# Response to Reviewer #2

*As associate editor, I would first like to thank you (authors) for sending the manuscript to ESurf and Peter van der Beek for providing a thorough review. It has unfortunately not been possible for me to secure additional reviews, but the review by Peter van der Beek provides a number of relevant points and constructive ideas. I encourage you to use all the reviewer comments to revise the manuscript including adding better and more detailed documentation to support the hypotheses presented.*

We appreciate the very thorough and detailed reviews provided by both and you and Peter van der Beek, and for steering our manuscript through a very helpful review process. We have considered all comments carefully, and propose a set of revisions to address the ideas and suggestions provided by you and Peter van der Beek.

*In addition to the reviewer comments I list below some additional reflections of my own:*

*General comments:*
*Most previous studies of mountain range height and glacial erosion have used correlations between ELA and max topography/hypsometric maxima along climatic gradients caused by temperature or precipitation to infer that glacial erosion influences mountain range height. To me such spatial correlations provide a stronger argument than the two isolated cases presented here. We know from global compilations of topography and ELA that many exceptions to the overall trend exist for numerous reasons. I therefore encourage you to expand your study and collect data from more tropical ranges. Do any of the tropical ranges stand high above the ELA? Or do the two cases documented here indeed represent a general pattern? That two selected ranges have heights that match the estimated ELA can easily be a coincidence. Even worse: Were the ranges selected for this study because they happen to have heights that match the ELA? You need to show us more data to answer such questions and to support the general points made.*

To be clear, the decision to focus on the Talamanca Range (CR) and the Central Range (TW) did not begin with their ELA-height match. Rather, we were initially struck by the following: even though global scale observations (e.g., Egholm et al., 2009, Fig. 1C) of the ELA-height match include the tropics, glacial erosion has *not been proposed as a mechanism for limiting tropical mountain height*. Our goal was to explore this possible mechanism through the study of tropical landscapes that are potentially the most prone to glacial limitation. We deduced that high mountain ranges (peak elevations above 2000 m) that are tectonically active, rapidly eroding, and circumferentially well-connected to external base-level forcing are likely the best recorders of glacial erosion. Those that best match such criteria are:

1) Finisterre Range, Papua New Guinea
2) Owen Stanley Range, Papua New Guinea
3) Merauke Range, Papua
4) Central Papua New Guinea Highlands
5) Crocker Range, Borneo
6) Leuser Range, Aceh Province of Indonesia
7) Central Range, Taiwan

8) Sierras Madre, Mexico/Guatemala
9) Talamanca Range, Costa Rica/Panama
10) Santa Marta, Venezuela
11) Mérida Range, Venezuela

There is a tradeoff between the geographic scale and the degree of detail in any analysis. In the submitted manuscript, we choose to apply detailed analysis of the Talamanca Range in Costa Rica (CR) and the Central Range of Taiwan (TW) because they exemplify the selection criteria, and because there are good constraints on the timing of deglaciation in both ranges. We recognize the need to apply a wider geographic analysis, and to this end we discuss the full list of tropical ranges above before describing in detail the rationale for focusing on these two in the revision.

Furthermore, in the revision we present a three-step analysis, progressively thinning the targeted mountain ranges and introducing more detailed analysis at each step. This three-step approach is detailed below:

***Step 1: Analyze the hypsometry of 1°x1° SRTM tiles of entire range***

In this step, we adapt the approach of Egholm et al. (2009), who found the hypsometric maximum (specifically, the highest modal elevation of multi-modal elevation distributions) of every glaciated tile between 60°N and 60°S. The tropical ranges we list above were included in this analysis, and the majority do not have a hypsometric maximum near the lower limit of late-Pleistocene ELA fluctuation. However, the hypsometries of many 1°x1° tiles covering these ranges do show evidence of *truncation* at or very close to the ELA. This nuance is obscured when only the hypsometric maximum of the tile is recorded.

In Fig. 1 and Fig. 2, below, we plot two examples (Merauke Range, Papua and Mérida Range, Venezuela) of tile hypsometry mosaics that are provided in the revised manuscript for each of the 11 mountain ranges listed above. Note that in both example mountain ranges plotted below there are peaks far above the LGM ELA (such as the presently glaciated Puncak Jaya in the Merauke Range of Papua).

Our goal is to use tile hypsometry to identify a subset of mountain ranges that may be subject to glacial limitation or, as we propose for CR and TW in the submitted manuscript, glacio-fluvial limitation, even if their tile hypsometry does not reveal a broad aerial extent of glacial landscapes.

***Step 2: Analyze hypsometry of selected mountain range on a progressively smaller scale.***
In this analysis, we will choose a subset of ~5 ranges in which we analyze hypsometry over a range of scales. The details of this method are presented in response to a comment below (Figs. 3-6).

***Step 3: Focused analysis of glacial landscapes in CR and TW.***
We will conclude our analysis with a detailed look at glacial landscapes in the Talamanca and Taiwan in order to assess the interplay between glacial and fluvial erosion in tropical highlands and the possibility of glacio-fluvial limitation of mountain height in the tropics.

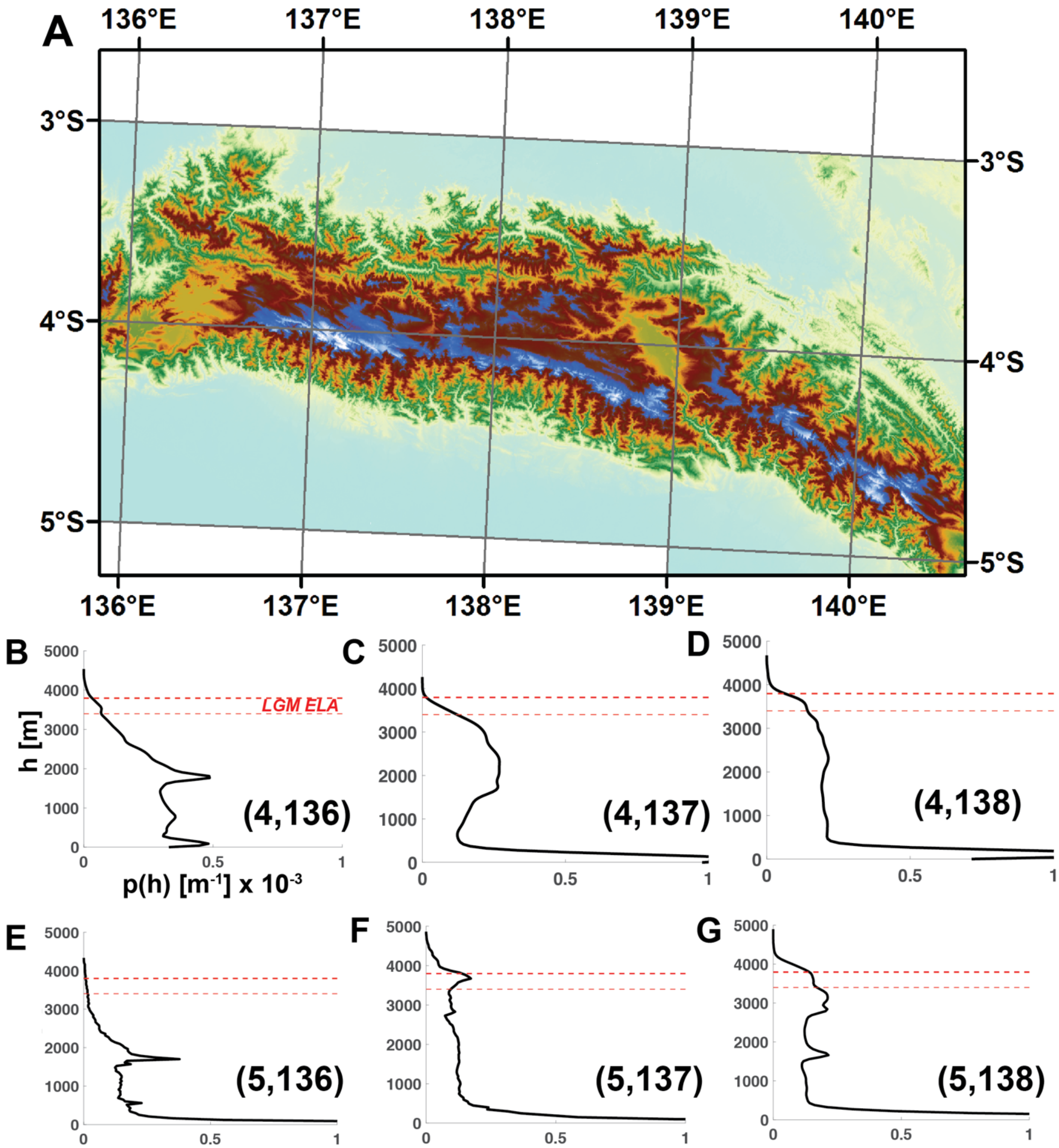



**Figure 1: Tile hypsometry of the Merauke Range.** A: Merauke range DEM. 0-3500 m is light blue through red, 3500-4500 m is dark blue to white. B-G: Elevation pdf of 1°x1° tiles, labeled by southwest corner of tile. Dashed red lines are approximate bounds of ELA variability in New Guinea (e.g., Prentice et al., 2005). Puncak Jaya (4844 m) is located in tile 5S, 137E.

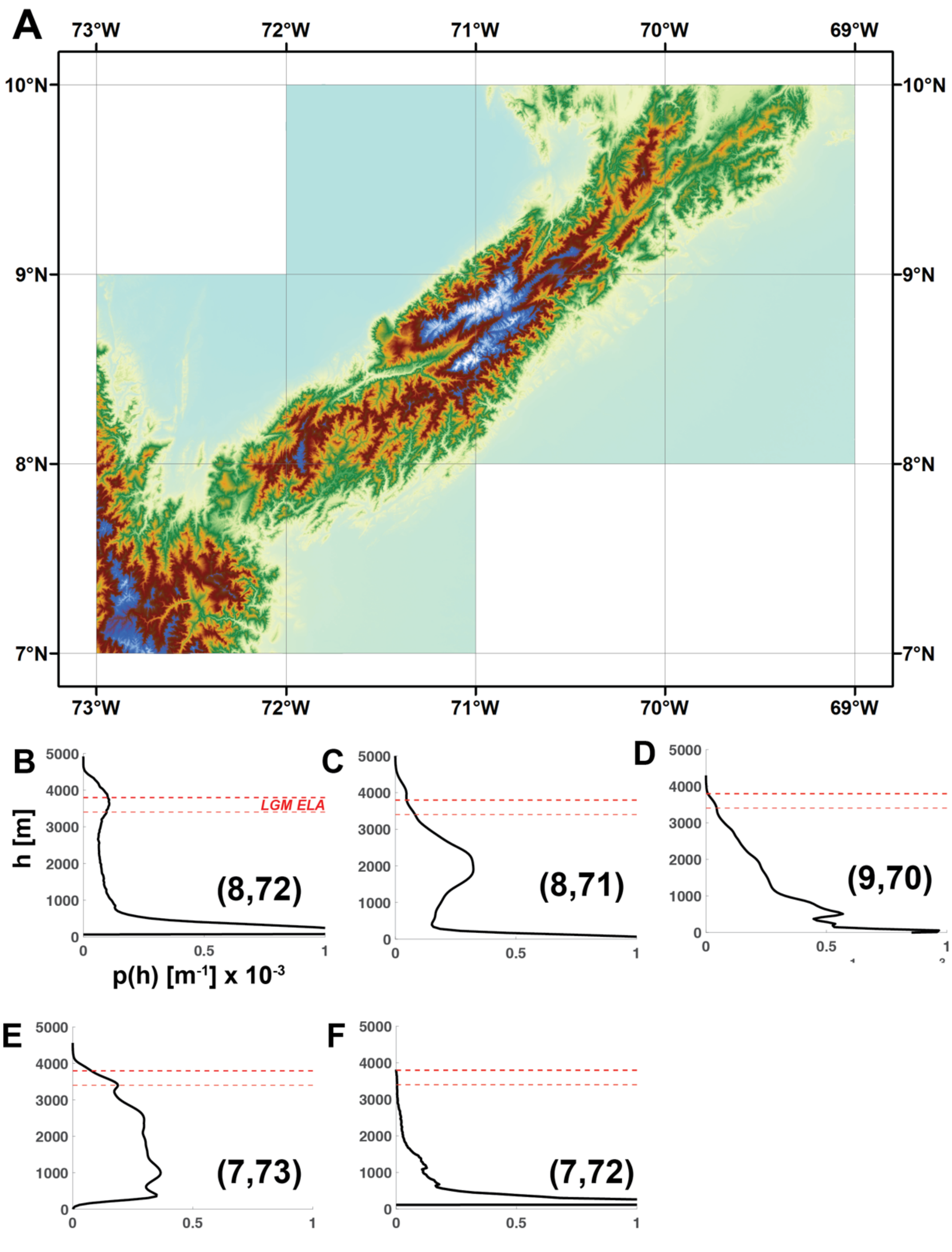



**Figure 2: Tile hypsometry of the Mérida Range.** A: Mérida range DEM. 0-3500 m is light blue through red, 3500-4500 m is dark blue to white. B-F: Elevation pdf of 1°x1° tiles, labeled by southwest corner. Dashed red lines are approximate bounds of tropical ELA variability (these bounds were estimated for the Mérida range by Stansell et al. 2007).

*Regarding the topographical analysis you compute the hypsometry for individual catchments (focused hypsometric analysis) instead of simply computing the hypsometry of a large area (the full range, or anything above a certain elevation). While this may open for more detailed insights, it also has disadvantages when it comes to hypsometric maxima, because a catchment defined by flow routing should always have a hypsometric maxima somewhere in between the max and min elevations in the catchment. Hypsometry of a catchment may therefore differ from the hypsometry of a mountain range, which can have a hypsometric max close to base-level. Your use of catchments at different scales only partly address this issue, and to me mountain range hypsometry is just a simpler metric to understand and use.*

We agree that the choice of scale in analyzing hypsometry is critically important, particularly when assessing the significance of glacial erosion in the landscape. Tile hypsometric analysis provides the benefit of comparing the aerial extent of glacial landscapes relative to flanking fluvial landscapes in a consistent domain size, but, as we have shown in the submitted manuscript, some glacial landscapes are obscured at this scale of analysis.

A central question we attempted to raise in the submitted manuscript is whether the absence of a hypsometric maximum in e.g. tile-scale analysis is indicative of the absence of (significant) glacial erosion. The tile hypsometry of CR and TW and many other tropical ranges show that glacial landscapes have a small areal extent relative to the fluvial catchments and depositional plains that surround them. Does this observation alone justify the claim that glacial erosion cannot impose the limit on mountain height in these places?

We argue that such a claim requires further justification for two reasons:

1) When the ELA is a relatively high elevation, fluvial catchments must be large (in elevation range) for glacial erosion to take place at all. Thus the absence of a hypsometric maximum at the ELA on the large scale does not indicate the absence of glacial erosion, or even glacial limitation (or glacio-fluvial limitation).
2) Glacial erosion and fluvial erosion can act in tandem to limit mountain height to the ELA, with fluvially-driven escarpments attacking glacial landscapes during warm periods. This process could limit mountain height near the ELA, but would not leave sufficient terrain at and above the ELA for a hypsometric maximum to manifest at this elevation.

We thus are left with the following problem: if mountain ranges truncate at elevations near the (cold-phase) ELA, as indicated in tile-scale hypsometric analysis for places like CR and TW, what scale of analysis is appropriate to assess the potential role of glacial erosion in limiting mountain height? We argue that different scales of analysis are needed to assess the overall significance of glacial landscapes in environments like those found in the tropics.

In step 2 of the updated analysis, we introduce a modified method of focused hypsometric analysis, which we call “progressive hypsometry.” The method involves a progressive measurement of hypsometry along nested catchments whose outlets span from the lowest to the highest elevations in a mountain range. We present the method as a way to assess the significance of hypsometric maxima found across a mountain range.

## *Progressive Hypsometry:*

1) **Segment landscape into large catchments that link the main divide to base level.**
2) **Map channel network:**
    a. map drainage using D8, steepest descent flow routing (Schwanghart and Scherler, 2014)
    b. define a channel network using an arbitrary flow accumulation area threshold *A_c*
    c. traverse downstream from each channel head *i=1…N* to the catchment exit to define a set of *N* along-channel pixel chains
    d. extend each chain *i* upstream from its channel head to the drainage divide by following path of greatest flow accumulation area, ensuring that each pixel chain spans the full range of elevation from ridge to exit
3) **Map progressive hypsometry (PH) along this network:**
    a. traverse each chain *i* upstream from the exit (shared by all chains)
    b. map along each chain a nested series of subcatchments, one per channel pixel *j(i)*
    c. calculate hypsometry for each nested subcatchment, and record its modal elevation *h_mode_j* and its outlet elevation *h_out_j*
    d. record as a set of *i=1…N* sequences of *[h_out_j(i),h_mode_j(i)]* pairs
4) **Identify all PH "benches", characteristic nested-catchment modal elevations:**
    a. perform change-point detection along each chain *i=1…N* to locate and define large jumps in *h_mode* at each *h_out*
    b. define the outlet elevation *h_out* at each jump as *h_change*
    c. designate the groups of between-jump modal elevations *{h_mode}* as "benches"
    d. define each bench modal elevation *h_bench = min{h_mode}*
5) **Identify the principal PH benches, their locations and jump heights:**
    a. concatenate all *N* sequences of *[h_change_k(i),h_bench_k(i)]*
    b. record as a single array of *M* jump-bench pairs *[h_change_m,h_bench_m]* where *m=1…M*

Fig. 3 demonstrates progressive hypsometry steps 1-4; Fig. 4 demonstrates the final progressive hypsometry step 5.

We propose this method as a solution to the problem of scale in hypsometric analysis: particularly when the aim is to assess the importance of glacial erosion. Rather than choosing one scale, either large or small, and checking for a hypsometric maximum at the ELA, we find the hypsometric maximum of catchments at virtually all scales in a targeted mountain range.

The proposed method does not fully address the criticism that glacial landscapes are not aerially extensive, because the hypsometric maximum of a catchment in many cases is a narrow elevation band, and not indicative of any unusual process at that elevation. Rather, progressive hypsometry identifies parts of the landscape where there is reasonable suspicion that glacial erosion has taken place by finding catchments with a hypsometric maximum at the ELA. More detailed analysis of such catchments is required to confirm that glacial erosion has taken place there. For places like Cerro Chirripó and Nanhudashan, the manuscript as written describes such analysis—although as this and Peter van der Beek's reviews have made clear, more clear documentation of these landscapes is needed.

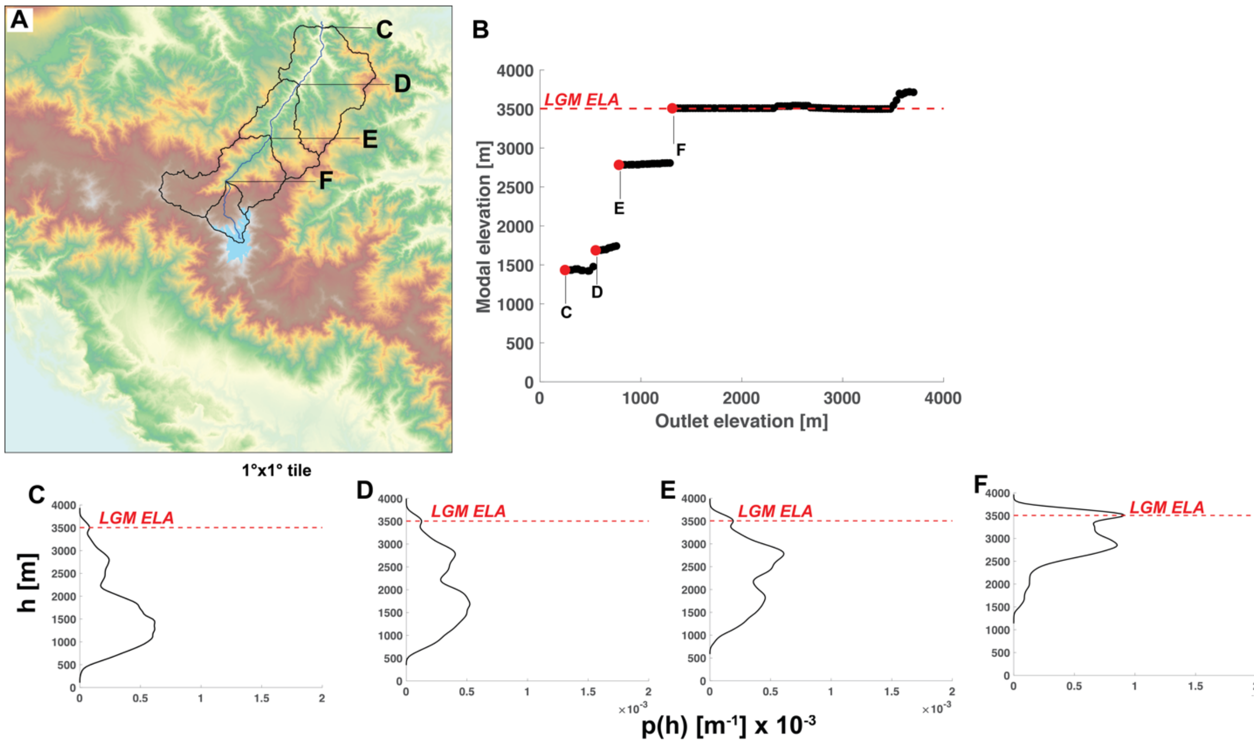



**Figure 3: Example of progressive hypsometry along one chain.** A: DEM of Cerro Chirripó, 0-4000 m is blue through white. Light blue is glacial extent at Chirripó. Dark blue streamline is example of one chain along which progressive hypsometry is performed. B: Modal elevation (hypsometric maximum) for each progressively higher outlet elevation along dark blue streamline. C-F: Elevation pdf of catchments associated with jump in modal elevation (hypsometric maximum) in B. Labels in A point to outlet elevations associated with each elevation pdf. Dashed red line is local estimated LGM ELA.

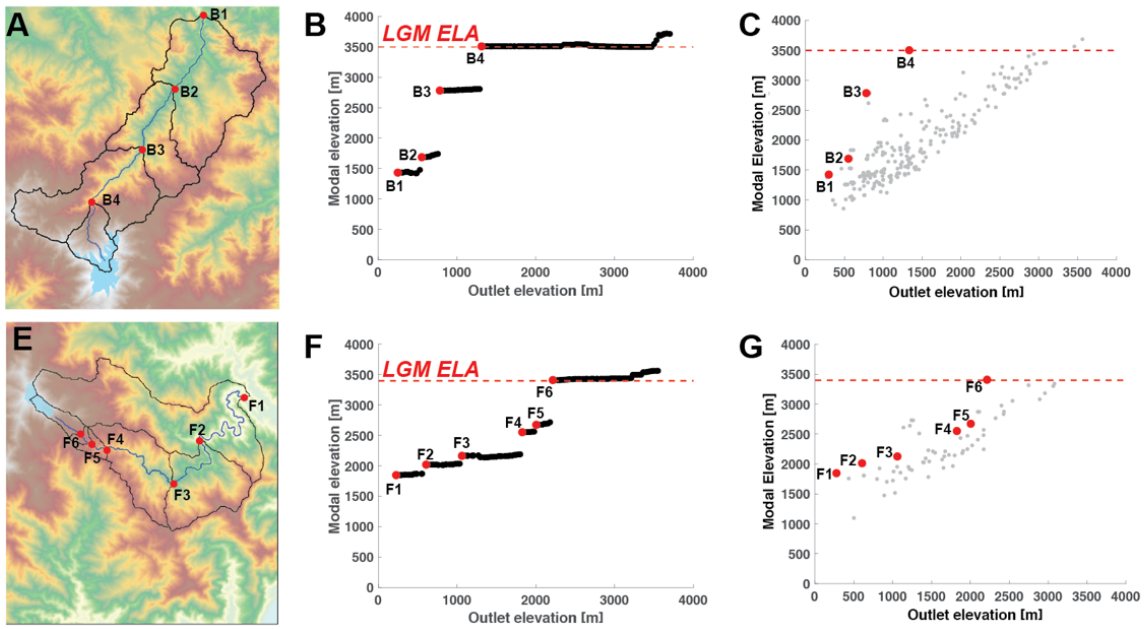



**Figure 4: Progressive hypsometry for large catchment.** A,E: DEM of Cerro Chirripó, CR and Nanudashan, TW, respectively. Catchments boundaries are examples of those extracted along one streamline for a single large catchment. Light blue in both plots is LGM ice extent. We chose to highlight subcatchments located at jumps modal elevation (B,F). B,F: Modal elevation (hypsometric maximum) for each progressively higher outlet elevation along dark blue streamline. C,G: All hypsometric steps from every streamline in large catchment in gray. Red points (B1-B4; F1-F6) correspond with red points on B,F.

Progressive hypsometry provides a detailed perspective on how elevation is distributed in the landscape. Below we present the tile hypsometry (Fig. 5a) and the progressive hypsometry (Fig 5b) of the central Talamanca Range, CR.

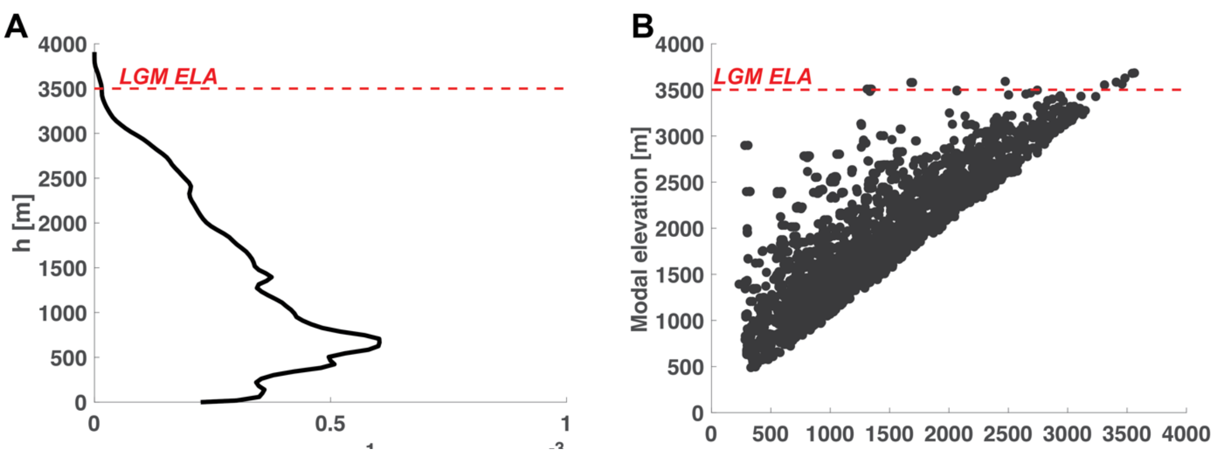



**Figure 5: Tile hypsometry vs. progressive hypsometry:** A: Hypsometry of Talamanca Range, SRTM tile with southwest corner 9°N, 84°W. B: Progressive hypsometry for all catchments in Talamanca SRTM tile.

In the tile hypsometry of the Talamanca it is apparent that relative to a span of elevations from sea level to ~4000 m there is very little area above ~3000 m, indicating that glacial landscapes around 3500 m occupy and very small fraction of the total mountain range, and depositional zones below 1000 m and topographic benches around 2500 m occupy the most area. Progressive hypsometry shows the distribution of elevation in *both* zones of the entire mountain range that are dominated by these prominent, low-sloping features and those that are not. For example, the progressive hypsometry plot Fig. 5b shows that some catchments have a hypsometric maximum associated with a topographic bench at 2500 m and an outlet as low as 250 m. In other catchments, sometimes with outlet elevations as low as ~1300 m, the hypsometric maximum is associated with glacial landscapes at 3500 m.

To summarize, progressive hypsometry can characterize the fine scale topographic patterns of entire mountain ranges, and can reveal features that go missed in tile hypsometry. This particular example shows the power of analyzing tile and progressive hypsometry together: on the scale of the entire Talamanca Range there is very little area above ~3000 m, but in the zone above 3000 m, the ELA (3500 m) dominates the elevation distribution.

Fig. 6 shows progressive hypsometry of three regions of the Talamanca Range, as an example of how progressive hypsometry can be deployed on a large scale. Only glaciated catchments have a hypsometric maximum near the ELA—elsewhere in the mountain range topographic benches are found at varying elevations, but never appreciably above the ELA.  Note that this figure includes primarily fluvial catchments, and that LGM glacial erosion only affected a small part of the mountain range.

We present this new method as a way to guide the assessment of glacially eroded landscapes in mountain ranges where glaciated valleys occupy a small fraction of the landscape. We stress that the presence of a hypsometric maximum at the ELA in a progressive hypsometry plot does not alone confirm the significance of glacial erosion or even that glacial erosion has even taken place, but rather is a reliable predictor that glacial erosion has acted in the landscape. Additional evidence is required to assess in full the quality of glacial erosion, such as the field evidence we present from Costa Rica.

The revised mansucript includes progressive hypsometry analysis of a subset of the list of 11 tropical mountain ranges provided above.

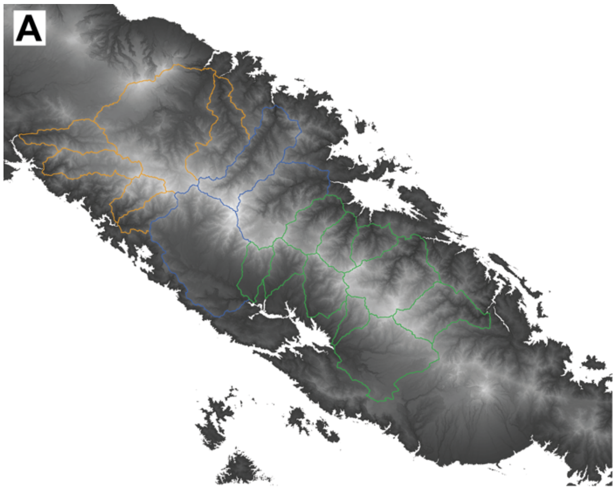
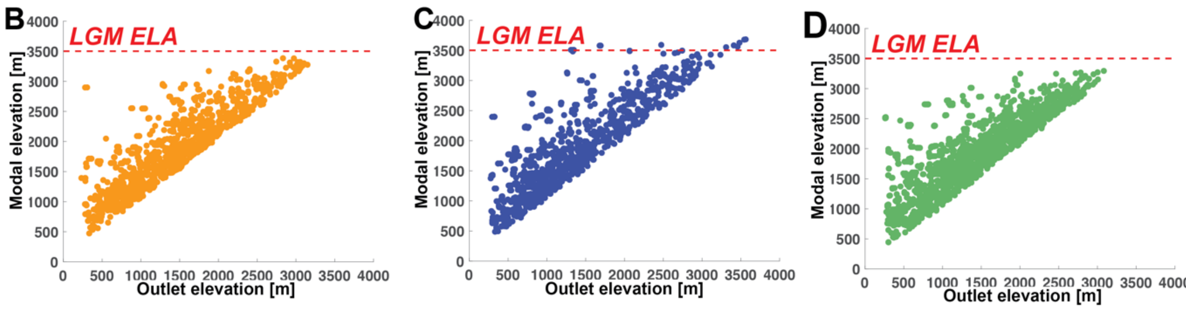



**Figure 6: Range-scale progressive hypsometry.** A: Talamanca Range, CR. 0-4000 m is black through white. Colored catchment boundaries are large catchments used to organize progressive hypsometry. B-D: Progressive hypsometry of corresponding to colored catchment outlines in A.




*Alternatively, you could also compare with focused hypsometries of catchments where there are no signs of glacial erosion. Do they have the same type of maximum or are they notably different?*

The method outline above characterizes the hypsometry of both fluvial and glacial catchments.

*It would be useful to also see longitudinal profiles of valleys with and without evidence of glacial erosion.*

We will provide these in a supplemental figure in an updated manuscript.

*I recommend that you also address the height of the ridges above the ELA. The ridges on the plateau are rather low and I would expect them to be higher, if glacial erosion around LGM was the main erosion mechanism at high elevation. Pedersen et al. (Geomorphology 122, p. 129-139, 2010) showed how ridge height above ELA seemingly depends on the rate of tectonic uplift. Tectonic uplift rates are high in both these ranges, so what keeps the ridges down to few hundred meters above the estimated ELA? Could it be periglacial slope processes, and would they have enough time to operate in the Holocene?*

Thank you for reminding us about this important reference, which is highly relevant to our work.

The height of ridges above the ELA in our focus areas are best explained by the combination of glacial erosion and scarp encroachment that act in concert to limit mountain height, and it is thus not surprising that the total relief of these glacial landscapes is relatively small. Pedersen et al. (2010) invoke a steady state balance between rock uplift and glacial erosion to explain the correlation between ridge height and uplift rate in glacially eroded landscapes at the mid-latitudes (p. 136). We argue that glacial landscapes in the tropics do not achieve a steady state balance with rates of rock uplift because they are destroyed relatively quickly by fluvial escarpments.

*More specific questions:*

*Page 3 Line 29: I do not see how it can be a provocative statement that glacial erosion limits the height of mountains – erosion does that. Please rephrase to explain the provocative part.*

Thank you for bringing this to our attention. We will rephrase in a revised manuscript.

*Page 4 line 5-10: This paragraph unfortunately repeats a misunderstanding that I think started with Hall & Kleman (2014): The glacial buzzsaw mechanism does not rely on horizontal erosion, and I do not think that any of the computational landscape models that you cite (e.g. Anderson, 2006; Egholm et al., 2009; MacGregor et al., 2009) even have horizontal erosion. The link between ELA and hypsometry arises because (vertical) glacial erosion is downwards limited by the mass balance of the glaciers (Egholm et al., 2009). Small glaciers do not erode deeper than the ELA because they cannot exist there. Larger glaciers can, however, because the ice flux into them keeps them alive well below the ELA. That larger glaciers cut deeper and faster than cirque glaciers is therefore not surprising, and not at all in conflict with models for the glacial buzzsaw. These two elements of a glacial landscape go hand in hand.*

This paragraph was in reference to Valla et al. (2011) who claimed that evidence of rapid glacial incision below the ELA "contradicted" the buzzsaw, but your comment demonstrates clearly that their findings are not necessarily such a contradiction. We will rewrite this paragraph.

In terms of "horizontal" erosion: our wording equates "horizontal" erosion with "headward" erosion, which arises from effective glacial erosion near the ELA that shifts up-valley. We view headward erosion as a form of horizontal erosion, even though none of the models cited explicitly parametrize horizontal erosion.

*Page 6, line 10: It would be good to have an uncertainty estimate for the ELA. It is important here because the differences in hypsometric maxima are rather small.*

We will include an ELA uncertainty in the revised manuscript.

*Page 7, line 21: Why not record the aggregate of many valleys? Sounds good to me.*

Hypsometric maxima at the "aggregate" scale are effectively recorded in progressive hypsometry, as large catchments are aggregates of many catchments.

*Page 9, line 31: This is where the uncertainty on the ELA becomes relevant.*

Agreed. We will address the uncertainty in a revised manuscript.

*Page 11, line 4: I do not think that you are constraining the timing of glacial erosion here. Your (few) boulder samples may constrain timing of deglaciation, but the (even fewer) bedrock samples do not show any clear pattern.*

This is a fair point. We will revise.

*Page 14, line 30 and many other places including the title: Why not just write "erosion" instead of "buzzcutting"? I don't think we really need more "buzzwords" than we already have.*

This a fair point. We will also revise this as suggested.

## References


Egholm, D. L., Nielsen, S. B., Pedersen, V. K., and Lesemann, J.-E.: Glacial effects limiting mountain height, Nature, 460, 884–5 887, doi:10.1038/nature08263, 2009.

Prentice, M.L., Hope, G.S., Maryunani, K., and Peterson, J.A.: An evaluation of snowline data across New Guinea during the last major glaciation, and area-based glacier snowlines in the Mt. Jaya region of Papua, Indonesia, during the Last Glacial Maximum: Quaternary International, 138-139, 93-117, doi:10.1016/j.quaint.2005.02.008, 2005.

Schwanghart, W., Scherler, D.: TopoToolbox 2 – MATLAB-based software for topographic analysis and modeling in Earth surface sciences: Earth Surface Dynamics, 2, 1-7, doi: 10.5194/esurf-2-1-2014, 2014.

Stansell, N. D., Polissar, P. J., and Abbott, M. B., Last glacial maximum equilibrium-line altitude and paleo-temperature reconstructions for the Cordillera de Mérida, Venezuelan Andes: Quaternary Research, 67, 115–127. doi:10.1016/j.yqres.2006.07.005, 2007.