RESPONSE TO REFEREE#1

We thank the reviewer#1 for the detailed review. 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 reviewer#1. 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

The study presents a multitemporal glacier inventory of Ladakh based on Landsat data for the years 1977, 1994, 2009 and 2019. The manuscript follows a clear structure, and most sections are well written. The study deals with large parts of the Upper Indus Basin (UIB) and three internal drainage basins (Tsomoriri, Tsokar and Pangong Tso) located in eastern Ladakh. The article is appropriate to support the publication of a useful and plausible data set. The data set solely contains Landsat data that can be used in future interpretations. However, I must mention several queries and specific comments.

Abstract

1. The sentence "Glacier inventories, and changes therein, play an important role in understanding glacier dynamics and water resources over larger regions" (line 11-12) should be modified. The expression "changes therein" is not precise and it is obvious that glacier changes are important to understand glacier dynamics.

Response: Thank you for the comment, we have now revised the sentence as per your suggestion, we have also revised the abstract as per the editors comment (Editors comment 1).

"Multi-temporal inventories of glacierised regions provides an improved understanding of water resources availability. In this study, we present a Landsat-based multi-temporal inventory of glaciers in four Upper Indus sub-basins and three internal drainage basins in the Ladakh region for the years 1977, 1994, 2009 and 2019. The study records data on 2257 glaciers (of individual

size >0.5 km2) covering an area of ~7923 ±106 km2 which is equivalent to ~30% of the total glacier population and ~89% of the total glacierised area of the region. Glacier area ranged between 0.5±0.02 and 862±16 km2, while glacier length ranged between 0.4±0.02 and 73±0.54 km. Shayok Basin has the largest glacierised area and glacier population, while Tsokar has the least. Results show that the highest concentration of glaciers is found in the higher elevation zones, between 5000 and 6000 m a.s.l, with most of the glaciers facing towards the NW-NE quadrant. The error assessment shows that the uncertainty, based on buffer-based approach, range between 2.6 and 5.1% for glacier area, and 1.5 and 2.6% for glacier length with a mean uncertainty of 3.2 and 1.8%, respectively. This multitemporal inventory is in a good agreement with previous studies undertaken in parts of the Ladakh region. The new glacier database for the Ladakh region will be valuable for policy making bodies, and future glaciological and hydrological studies. The data can be viewed and downloaded from PANGAEA, https://doi.org/10.1594/PANGAEA.940994."

2: The study deals with 2257 glaciers larger than 0.5 km^2 covering 7923 ± 212 km^2. It is not clear what is meant by "equivalent to ~30 % of the glaciers and ~89 % of the glacierised area" (line 14-15).

Response: By that sentence we meant that out of the entire glaciers of studied region, glaciers >0.5 km^2 comprise ~30% of the total glacier population and ~89% of the glacierised area. These figures are based on the total number of glaciers reported by RGI 6.0 and our study. We have now revised the sentence accordingly.

"The study records data on 2257 glaciers (of individual size >0.5 km2) covering an area of ~7923 ±106 km2 which is equivalent to ~30% of the total glacier population and ~89% of the total glacierised area of the region."

3: The term "deglaciation" is used two times in line 19 and could be replaced by area loss.

Response: We have removed the sentence as per the Editors comments.

4: In the last part of the abstract (line 20-23) the authors should inform about the type of climate data used and the length of the observation period.

Response: We have removed the section on the climate data analysis as per the Editors comments.

Introduction

5: Many articles on Himalayan glaciers begin with this kind of introduction like … third pole, water tower for large populations in adjoining lowlands, and so forth. However, the specific characteristic of glaciers in the cold-arid region of Ladakh should be highlighted in this context.

Response: We have now revised the section accordingly.

"Any change to the Himalayan cryosphere would have a direct impact on the hydrology, further influencing the communities downstream whose livelihood and economy relies on, and are supported by, the major river systems e.g., the Brahmaputra, Ganges and Indus, among others. In high altitude arid regions like Ladakh, where the majority of glaciers are small and restricted to higher altitudes, meltwater serves as an important driver of the economy, especially in years with low winter precipitation when glacier melt becomes the major (or only) source of water (Schmidt & Nüsser, 2012, 2017)."

6: Some of the urban agglomerations (Dhaka, Kolkata, Karachi) are less or not at all dependent on the glaciers of Ladakh. It might be more important to refer to basic studies on socio-hydrological interactions in Ladakh and the direct problems of water scarcity for irrigated cultivation (e.g. Nüsser et al. 2012 in Mountain Research and Development).

Response: We have removed the sentence and included more information specific to Ladakh region. See the response to the comment 5 above.

7: Line 27: What is the meaning of hydro-economy. This term is a bit vague and can mean different things including hydropower generation and irrigated crop cultivation.

Response: Hydro-economy means the economy that revolves around water which includes agricultural irrigation, domestic consumption, industrial use and hydro-power generation among others. Himalaya is large and there are several sectors that make use of the water coming from the region, hence the term "hydro-economy".

8: Line 28 it should read "Himalayan cryosphere"

Response**:** Corrected.

9: Line 40 it should read ", not all regions of Ladakh". In this context the authors should mention glacier studies that have been conducted in Ladakh. Maybe at the end of this paragraph (line 43).

Response: We have revised the section accordingly.

"However, not all regions of Ladakh have been analysed at the same level of spatio-temporal detail. In particular, our knowledge of glacier dynamics and their response to climate change is still incomplete in the cold-arid, high-altitude Ladakh region (~105,476 km2) comprising both, the Himalayan and Karakoram ranges. Few studies have focused on the glaciers of this region (e.g. Bhambri et al., 2011, 2013; Chudley et al., 2017; Negi et al., 2021; Nüsser et al., 2012; Schmidt & Nüsser, 2012, 2017; Shukla et al., 2020). "

10: Line 47-48 The inventories by GSI and SAC are manually demarcated. "among others" needs references.

Response: We have checked the sources again and found that GSI inventory (GSI 2009) and SAC inventory (SAC 2011) was developed with the help of Survey of India toposheets of 1:50000 scale with contour interval of 40m or degree sheets maps on 1:250000, whichever were available with combined aid of aerial photography and satellite imagery. However, the methodology used is not clear, whether it was developed through automated, semi-automated or manual approach, for these inventories. Therefore to avoid any confusion, we have now revised the manuscript accordingly and also provided references for the term "among others".

"Glacierised area estimations have often relied on global and regional glacier inventories such as the Randolph Glacier Inventory (RGI), Global Land Ice Measurements from Space (GLIMS), Geological Survey of India (GSI) inventory and Space Application Centre India (SAC) inventory, among others (Chinese Glacier Inventory (CGI), Glacier Area Mapping for Discharge from the Asian Mountains (GAMDAM), International Centre for Integrated Mountain Development (ICIMOD)). However, given the large scale of these inventories, automated techniques are employed, in most of the cases, to map and calculate glacier extent with differing levels of success. Additionally, the varying quality of satellite imagery acquired from different time periods are sometimes necessitated in high mountain areas, such as Ladakh."

11: Line 50: why necessitated?

Response: Additional imageries of varying qualities are required because of majorly two reasons i.e. cloud cover and seasonal snow which is frequent in high altitudes of Himalaya.

12: Line 52: it should read "entire Ladakh region"

Response: Corrected.

13: Line 62: it should read images or imagery

Response: Corrected

14: Line 65-67. This sentence is important and should come earlier in the introduction.

Response: Rearranged

15: Line 67: instead of arid season, lean or dry season might be more appropriate.

Response: Corrected

16: Line 68: it should read "can be viewed and downloaded from…"

Response: Corrected

Study area

17: The main problem is the unclear use of the terms UIB, Ladakh and study area. This should be consistent from the title and abstract to the conclusions. The study focuses on the upper part of the UIB above Skardu. The title focuses on the Ladakh region. In some section of the article spatial denominations are not consistent. Do the authors refer to entire UIB in line 83? In a later section (line 132) the authors state "…the entire UIB, upstream of Skardu, was investigated."

Response: UIB in the manuscript refers to the Upper Indus Basin area upstream of Skardu region only, which we have now cleared at the beginning of the section 2: Study area.

"This study focuses on glaciers in the Upper Indus Basin (UIB) upstream of Skardu and three internal drainage/endorheic basins (IDBs) within Ladakh, namely Tsokar, Tsomoriri and Pangong Basins."

We have now revised the terms accordingly to avoid further confusion. The combined area of UIB and IDBs are now referred to as Ladakh region throughout the manuscript as majority of the area falls under the Ladakh region. However, individually they are still referred to as UIB or IDBs as they are the subsets within the region.

"Since the majority of the investigated area (UIB and IDBs combined) falls within Ladakh, the combined area of UIB and IDBs will be referred to as "Ladakh region" hereafter."

We have also revised the line 132.

"A small portion of the leftover area from UIB after second-order tributary basin delineation was merged into the Leh Basin in order to investigate the UIB upstream of Skardu. 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."

18: Figure 1: It might be informative to point out the location of the three endorheic basins (Tsomoriri, Tsokar and Pangong Tso) for those who are not familiar with the region. Pangong and Tsokar can be detailed in the same way as Tsomoriri. In Figure 2a this information is presented. In the figure caption it should read stars (line 77) because it is plural.

Response: We have now revised the figure accordingly.

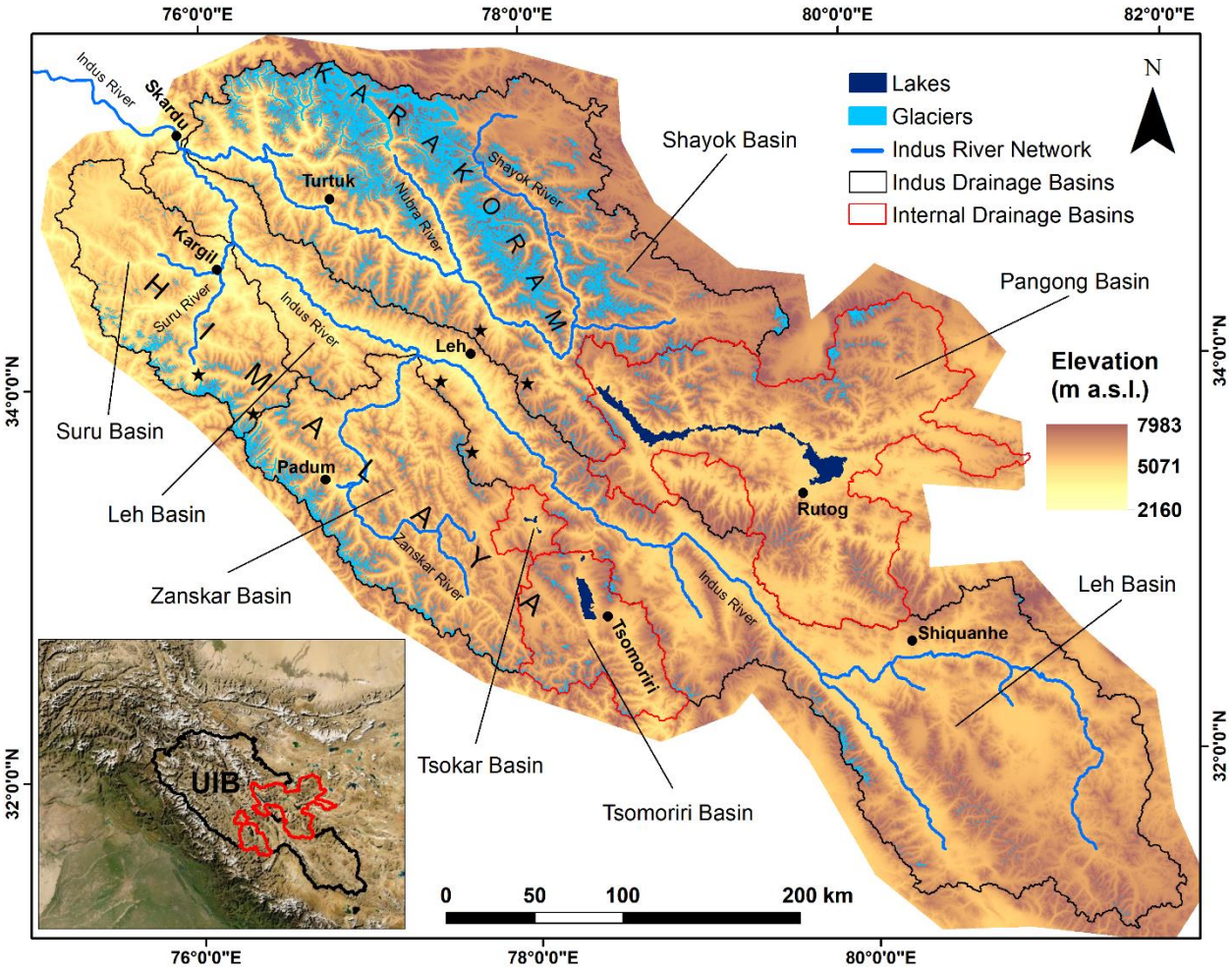

Figure 1: Location map of the study area: the boundaries of studied Upper Indus Basin and internal drainage basins are outlined in black and red on the digital elevation model (DEM) and in the inset map. Inset map shows the study area with respect to the Himalayan and Karakoram region. Black dots and stars represent the respective basins' major settlements and field investigated glaciers. ASTER Global DEM was used to produce the base map.

19: Line 94-95: Census of India 2011 and Census of China cannot be found in the reference list

Response: We have now added the sources to the reference list.

"Census of India (2011), Jammu and Kashmir, Series 02- Part XII A-B, District Census Handbook, Leh and Kargil. India - Census of India 2011 - Jammu & Kashmir - Series 02 - Part XII A - District Census Handbook, Leh (censusindia.gov.in). Last assessed on 30 September 2021.

National Bureau of Statistics. (2020). Communiqué of the seventh National Population Census. http://www.stats.gov.cn/tjsj/. Accessed 30 September 2021."

Data and methods

20: Line 106 it should read ASTER GDEM

Response: We have now corrected it.

21: Table 1: it would be informative to add a last column "Number of Images" in the table. How many MSS, TM, OLI images have been used in this study. The details are presented in the supplement, but the reader should get this basic information in Table 1.

Response: We have now revised the Table 1 accordingly.

"Table 1: Information on the satellite imagery used in this study (Detailed info. in Table S1).

Dataset	***Year of Acquisition***	***Spatial Resolution***	***No. of image used***	***Source***	***Purpose***
Landsat MSS	*1977±5*	*60m*	*17*	*https://earthexplorer.usgs.gov/*	*Glacier area mapping*
Landsat TM	*1994±1, 2009*	*30m*	*14, 18*		

Landsat OLI	*2019±1*	*15m*	*14*		
ASTER GDEM	*2000-2013*	*30m*	*17*	*https://earthdata.nasa.gov/*	*Topography and basin delineation*

“

22: Line 165 to 166: Which DEM was used?

Response: We have used ASTER GDEM to get these attributes such as mean elevation, mean aspect and mean slope. We understand that the ASTER GDEM is a product of a collage of images with different acquisition dates which in turn lead to biases in the region of ice or snow cover. However, ASTER GDEM was used only to get secondary information for the inventory which can be improved in our future studies. Our major objective in this study is to give the best possible spatial extent of glaciers larger than 0.5 km^2 in the Ladakh region.

23: Line 170: misleading might not be the appropriate word in this context.

Response: We have now revised the entire section as per the Editors comment.

“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).”

24: Line 183: Kanda et al. (2020) with brackets

Response: The section has been removed following the editors comment.

25: Line 194 to 203: Some grids have no ground stations for corrections. What is the range of bias?

Response: The section has been removed following the editors comment.

Results

26: The section should not begin with a table and a figure

Response: Corrected.

27: Figure 3: Although one has to expect the majority of glaciers on northern aspects, the complete absence of southern aspects needs to be checked. What is with the large valley glaciers like the Siachen glacier and some glaciers on the southern faces of Nun and Kun in western Ladakh?

Response: We have rechecked our dataset concerning the aspect of glaciers in all the basins. We found our data in the figure to be accurate as per our analysis. In addition, the southern facing glaciers are not absent but relatively lower than those with other aspects. For example in case of Shayok basin, 8, 6 and 9% of the glacierised area has an aspect of South east, South and South west which is equivalent of 437, 350 and 471 km^2, respectively. In Zanskar and Pangong basins, the aspects are 6, 2 and 0.2%, and 19, 8 and 0.4% towards South east, south and South west, respectively. We have revised the manuscript accordingly

"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)."

28: Figure 4: in the figure the term "glaciated area" is used and the figure caption uses "glacierized area". This must be consistent.

Response: The section has been removed following the editors comment.

29: In several parts (line 237, line 248, line 258) the authors use the term "Deglaciation". Area loss might be more appropriate. (later again in lines 350 and 360)

Response: Correction is done wherever necessary.

30: Lines 271 and 276: It should read "…between XXX and XXX%")

Response: The section has been removed following the editors comment.

Discussion

31: The heading "Description …" is unusual in the discussion.

Response: The subheading has now been revised

32: Line 316: It should read "open-source file format"

Response: Corrected.

33: Line 321: "Jawaharlal Nehru University and University of Aberdeen glacier IDs" is not clear.

Response: the "Jawaharlal Nehru University and University of Aberdeen glacier IDs" are the new glacier Ids that were assigned to the glaciers of this new inventory. We have now revised the sentence for more clarity.

"For each region, there is one file for basin outlines, and four files for glacier and lake (if present) outlines for 1977, 1994, 2009 and 2019. Each glacier outline file contains glacier Ids (New glacier Ids, Randolph Glacier Inventory 6.0 Ids, and Global Land Ice Measurements from Space initiative Ids), coordinates (latitude and longitude), elevation (maximum, mean and minimum), aspect (mean), slope (mean), area, length (maximum), area uncertainty and length uncertainty. Whereas, the Lake Outline file contains coordinates, area, elevation and area uncertainty. "

34: In the comparison with recent studies (section 5.4), the authors should also refer to the study by Bhambri et al. 2013: Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram

Response: We have revised the section accordingly and compared our results with Bhambri et al 2013 as well.

35: Some brackets are needed in lines 404, 408, 422

Response: Corrected.

Conclusions

36: Line 448: What are “more favorable climatic conditions”? For agriculture or for plant growth?

Response: The section has been removed following the editors comment.

References

37: L 510: Reference Frey et al. 2014 title needs to be corrected

Response: Corrected