Responses to reviewers for Sasaki et al, submitted to *The Cryosphere*

We'd like to thank both reviewers for their very valuable inputs and thorough reviews. Our answers to each comment are indicated in blue below.

Reviewer 1

The authors established the automatic detection method for snowline altitude in the Himalayan region by using many images obtained from various satellites. Overall, the manuscript is written well. However, further manuscript improvement is necessary for the publication on The Cryosphere. I suggest the revision of the structure in the manuscript, the reconsideration of the analysis method for seasonal and interannual changes in SLA, and the enhancement of the study's significance. Please see the following comments. I hope my comments help to improve the manuscript.

We'd like to thank the reviewer for their very valuable inputs and thorough review. The Reviewer has provided many constructive comments and suggestions, which will improve the manuscript. Our answers to each comment are indicated in blue below.

Major comments:

1. I suggest you come up with a structure, figure, and table to explain the methodology. This is because you used various data (satellite images, DEM data, and reanalysis data) through many processes. A little confusing for me. Refer to the specific comments below.

Thank you for the suggestion. Our approach follows that of (Girona-Mata et al., 2019) closely, so we had not thought that such a figure would be necessary, but we appreciate that a methodological figure would enable the reader to follow the analyses more easily.

Outcome: We have adapted Figure R1 (below) from Figure S2, to illustrate the methodological workflow in the manuscript, and will include this in the main text as a new Figure 2.

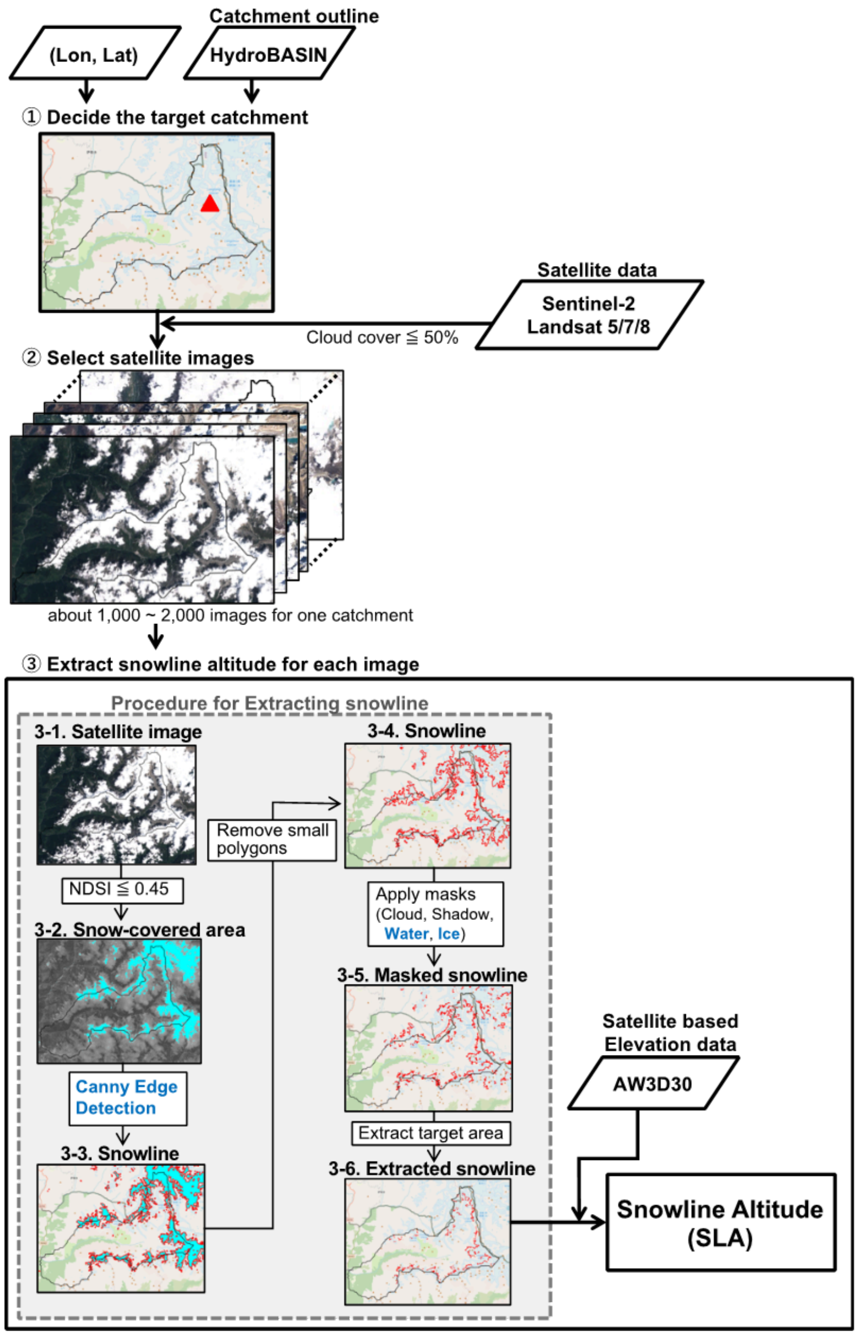

Figure R1. Schematic diagram of the snowline detection algorithm with a sample image obtained from Sentinel-2. The parts highlighted in blue represent updates to the method of Girona-Mata et al. (2019). By inputting longitude and latitude, all procedures are automatically performed on the Google Earth Engine platform.

2. I have concerns you use both Landsat-8 and Sentinel-2 for the trend analysis. This is because the accuracy of SLA using Landsat-8 is obviously lower than that using Sentinel-2 as you show Table 2 and Figure S3. I understand the advantage of detecting more SLA by using Landsat-8. However, you should explain the disadvantages too in the manuscript. In

addition, I suggest you unify the satellite for the analysis images to discuss the SLA trends. The trends range from -15.6 m yr-1 to +14.4 m yr-1. Compared to the seasonal variations, the trends are sensitive to the bias resulting from the use of different satellites. If you choose a single satellite for the trend analysis, you might be able to see clear trends.

The reviewer raises a valid concern about the possible sensitivity of the trend analysis to the spatial resolution of the different satellites. We would like to highlight that the trend analysis is not only dependent on Sentinel-2 and Landsat8, but also the TM and ETM+ sensors on Landsat 4, 5 and 7, which are essentially equivalent to Landsat8 (and now 9) in spatial and spectral resolution but much poorer in terms of radiometric resolution, which can lead to saturation in the visible bands (Knap et al., 1999).

The reviewer interprets that the Sentinel-2 snowlines perform better than those derived with Landsat8 for our evaluation scenes (original Table 2, Figure S3). Our analyses actually show that the seasonal snowlines retrieved by the distinct sensors are nearly equivalent (Figure S4). Indeed, the spatial resolution difference between Landsat and Sentinel-2 (30m vs 10m) should, at worst, lead to an increased SLA detection error of a similar scale (30m vs 10m); slopes steeper than 50 degrees tend to rapidly shed snow and are likely to be self-shadowed (and therefore masked in our workflow).

First, relating to the apparent performance difference, we do not think that this is due to the sensor differences. In investigating the performance difference between the two sensors, we found that the detected snowlines corresponded very closely in space to the manual snowlines for all scenes, and were surprised by the degree of mismatch between the automatic and manual SLA values. After a closer look, it has become apparent that this is primarily due to spatial sampling biases, as the manual snowlines cover only a small portion of the entire scene. Thus, the apparent better performance of S-2 was due to chance. However, this indicates that we were not using a robust measurement of performance.

To better evaluate the ability of our automated method to retrieve snowline information, we have entirely revised our evaluation of the remotely-sensed data. We focus on the automated method’s ability to retrieve the snowline boundaries. We do this, in a similar manner to Girona-Mata et al (2019), by determining the nearest automatically detected snowline point for each manual snowline point, in order to measure the distance between the points (a metric of the retrieval success) and the corresponding elevation difference (the consequence for our measurements). We now do this for each of the 12 validation scenes and against both independent candidate manual snowline interpretations.

We show examples here for Landsat-8 and Sentinel-2 scenes, which highlight that the detected snowlines correspond very well in space (Figures R1 and R2). Specifically, we find that the method successfully retrieves a snowline for both sensors to a comparable degree. In both cases, the snowline generally corresponds very well in space, and therefore in elevation (as hypothesized above - within approximately one pixel). We note that some manually-derived snowline points do not correspond clearly to a point on the automatic snowlines (lateral distances of greater than 100m), usually due to cloud cover, but these errors are strongly overcome by the general close agreement. Through this point-by-point comparison of nearly 90000 manually mapped snowline positions, we determine an NMAD of 8.6m against operator 1 and 10.2m against operator 2. On the overall comparison of scenes (new Table 2, also depicted below) we see clearly that 11 of the 12 scenes corresponded very closely, with one scene showing slightly less favorable agreement as there was little overlap between the automatic and manual coverage..

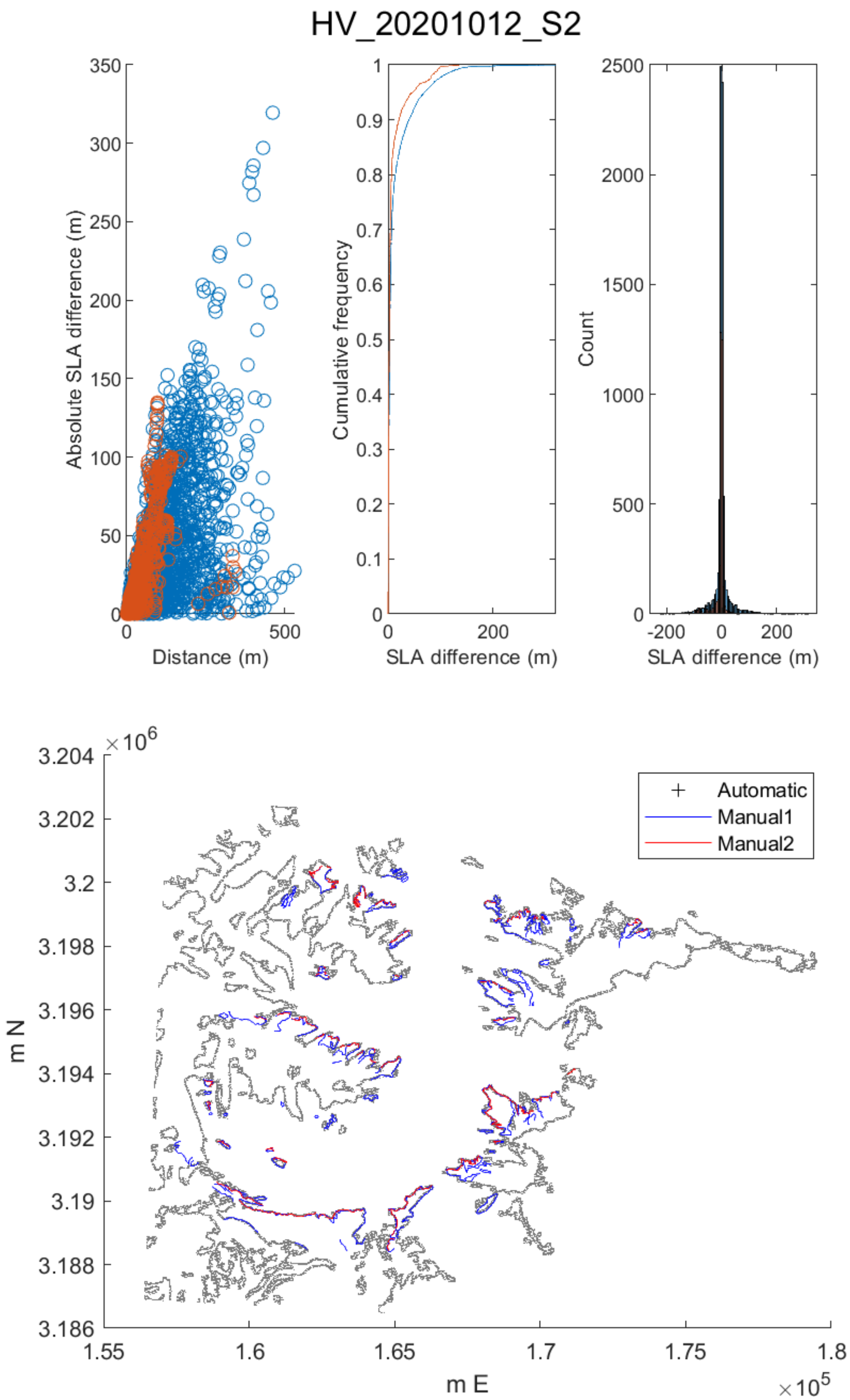

Figure R1. Correspondence of manual and automatic snowlines at the Hidden Valley site in October 2020. The manual snowlines were delimited from a cloud-free PlanetScope image, the automatic snowlines from Sentinel-2. Comparing corresponding nearest snowline points, the automatic snowline had a bias of -4.7m (-5 m) elevation and 41 m (18 m) relative to the Manual1 (Manual2) snowline.

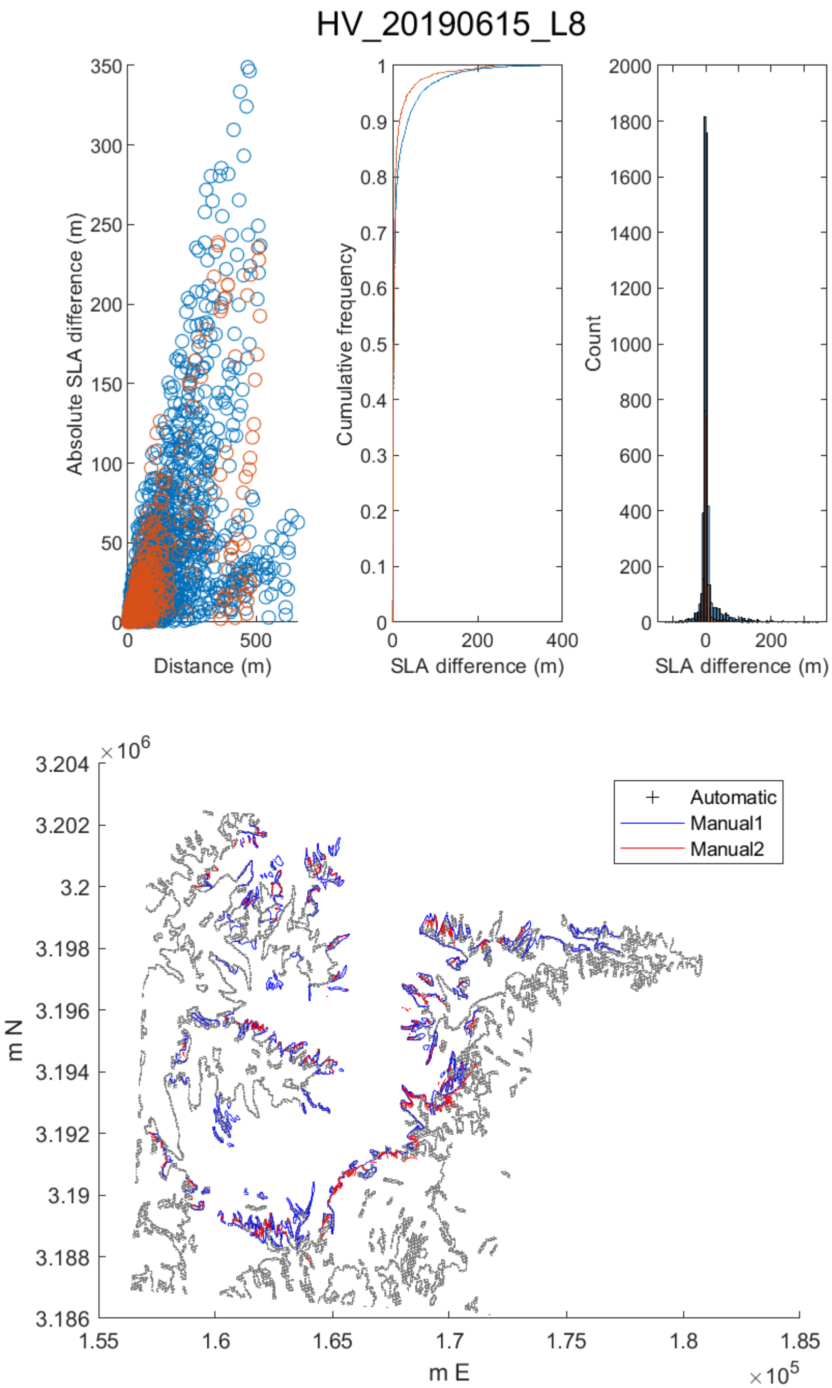

Figure R2. Correspondence of manual and automatic snowlines at the Hidden Valley site in June 2019. The manual snowlines were delimited from a cloud-free PlanetScope image, the automatic snowlines from Landsat 8. Comparing corresponding nearest snowline points, the automatic snowline had a bias of 7.8m (3.6 m) elevation and 45 m (30. m) relative to the Manual1 (Manual2) snowline.

Table 2. Performance of the automated snowline in comparison to manually digitized snowlines by operators 1 (M1) and 2 (M2), reporting the median absolute deviation (MAD) for horizontal distances (D) and vertical differences (H) of nearest pairs of snowline points in the dataset. The poor performance for the RW scene on 2020.04.20 is due to little overlap in measurement area, leading to large spatial distances for nearest points, and therefore large height differences.

Site	**Sensor**	**Date**	**M1 MAD D (m)**	**M1 MAD H (m)**	**M2 MAD D (m)**	**M2 MAD H (m)**
24K	L8	2020.12.29	20.35	9.77	19.83	8.71
HV	L8	2019.06.15	9.55	3.14	9.28	2.68
HV	S2	2020.05.23	9.79	2.92	9.96	3.32
HV	S2	2020.10.12	9.88	3.26	9.25	2.31
HV	S2	2020.12.30	10.55	3.42	10.23	3.06
Lang	L8	2016.02.12	15.30	6.73	15.39	5.63
Lang	L8	2017.11.12	14.96	5.73	17.34	7.50
RW	L8	2019.12.30	21.62	9.79	18.80	8.42
RW	S2	2020.05.17	17.74	8.25	17.47	7.74
Sato	L8	2017.09.13	16.49	9.07	15.75	7.22
Sato	L8	2021.01.27	16.20	8.54	15.88	7.30
		mean	14.77	6.42	14.47	5.81

We appreciate that the reviewer may wish to see additional evidence of the comparability of sensors' results and the susceptibility of the trends to possible bias between sensors. We have therefore, following their suggestions, also investigated the sensitivity of our derived trends to the inclusion of Sentinel-2 data. Below (Figures R3-R7) please find a depiction showing that the inclusion of additional observations from Sentinel-2, despite having no influence on the seasonal pattern, can have a moderate numerical effect on the overall trend. However, this effect 1) varies from site to site, and 2) never changes the sign nor the significance of the trend. Nevertheless, in the text, we will report trend values including and excluding Sentinel-2 data, and include these figures in the supplementary material.

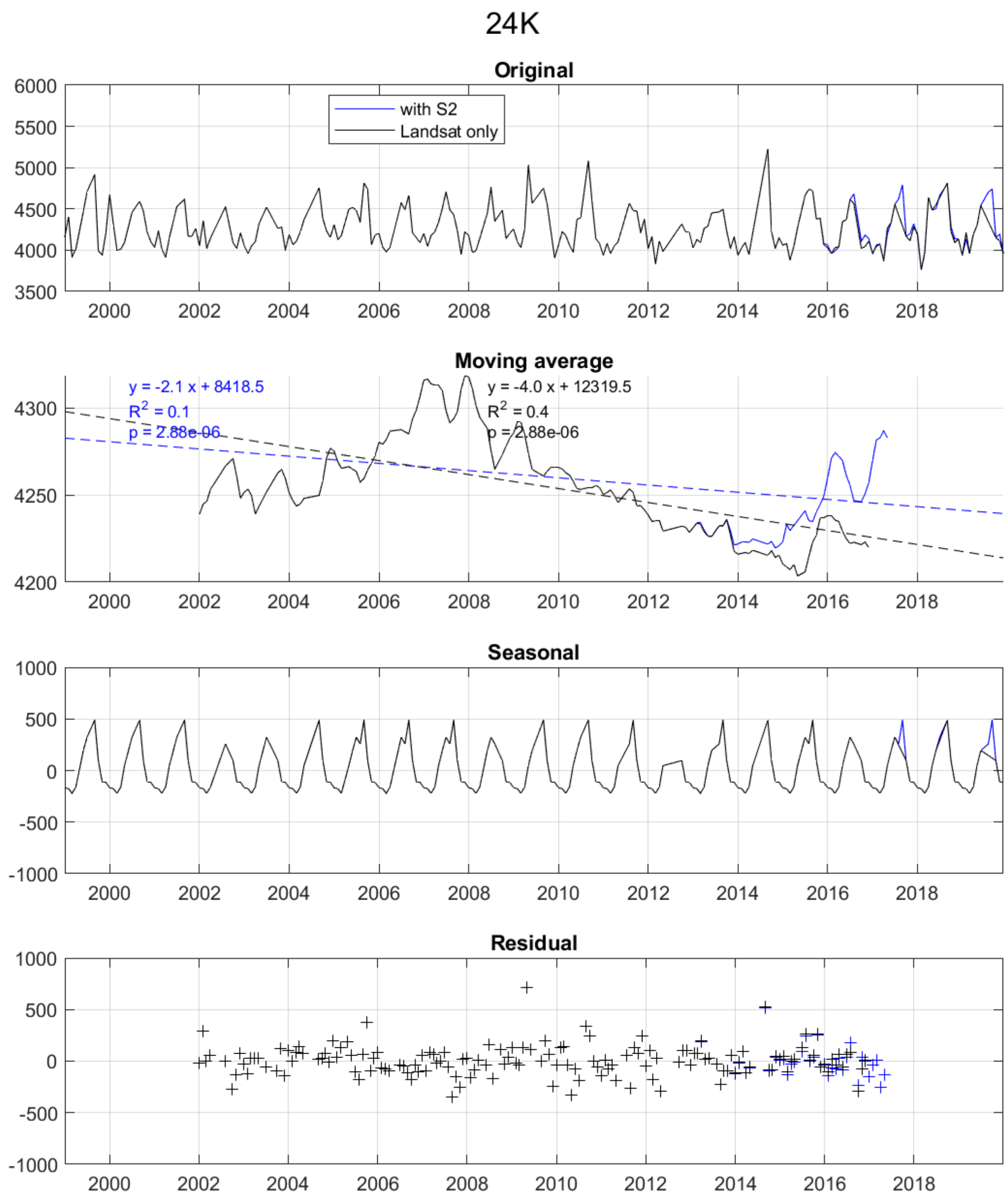

Figure R3. Decomposition of seasonal snowline and trends for the 24K site, with and without inclusion of Sentinel-2 data.

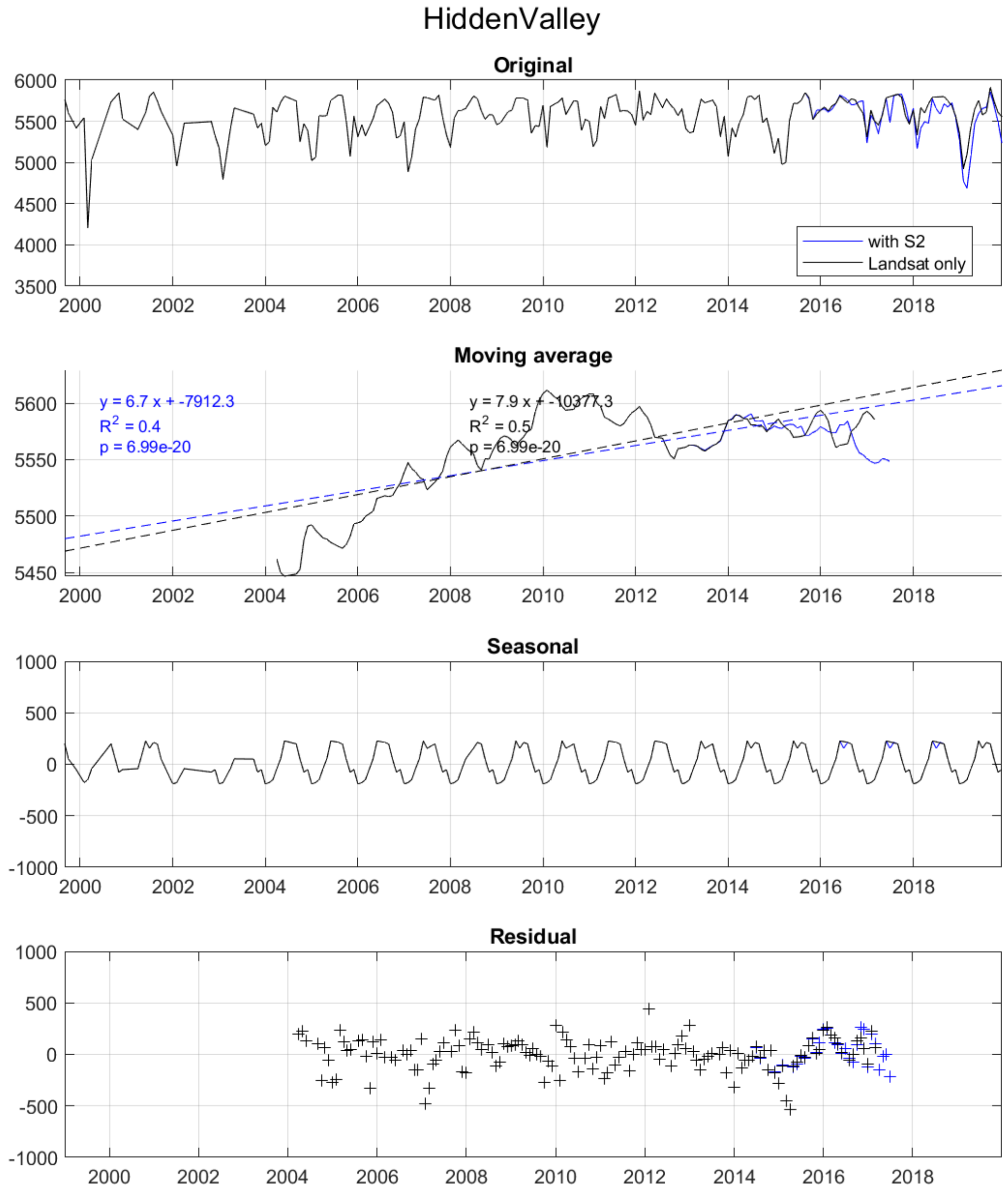

Figure R4. Decomposition of seasonal snowline and trends for the Hidden Valley site, with and without inclusion of Sentinel-2 data.

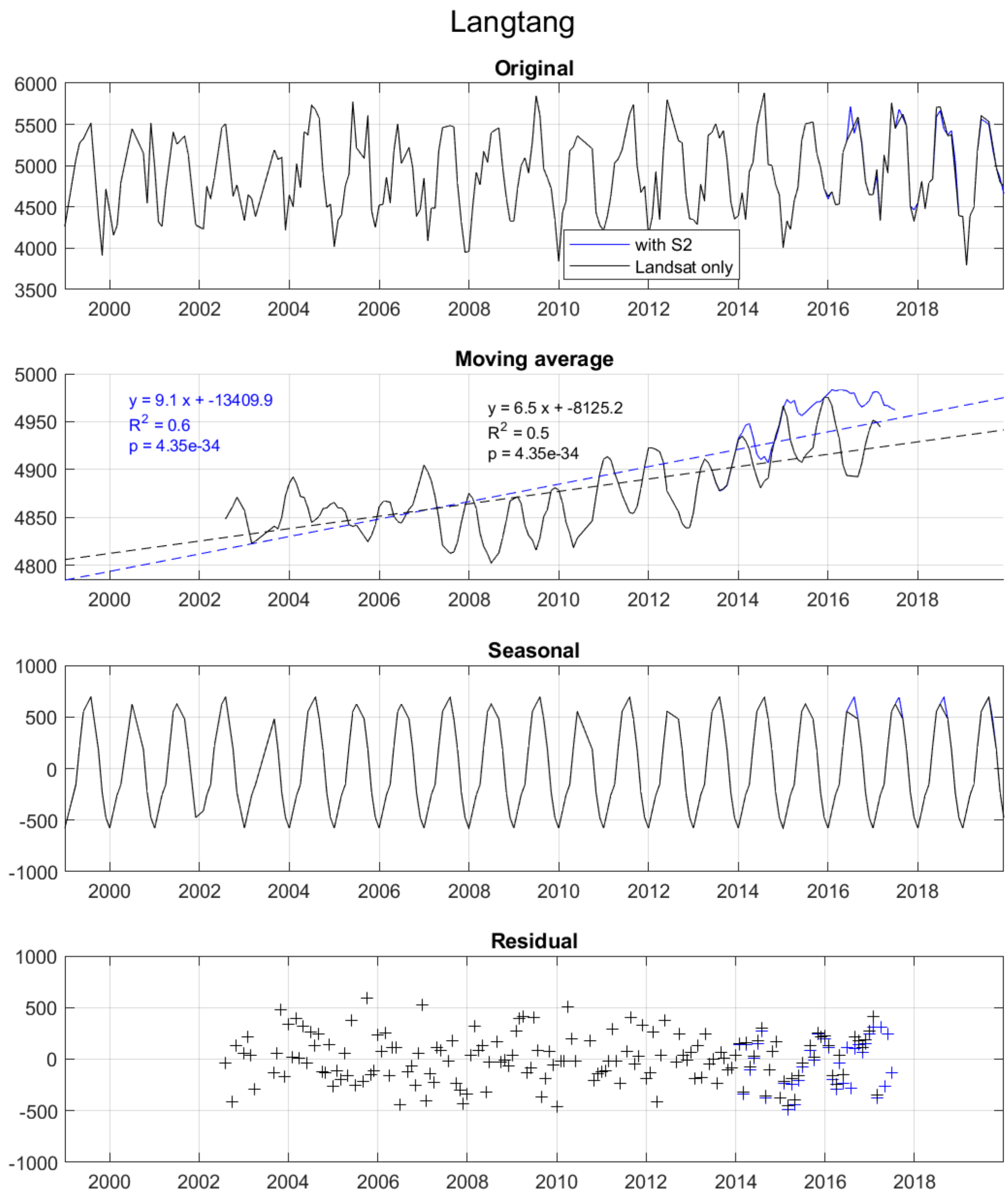

Figure R5. Decomposition of seasonal snowline and trends for the Langtang site, with and without inclusion of Sentinel-2 data.

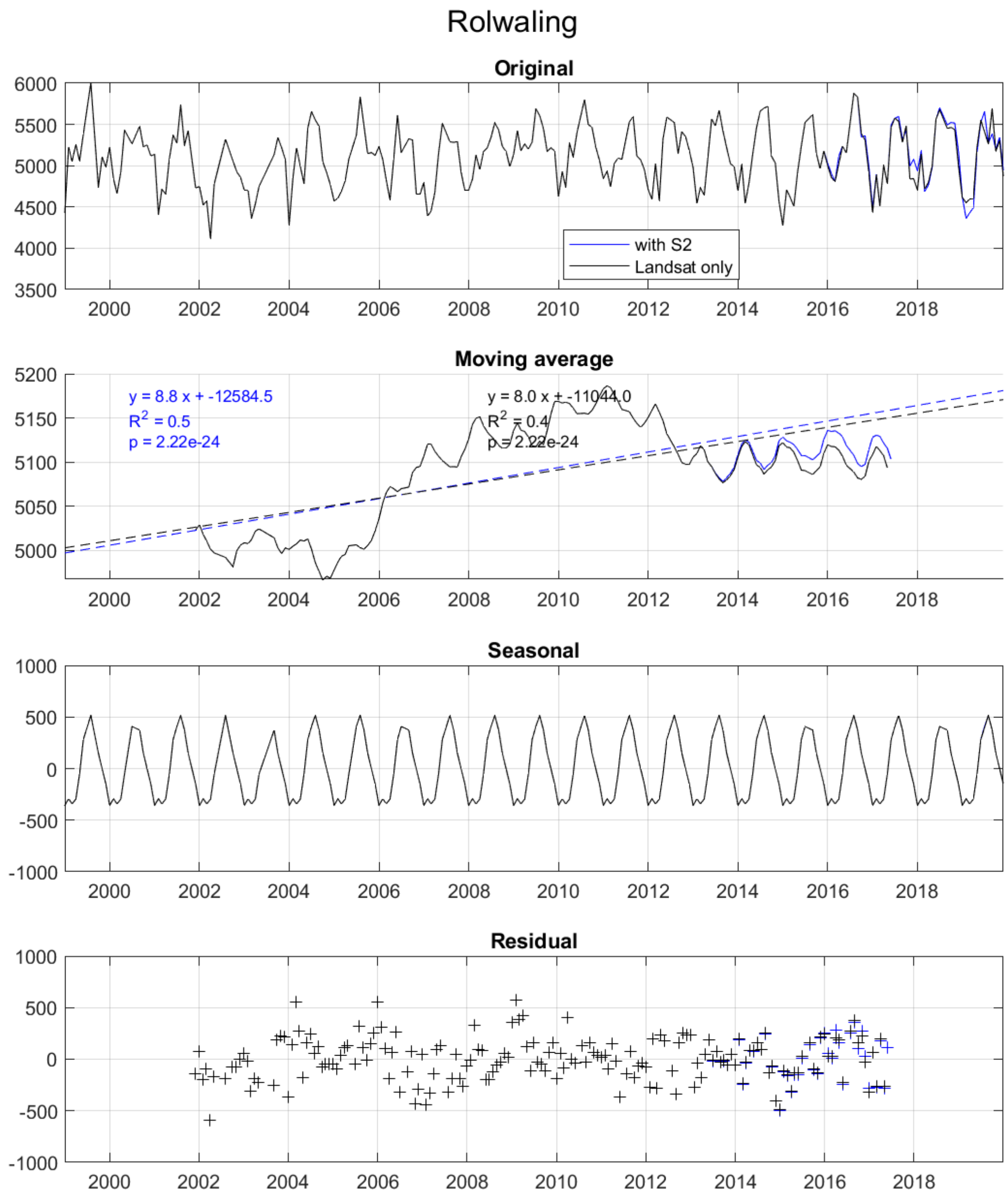

Figure R6. Decomposition of seasonal snowline and trends for the Rolwaling site, with and without inclusion of Sentinel-2 data.

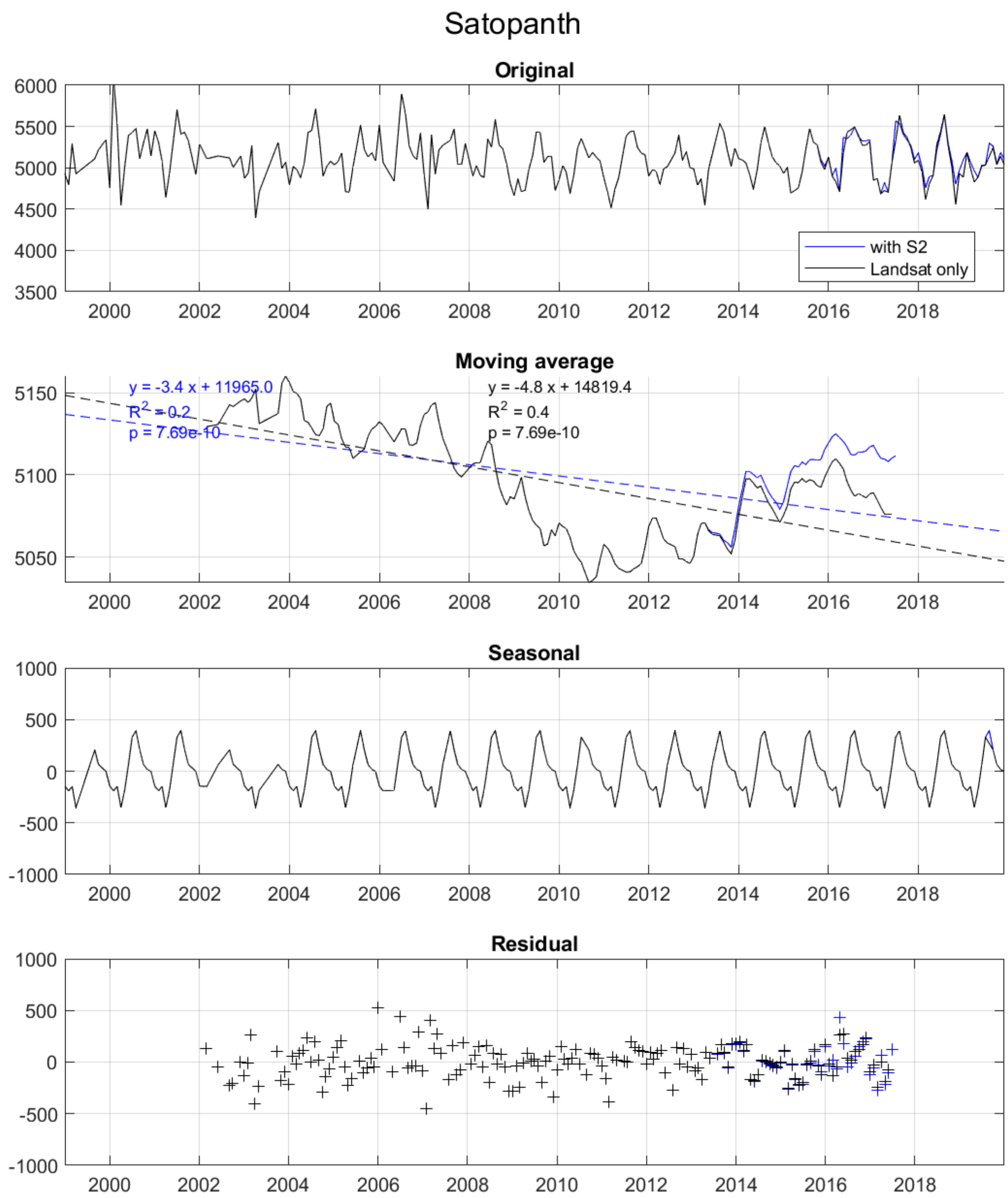

Figure R7. Decomposition of seasonal snowline and trends for the Satopanth site, with and without inclusion of Sentinel-2 data.

Outcome: To address these concerns, we will take the following steps:

1. We will update the evaluation of the performance of the automated method with respect to our manually-derived snowline data, reporting the spatial and elevation

correspondence of these datasets for each scene, following Figures R1 and R2 (similar figures will be included in the supplementary material for all evaluation scenes), and include the updated Table 2 in the manuscript.

2. We will include discussion of the influence of inclusion of Sentinel-2 data for both seasonality and long-term trends identification. Please note that we have also performed testing of the trend retrieval from temporally-biased data, which is presented in our response to Reviewer 3. Our method works quite well for this, not excluding the possibilities of differing SLA retrieval biases between sensors or preferential seasonal sampling differences.

3. The significance of this study seemed weak. This is because it was unclear how much of the change in the detected SLA was related to the snow melt amount. Could you calculate the variation of the snow area with SLA changing in each catchment? Since it is a given that SLA has a sensitivity to weather conditions such as air temperature, I would like to see more value in this study by adding new findings. At least, you should quantitatively mention how this study contributes to the understanding of the hydrological cycle in the Himalayan region.

Thank you for this constructive criticism. We are sorry to hear that the significance of the study did not seem strong to the reviewer, and we will be sure to make this clearer in the revised manuscript. Determining the amount of snow melt (i.e. changes in catchment-wide SWE) in each catchment is outside the current scope of the study, as SWE is not directly retrievable at high resolution from remote sensing measurements. Our objective is to measure changes (seasonally and decadally) in the altitudinal coverage of snow in the catchments, and to understand its links to meteorological factors and climatic changes. We find this to be a compelling topic of research, as SLA can be used to evaluate distributed modelling results (Buri et al., 2023, 2024; Robinson et al., 2025), thus providing constraint on SWE changes, yet is retrievable at high resolution (e.g. considerably better than 500m MODIS coverage) relevant for constraining models in mountainous areas. This is especially important for catchments without in situ measurements. The snowline, as we derive it, is also relatively less sensitive to cloud coverage than catchment-wide snow-covered area. Consequently, the methodological advance in this study can enable future efforts to easily leverage snowlines to help constrain catchment processes within models at a variety of sites and spatial scales.

Further, although studies of changes in snow-covered area exist, area represents an integration of catchment hypsometry (Tang et al., 2022), and we consider snowline changes to be a cleaner metric of climatic change, yet few past studies have attempted to understand long-term snowline changes; we do. We further note that both seasonal and long-term variations in snowline provide useful information about the local controls of snow processes (e.g. Girona-Mata et al, 2019; this study). For example, the investigation of aspect-dependence of snowlines provides insights into the seasonal radiative controls on snowcover (Figure 4), and this study highlights that a variety of process manifestations occur across this section of the Himalaya.

Outcome: We will modify the text (both the motivation and the discussion/conclusions) to better highlight the significance of the study in terms of methodology and utility, in terms of seasonal process inference, and in terms of decadal SLA change. We will also indicate the importance as an indicator of the annual water cycle within catchments, both for seasonal storage and for blue water generation.

Specific comments:

L23: Remove “as Heading 1”.

We will do this.

L12: Remove or replace “Globally” in this sentence because you didn’t evaluate this algorithm globally.

Agreed, we will change this to ‘for areas of interest’.

2 Study site and data: I suggest the order of this section be replaced with the method section. The explanations of the data in this study appear suddenly, it is hard to read for me.

Thank you for the suggestion. We will combine and restructure these sections. The ‘Data’ must nevertheless come before the actual methods, but we will reframe to use the study sites as initial sites of interest. Consequently, in the revised manuscript, we will implement a combined 'Methods' section that includes subsections of ‘Detection of Snowline’, ‘Study sites and Evaluation’, and ‘Detection of changes’.

3 Method: This is the evaluation paper for the SLA detection algorithm, you should move Table S2 to the main manuscript to show the detection method for SLA even if the flow is similar to that proposed by Girona-Mata et al. (2019). I suggest you add more detailed information, you used satellite products, atmospheric datasets, new categories (ice and water surfaces), and the point that you newly used Google Earth Engine, to the table. In addition, change and enhance the line color for the snowline. It is hard to see the black line (it is the same color as the catchment area!). It might be kind to add the explanation, you updated the previous study, to the caption.

Thank you for the helpful suggestion. Following on your main comment (1) above, we will create such a figure, adapted from Figure S2, for inclusion in the main manuscript. We will endeavour to make this figure complete and visually clear.

Figure 1: Add the category of Snow to Overview in the legend. Does the white area mean the snow area, right? Also, I could not find the category of Water from the histograms. Also, it would be good if you could show the SLA in the figures (if possible).

Thank you for the helpful comments. We will revise this figure according to your comments, also to improve the readability according to the comments of Reviewer 2. The white areas are mostly snow (some are cloud) but as evident from the background Sentinel-2 images, as this is a transient landcover class. There are indeed water areas, but it appears that this landcover class did not display properly - the lake of Tsho Rolpa in RW should be evident at the glacier terminus. However, the water areas, while important to remove for snow-cover detection purposes, are relatively small and hard to spot at this scale. We would prefer not to depict the SLA in these figures, as that would be a primary result. Please see below for a revised version of Figure 1:

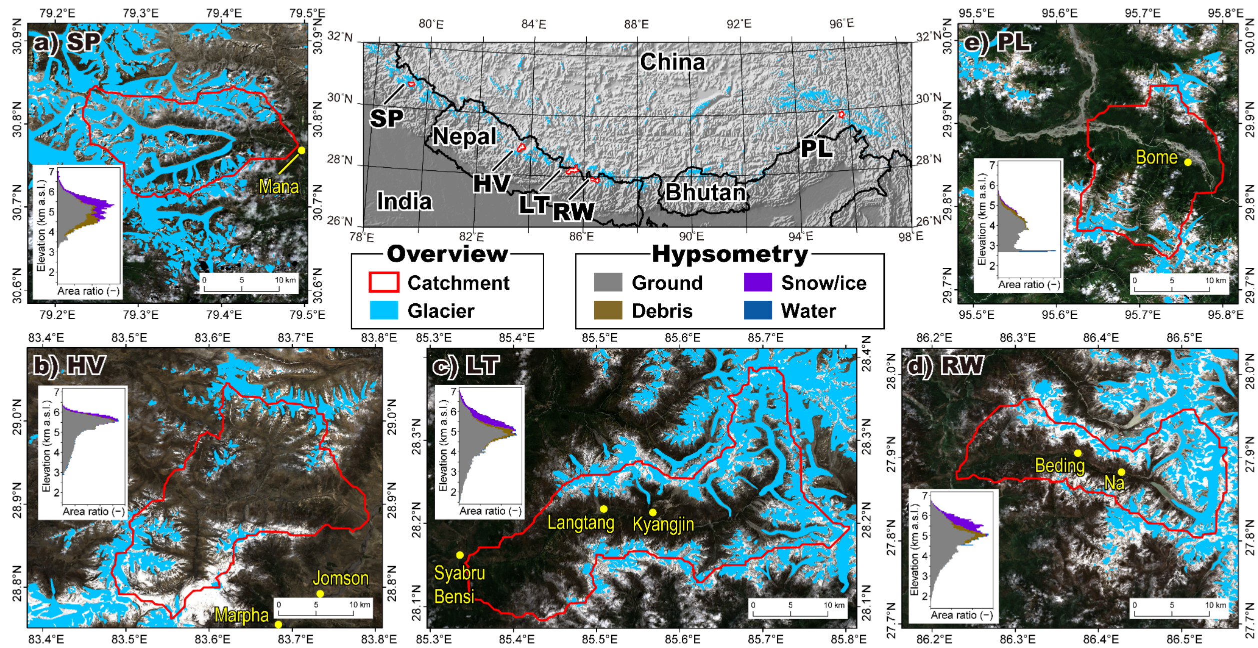

Figure 1 (revised).

L 73: Modify the table number. Do you have any references for the values?

Thank you. Indeed, this caption should have read that the catchment geometric characteristics were derived from the HydroBasins level 9 catchment boundaries and the ALOS World 3D 30m DEM, while th climatological characteristics were determined from ERA5, downscaled with an adiabatic lapse rate to the median catchment snowline elevation. We will ensure that the figure number and caption is corrected in the revised manuscript.

L77: What do you mean by “level”? Please explain it briefly.

The HydroBasins product is a nested hierarchy of watershed boundaries; the ‘level’ is the hierarchical level of nesting; this is their terminology, and basically refers to the approximate size and stream order of the catchment. We will slightly elaborate this in the revised text.

L94-95: I don’t understand the expression that the SLA automatically detected using manual delineation. Is it manual or automatic?

Apologies for the confusion. This will be revised to ‘to evaluate the automatically detected snowlines against snowlines detected manually.’ The manual delineations are the reference dataset for this comparison.

Figure S3: What are the vertical lines in the panels (for example, the lines around the x-axis = 5500 m)? Probably, those mean the median values, but you should add an explanation in the caption.

The reviewer is correct, these are the median values. We will include this in the revised manuscript.

4 Results: The Results section should be nominally limited to new results from the current observation or calculation and not include a literature review (L197, 277…). In addition, I saw the words “consider” and "suggesting" in the results section (L186, 261). The author’s speculation should be described in the discussion section. Please move the speculations to the discussion section.

Thank you for noting this; we will carefully re-examine the manuscript to relocate any interpretations and speculations to the discussion section, and to eliminate any instances of literature review, including those which you note.

L164-177: You should explain the differences in accuracy between Landsat-8 and Sentinel-2. The results from Sentinel-2 are better.

Thank you. Indeed, the comparison of accuracy and results from the different sensors has been significantly expanded in response to your main comment 1, although our investigations indicate that the performance for Landsat-8 and Sentinel-2 are very similar.

Figure 3: I suggest you show the SLA anomalies. Or, please add the value of the trend to the figure. It is hard to see the trends.

Thank you for the suggestion. We were not able to produce an aesthetic version of the figure that depicted the anomalies. We will, however, indicate the trends in the modified figure caption.

Figure 5: Why don’t you show seasonal anomalies of the SLA? Hard to see the differences…

Thank you for the suggestion. As above, we were not able to produce an aesthetic version of the figure that depicted the anomalies. Indeed, the changes between periods are much smaller in magnitude than the seasonal variability. For this reason, we have depicted the periods of statistically-significant change with the background shading.

Figure 6: I suggest you add the correlation coefficients of the interannual changes in the atmosphere variables with those in the SLA to the panels. Before the result of multiple regression analysis, I would like to see relationships between SLA and a single variable.

Thank you, this is a good suggestion and we have included correlation coefficients for each individual parameter in the modified Figure (shown below).

L296-298: I think an increase in cloud cover causes an increase in downward longwave radiation. Could you not consider that variations in downward longwave radiation contribute to SLA variations?

We absolutely agree that cloud cover changes, if present, could also affect the snow persistence, and therefore the SLA trends. We have included this variable in the revised Figure 6 (below) and the revised regression analysis (Tables 3 and 4, below). Cloud cover is correlated with SLA changes at two sites, and improves the multivariate regression at two sites.

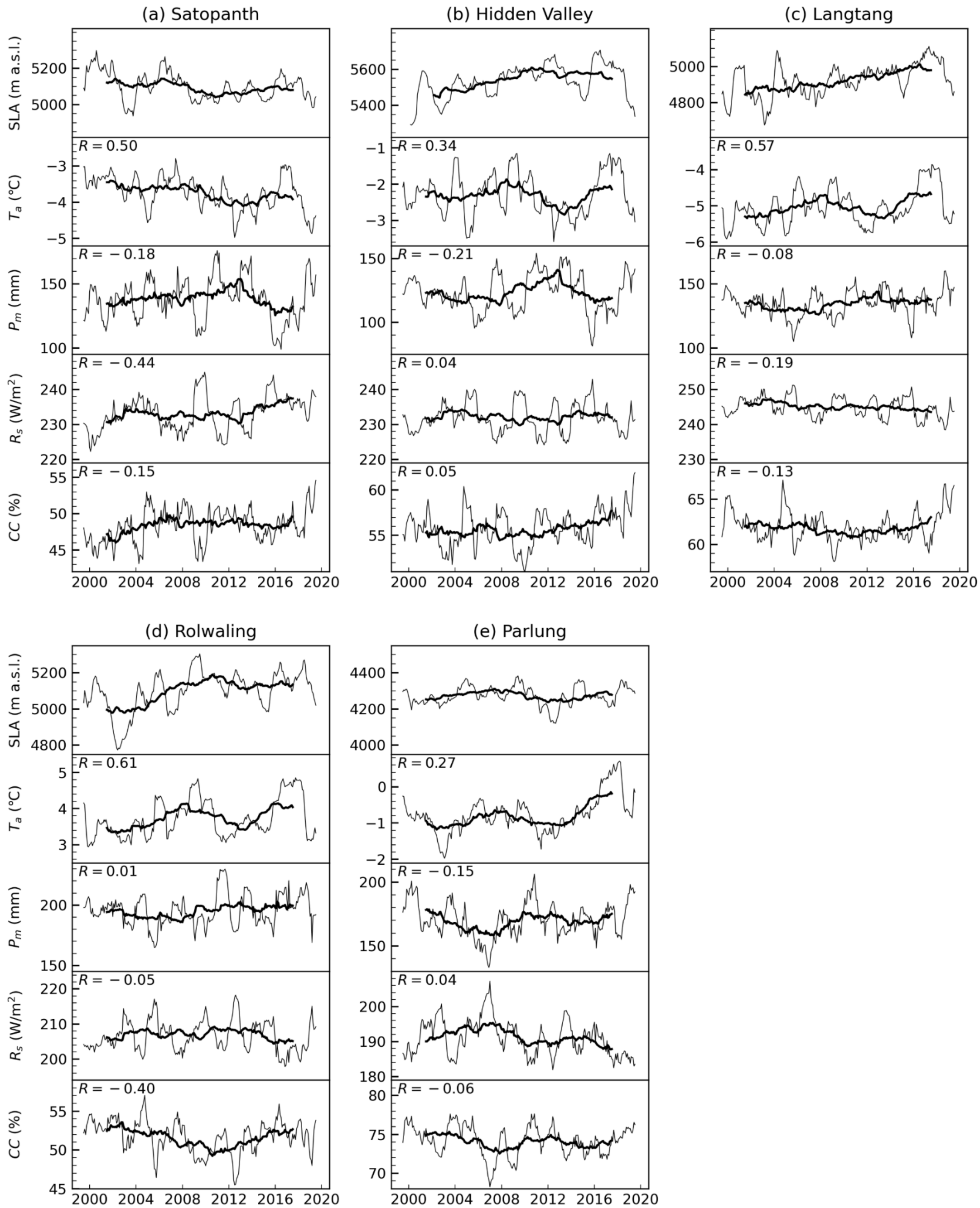

Figure 6 (revised to include cloud cover and show correlation coefficients).

Table 3 (revised to include cloud cover). Correlation coefficients (R) between SLAs and single variables (air temperature, precipitation, solar radiation, and cloud cover) calculated using 12-month and 60-month moving averages. Coefficients with p-values < 0.05 are shown in bold.

		12-month R (p-value)	**60-month R (p-value)**
Satopanth	Air temperature	**0.50 (<0.001)**	**0.80 (<0.001)**
	Precipitation	**− 0.18 (0.004)**	**− 0.44 (<0.001)**
	Solar radiation	**− 0.44 (<0.001)**	− 0.11 (0.129)
	Cloud cover	**− 0.15 (0.017)**	**− 0.34 (<0.001)**
Hidden Valley	Air temperature	**0.34 (<0.001)**	− 0.07 (0.34)
	Precipitation	**− 0.21 (<0.001)**	**0.51 (<0.001)**
	Solar radiation	0.04 (0.51)	**− 0.36 (<0.001)**
	Cloud cover	0.05 (0.47)	**0.18 (0.017)**
Langtang	Air temperature	**0.57 (<0.001)**	**0.45 (<0.001)**
	Precipitation	− 0.08 (0.207)	**0.59 (<0.001)**
	Solar radiation	**− 0.19 (0.003)**	**− 0.69 (<0.001)**
	Cloud cover	**− 0.13 (0.037)**	**− 0.15 (0.031)**
Rolwaling	Air temperature	**0.61 (<0.001)**	**0.71 (<0.001)**
	Precipitation	0.01 (0.864)	**0.40 (<0.001)**
	Solar radiation	− 0.05 (0.410)	0.11 (0.146)
	Cloud cover	**− 0.40 (<0.001)**	**− 0.76 (<0.001)**
Parlung	Air temperature	**0.28 (<0.001)**	**0.43 (<0.001)**
	Precipitation	**− 0.15 (0.019)**	**− 0.67 (<0.001)**
	Solar radiation	0.04 (0.549)	**0.58 (<0.001)**
	Cloud cover	− 0.06 (0.334)	**− 0.51 (<0.001)**

The inclusion of cloud cover substantially improved the multivariate correlations for Hidden Valley and Rolwaling, as shown in the modified Table 4 (below).

Table 4. Results of the multiple regression analysis using 12-month moving averages of climate data and SLA. Influential factors (p-value < 0.05 and |t-value| > 2.0) are shown in bold. A positive or negative t-value indicates a contribution to the increase or decrease of SLA, respectively.

		Coefficient	**Standard error**	**t-value**	**p-value**
Satopanth	Air temperature	6.05	11.18	0.54	0.580
	Precipitation	**− 2.81**	**0.39**	**− 7.24**	**<0.001**
	Solar radiation	**− 11.85**	**1.17**	**− 10.12**	**<0.001**
	Cloud cover	− 0.13	1.97	− 0.07	0.948
Hidden Valley	Air temperature	**68.26**	**12.82**	**5.32**	**<0.001**
	Precipitation	0.10	0.62	0.17	0.869
	Solar radiation	**5.56**	**2.45**	**2.27**	**0.024**
	Cloud cover	**10.52**	**3.29**	**3.20**	**0.002**
Langtang	Air temperature	**94.58**	**12.49**	**7.58**	**<0.001**
	Precipitation	− 0.34	0.78	− 0.43	0.667
	Solar radiation	− 2.98	3.12	− 0.95	0.341
	Cloud cover	− 0.39	3.68	− 0.11	0.916
Rolwaling	Air temperature	**87.45**	**13.19**	**6.63**	**<0.001**
	Precipitation	0.74	0.70	1.06	0.290
	Solar radiation	**− 8.47**	**3.23**	**− 2.63**	**0.009**
	Cloud cover	**− 32.63**	**4.50**	**− 7.26**	**<0.001**
Parlung	Air temperature	**32.41**	**7.71**	**4.20**	**<0.001**
	Precipitation	− 0.43	0.40	− 1.08	0.286
	Solar radiation	1.34	1.34	1.00	0.317
	Cloud cover	3.09	2.66	1.16	0.248

L376-379: The algorithm you proposed might be able to detect SLA globally, but the evaluation has not been done globally. You should add an explanation that further evaluation is necessary to apply the algorithm to glaciers worldwide.

The reviewer is absolutely correct that application to very different regions would require further evaluation, even if the core algorithm could remain the same. For instance, sea surfaces, certain salt deposits, and vegetated areas might all need additional treatment for a global application. There are further excellent opportunities for snowcover and snowline detection using machine learning or AI tools, which could be a future synergy with our tool.

Outcome: We will modify this text to highlight the need for further evaluation before application at the global scale.

L385-387: Related to major comment 3, please add more discussion and/or future challenges regarding effects of SLA variations on hydrological cycle (water resource management, surface mass balance, etc.)
Thank you for this comment. Please see our answer to main comment 3.

References in revision statements:

Buri, P., Fatichi, S., Shaw, T. E., Fyffe, C. L., Miles, E. S., McCarthy, M. J., Kneib, M., Ren, S., Jouberton, A., Fugger, S., Jia, L., Zhang, J., Shen, C., Zheng, C., Menenti, M., & Pellicciotti, F. (2024). Land surface modeling informed by earth observation data: Toward understanding blue–green–white water fluxes in High Mountain Asia. *Geo-Spatial Information Science*, *27*(3), 703–727. https://doi.org/10.1080/10095020.2024.2330546

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