Response from Authors to Reviewer 2 (RC2)

Summary:

Review of – Slowdown of glacier velocity emerging in the Zanskar Himalaya
By Tirthankar Ghosh, RAAJ Ramsankaran, Felicity S McCormack, Andrew N Mackintosh
In this manuscript, the authors quantify multi-decadal change in glacier dynamics in the Zanskar Basin (Ladakh Himalaya) by estimating interannual surface velocities from Landsat feature tracking (1992–2023) and relating these to surface elevation change from the Hugonnet et al. dataset. The authors analyse 12 selected glaciers spanning a range of sizes, slopes, aspects, debris cover fractions, and terminus types. The manuscript is well written overall and complements other available papers on the region. However, some revisions would be useful to improve the final version of this. Firstly, given that most of the results in this paper are based on the optical feature tracking velocity maps, it would be ideal to either make these rasters available directly or at a minimum add some vector plots to the supplementary material. The absence of this makes evaluating underlying data quality more challenging. The discussion of the processes driving glacier acceleration and slowdown could use some edits, particularly capturing the more complex links to glacial hydrology that are currently absent. Also, the discussion of non-climatic drivers (including lake impacts) has some weaknesses in the causality inferences, with differences in glacier size/thickness not being discussed. None of these revisions will fundamentally alter the manuscript and I expect it to be suitable for publication in TC with appropriate edits.

We thank Dr Maximillian Van Wyk de Vries for reviewing and providing thoughtful and constructive feedback on our manuscript. We also appreciate the time and effort for the same. We have 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:

The title could be clearer – there's some ambiguity around what 'emerging' means

Thanks for the suggestion. We have changed the title to *"Thinning-induced glacier deceleration in the Zanskar Himalayas"*

L13 – a brief word about why they were selected – 'representative'? 'distrubuted'? 'large'?might help

Thanks for the suggestion. We have updated the sentence as:
"…12 selected glaciers with varied morphological characteristics in the Zanskar Basin of the Ladakh Himalayas"

L20 'glacier health' avoid this term. Spell out what you mean. Also you just noted acceleration of some lake termini – would this not be an acceleration in the face of climate change? Maybe caveat to capture the complexity.

Thanks for this suggestion. Yes, we agree to the argument and have updated the text. The sentence now reads:

"While glacier mass loss, particularly through thinning, and associated reduction in driving stress was identified as the primary driver of velocity deceleration, glacier-specific characteristics, such as geometry, topography, debris cover and terminus type, also influenced glacier response. For example, some lake-terminating glaciers exhibited local increases in ice velocity near their termini. Overall, our results confirm loss of ice mass in this region, which generally corresponds with a reduction in surface velocity."

L25 Perhaps note here these figures exclude the ice sheets. If we include Antarctica/Greenland they are much lower.

Thanks for the suggestion. We have updated as suggested. It now reads-

"Globally, glacier mass outside of Greenland and Antarctic ice sheets is projected to decline by 26 ± 6% to 41 ± 11% by the end of the 21st century (relative to 2015), under emission scenarios that correspond to +1.5 °C and 4 °C warming, respectively (Rounce et al., 2023)."

L28 glaciated ice -> ice
Updated as suggested.

L32 'caters to a population of over a billion people' while >1 billion live in the catchments, the glacial water fraction is negligible for many of these. As written this somewhat oversells the importance of glacial water (which is nevertheless locally crucial). Please reword to better capture this.

Thanks for noting this. We have updated and reworded this section. It now reads:

"For example, the meltwater generated from Himalayan glaciers and snow modulates the discharge of major river systems such as the Indus, Ganges, and Brahmaputra. While the glacial contribution to total runoff varies across the catchments, it underpins the water security of upstream populations and the broader hydrological systems upon which over a billion people downstream depend, recharges river-fed aquifers, and contributes to global sea level rise"

L35-40 Glacier basal hydrology is of course a critical driver of velocity which can substantially complicate this relationship. Many glaciers undergo a large seasonal cycle in velocities which of course does not reflect equivalent seasonal mass changes. Can you please say a little more about this here, and how it can be mitigated when interpreting changes in velocity (e.g. long timeseries, multi-glacier analyses, context-aware). You do this all already so this can strengthen your case.

Thanks for this suggestion. Yes, we agree that glacier basal hydrology has an important role in velocity and needs to be mentioned here. We have modified this section to include the subglacial hydrology. This is how it reads:

"As glaciers flow due to their weight and gravity, by the processes of internal deformation and sliding at the bed, basal hydrology can substantially complicate this relationship (Bindschadler, 1983; Minchew and Joughin, 2020). Variations in meltwater supply to the bed modify the basal water pressure, which in turn regulates basal sliding (Bindschadler, 1983). As a result, many mountain glaciers exhibit pronounced seasonal velocity cycles, with speed-

ups during periods of enhanced surface meltwater input to the bed. These short-term hydrologically driven fluctuations can obscure longer-term dynamic trends if not carefully accounted for. Such effects can be mitigated using long time series spanning multiple decades, which average out seasonal variability and highlight persistent interannual to decadal trends. Furthermore, glacier-specific, process-based understanding can also help better interpret these results. These flow processes are also influenced by other internal factors, such as ice temperature, glacier geometry, bed characteristics, as well as external factors such as air temperature and precipitation (Cuffey and Paterson, 2010; Iken and Bindschadler, 1986)"

L43-45 Worth noting here that people have been doing satellite-based feature displacement tracking for ice velocity basically as long as GNSS has been around.

Thanks for noting this. We have updated the section. This is how it reads-

"Historically, glacier velocity has been monitored through the simultaneous development of on-field and satellite remote sensing-based measurements, both of which are established standards in glaciology (Hooke et al., 1989; Stevens et al., 2023; Vincent et al., 2022)"

L50 Satellites do not provide higher temporal resolution than a ground-based GNSS station. You can get sub-minute timings from the latter. This paper may be of interest to review – we compare satellite and ground based data (https://doi.org/10.5194/tc-17-4063-2023).

Thanks for noting this. We have updated it as suggested. It now reads-

"By contrast, satellite-based remote sensing methods, such as feature tracking, provide a wide spatial coverage and an easy-to-access dataset."

L55 Agreed that they are interesting but perhaps can be worded differently here. Agarwal et al might be relevant for this section too – a detailed regional analysis with some similar objectives to your study https://doi.org/10.1016/j.scitotenv.2023.165598.

Thanks for this suggestion. We have reworded this section and now include Agarwal et al., (2023). This is how it reads-

With the availability of more satellite datasets, many ice velocity studies have been carried out in the Himalayas, providing critical insights into glacier spatio-temporal patterns and evolution. Several studies have revealed heterogeneous patterns in the velocity of the Himalayan glaciers (Bhambri et al., 2011; Dehecq et al., 2019; Garg et al., 2025; Tripathi et al., 2023). Findings from these studies show that glacier velocity varies spatially and temporally, region-wise and within the same glacier, depending on factors such as elevation, slope, size, debris cover fraction, land vs lake terminating, mass budget and other local conditions such as ice thickness and basal conditions (Agarwal et al., 2023; Bhushan et al., 2018; Dehecq et al., 2019).

L70-75 Could you speak on the concept of peak water here? This matters more for water security than the 'glacier mass loss' values – if peak water is still in the future then greater mass loss might actually lead to a short term increase in water availability. The timescale of interest matters here. Huss and Hock have a global compilation if there are no specific local studies.

Thanks for this suggestion. We agree that discussing the concept of peak water gives another perspective in this section. We have modified this section as:

"The implications for regional water security from this ice loss 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). With peak water for the region projected to occur around ~2028, as reported by Huss and Hock, (2018), the current acceleration in mass loss represents a critical transition from a short-term increase in water availability to a long-term reduction of streamflow, making this region extremely vulnerable to water shortages."

L86 These are some good studies overall, and you might rewrite this sentence in a more positive way e.g.'despite the insight these provide into xx, gaps in our understanding of yy remain'.

Thanks for the suggestion. We have reworded this to:

"Despite the insights these studies provide into discrete periods of glacier surface velocity, gaps remain in our understanding of continuous, long-term velocity evolution and thinning. Thus, a comprehensive analysis of the glacier dynamics in the Ladakh region is still missing."

L87 Does Dehecq et al not cover the whole HMA including this area?
Yes, Dehecq et al do cover this region. But it lacks a detailed glacier-wise analysis.

L92 'glacier flow trend' -> 'glacier surface velocity trend'
Updated as suggested.

L94 What 'reanalysis' was done here?
In this objective, by "reanalysis" we meant using the dataset to perform data extraction and do statistical analysis for our region of interest. However, we have reworded this objective to-

"Extract and evaluate the glacier surface elevation change using the existing dataset by Hugonnet et al., (2021) for the selected glaciers."

L96 This seems a risky aim as worded, as exact determination of these processes is not always possible, particularly with only this remote sensing data.

Thanks for noting this, and we agree to that. We have reworded the objective to-

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

L97 This is not clear. Do you mean whether temperature vs precipitation are the key drivers? Can you expand this question to make it clearer.

Thanks for the suggestion. We have included this objective in our 3rd objective, as we feel it was redundant.

L139 Can you say exactly which Landsat mission you got images from. Were you forced to use post-SLC failure L7?

Thanks for this suggestion. The Landsat missions used to collect images were already reported in this section. We used the Landsat 5, 7, 8 and 9. Though we have updated this section with the detailed sensor names (e.g, TM, ETM+, etc).
We did not use any post-SLC failure images from Landsat 7. (see supplementary for details of the images used)

L153 Did you just do sequential image matching across years (e.g. 2015-2016)? Or was multiyear matching also done (e.g. 2015-2017, 2018, 2019). For these v. slow glaciers with limited decorrelation the latter can be useful and reduces dependence on single images but unsure what was done here.

In this study, we performed a sequential matching. We agree, multi-year matching can increase displacement magnitude and improve signal-to-noise ratios, particularly for very slow glaciers, but it inherently averages velocity over longer time intervals. Furthermore, the glaciers analysed here exhibit measurable displacements over annual timescales that remain above the detection threshold of the correlation method, and the algorithm performed well in capturing them.

L171 Could you briefly note how the SNR is calculated or reference a paper that does. This is calculated in a few different ways.

Thanks for this suggestion. We used the method as proposed in Leprince et al., (2007) incorporated in COSI-Corr algorithm. We have updated this section by referring to (Leprince et al., 2007).

L191 – 194 If using a median smoothing kernel then "smooth the velocity outputs without losing their details" is probably not true, rather "smooth with acceptable loss of detail". Worth noting that this procedure commonly erodes the glacier boundary by 1-2 pixels with the 'stationary' pixels winning out on the median. Probably still acceptable but worth noting especially for small glaciers.

Thanks for this suggestion. We agree to what was discussed above. We have modified this section to-
"Finally, we used a 3-pixel * 3-pixels median filter on the velocity maps to remove any outliers (noise) within the maps and to smooth the velocity outputs with an acceptable loss of details"

L220-225 This is described as a more information rich-approach than 'whole glacier averages' – but the baseline Hugonnet dataset is already a spatially distributed dataset so this is losing information. Might be worth instead framing it in terms of noise suppression and interpretability (i.e. dimensionality reduction).

Thanks for noting this and the suggestion. We have updated this sentence to-

"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. Aggregating the data into elevation bins acts as a form of suppressing spatial noise while preserving the dominant elevation-dependent signals for better interpretations"

L225-226 this is only true for 'all else equal' – as your subsequent lake analyses show is not always true.

Thanks for noting this. Previously, we have already noted some exceptions here. However, we have reworded this section for better clarity. It now reads-

"However, there could be some exceptions, for example, differential surface thinning rate, leading to increased surface slope, may increase the driving stress or some complex feedback mechanisms from proglacial lake-ice interaction"

L247 onwards – I am not sure that the velocities reported to the nearest 0.01m are warranted here.
Modified as suggested throughout the manuscript.

L284 Looking at the graphs for G5 and G11 that doesn't seem to tell the whole story.
Thanks for noting this. We have removed this part. This section was based on the analysis done for the time ranges as written in the manuscript (1992-2000, 2001-2010, 2011-2023). The relative higher velocity in some years corresponded to overall positive trend in specific decadal ranges for few glaciers, leading to misinterpretation of velocity evolution. The modified section now reads-

"We considered three decades from our study period (1992-2000, 2001-2010, 2011-2023) to understand decadal flow pattern changes. Despite the data gaps between 2001 and 2010, we can discern a broad understanding of changes in the flow trend over this 31-year period. From 1992 to 2000, all glaciers exhibited an increase in velocity. In contrast, from 2001 to 2010 and 2011 to 2023, the glaciers generally show reduced flow speeds"

L289 Is 5000m exactly the ELA on all these glaciers? If not, can you either repeat this with the actual ELA or reword?
Thanks for noting this. Here, 5000m threshold was selected not to signify the ELA of the glaciers, but rather based on the mean elevation distribution of them. For more clarity, we have reworded this sentence to-

"To analyze the relationship between ice velocity trend and elevation, we categorized the glaciers into two elevational zones based on the regional mean elevation: a lower-elevation zone (< 5000m) and an upper-elevation zone (> 5000m). It is important to note that this 5000m threshold was chosen to represent the average elevational distribution of the glaciers in our study area and is not intended to represent the Equilibrium Line Altitude (ELA)."

L315 Could you plot the annual velocities as lines rather than scatterplot? It is very hard to keep track of. If the lines are colored with a continuous gradient from start-end it becomes easier.

Thanks for this suggestion. The figure will be updated as suggested.

L375 To me this reads as all covariates of ice thickness – area and length are themselves strongly correlated (0.97) and both will relate to how large and thick the ice is. Slope anticorrelating with velocity is contrary to usual expectations, but should also be because slope and thickness anticorrelated.

Thanks for noting this. We agree with the reviewer's interpretation of the physical drivers. We have revised the text to explicitly mention the high correlation (0.97) between area and length as redundant thickness proxies. We also added a clarification explaining that the negative correlation between slope and velocity likely stems from the anti-correlation between slope and ice thickness, where thickness remains the dominant control on velocity in this dataset. This is how it reads-

"The matrix indicates that glacier length and area have the strongest positive correlations with mean velocity, with a correlation coefficient of 0.75 and 0.67, respectively, which could be related to how large and thick the ice is. In contrast, slope
(r = -0.37) and aspect (r = -0.36) shows a moderate negative correlation with velocity. While steeper slopes generally increase gravitational driving stress, the negative correlation observed here likely reflects the inverse relationship between slope and ice thickness; in this study area, steeper glaciers could be thinner, and the reduction in thickness exerts a stronger limiting influence on velocity than the slope gradient provides."

L426-432 This would be a good place to say more about the subglacial hydrology links to velocity which is currently missing.

Thanks for the suggestion. We have now incorporated discussions on subglacial hydrology and its potential links with glacier accelerations. This is how it reads-

"For G4 and G5 (top-heavy glaciers) and DDG (equidimensional hypsometry), sustained ice flux from upstream likely contributes to maintaining flow toward lower elevations. However, the dynamic behaviour of these lower ablation zones cannot be explained by geometry alone. Enhanced surface melt in recent years likely increases meltwater inputs to the glacier bed through moulins or crevasses, promoting periods of elevated basal water pressure and reducing effective pressure at the ice-bed interface, which can lead to higher basal sliding. HG, a heavily debris-covered glacier with a bottom-heavy hypsometry, which is likely more sensitive to such hydrological controls near ablation zone. While debris can modulate surface melt spatially, meltwater routed through crevasses, ice cliffs, and supraglacial ponds can still reach the bed and locally enhance sliding. Bhushan et al. (2018) also reported a dynamically active trunk of DDG (>20 m year⁻¹ in 2013–2014), consistent with our mean flowline velocities. This highlights the complex interplay between glacier geometry, debris, subglacial hydrology evolution, and dynamics."

L439-441 In isolation I am not sure how much this tells us – they could simply be larger/thicker glaciers as this has not been controlled for.

Thanks for noting this here. We agree to the fact that it could simply be related to the geometry of the glacier. However, we have modified this section by discussing these potential biases in result interpretation based on the current datasets.

"Glacier velocities across the study region show clear differences between lake-terminating and land-terminating glaciers, with the former generally maintaining higher surface flow speeds – often up to twice that of their land-terminating counterpart. For instance, mean velocity along the central flowline for DDG and G10 corresponds to 57.98 m year^{-1} and 38.52 m year^{-1}, respectively, which is significantly higher than other glaciers. While glacier size and thickness have controls on driving stress and could partly explain these higher velocities, the dynamic influence of proglacial lakes likely provides an additional control on them."

Also in second paragraph we modified the text to-

"The contrasting behaviour of lake-terminating glaciers may therefore be explained in two ways: (a) less buttressing and altered local force balance at the ice-lake margin, and (b) enhanced surface lowering near the terminus. The latter, in particular, influences the flow characteristics by regulating the glacier's dynamic thinning phenomenon, as also discussed and found in the majority of lake-terminating Himalayan glacier studies (King et al., 2019; Pronk et al., 2021). At the same time, glacier geometry must also be considered, as longer and thicker glaciers can sustain higher driving stresses and therefore higher flow speeds independent of terminus conditions. However, the relative contribution of these geometric effects versus lake-related dynamic processes cannot be resolved with the present data, as our observations do not directly constrain them. This warrants further investigation."

L447 Not sure you have discussed/shown evidence for dynamic thinning here.

Thanks for noting this. We have reworded the sentence, as we explicitly do not show evidence of dynamic thinning. It now reads-

"This thinning and retreat could be related to calving, which was evidenced in 2023"

L460 The high velocity is not particularly apparent in these figures. Here and throughout it would be good to add the velocity vectors on top of the speed field, this is helpful for evaluating data quality. Also, could you use colour base images – the lakes would be much clearer.

Thanks for the suggestions. Figures will be updated as suggested.

L480 perhaps 'detailed' rather than 'comprehensive'

Modified as suggested.

L485-487 I am not sure what this sentence is getting at. As I mentioned above, I think most of this can be summed up as 'larger glaciers tend to be thicker and flow faster' – not particularly insightful in itself.

Thanks for noting this. However, here we not only intend to talk about 'large glaciers tend to be thicker and flow faster', but also the heterogeneity in spatial and temporal evolution of

velocity in similarly sized glaciers within similar climate forcings, which could be linked to the mentioned characteristics of these glaciers (debris cover, hypsometry, subglacial conditions, to some extent ice-lake feedback).

L487-488 Again, the absolute velocity being different does not tell us much unless you have controlled for some other parameters here. If we compare a large lake terminating glacier with a small, thin land terminating glacier we cannot attributed the absolute velocity difference only to the lake.

Thanks for noting this. As we agree to the previous comments on lake-ice mechanisms and causality inference. We have modified this section and reworded to-

"Though lake-terminating glaciers exhibited persistently higher velocities compared to land-terminating ones, consistent with previous findings across the Himalayas, the specific mechanisms driving this difference cannot be conclusively resolved here, given current data constraints"

References:

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