RESPONSE TO EC1

We thank the editor for the time in reviewing the manuscript. We have carefully modified the manuscript according to the comments and suggestions. Below, we provide our responses (normal texts) to the comments (**Bold texts**) made by the editor. The *italics texts* are used to highlight the specific changes that were made in the manuscript.

The revised dataset can be viewed and downloaded using the following link: https://www.pangaea.de/tok/6d533482a662ef2124ed91eabdeec7b358dd8058

1. **ESSD does not publish science papers, and there is a significant amount of science in your manuscript. It begins on L18 when you discuss deglaciation trends and then L20 when you discuss external factors contributing to the deglaciation.**

Response: We have made the necessary changes and the manuscript is now revised accordingly.

2. **The ERA5 modeling effort should be removed. Sections 3.5, 4.5, 5.2 and the middle two paragraphs of 7.Conclusion should be removed.**

Response: We have removed these sections in the revised manuscript.

3. **Even sections 4.2, 4.3, 4.4 could be removed as this trend analysis is external to the data product, where more focus is needed. However, if these sections stay I am not opposed to it.**

Response: We have also removed the required sections as per your suggestions. We have also made new additions to the results focusing on data only. The new additions include (4.1) General statistics, (4.2) Glacier distribution in the Ladakh region and (4.3) Glacier hypsometry, slope and aspect.

"4.1. General statistics

"In total, 2257 glaciers (>0.5 km2) were compiled in the current inventory (Table 2), with a total glacierised area of ~8511±430, 8173±215, 8096±214 and 7923 ±106 km2 for the years 1977, 1994, 2009 and 2019, respectively. The glacierised area corresponds to ~6% of the Ladakh region with individual areas ranging between 0.5±0.02 and 862±16 km2. Glacier length in the Ladakh region varies between 0.4±0.02 and 73±0.54 km with a mean length of 2.9±0.05 km. About 90% of the glaciers are shorter than 5km in length while only 6% of glaciers have a length of < 1km. Larger glaciers are mainly located in the Shayok and Zanskar Basins with the Siachen Glacier being the largest (862±16 km2), longest (73±0.54 km) and covers the greatest elevation range of ~3616m (3702-7318m a.s.l.). The major lakes in each endorheic basins of Pangong, Tsokar and Tsomoriri occupy an area of 3, 2 and 2.5%, respectively. The lake areas for the year 1977, 1994, 2009 and 2019 were 610±14, 619±8, 669±8 and 705±8 km2 for Pangong, 13.5±0.9, 17±0.7, 18.3±0.7 and 18.8±0.6 km2 for Tsokar and 140±2.6, 141±1.3, 141±1.3 and 141±1.1 km2, respectively."

4.2.Glacier distribution in the Ladakh region

"Glacierised areas and population in the Ladakh region vary across basins. Shayok Basin has the largest distribution of glacierised area and population (74% and 56%), whereas the Tsokar Basin has the least (0.04% and 0.1%), respectively (Table 2). Based on size distribution, the glacier area category of 1-5km2 comprises the highest area (28% of the total), while the category of 50-100km2 occupies the least glacierised area (9%) of the region. Most glaciers (~90% of the total) in the Ladakh region have an area of <5km2 but occupy only 37% of the total glacierised area. The population and area of glaciers in each area class are different in each basin but the proportion of glaciers, smaller than 5km2, is greater than 87% in all basins. Glaciers larger than 100 km2 (n=7, < 1% of the total) are only present in the Shayok Basin and occupy ~24 and 32% of the total glacierised area of Ladakh and Shayok Basin, respectively.

4.3.*Glacier hypsometry, slope and aspect*

"Figure 3 (iii and iv) shows the glacier elevations and hypsometry with 100m elevation intervals of seven basins of the Ladakh region. The highest and lowest glacier elevation are 7740 and 3249m a.s.l., both in the Shayok Basin. Whereas mean elevation of the glacier ranges between 4345-6355m a.s.l. (Figure 3iii). Small glaciers mainly occupy the higher elevations above 5500, and vice versa. The majority (73%, 5810 km2) of the glacierised area is distributed in the 5000-6000

m a.s.l. elevation range, while only 14% is located below 5000m, and 13% above 6000m a.s.l. (Figure 3iv). The mean slope of these glaciers ranges between 8 and 46º, and is found to decrease with increasing glacier area. Glaciers with an area greater than 100 km2 (n- 7, <1% of the total) have the lowest mean slope of 13º whereas, higher mean slopes (23º) are found for smaller glaciers (43% of the total). Overall, the mean glacier slope is ~21º (Figure 3v). Around 74% (1665) of the glaciers face the northern quadrant (NW-NE) amounting to ~50% (3940 km2) of the glacierised area. While 9, 5, 3, 3 and 4% of the glaciers face East, South-East, South, South-West and West which constitute 24, 6, 8, 6 and 6% of the glacierised area, respectively. However, the orientation and respective area coverage of glaciers vary within individual basins (Figure 3i, ii).”

5. **In Section 3.4 you attribute uncertainty to satellite resolution, but it seems like there may be other factors that contribute to uncertainty than only this.**

Response: We understand that there might be several other factors that influence the outlines, such as a shift between temporal satellite scenes (orthorectification). Although, most of these are difficult to quantify systematically, also due to the lack of reliable reference data (Racoviteanu et al., 2009; Shukla et al., 2020), they tend to be rather small. For example, the uncertainties arising from orthorectification are negligible (Heid and Kääb, 2012). Nonetheless, we have now revised the uncertainty section and have improved uncertainty estimation and reporting, where possible. The uncertainty for glacier area, glacier length and lake area, through buffer-based approach, are now included in the dataset. The widely used buffer-based approach gives more realistic results when it comes to a large set of glaciers as it varies based on the size of the glacier and the quality of the images (Mölg et al., 2018; Paul et al., 2017).

“This study involves the use of satellite imagery to extract various glacier parameters. It is therefore subject to uncertainties which may arise mainly from four different sources: (1) the quality of the image (with potential issues due to seasonal snow, shadows and cloud cover), (2) sensor characteristics (spatial/spectral resolution), (3) interpretation of glacial features and methodology used, and (4) post-processing techniques (Le Bris & Paul, 2013; Paul et al., 2013, 2017; Racoviteanu et al., 2009, 2019). Error due to sources 1, 3, and 4 are generally minor and can be visually identified and corrected (section 3.3), but an exact quantification is difficult due to

the lack of reference data available from the region (Racoviteanu et al., 2009; Shukla et al., 2020). Type 4 errors are significant and have an impact on both glacier area and length estimation. Therefore, we applied a buffer-based assessment to glacier areas with the buffer width set to one-pixel for debris covered and a half-pixel for clean ice (Bolch et al., 2010; Granshaw & Fountain, 2006; Mölg et al., 2018; Paul et al., 2017; Racoviteanu et al., 2009; Shukla et al., 2020; Tielidze & Wheate, 2018), given that the level 1TP Landsat images were corrected to sub-pixel geometric accuracy (Bhambri et al., 2013). A buffer-based method provides the maximum and minimum estimates of uncertainty with respect to glacier size, where the values vary with size of the glacier and spatial resolution of the imagery used. Thus, it is more specific to the dataset and most recommended when there is no reliable reference data available (Paul et al., 2017; Racoviteanu et al., 2009; Shukla et al., 2020). The same approach was also followed to estimate the uncertainties in lake areas with one-pixel as the buffer width.

The associated uncertainty for smaller glaciers (<0.5 km2) amounts to ~12-25%. Therefore, all the glaciers with an area of less than 0.5 km2, which comprise ~70% and ~10% of the total glacier count and glacierised area respectively, are not included in this study. For the remaining glaciers, the uncertainty in glacier area ranged between ±2.1 and ±7.2% depending on the spatial resolution of the satellite imagery and the individual glacier size. The highest uncertainty was for the year 1977 due to the coarser spatial resolution of Landsat MSS data when applied to the smallest glaciers (0.5-1 km2). For most of the glaciers, lengths are assumed to be accurate to ±1 pixel at the terminus (Le Bris & Paul, 2013). Therefore, a buffer of one-pixel was set to determine the uncertainty in glacier length. The length uncertainty ranged between ±1.5 and ±2.6% with maximum uncertainty observed for the smallest glacier category (0.5-1 km2). The methods yielded an overall uncertainty of 4.2, 1.8 and 1.5% for glacier area, glacier length and lake area, respectively (Table S2).

Uncertainties related to other attributes (mean elevation, mean slope and mean aspect) of the inventory are difficult to estimate due to the use of the ASTER GDEM product in this study, which was developed using a collage of archived scenes acquired between 2000 and 2013. In addition, the local undulations and surface change over time will have only marginal effects on parameters (elevation, slope and aspect) that are averaged over the entire glacier as averaging compensates for most of the changes (Frey & Paul, 2012). However, for parameters like maximum and *minimum elevations, where one cell is used and no averaging is applied, the uncertainty is ~ ±9m, as the vertical accuracy of ASTER GDEM is ±8.55m for glacierised areas of high Asia (Yao et al., 2020) and ±8.86m elsewhere (Mukherjee et al., 2013).”*

6. **In Section 5.3 you compare to other inventories and have justification for various differences - but are all of the errors attributed to the other inventories, and yours is only uncertainty based on satellite resolution?**

Response: We have now revised the section in the manuscript accordingly. Our approach was similar to GAMDAM and ICIMOD inventories, where they have used a Normalized Standard Deviation approach on the outlines/datasets produced by several operators on same subset of glaciers. Their approach is also influenced majorly by the satellite resolution. According to Paul et al., 2017, the method used by GAMDAM and ICIMOD gives more realistic estimate than the buffer-based approach if it is performed on the entire population of glaciers in a dataset, rather than on a subset of glaciers. However, the approach requires higher workload (digitization of all the glaciers by several analyst) and it would be too time consuming to apply on the current inventory which deals with >2000 glaciers in four time periods each. For RGI inventory, an entirely different approach on error estimation was adopted than the present, GAMDAM and ICIMOD approaches due to the fact that the data produced in RGI is global, deals with an extremely large set of glaciers which were sourced from different analysts involving different methodologies. Therefore, we believe that the uncertainty based on the buffer-based approach is one of the best to use in the present study. We have now included the following text in the manuscript to clarify this:

“The comparison involves glacier outlines for 2009 from the present study and excludes glaciers smaller than 0.5 km2 from regional inventories to achieve the closest match temporally and for glacier size categories. This should be taken as a first order comparison, given the fact that the uncertainties have been estimated with different approaches for the different inventories. Specifically the uncertainty estimated for the GAMDAM and ICIMOD inventories differs only slightly to the one applied here, given that they used a normalized standard deviation approach on the datasets produced by several operators on the same subset of glaciers (Bajracharya et al.,

2011, 2019; Guo et al., 2015; Nuimura et al., 2015; Sakai, 2019). Whereas, in case of RGI 6.0 inventory, the uncertainty estimation approach differs significantly from the one presented here, because their errors were calculated on a collection of glaciers due to the vast quantity of data acquired from multiple sources and approaches used to produced them (Pfeffer et al., 2014).''

7. **For section 5.4 can you take the other recent studies you compare against, and compare like with like? That is, limit them (or you) to the same subset of glacier size, and then quantitatively compare both some individual glaciers and the bulk properties of the two datasets? This could then lead to a significantly more robust validation discussion and uncertainty results.**

Response: We have now revised the manuscript according to the comments. We have also tried to compare like with like. However, comparing with the exact location or data or time period was difficult as all the studies undertaken in the Ladakh region have either different time periods, or do not have the data in the public domain (except the stats from the literature and Shukla et al., 2020's entire dataset: https://doi.pangaea.de/10.1594/PANGAEA.904131). We have also undertaken a comparative analysis on 21 individual glaciers from across the region and the bulk properties of the dataset. This additional analysis was quite helpful and we have now included two figures and a supplementary table, detailing how our glacier outlines compare with other studies. We have also revised the section:

''The data from the recent spatio-temporal change studies from different sub-regions of Ladakh (Figure 5) are not in the public domain, except from Shukla et al., 2020. Hence, it is not possible to use these to validate our results. Therefore, our comparison mostly focuses on the rate of change for some of the individual glaciers (n=21, Figure 5) from the literature and the bulk properties of a set of glaciers in different regions (Table S3, Figure 6). Our results agree well with the studies conducted by others (Bhambri et al., 2013; Chudley et al., 2017; Garg et al., 2022; Garg et al., 2021; Negi et al., 2021; Schmidt & Nüsser, 2012, 2017; Shukla et al., 2020) on individual glaciers of various sizes as well as on a set of glaciers, respectively (Figure 6, Table S3). However, the results differ significantly only on some glaciers and especially in a part of the Shayok Basin (e.g.

Kumdan (D), Aktash (E) and Thusa glaciers(I)). In the Shayok Basin surge-type glaciers are common (Bhambri et al., 2013, 2017), the difference in analysis period between the present and other studies is the likely cause of the difference in glacier area statistics. Figure S2 presents the dynamics of the Kumdan and Aktash glaciers as an example of surge type glacier of this region.

No significant difference was observed in rate of change of glacierised areas between the present study and other studies in the Leh, Tsomoriri, Zaskar and Suru Basins. In contrast, the number of glaciers and glacierised area vary among these studies (present and others) but paint a similar picture of relatively lower retreat in the Shayok Basin (Bhambri et al., 2013; Negi et al., 2021), higher in Leh, Tsokar, Tsomoriri (Chudley et al., 2017; Schmidt & Nüsser, 2012, 2017) and moderate in Zanskar and Suru Basins (Garg et al., 2022; Garg et al., 2022; Shukla et al., 2020).''

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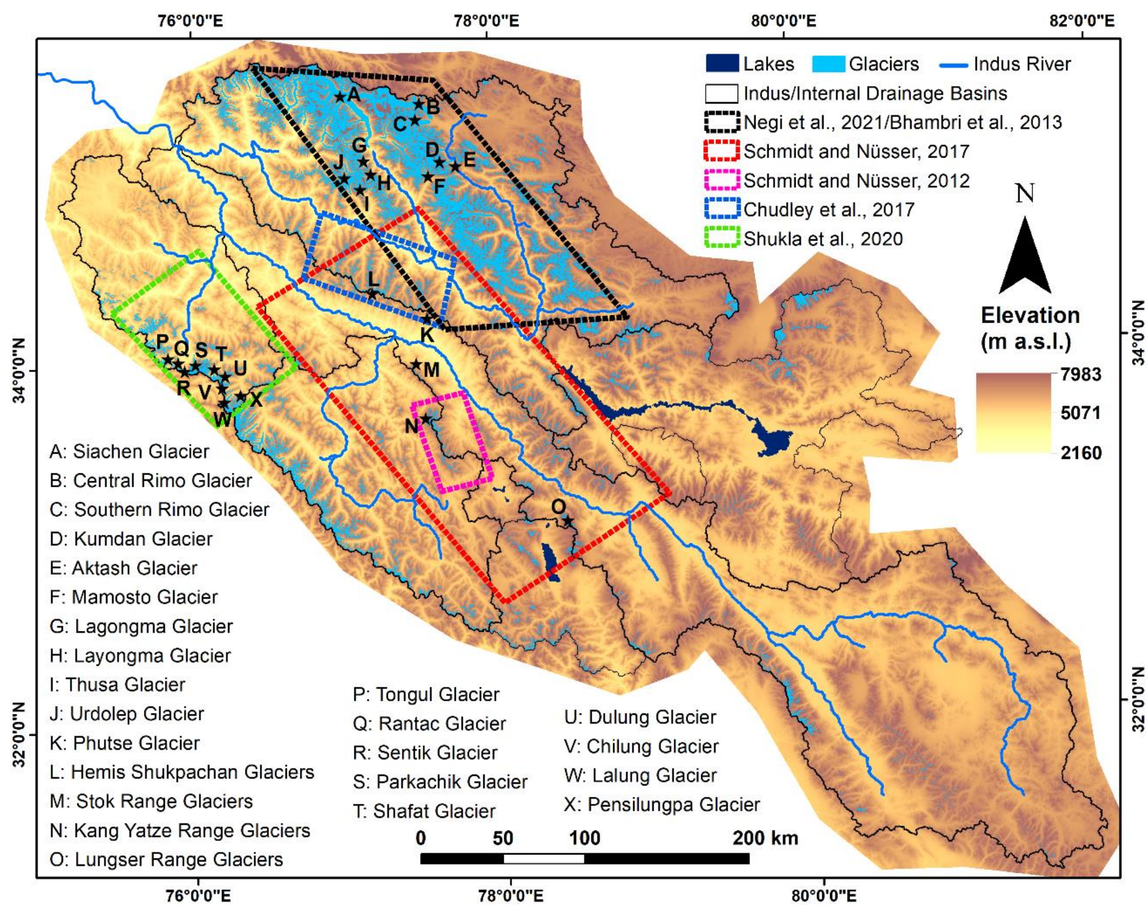

Figure 5: Presents the spatial extent of different studies undertaken in Ladakh region. Black stars represent the individual glaciers.

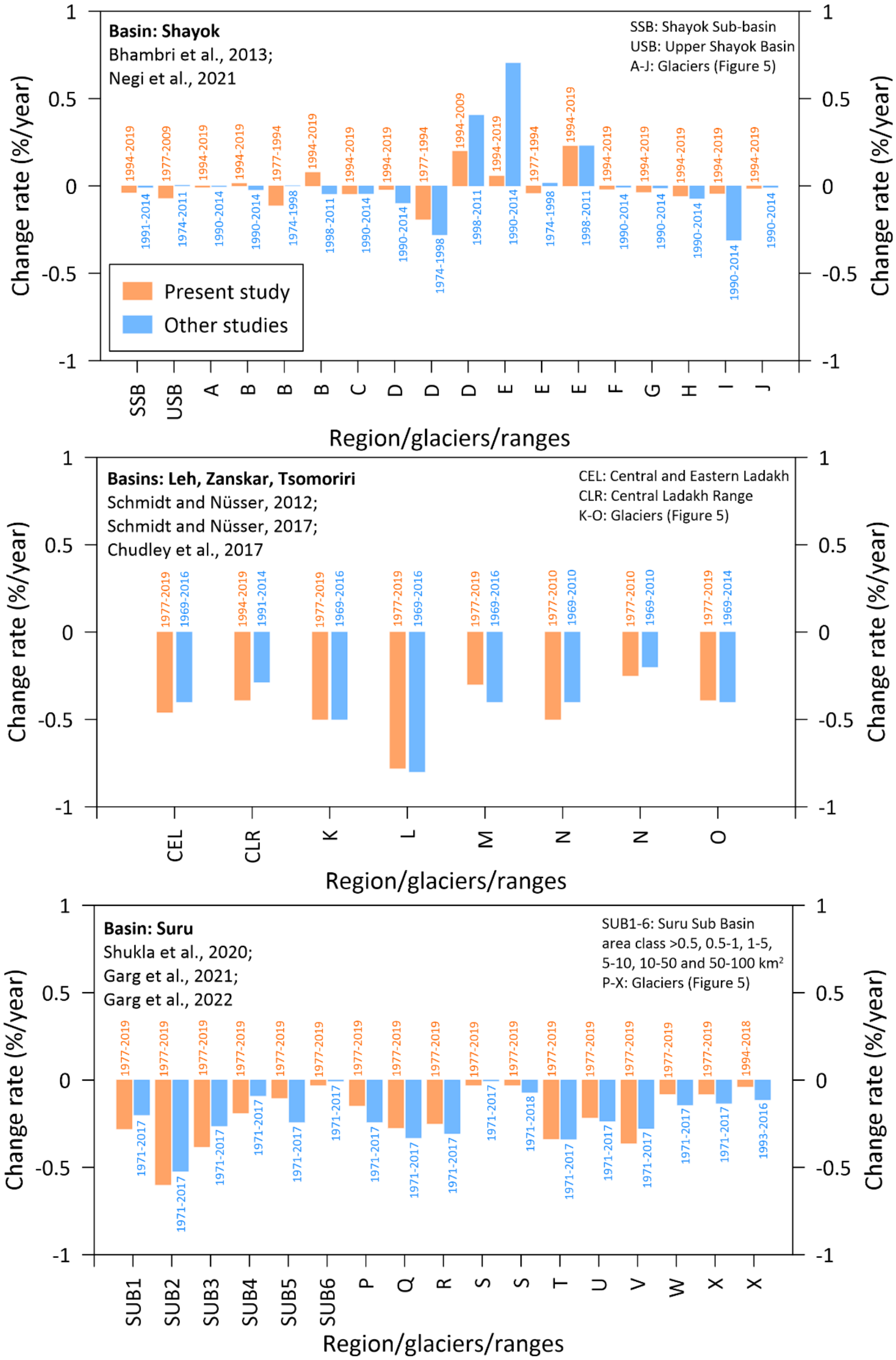

Figure 6: Comparison between the present study and other studies undertaken in different basins of Ladakh region over different time periods

Table S3: Comparison of glacier change attributes between the present study and others recent studies.

Source	Basin	Range/ Glacier/	Code	**Other recent studies**					**Present study**				
				No. of	**Size (km²)**	**Year**	**Total**	**Retreat rate**	**No. of**	**Size (km²)**	**Year**	**Total**	**Retreat**
Negi et al., 2021	Shayok	Shayok sub-basin	SSB	569	>1	1991-2014	-0.19	-0.008	603	>1	1994-2019	-0.94	-0.038
		Siachen Glacier	A	1	>100	1990-2014	-0.08	-0.003	1	>100	1994-2019	-0.28	-0.007
		Central Rimo Glacier	B	1	>100	1990-2014	-0.52	-0.022	1	>100	1994-2019	0.61	0.015
		Southern Rimo Glacier	C	1	>100	1990-2014	-1.05	-0.044	1	>100	1994-2019	-1.87	-0.045
		Mamosto Glacier	F	1	50-100	1990-2014	-0.17	-0.007	1	50-100	1994-2019	-0.79	-0.019
		Kumdan Glacier	D	1	50-100	1990-2014	-2.35	-0.098	1	50-100	1994-2019	-0.84	-0.020
		Urdolep Glacier	J	1	10-50	1990-2014	-0.19	-0.008	1	10-50	1994-2019	-0.59	-0.014
		Layongma Glacier	H	1	10-50	1990-2014	-1.71	-0.071	1	10-50	1994-2019	-2.39	-0.057

		Lagongma Glacier	G	1	10-50	1990-2014	-0.27	-0.011	1	10-50	1994-2019	-1.47	-0.035
		Aktash Glacier	E	1	10-50	1990-2014	16.88	0.703	1	10-50	1994-2019	2.39	0.057
		Thusa Glacier	I	1	10-50	1990-2014	-7.47	-0.311	1	10-50	1994-2019	-1.81	-0.043
Bhambri et al. 2013		Upper Shayok Basin	USB	136	>0.2	1974-2011	0.144	0.004	570	>0.5	1977-2009	-2.2	-0.069
		Central Rimo Glacier	B	1	>100	1974-1998	0.04	0.002	1	>100	1977-1994	-1.88	-0.111
		Central Rimo Glacier	B	1	>100	1998-2011	-0.59	-0.045	1	>100	1994-2009	1.16	0.078
		Kumdan Glacier	D	1	50-100	1974-1998	-6.71	-0.279	1	50-100	1977-1994	-3.24	-0.191
		Kumdan Glacier	D	1	50-100	1998-2011	5.27	0.406	1	50-100	1994-2009	2.98	0.199
		Aktash Glacier	E	1	10-50	1974-1998	0.37	0.016	1	10-50	1977-1994	-0.78	-0.048
		Aktash Glacier	E	1	10-50	1998-2011	2.99	0.230	1	10-50	1994-2009	3.42	0.228
Schmidt and Nüsser, 2017;	Leh/ Zanskar/	Selected regions of central	CEL	1800	>0.03	1969-2016	-19	-0.4	517	>0.5	1977-2019	-19.3	-0.46

		and eastern Ladakh											
		Phuche Glacier	K	1	0.5-1	1969-2016	-18.0	-0.50	1	0.5-1	1977-2019	-21.0	-0.50
		Hemis Shukpachen Glaciers	L	5	0.2-1	1969-2016	-38.0	-0.80	2	0.5-1	1977-2019	-33.0	-0.78
		Stok Range	M	7	0.2-1	1969-2016	-22.4	-0.40	3	0.5-1	1977-2019	-10.5	-0.30
		Kang Yatze	N	35	0.5-1	1969-2010	-18.8	-0.40	26	0.5-1	1977-2010	-24.0	-0.50
		Kang Yatze	N	25	>1	1969-2010	-12.2	-0.20	17	>1	1977-2010	-11.0	-0.25
		Lungser Range	O	39	0.5-5	1969-2014	-17.7	-0.40	22	0.5-5	1977-2019	-16.4	-0.39
Chudley et al, 2017	Leh/ Shayok	Central Ladakh range	CLR	76	1-5	1991-2014	-6.6	-0.29	82	1-5	1994-2019	7.1	-0.39
Shukla et al., 2020	Suru	Suru Sub-basin	SUB1	130	>0.5	1971-2017	-9.08	-0.20	136	>0.5	1977-2019	-14	-0.28

		Suru Sub-basin	SUB2	22	0.5-1	1971-2017	-24.04	-0.52	22	0.5-1	1977-2019	-25.18	-0.60
		Suru Sub-basin	SUB3	47	1-5	1971-2017	-12.10	-0.26	47	1-5	1977-2019	-16.03	-0.38
		Suru Sub-basin	SUB4	15	5-10	1971-2017	-4.15	-0.09	15	5-10	1977-2019	-7.91	-0.19
		Suru Sub-basin	SUB5	6	10-50	1971-2017	-11.11	-0.24	6	10-50	1977-2010	-4.33	-0.10
		Suru Sub-basin	SUB6	1	50-100	1971-2017	-0.28	-0.01	1	50-100	1977-2010	-1.24	-0.03
		Tongul Glacier	P	1	5-10	1971-2017	-11.07	-0.24	1	5-10	1977-2019	-6.14	-0.15
		Rantak Glacier	Q	1	5-10	1971-2017	-15.23	-0.33	1	5-10	1977-2019	-11.52	-0.27
		Sentik Glacier	R	1	1-5	1971-2017	-14.06	-0.31	1	1-5	1977-2019	-10.48	-0.25
		Parkachik Glacier	S	1	10-50	1971-2017	-0.27	-0.01	1	10-50	1977-2019	-1.24	-0.03
		Shafat Glacier	T	1	10-50	1971-2017	-15.57	-0.34	1	10-50	1977-2010	-14.18	-0.34

		Dulung Glacier	U	1	10-50	1971-2017	-10.81	-0.24	1	10-50	1977-2010	-9.05	-0.22
		Chilung Glacier	V	1	5-10	1971-2017	-12.74	-0.28	1	5-10	1977-2019	-15.20	-0.36
		Lalung Glacier	W	1	10-50	1971-2017	-6.57	-0.14	1	10-50	1977-2019	-3.35	-0.08
		Pensilungpa Glacier	X	1	10-50	1971-2017	-6.14	-0.13	1	10-50	1977-2019	-3.39	-0.08
Garg et al., 2022		Parkachik glacier	S	1	10-50	1971-2018	-3.30	-0.07	1	10-50	1977-2019	-1.24	-0.03
Garg et al., 2021		Pensilungpa Glacier	X	1	10-50	1993-2016	-2.59	-0.11	1	10-50	1994-2018	-0.94	-0.04

8. Glacier product does not have uncertainty for area, Lmax, slope, etc.

Response: We have now added the uncertainty of area and Lmax to the individual glaciers across the basins and time periods of the dataset. The dataset is now revised with new additions i.e. U_Area (Uncertainty in glacier area) and U_Lmax (Uncertainty in maximum glacier length). Please see the response to the comment number 4 for more detail on this. The revised data can be accessed using the following link

https://www.pangaea.de/tok/6d533482a662ef2124ed91eabdeec7b358dd8058

9. **Lake data product does not have uncertainty. The lake product is not widely discussed in your manuscript that focuses on glaciers. Why is this included and why only at one time?**

Response: We have provided lake outlines as the study includes three endorheic basins. We have now extended the lake outlines for the four periods (1977, 1994, 2009 and 2019) including the attributes like coordinates, mean elevation, area and area uncertainties. We have also revised the manuscript accordingly and discussed the lakes in methods, uncertainty and results sections.

For example:

''Delineation of the three endorheic basins (IDBs) that lie partially or completely in the Ladakh region, i.e., Tsokar, Tsomoriri and Pangong Basins, was also carried out using the same method with the help of respective lakes as a pour point. The digitisation of the three lakes (Tsokar, Tsomoriri and Pangong Lake) was carried out manually for the years 1977, 1994, 2009 and 2019 using Landsat imagery.''

Also see the response to comment number 4 for more detail on this.