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# *Response to the interactive comment on* "Distributed summer air temperatures across mountain glaciers: climatic sensitivity and glacier size" *by* Thomas E. Shaw et al.

**Anonymous Referee #1**

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Shaw and others present an analysis of air temperatures observed over the surfaces of several mountain glaciers on the Tibetan Plateau. The study follows similar work conducted in western Canada (Shea and Moore, 2010), the Italian Alps (Carturan and others, 2015), and Chile (Ayala and others, 2015), which demonstrates that air temperatures observed over the surface of melting glaciers are predictably different from off-glacier 'ambient' temperatures that would be expected at the same elevation. Flow length appears to play a control on air temperatures, and the authors investigate their findings from the Parlung catchment in the context of a number of similar studies and datasets. Overall the paper is well-written, though the language could be simplified in many places to reduce the manuscript length and improve readability.

*We thank the reviewer very much for their constructive comments on our manuscript. We have taken on board all their comments, and as a result we now have an improved manuscript. The main changes in the manuscript, in response to the reviewer's suggestions, are the following (which we respond to specifically below):*

1) *We have adjusted the title to more appropriately reflect the content of our work, giving specific mention to the Tibetan Plateau case study and given the revised terminology.*
2) *Simplified the text following both reviewer's comments to be more clear and and reduce the manuscript length in places.*
3) *Added additional analysis and discussion that clarifies the expected uncertainties in parameters of the Shea and Moore (2010) approach (i.e. k1 and k2 parameters) when using different lapse rates for off-glacier air temperature extrapolation at three of the 'global' sites.*
4) *Adjusted the terminology of climatic sensitivity to a temperature sensitivity throughout the manuscript.*
5) *Changed and adjusted a few figures based upon the requests of both reviewers (Figures 1, 3, 7 and 10).*

General comments: - As the paper is mostly focused on the datasets from the Tibetan Plateau, the title is bit misleading. Yes, there are some comparisons made with other datasets, but the title implies a global scale analysis.

*We thank the reviewer for raising this point. We have adjusted the title to: "**Distributed summer air temperatures across mountain glaciers in the south-east Tibetan Plateau: temperature sensitivity and comparison with existing glacier datasets** ".*

- Sec. 4.3; The methods for analyzing the 'global' temperature datasets given in Table 2 are well-motivated, but questionable. An assumption of a constant 6.5C/km lapse rate will likely result in substantial errors in the estimated ambient air temperatures, which will then skew the values calculated for k1 and k2. I think the approach here needs to be improved before such comparisons can be made.

*We thank the reviewer for their comment. We agree that using the environmental lapse rate (ELR) to calculate the sensitivity of the k1 and k2 parameters entail limitations (as the reviewer points out, the estimated air temperature might be affected by errors and so might be the k1 and k2 values). We note, however, that only three sites (Peyto, Universidad and Djankaut Glaciers) of the 11 examined relied upon the ELR to extrapolate air temperatures to the elevation of the on-glacier observation stations. For all remaining sites we used published values of the calculated lapse rates and/or local station data to construct our best possible 'catchment lapse rate' (i.e. for Parlung Glaciers).*

*To address the reviewer's comment for those three glaciers, where we relied upon the ELR in the absence of local lapse rates, we recalculated k1 and k2 with new lapse rates within a suitable range for off-glacier conditions in summer. We adjusted the lapse rate value +/- 1.5°C km-1 around the ELR (resulting in a range of -5 / -8°C km-1) and found changes of k2 within ~0.03 (see Figures R1- R3 below).*

*The differences in sensitivities (k2 parameter) for all three glaciers are in the range of <0.01 - 0.03, and are shown in the figures below, which correspond to Figure 8 of the original manuscript. It is apparent that the changes in the lapse rate result in negligible changes in both k2 as well as its relationship to the flowline.*

*The differences in the k1 parameters at all glaciers are <0.01 for the different tested lapse rates.*

*In addition to the test described above, for Peyto glacier we also calculated and tested an additional lapse rate, as on this glacier the uppermost on-glacier AWS is close to a mountain ridge at the upper limits of the glacier accumulation zone. Because of the short flowline distance at this location, we can assume that the boundary layer effect is minimal and temperatures on the glacier at this AWS approximately equal the 'ambient' off-glacier air temperature. We thus also tested an off-glacier to on-glacier lapse rate calculated between this on-glacier station and the off-glacier AWS (labelled 'Off-On' in Figure R1). This is important because higher elevations will often be more sensitive to changes in the temperature lapse rate (when temperature is extrapolated from a low elevation AWS). Using this 'Off-On' lapse rate, gives us a k2 value of 1 at the highest station, but provides an estimate of k2 at the other on-glacier AWS. We show in Figure R1 that these changes have a minimal impact on the k2 sensitivity on Peyto Glacier (maximum k2 difference = 0.02).*

*We have now indicated in the revised paper the glaciers where the ELR was used in Table 2 and have added a brief mention of the calculated k2 differences found from adjusting the lapse rate in the methodology section 4.4.*

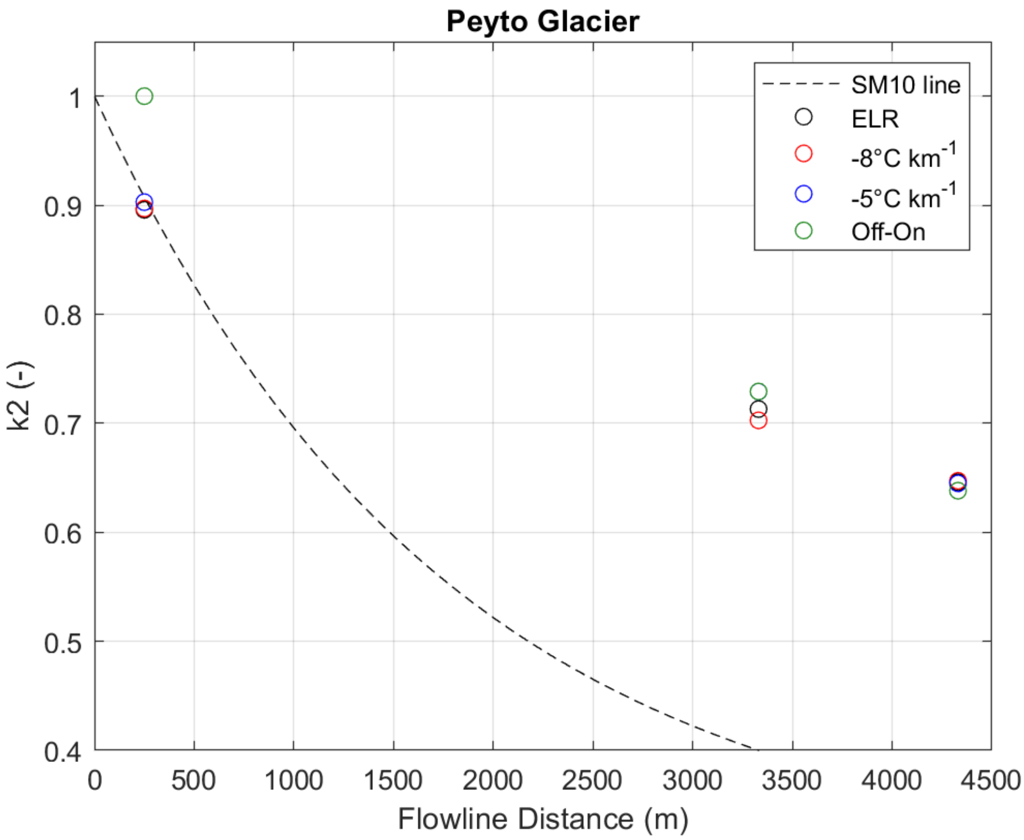


*Figure R1: The calculated k2 parameters for Peyto Glacier using difference lapse rates. The lapse rates used are: ELR (-6.5°C km-1 - black), -5°C km-1 (blue), -8°C km-1 (red) and a lapse rate derived between the off-glacier forcing AWS and the highest elevation on-glacier AWS. For the latter, we assumed no boundary layer cooling of the glacier at the top of the flowline.*

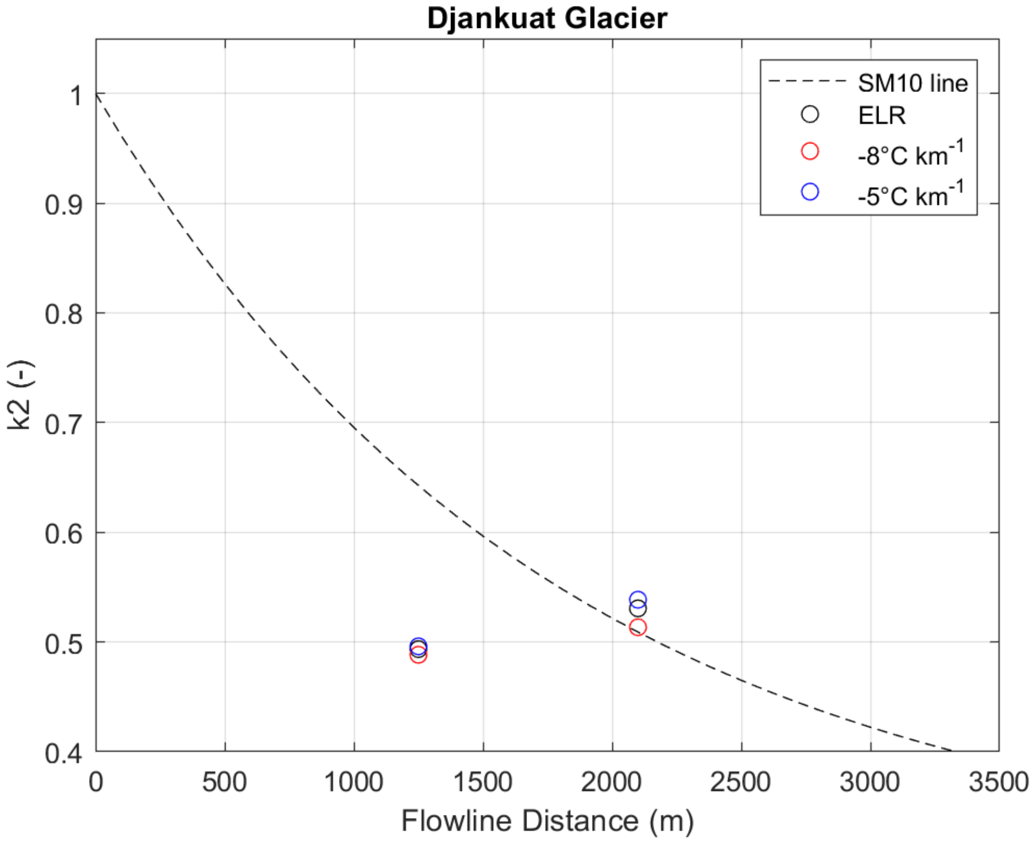


*Figure R2: As Figure R1, but for Djankuat Glacier.*

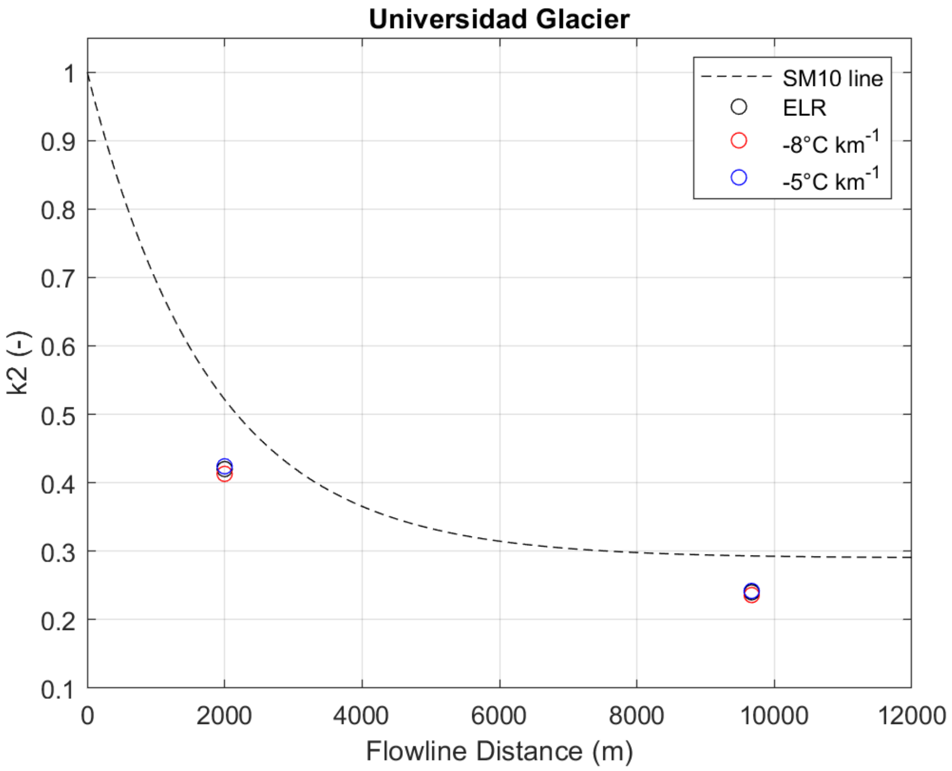


*Figure R3: As Figure R1, but for Universidad Glacier.*

- The parameter k2 is termed "climatic sensitivity", but this is also a bit confusing. I would interpret climatic sensitivity as being related to changes in climate (e.g. mm w.e. /C). Specifically, k2 is unitless and it defines the relation between Ta_glac and Ta_amb during katabatic flows, so it really just quantifies the "cooling effect" a glacier has on the air mass immediately above it (1 = no cooling, 0.10 = strong cooling). My suggestion would be to use a different term, though I'm not sure "cooling effect" is the right one.

*We agree with the reviewer that "climatic sensitivity" is not an unambiguous term and is used with different* *meanings by different scientific communities, and that our use here might thus appear slightly misleading to some readers. We use this term based on many of the previous works on air temperature estimation (Greuell and Böhm, 1998; Oerlemans, 2010; Carturan et al., 2015). It was first introduced by Greuell and Böhm (1998) to indicate the sensitivity of the glacier temperature to the ambient conditions. We would argue that the term 'cooling effect' is equally misleading due to the fact that temperatures are not only cooled (a static bias of X °C compared to the off-glacier temperature), but also that the diurnal cycle is 'dampened' (Carturan et al., 2015). Because the k1 and k2 parameters represent a ratio of the on and off-glacier temperature, they represent a sensitivity of the above-glacier temperature to the external conditions. We recognise that a climatic sensitivity is often used to indicate a rate of melting per unit temperature increase. We believe that the term temperature sensitivity is perhaps more appropriate in this study. To dispel ambiguities as much as possible, however, we have clearly explained our definition at the beginning of the manuscript, and also make now the distinction to the other meaning climate sensitivity as used in the literature. We have also made efforts to adjust this within the manuscript and provide specific definitions in the introduction to avoid any misinterpretation.*

Specific comments: - L26: remove "several, "

*We have adjusted this in line with the reviewers comments.*

- L26: see comments on "climate sensitivity"

*This has now been adjusted throughout, except where we give mention to the term 'climatic sensitivity' as termed by those earlier studies (e.g. Greuell and Böhm, 1998, Oerlemans, 2010).*

- L30: "slower decrease of climate sensitivity" is tough to parse. How about "Beyond this distance. . .glacier datasets show little additional cooling effects."

*We thank the reviewer for the suggestion and have adjusted this based upon their suggestion.*

- L31-32: It's not the observations that are sensitive, it's the glaciers themselves: "In general, small glaciers. . .have little cooling effect and are thus highly sensitive to changes. . ."

*Changed now based upon the reviewer's suggestion.*

- L37: the "beyond" here seems to imply past or in front of the glacier. Suggest rephrasing.

*We have now written as 'beyond this distance', referring to the 2000-3000 m flowline distance from the previous sentence.*

- L47: suggest ". . .the use of linear temperature gradients, typically..." - L48-53: suggest shortening and simplifying: "A free-air ELR cannot be reliably used to estimate near-surface air temperatures above melting glaciers, where steep gradients are found within 10 m of the surface (REFS)."

*We have adjusted this in line with the reviewers comments.*

- L55: clarify that the overestimation occurs in energy balance models.

*Done - we have added also that models of intermediate complexity (ETI models) are affected:*

*"While models applying the degree day approach can make use of off-glacier temperatures as forcing because they are heavily reliant on calibration, for physically based models and models of intermediate complexity (Pellicciotti et al., 2005; Ragettli et al., 2016) it is key to resolve the air temperature distribution over glaciers, especially for turbulent flux calculations."*

- L65-69: This is important, and I'd suggest moving it upwards as a standalone para graph that also highlights that there are two main models for melt estimation.

*We agree with the reviewer and have moved this earlier in the paragraph.*

- L73: "western Canada" or "southern Coast Mountains", not Canadian Rockies.

*Changed*

- L83-84: for clarity, remove "based upon. . .(1998)" – Gruell and Bohm is described in the next sentence

*Updated now.*

- L88: remove ",however,"

*Done*

- L95: "The ModGB. . ."

*We have adjusted this now*

- L103: ". . .though it does not explicitly account for physical processes that would reduce the glacier cooling effect at the glacier terminus."

*Updated with the reviewer's suggestion.*

- L106: see general comments above

*Changed now based upon the reviewer's suggestion.*

- L113: can you stick with 'transferrability'? "generalizability" is a mouthful, and not commonly used in this field

*We have adjusted this throughout the text to read as transferability or ease of applicability where more appropriate (also in response to Reviewer #2).*

- L113-L114: "As such, the transferability of near-surface air temperature models remain largely unknown. Analysis . . ."

*We have adjusted this in line with the reviewers comments.*

- L115-116: simplify: "In this study, we use new datasets of on-glacier air temperatures observed at three glaciers . . ."

*We have simplified this now using the reviewers suggestion.*

- L118: the word 'distributed' is probably unneeded

*Removed*

- Sec 3.3 can be moved up and included with the 3.1, which can be renamed "Meteorological observations", but just start with "Air temperatures (Ta), incoming shortwave,. . ."

*We have merged these sections now based upon the reviewer's advice.*

- L193-194: remove the first part: "Flowline distances (m) for each glacier were calculated with the TopoToolbox. . ."

*Done*

- L200: remove "between the aforementioned studies."

*Removed as suggested.*

- L206-207: Feels like this needs a more general introduction: "Our methods consist of (1) aggregating temperature observations based on off-glacier temperatures, (2) generating off-glacier temperature gradients to compare on and off-glacier temperatures, and (3) estimating the glacier cooling effect on near-surface temperatures by fitting parameters to the SM10 model." Your rationale can then be moved into the individual subsections.

*Thanks a lot for this. We followed the reviewer's advice and have included the suggested paragraph in the text.*

- L226: replace "within the glacier boundary layer" with "between ambient and on glacier temperatures"

*Changed based upon the reviewer's suggestion.*

- L226 – 229: this could be simplified to read "We calculate hourly ambient lapse rates from the off-glacier weather station and temperature loggers T1_94, T2_94, and T1_390. These sites are assumed to be unaffected by the glacier cooling effect."

*We have simplified this as suggested.*

- L234: ". . .T-logger to quantify the difference between ambient and on-glacier Ta at each site. . ."

*Adjusted*

- Eq 1: asterisks should be superscript in this equation, and see general comments above

*Adjusted*

- L276: suggest using 'transferability' instead of 'generalisability'

*Done*

- L284: is the ELR suitable for all sites and seasons?

*See above response to the reviewer's main comment.*

- L308: since there is a scale break in the figure, it is tough to see this as 'linear'

*We understand the reviewers point and now present the same figure (Figure 3) without the scale break. We intended to add clarity to the figure this way, but now remove it as information (about linearity etc) was potentially lost.*

- L349 – 351: Simplify! "For P90 conditions (Fig 6a), differences between TaAMB and observed on-glacier temperatures are up to 5.8 C at flowline distances greater than 7000 m."

*Adjusted*

- L351: avoid ‘heighten’ in this context

*We have reworded this to “increase” to be more clear that we refer to air temperature biases.*

- Sec. 5.2 : avoid using “offset”

*Adjusted to ‘ difference’ or similar throughout*

- Figure 7: perhaps show these relations as scatterplots. Tough to interpret the relation using line and bar plots.

*We have now added subplots to show the relationship of Ta differences and SWIN as suggested by the reviewer.*

- L352 – 353: RH will typically be high when temperatures are low, so this is not surprising.

*We agree with the reviewer that this is not such a surprising result and we therefore do not explore it or discuss in detail . We adjusted the sentence:*

*“This is generally associated with drier conditions, and for hours of greater relative humidity (AWS_Off), when conditions are generally cooler, differences are unsurprisingly smaller (Figure 6b).”*

- L382: “notably distinct” doesn’t really fit with the results in the table, as the coefficients of SM10 are within the confidence intervals of the other datasets

*This is a good point, and we thank the reviewer for bringing it to our attention. The text has been adjusted accordingly to include this:*

*“Accordingly, the exponential functions that are fitted to the observations at Parlung glaciers and those of the original study are distinct (red and blue lines in Figure 8, Table 3), although within the confidence intervals of each other.”*

- L430: need to specify energy balance models. Temperature indexed approaches don’t need this correction if the melt factors are calculated with off-glacier temperatures.

*Intermediate models, such as the Enhanced Temperature Index (ETI) however do calibrate to on-glacier observations… So while EB models are the key subject here, we include mention to ETI models too.*

- L474: “While the data from the Parlung catchment. . .”

*Done.*

- L493: southern Coast Mountains (not Canadian Rockies)

*Changed following the reviewer’s suggestion.*