Response to the Comments of Reviewer 3 (RC4)

The authors sincerely thank reviewer-3 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: This is a worthwhile and interesting study that explores new snow depth retrieval methodologies using passive microwave observations and associated datasets such as terrain and MODIS snow cover. A particular strength is the focus on the Western Himalaya and the use of a substantial dataset of in-situ snow depth measurements for training and validating the snow depth retrievals. An interesting aspect of the study is the way the high-resolution datasets (e.g., MODIS and terrain) are used to localise the 10 km passive microwave dataset down to 500 m. While the study could have used a more sophisticated machine learning approach, it instead uses multiple-parameter regression models, including linear, power, logarithmic and so on. This is actually a very positive aspect of the study as the resulting simple models are clear and can easily be re-used by other investigators, both for retrievals and as a simple way of assessing sensitivity of snow depth to the various different parameters.

The work is clearly written and mostly well-presented, although some copy editing would be required in places. The main issue to be addressed is the use of the AMSR2 official snow depth product as a reference against which to assess the performance of the new algorithm. As is shown in figure 7, the official algorithm provides zero snow depth over most of the Western Himalaya at a moment when MODIS suggests the area is almost completely snow covered. The areas where AMSR2 does produce non-zero snow depths appear to be topographically linked - for example lower or flatter terrain areas. This suggests the AMSR2 algorithm is not working adequately, so it is a poor reference against which to compare. I wonder if it is possible that some bad quality flags have been set for this product, even if the data is not officially flagged as missing. The most problematic aspect of the use of the AMSR2 snow depth is that thanks to the zero values, it has apparently better performance in low snow depth conditions, in RMS error terms, than the new multi-factor retrieval. This is almost certainly a spurious result (it is surely better to produce snow where it lies, even if too deep, than to “game” the results by setting almost all depths to zero). The comparison to AMSR2 needs to be de-emphasised within the results, and ideally a more adequate reference should be chosen, such as one of the legacy algorithms investigated elsewhere. Given this one main issue and a number of smaller but important points, mainly relating to clarifying the work so that it can be re-used other scientists, I recommend major revisions.

Author response: The authors thank the reviewer for the constructive feedback for improving our manuscript. The authors have done additional proofreading of the manuscript with the help of Grammarly tool to improve the manuscript.

The authors partially agree with the reviewer's opinion that AMSR 2 is a poor reference for comparing the performance of the multifactor model. AMSR2 SD and GlobSnow SD products are the operational PMW SD products available at the time of this manuscript's preparation. GlobSnow product completely masks the WH region and provides no SD information. The authors' also have similar observations, i.e., the AMSR2 SD product having better performance in shallow snow depth conditions is spurious because most of the observations given by AMSR2 had SD<60 cm. The authors' intention in comparing the AMSR2 SD product with multifactor model is to demonstrate (i) the quality of the AMSR2 product over WH (which is not presented previously by other researchers) and (ii) how the developed model is performing against the operational products. This has been already mentioned in the L 135 of the manuscript. Apart from comparison with the AMSR2 SD product, the authors have also compared one legacy model, i.e., Chang's model, and two regional models in this study, as given in different sections of the manuscript. Further, it is essential to note that the comparison against the AMSR2 product and other empirical models is only part of the evaluation. The model is primarily evaluated by comparing it with the in-situ SD observations collected from the snow observatories during the testing period, i.e., 2017-18 to 2018-19.

<u>Response to major comments:</u>

Reviewer comment 1: The AMSR2 snow depth product needs to be described in more detail in the relevant methodology section, e.g., an overview of how the AMSR2 product is derived, whether there are any quality flags or areas where the product is known to perform poorly.

Author Response: We are thankful to the reviewer for the valuable suggestions. The detailed description about the AMSR2 SD product, product generation, and its performance is provided as a new subsection (section 2.4) under the study area and datasets section.

"In this study, the AMSR2 SD products have been downloaded from the (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 multifactor model 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 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) upto 30 cm of ground SD. However, AMSR2 SD products have not been evaluated for Indian Western Himalayan regions till date."

Reviewer comment 2: AMSR2 instrument should have a citation and there should be a DOI for the data (as for other datasets used).

Author Response: As suggested citation for AMSR2 instrument is updated, and DOI for the other datasets are added wherever available in revised manuscript.

"AMSR2 is a PMW sensor onboard the Japanese Aerospace Exploration Agency (JAXA)'s Global Change Observation Mission 1st - Water (GCOM-W1) SHIZUKU, launched in May 2012 (Imaoka et al., 2012)."

DOI for MODIS landcover data: https://doi.org/10.5067/MODIS/MCD12Q1.061

Imaoka, K., Maeda, T., Kachi, M., Kasahara, M., Ito, N., & Nakagawa, K. (2012, November). Status of AMSR2 instrument on GCOM-W1. In Earth observing missions and sensors: Development, implementation, and characterization II (Vol. 8528, pp. 201-206). SPIE

Reviewer comment 3: The multi factor model targets dry snow conditions and hence the study is performed only in the winter period. It would be helpful to mention this in the abstract and conclusions since this appears to be the main limitation on the validity of the model, other than the geographical specificity.

Author Response: The authors are thankful to reviewer for the valuable suggestion and totally agree with reviewer's observation; therefore, in the revised manuscript changes are made in the abstract and conclusion section as suggested by the reviewer.

Abstract section - *"Multifrequency brightness temperature (TB) observations from Advanced Microwave Scanning Radiometer 2 (AMSR2), SCDs data, terrain parameters (i.e., elevation, slope and ruggedness), geolocation for the winter period (October to March) during 2012-13 to 2016-17 are used for developing the SD models for dry snow conditions."*

Conclusions section - *"The multifactor model is applicable only to dry snow conditions. However, in WH even during the peak winter substantial area is covered by wet snow. This constrains the utility of multifactor model for these regions."*

Reviewer comment 4: Of the 40-brightness temperature difference (BTD) pairs tested, only 8 are retained. The paper describes these 8 BTDs, but not the other 32. It is important to describe also which BTD pairs were rejected, to indicate what does not predict snow depth.

Author Response: As suggested, along with the 8 BTD pairs that are retained, the 32 rejected BTD pairs have been added into the Table of the revised manuscript.

Table 4. BTD SD model (with descending observations) relation with SD and evaluation using LOOCV method

	Sr. No.	Independent Variable (x)	Linear Regression Model	RMSE (in cm)	R
Selected parameters	1	BTD (36H-89V)	y = - 2.24x + 107.05	91.63	0.39
	2	BTD (36V-89V)	y = - 2.16x + 81	92.24	0.37
	3	BTD (10V-23H)	y = 4.12x + 31.05	92.45	0.35
	4	BTD (23H-89V)	y = - 1.78x + 122.17	92.46	0.36
	5	BTD (10V-18V)	y = 7.43x + 52	92.58	0.25
	6	BTD (10H-23H)	y = 4.12x + 56	93.78	0.20
	7	BTD (10H-18H)	y = 5.66x + 58	93.47	0.21
	8	BTD (18H-89V)	y = - 1.61x + 122.34	93.92	0.24
Rejected parameters	9	BTD (10H-36H)	y = 0.85x + 70.11	102.20	0.17
	10	BTD (10H-89H)	y = -0.91x + 114.15	102.16	0.18
	11	BTD (10H-18V)	y = 2.84x + 89.85	102.20	0.17
	12	BTD (10H-23V)	y = 3.29x + 78.28	102.15	0.18
	13	BTD (10H-36V)	y = 0.55x + 77.67	102.21	0.16
	14	BTD (10H-89V)	y = -1.15x + 177.36	102.14	0.19
	15	BTD (10V-18H)	y = 5.10x + 30.11	102.04	0.20
	16	BTD (10V-36H)	y = 1.21x + 56.24	102.17	0.18
	17	BTD (10V-89H)	y = -0.66x + 110.16	102.19	0.17
	18	BTD (10V-23V)	y = 4.93x + 44.79	102.03	0.20
	19	BTD (10V-36V)	y = 1.08x + 63.64	102.18	0.17
	20	BTD (10V-89V)	y = -0.92x + 116.53	102.17	0.18
	21	BTD (18H-23H)	y = 3.18x + 77.95	102.19	0.17
	22	BTD (18H-36H)	y = 0.18x + 83	102.23	0.16
	23	BTD (18H-89H)	y = -1.4x + 122.75	102.09	0.20
	24	BTD (18H-23V)	y = -3.92x + 75.13	102.26	0.17
	25	BTD (18H-36V)	y = -0.51x + 90.15	102.24	0.16
	26	BTD (18V-23H)	y = 6.1x + 32.36	102.08	0.20
	27	BTD (18V-36H)	y = 0.86x + 68.45	102.21	0.17
	28	BTD (18V-89H)	y = -1.14x + 122.94	102.13	0.19
	29	BTD (18V-23V)	y = 6.35x + 61.65	102.13	0.18
	30	BTD (18V-36V)	y = 0.43x + 78.64	102.22	0.16
	31	BTD (18V-89V)	y = -1.4x + 126.53	102.10	0.20
	32	BTD (23H-36H)	y = -0.09x + 86.33	102.23	0.16
	33	BTD (23H-89H)	y = -1.57x + 123.73	102.06	0.20
	34	BTD (23H-36V)	y = -1.16x + 93.49	102.23	0.17
	35	BTD (23V-36H)	y = 0.68x + 74.51	102.22	0.16
	36	BTD (23V-89H)	y = -1.36x + 125.26	102.09	0.20
	37	BTD (23V-36V)	y = -0.07x + 86.26	102.23	0.16
	38	BTD (23V-89V)	y = -1.62x + 126.92	102.06	0.20
	39	BTD (36H-89H)	y = -2.10x + 113.67	102.01	0.20
	40	BTD (36V-89H)	y = -1.91x + 118.52	102.03	0.19

Note: y = SD (cm)

Reviewer comment 5: The paper needs to describe how it deals with missing data in any of the many input datasets, if there is any, and if there is not, to clearly state that.

Author Response: In this study, there is no missing values in the input datasets and same has been mentioned in the section 3.1 i.e., data pre-processing section of the revised manuscript also.

"There are no missing values for AMSR2 TB, SRTM elevation, SCD observations for the in-situ stations over WH region"

Reviewer comment 6: The paper needs to explain the meaning of x_1 to x_13 in table 5 (see also line 371-372), without which the equations cannot be re-used by others.

Author Response: In the revised manuscript, meaning of x_1 to x_{13} has been added. In Table 5 notes the details are updated as below.

" x_1 to x_5 are latitude, elevation, slope, ruggedness, and SCD, respectively; x_6 to x_{13} are the BTD of 10H18H, 10H23H, 18H89V, 36H89V, 36V89V, 23H89V, 10V89V, 10V23H, respectively; V is the vertical polarization, and H is the horizontal polarization; and 10, 18, 23, 36 and 89 is the frequency in GHz of the corresponding BT channels"

Reviewer comment 7: Given the poor quality of the official AMSR2 snow product in the case study in this paper, the detailed analysis and comparison in table 7 is of very little interest to the community. It has already been established in Figure 4 and Table 6 that the AMSR2 product is not adequate in this example. Table 7 and associated text should ideally be removed.

Author Response: The authors partially agree with the opinion expressed by the reviewer. It is true that the poor performance of AMSR 2 is already established in the previous sections. However, the mean SD is diverse for same elevation and SCD classes in different WH zones. Further, given the topographic setting, the climatic and snow conditions are different in the same elevation range for different WH zones. Other than comparing both products, the section attempts to provide these heterogeneities and the variation in the model performance under these conditions. Hence, authors opine that the table can be of interest to some of the readers looking at how the model performance vary under these conditions. Therefore, authors suggest the reviewer to consider the inclusion of table into the manuscript as it is.

Reviewer comment 8: Line 441 the snow depth classes are supposed to be grouped according to in-situ measurements, but since this analysis is done over the whole Western Himalaya, there cannot be in-situ measurement everywhere, so it is not clear what is going on.

Author Response: In this study, SD classes are grouped according the in-situ measurement collected in three different zones of Himalaya (i.e., LHZ, MHZ, and UHZ). The same information is present in the L441 of the preprint and is rephrased for improving the clarity. Figure 4 shows the spatial distribution of mean SD of stations. In the figure it can also be seen that in-situ stations are distributed over all three WH zones.

"In each WH zone, the AMSR2 SD products and multifactor SD model estimates are grouped into five SD classes, i.e., 0-25 cm, 25-50 cm, 50-75 cm, 75-100 cm, and >100 cm based on in-situ SD observations during 2017 -18 to 2018 -19."

Reviewer comment 9: Line 321 "a total of 72 parameters" - as with the 32 BTDs that were rejected, it is as important to know which parameters did not correlate well with snow depth, as much as those that did. Hence, in case there are any other rejected parameters that have not been described in the text, it also needs to be clear what these were, at least in summary form.

Author Response: The authors regret the typographical mistake in the L321. It should be 57 parameters. The same has been used elsewhere in the manuscript. The authors agree with the reviewer's suggestion. This has been already addressed. Kindly refer to the response given to the comment 4.

Reviewer comment 10: The MODIS snow cover days predictor is not clearly enough defined. I still am not sure if it is the days per year (making this a fixed map) or if it is the presence of snow cover on that specific day the snow depth retrieval is made. The text probably needs to be clearer here (see also point 6)

Author Response: MODIS SCD indicates how many days in a year (i.e., 364/365 days), a pixel covered with snow. In Himalaya, 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. Therefore, SCDs map will also change every day, month and years. For every day in a year SCD map has been generated and in the developed model SCDs map is variable. Reviewer 2 also have mentioned some suggestions with regard to SCD. The following changes have been incorporated 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."*

Response to Minor issues:

1: Linę 264: "Grody's decision tree" should more fairly be "Grody and Basist's decision tree".

Author Response: As suggested, we have updated in the revised manuscript.

"Grody and Basist's decision tree makes use of different filters (see Figure. 3) based on the values of TB observations to separate snow from non-snow pixels"

Reviewer comment 2: In defining Eq. 1- 4, "i" needs defining

Author Response: Agreed. 'i' represents the number of parameters in the model. Accordingly, the information is updated into the manuscript.

"where, y is the ground observed SD values; x_1, x_2, ..., and x_i are the screened parameters; α_0, α_1, α_2, …, and α_i are the regression coefficients of the multiparameter models, and i represents the number of parameters."

Reviewer comment 3: It seems incorrect to have two constant offset coefficients in equations 1, 2, and 4, since it is only possible to estimate one. One of alpha_0 and c_i should probably be removed. In any case, only one constant offset coefficient is seen in Table 5, so the equations do not appear to be consistent.

Author Response: The authors sincerely apologize for this mistake and totally agree with the observations of the reviewer. α_0 is now removed the equations (7) – (11) in the revised manuscript (previously numbered as (1)-(4)); however, c represents the error term in the equations. In the revised manuscript, changes have been incorporated as follows.

"

$$y = \alpha_1 x_1 + \alpha_2 x_2 + \cdots + \alpha_i x_i + c \quad (1)$$

$$y = \alpha_1 Inx_1 + \alpha_2 Inx_2 + \cdots + \alpha_i Inx_i + c \quad (2)$$

$$y = cx_1^{\alpha_1} x_2^{\alpha_2} \ldots\ldots\ldots\ldots\ldots x_i^{\alpha_i} \quad (3)$$

$$y = \alpha_1 \frac{1}{x_1} + \alpha_2 \frac{1}{x_2} + \cdots + \alpha_i \frac{1}{x_i} + c \quad (4)$$

"

Reviewer comment 4: Line 362 could mention the likely reason for why descending and ascending passes have different results, namely as stated on line 527 that one local time is during daylight and hence more prone to melting snow.

Author Response: The authors are thankful to the reviewer for the valuable suggestion. In the revised manuscript changes have been incorporated as given bellow.

"*The SD models built with TB observations from descending orbital passes have relatively higher correlation and lesser RMSE compared to those from ascending pass TB data when analyzed with in-situ SD. This is mainly because descending orbital passes occur in the morning time with no melting of snow; however, ascending orbital passes occur in the afternoon time with substantial melting of snow in the study area. Therefore, only descending pass TB observations are used in the study."*

Reviewer comment 5: Line 384-385 - consider using a table rather than loading the text with so many numerical results.

Author Response: As suggested by reviewer, the lines 383-385 containing the numerical results are removed, and shown as Table 6 in the revised manuscript.

"The R, RMSE (in cm) metrics of power, linear, logarithmic, and reciprocal models in different WH zones are shown in Table 6.

Table 6. Comparative analysis of multifactor SD models during 2017-2019 for WH zones

	Western Himalayan Zones					
	Lower Himalayan		***Middle Himalayan***		***Upper Himalayan***	
Models	*R*	*RMSE*	*R*	*RMSE*	*R*	*RMSE*
Power	*0.65*	*22.7*	*0.76*	*19.2*	*0.89*	*22.6*
Linear	*0.64*	*29*	*0.68*	*22.8*	*0.75*	*33.5*
Logarithmic	*0.38*	*52*	*0.14*	*41*	*0.73*	*36.9*
Reciprocal	*0.09*	*121.3*	*0.47*	*26.7*	*0.61*	*43.2*

"