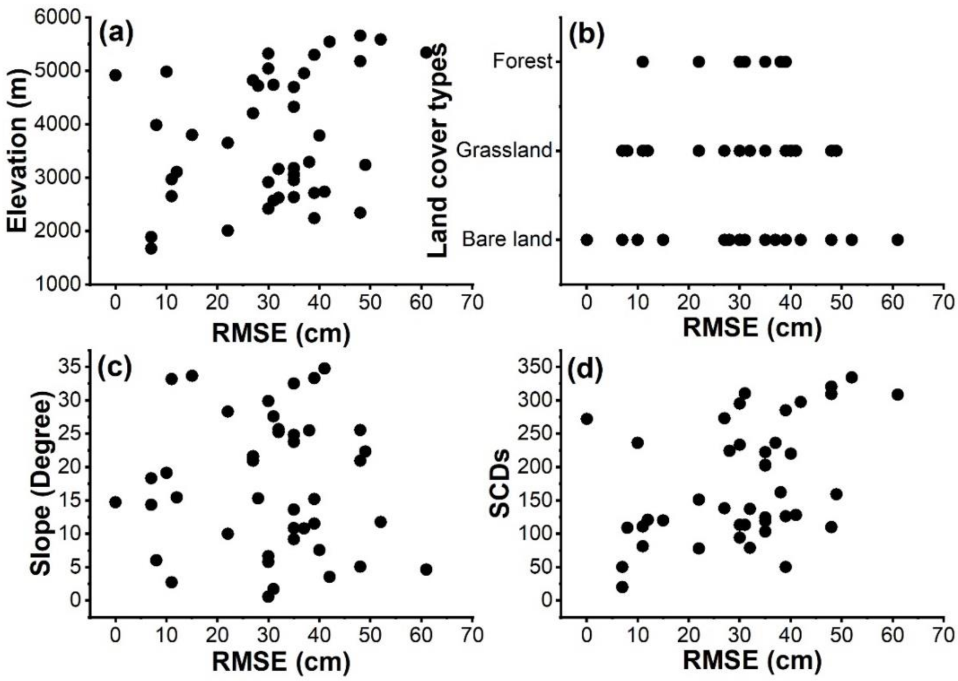

Figure 9. Scatter plots for RMSE of multifactor SD model for varying (a) elevation, (b) slope, (c) land cover types, and SCDs of the 43 ground stations

20. Table 1: The first two links in the table did not work for me. Full citations and access dates would also be helpful.

Author response: The two links in the table are updated now with the following respectively.

1. https://gportal.jaxa.jp (last accessed on: 26/ (last accessed on: 26/11/2023)
2. https://lpdaac.usgs.gov/products/mcd12q1v006/ (last accessed on: 26/11/2023)

21. Table 6: Was the number of observations consistent between snow depth classes? On line 455 it is stated that only four of the 43 in-situ stations have mean snow depths of less than 25 cm. If there are fewer observations within this class it may influence the resulting error.

Author response: The authors would like to inform the reviewer that the number of samples considered for calculating accuracy metrics in each snow depth class are different. As mentioned in the manuscript, there are only four stations which have a mean snow depth of less than 25 cm. However, it is important to note that all stations have observations with SD < 25 cm, though mean is higher than 25 cm. Approximately 20% of the in-situ SD observations in WH have SD <25 cm and represent sufficient number of samples in each WH zone. A figure representing the distribution of in-situ SD observations is attached here for reviewer's consideration. The metrics for each SD class is calculated by matching the estimates from each SD product with in-situ observations. Therefore, the authors believe it is acceptable to use the way samples are used for evaluation of model estimates.

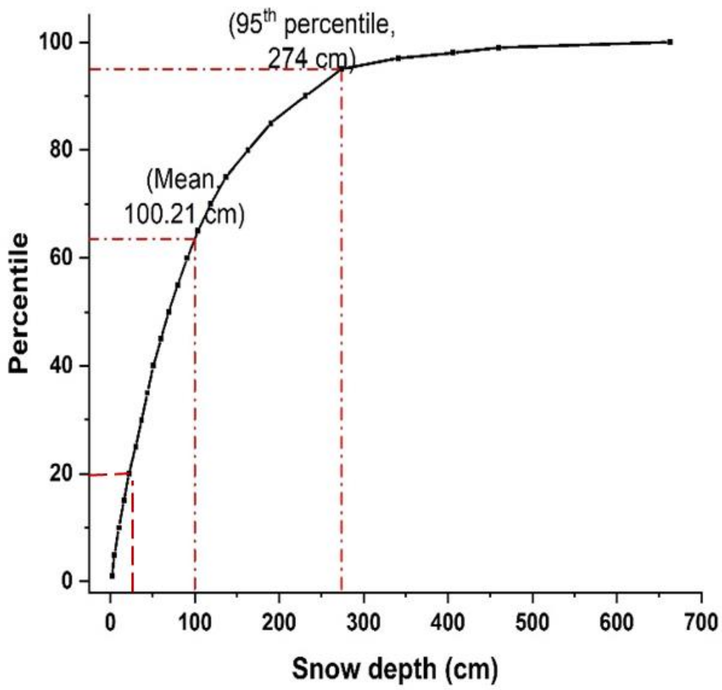

Figure: Cumulative distribution of in-situ SD over WH

22. Table 7: The font for ‘Lower Himalayan Zone,’ ‘Middle Himalayan Zone,’ etc. should face the same direction as model names and RMSE values.

Author response: The font facing direction is adjusted accordingly as pointed out by the reviewer.