Response from Authors to Anonymous Reviewer 1 (RC1)

Summary:

Ghosh et al. (2025) present a comprehensive analysis of long-term glacier surface velocity and elevation changes in the Zanskar Basin, Ladakh Himalaya. Utilizing satellite remote sensing data, primarily from Landsat imagery processed via COSI-Corr for velocity estimation and reanalyzed elevation data from Hugonnet et al. (2021), the study examines 12 selected glaciers to characterize trends in flow deceleration and thinning. The main findings indicate an overall velocity slowdown of -2.4 m yr^{-1} $decade^{-1}$, with thinning accelerating from -0.22 m yr^{-1} (2000–2005) to -0.57 m yr^{-1} (2015–2020). The authors attribute these changes to climate-driven mass loss, which reduces gravitational driving stress and is modulated by glacier geometry, debris cover, and terminus type (e.g., lake-terminating glaciers exhibit localised accelerations). However, weaknesses were observed in inconsistent terminology, insufficient methodological details, and potential biases in ERA5 climatic data. The use of median rather than mean values for velocity and elevation changes may hinder comparisons with prior studies that use mean velocity and elevation changes. The discussion could be enhanced by incorporating regional contrasts, such as the accelerating surrounding Karakoram glaciers (Heid and Kääb, 2012), to better contextualise the slowdown of Zanskar's glaciers. Please see my following suggestions. I hope this will help improve the text.

We thank the Anonymous Reviewer for reviewing and providing thoughtful and constructive feedback on our manuscript. We also appreciate the time and effort for the same. We updated some texts for better clarity and readability of the manuscript. Please find the line-by-line response (in blue) to all the comments (in black) below-

Note: The changes made in the manuscript are presented here in *italicised* text

Line-by-Line comments

L9: Several sentences include the term 'Glacier' twice or three times (L9, L16-19, L20, L23, L24, L40-41). For example, in this study, we have selected 12 glaciers as test glaciers to study the evolution of inter-annual glacier surface velocity and glacier surface elevation change (L110-111). This sentence contains the word 'glacier' four times.

Thanks for pointing this out. The sentences were modified, accounted for in the suggested lines as well as throughout the manuscript. For example:

Previously: "Trends in glacier surface velocity provide insight into the response of glaciers to climate change as well as local drivers of ice dynamics"

modified to: *"Trends in surface velocity provide insight into glacier response to climate change as well as local drivers of ice dynamics."*

L11: Remote Sensing provides a tool; what type of tool is it? You may mention the image correlation here.
Modified as suggested. The sentence now reads-

"Remote sensing-based image correlation provides a tool for observing surface velocity over multiple glaciers in a remote and challenging area for field work, providing key observations for tracking changes in this important region"

L15: After point 1, a digit is sufficient, for example, -2.4 instead of -2.43 throughout the manuscript. Also, what does an uncertainty ± represent?

Thanks for this suggestion. Changes were made across the manuscript.
The uncertainty reported here is the 1σ standard deviation of the data.

L15-16: Somewhere written year-1 and somewhere written yr-1. Please maintain consistency throughout the entire manuscript.

Thanks for pointing this out. The unit representation has been changed wherever required to maintain the consistency. We now use year^{-1} throughout.

L16: Between 2000 and 2005, instead of 2000-2005. Please maintain consistency throughout the entire manuscript.

Thanks for the suggestion. We have made all the changes.

L28-29: Please use the word 'glacierized' instead of 'glaciated', as the latter word implies a former glacier area that has deglaciated now. Please check throughout the manuscript.

Thanks for pointing this out. We have updated this terminology where required.

L35: You may replace 'impacted' with 'reduced'.

Changes made as suggested.

L38: Weertman (1957) is an outdated reference; you may replace it with more recent references.

Thanks for noting this. We updated and added Minchew and Joughin, (2020) to the citation. However, as Weertman (1957) is the classic and foundational study on glacier sliding, and we keep this as well.

L44: First mention the complete form of DGNSS and then write its acronym.

Thanks for this suggestion. We have made the necessary changes. This section now reads-

"For example, Differential Global Navigation Satellite Systems (DGNSS) can be used to track the position of ground stakes on a glacier over time, from which ice surface velocity can be estimated (Azam et al., 2012; Sugiyama et al., 2013)"

L45: Surface velocity can be estimated; a reference is needed.

Thanks for pointing this out. We have added- Azam et al., (2012) and Sugiyama et al., (2013)

L48: Two times mention 'particular' and 'particularly' in a single sentence.

Thanks for noting this. We have updated it, and now it reads-

"....characterise the evolution of a glacier system, particularly mountain glaciers, which are remote and difficult to access."

L49-50: Satellite-based remote sensing methods. Please describe the specific techniques here.

Thanks for this suggestion. We have reworded the sentence as-

".....satellite-based remote sensing methods, such as feature tracking, provide.."

L58: Please describe what other local conditions are.

Thanks for the suggestion. We have updated the sentence as

"....other local conditions such as ice thickness and basal conditions"

L73: The three-year mass balance of Rulung Glacier and the four-year mass balance of Stok Glacier do not present a declining trend. To understand the trend in mass balance, we require a long series of in situ measurements. You may mention here the negative mass balance only.

Thanks for noting this. We have updated this section based on this comment and the comment from Reviewer 2. It now reads-

"Various in-situ mass balance measurements suggest a negative ice mass change in these glaciers (Azam et al., 2025; Mehta et al., 2021; Shrivastava et al., 1999; Soheb et al., 2020). While these values quantify ice loss, their implications for regional water security are governed by the timing of 'peak water'- the tipping point where annual meltwater discharge reaches its maximum before declining due to reduced glacier volume (Huss and Hock, 2018)."

L75-76: Correct the reference of Soheb et al. (2020) and Mehta et al. (2021).

Thanks for pointing this out. Updated as suggested.

L93: Omit Western Himalaya.

Updated as suggested.

L97: Test……..reframe this sentence.

We have removed this objective, and included it in the third objective and reworded as-

"Evaluate the factors influencing glacier velocity, including changes in surface elevation, morphology and extent"

L110: Why were selected 12 glaciers? Please give the justification. What is the range of area and elevation of these glaciers? Please add 2-3 sentences on this.

Thanks for this suggestion. We have updated the section as-

"In this study, we have selected 12 glaciers to study the evolution of inter-annual glacier surface velocity and surface elevation change. We selected the glaciers capturing the morphological and glaciological diversity of the region based on their size, elevation, degree of debris cover, terminus type, orientation, and slope. From small mountain glaciers (G12; 3km^2) to large valley glaciers (DDG;68 km^2) and a mean elevation ranging from 4800m to 5400m (Table 1). The glaciers are given unique IDs based on their known name (DDG- Drang Drung Glacier, HG- Hagshu Glacier); the remainder are denoted G3 to G12 (shown in figure 1). Refer to Table 1 for further details"

L139: Green (B2 band), why was the Green band? Please explain here.

Thanks for noting this. We clarify this by rewording the sentence as-

"In this study, we used the panchromatic band (B8) of the Landsat series 7 Enhanced Thematic Mapper Plus (ETM+), Landsat 8 and 9 Operational Land Imager (OLI) and the Green (B2) band from Landsat 5 Thematic Mapper (TM), which is closest to the wavelength range of the panchromatic band"

L158: There is some confusion. Did you co-register the Landsat images, as these images are already orthorectified? If not performed, please omit this.

Thanks for pointing this out. We did not co-register images. It was written about the capabilities of the tool. However, we have omitted this sentence for clarity.

L162: What is the "salt-and-pepper" effect?

By "salt-and-pepper" effect, we meant to signify the noisy pixels within the velocity raster. We have removed the term as it was redundant with the preceding word 'noise'.

L166: 4*4 pixels, but Landsat 5 does not contain a panchromatic band. Possibly you used 2*2.

Thanks for pointing this out. Yes, Landsat 5 does not contain panchromatic band and we used 2*2pixel . We have added the information and updated it as-

*"A step size (refers to the spatial resolution or the distance between the centres of the image patches) of 4*4 pixels for all except for Landsat 5 (30m spatial resolution), where a 2*2 pixel step size was set, resulting in a resultant output of 60m spatial resolution velocity fields"*

L176-178: I feel five iterations are best, whereas two iterations may give some noise. Please carefully check and rewrite.

Thanks for noting this. In this study, we used iterations of 4. We have updated the text as-

"The Robustness iteration, which is a quality control loop that ensures the derived displacement or velocity vectors are consistent and robust against errors or noise, was set to 4"

L204: It may also arise due to a horizontal shift in two images; you may mention this here.

Thanks for suggesting this. We have updated the sentence by adding this. It now reads-

"For example, it may arise due to a change in surface characteristics between the two images, such as snow cover change, varying sun angles and shadows, and also due to a horizontal shift in the two images"

L213: Please provide more details on pairwise uncertainty in the supplementary material.

Thanks for the suggestion. In the supplementary, we have already reported the pair-wise uncertainty of all the velocity results under section Table S2. However, it was not referred in the main text. We have now added it and modified to-

"This method was applied to all the velocity datasets generated. The uncertainties range from 0.85 m year^{-1} to 5.49 m year $^{-1}$, which are of similar magnitude to previous studies (Bhushan et al., 2018; Das and Sharma, 2021; Shukla and Garg, 2020). All the pair-wise uncertainty is listed under Supplementary Table S2."

L221-223: Please reframe this sentence, and replace glacier mass balance with elevation changes.

We have updated as suggested. It now reads-

"Bin-wise elevation change analysis is an effective approach for capturing the spatial heterogeneity of glacier responses to climate forcing, revealing how processes operating at different elevations shape overall surface elevation change and dynamics."

L229: Equation 5, how are these parameters calculated in this equation? What is the uncertainty in these estimates? Please describe in the text. I also could not find how this equation helps to interpret the result of glacier surface flow velocity in the manuscript.

Thanks for noting this. However, we did not explicitly calculate the parameters in equation 5. This was provided for reference to the readers to show the relationship between driving stress with gravity, ice thickness and slope (Cuffey and Paterson, 2010). As we refer to the concept of driving stress in subsequent sections, we believe this might help the readers to understand how we draw our conclusions.

L242: ERA5 Land reanalysis climate data: Many studies have reported biases in the ERA5 land reanalysis dataset in mountainous areas. Our own study found a 5- to 8-degree temperature difference between the automatic weather station and the ERA5 Land dataset in different seasons, without bias correction, in the Central Himalaya. Such climatic trend analysis without bias corrections is not appropriate and provides unrealistic trends. I would suggest conducting bias correction in ERA5 data using nearby IMD sites or the IMD grid dataset.

Thanks for pointing this out and the suggestion. We agree with the reviewer's comment that ERA5-Land reanalyses can contain significant biases in mountainous regions. Since we do not perform any quantitative meteorological analysis or use it as a forcing data and restrict to only trend analysis, we believe using raw ERA5-Land is suitable for the present study. Moreover, the study by Mandal et al., (2024) has shown that ERA5-Land is fairly reliable for

the same region by comparing the raw data using statistical assessment with nearby station datasets (see figure 2). Given that we do not use the data to drive models, we do not think it would add any value to bias correct using the IMD (or other) datasets.

L247: Section 4.1, Glacier velocity trend and surface elevation change: Both sections must be presented separately. Also, section 4.3 "elevation-wise glacier velocity trend is actually section 4.2 (possibly typo mistake), which can be merged with section 4.1 (glacier velocity trends) following the removal of surface elevation change.

Thanks for the suggestion. We have modified the sections and updated the indexing. They are now in the series of-

Section 4.1- Glacier Velocity Trends
Section 4.2- Glacier Surface Elevation Change
Section 4.3- Non-climatic factors
Section 4.4- Climatic Trends

L257-258: In the result and discussion section for surface flow velocity and elevation changes, the median flow velocity term and median elevation change term are frequently used. However, most of the previous studies use mean or average surface flow velocity or mean elevation change values. It is not straightforward to compare the median surface flow velocity with the previously published mean surface flow velocity.

Thanks for noting this. Upon receiving this feedback, we conducted a comprehensive audit of our data processing scripts and analysis. We discovered a terminological inconsistency in the original draft: while our calculations were correctly outputting the mean, the text and figure labels erroneously identified these values as medians. We have corrected all text, figure captions, and label inconsistencies related to this.

L260: Use 24.5 ±5.7 instead of 24.50±5.73 throughout the manuscript.

Thanks for the suggestion. We have updated this throughout the manuscript.

L263: T-statistic test, please describe this statistical test in detail in the methodology section for the interest of readers.

Thanks for the suggestion. We have added and described the t-test under section 3.4 Data analysis and supporting datasets. It reads-

"A T-statistic test that compares the means of two groups while considering how much the data "spreads" (variance) was used to calculate the p-value in our data analysis (Kim, 2015). The p-value, derived from this statistic, represents the probability of observing results as extreme as the sample, assuming the null hypothesis. A p-value below 0.05 generally indicates statistically significant results (rejecting the null hypothesis)."

L281: Between 2001 and 2010, instead of between 2001-2010. Please carefully review the entire manuscript for any similar text.

Thanks for the suggestion. We have made all the changes as required throughout the manuscript.

L283: From 1992 to 2000 instead of from 1992-2000.

Thanks for the suggestion. We have update throughout the manuscript.

L296-300: This is related to methodology, not related to the result section. Please shift to the relevant section and write only the results here.

Thanks for pointing this out and the suggestion. We have shifted this section to Methodology under section 3.4 Data analysis and supporting datasets.

L326: omit theory.

We have updated as suggested.

L326: median glacier surface elevation change. Primarily, studies use mean glacier elevation changes. Please see my previous comment.

Please see the above point.

L327: What are bottom-heavy glaciers? First, define these terms.

Bottom-heavy glaciers feature a disproportionately large area at lower elevations (Jiskoot et al., 2009). We have defined these terms in Methodology under section 3.4 Data analysis and supporting datasets for reference to readers. The modified text reads-

"Additionally, we used the Hypsometric Index to calculate and classify the glaciers as very bottom-heavy (HI > 1.5), bottom-heavy geometries (1.2 < HI ≤ 1.5), very top-heavy (HI < −1.5), top-heavy (−1.5 < HI < −1.2), and equidimensional glaciers (−1.2 < HI < 1.2) following Jiskoot et al., (2009). While top-heavy glaciers concentrate their mass at higher elevations within expansive accumulation zones, bottom-heavy glaciers feature a disproportionately large area at lower elevations."

L355; Figure 8: In sub-panel A, also show Drun Drung glacier in the subset, as shown in sub-figure b.

Thanks for the suggestion. We have updated the figure with inset in panel a.

L380; Figure 9: In this figure, you mentioned median velocity and mean elevation, whereas in text L326, you mentioned median glacier surface elevation change. Please correct it throughout the manuscript.

Thanks for noting this. However, in the figure, the 'mean elevation' is the elevation from the DEM and not the surface elevation change. Whereas, in L326, we discuss the results from surface elevation change analysis from Huggonet's data.

L386; 4.4 Climatic trends: Please see my previous comment on the ERA5 Land dataset without Bias correction, such trends are not appropriate. Additionally, please describe how the calculated uncertainty of the ERA5 land dataset is ±0.01 °C in the methodology.

Thanks for pointing this out. While the absolute values of meteorological variables such as temperature and precipitation require bias correction to be reliable, the trends (which are more a function of the large-scale circulation and its changes through time) are appropriate. For the second part of the comment, we have updated it in the methodology. It now reads-

"Data from the nearest grid to the study location were extracted for further analysis. The uncertainty was estimated based on the 1σ (standard deviation) of the data."

L396: The discussion section can also be improved. Please see the following papers, which can help enhance the discussion section, particularly regarding the increase in lake-terminating glacier flow velocity and its comparison with the Karakoram region.

Thanks for the suggestion. We have incorporated these studies and modified the discussion sections as follows-

For overall discussion on glacier velocity and elevation change-

"……Although previous studies have reported a slowdown of glaciers in the Ladakh region, a contrasting increase in glacier velocity was found in the Drang Drung Glacier. For example, the results from the study by (Singh Jasrotia et al., 2024) show velocity increased from 71 ± 6.1 m year^{-1} in 1999 and 2000 to 140 ± 7.4 m year^{-1} in 2019 and 2020 (by ~ 50 %), which contrasts with our findings, and is likely an artefact of their consideration of two timeframes only. Overall, our declining glacier velocity trends align with patterns observed for nearby glaciers in other studies. However, our results contrast with recorded flow acceleration of Karakoram glaciers, reported by Heid and Kääb, (2012), which was due to positive mass balance, and also glacier surging in this region."

For discussion on lake-terminating glaciers-

"... Such lake expansion could alter the local force balance near the termini, promoting frontal acceleration (Pronk et al., 2021). A recent study on Bhutan lake-terminating glaciers found, despite high thinning rates, some glaciers showed acceleration near the terminus, which is potentially due to increased meltwater flux (Hyde et al., 2025). A similar conclusion was drawn by Wu et al., (2020) for a lake-terminating glacier in Kangri Karpo Mountains in South-Eastern Tibet."

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