Answers to Referee #2 on the manuscript *Understanding monsoon controls on the energy and mass balance of Himalayan glaciers.*

We answer all comments point-by-point below each statement in blue font.

This is an interesting concept and topic of research and a number of new analyses are presented in this manuscript. But I find that I am overwhelmed by the lack of synthesis in the analysis and the writing.
It is difficult to tie the in situ weather station and modeling results with the actual conclusions stated. This is partly because the paragraphs seem to jump from one flux to another or from one variable to another from sentence to sentence. I am left wondering if these conclusions are actual supported by the work in the manuscript or are rather just assertions? They might be but the figures, analysis and writing do not clearly support the conclusions in the discussion/ conclusions section.

We thank the referee for their comments. To address the referee's main concern regarding a lack of synthesis, we will introduce a number of improvements to both text and figures to explicitly link our results to the interpretations and conclusions. To provide the manuscript a logic thread and focus, we will formulate up front (in the revised *Introduction*) a clear set of research questions, replacing the more vague "research objectives" of the submitted version.

The new research questions are
1) Which energy and mass fluxes dominate the seasonal mass balance of glaciers in the Central and Eastern Himalaya?
2) How does debris modulate the ablation season energy balance in comparison to clean-ice surfaces?
3) How does the monsoon change the glacier surface energy balance?

We will give the manuscript a new structure and organise both results and discussion around the research questions listed above. The *Discussion*, in particular, will be structured to respond to each of them separately. The new overall structure of the manuscript will be as follows and is explained in details below:

Results:

First, in order to make our *Results* more structured and to link them to the revised figures systematically, we will adjust them as follows:

- We will maintain the subsections *Modelled mass balance* and *Modelled energy balance.* We will shorten these sections to focus them only on results required to answer our research questions, e.g. common energy balance patterns for all sites and the role of snow accumulation
- We will move the model evaluation from the *Results* (it was described originally in the *Modelled mass balance* section) to the *Methods.*
- we will introduce two new subsections: *Impact of debris cover* and *Impact of the monsoon,* to separate those aspects, and we will split the latter into three subsections, one each for surface type: *Impact of the monsoon on clean-ice sites, Impact of the monsoon on debris covered sites* and *Impact of the monsoon on thinly debris covered sites.*
- We will also move some of the content of the section *Turbulent fluxes at debris-covered sites and their controls* to the *Methods,* as indeed we described some of the methodology in that section.

We will streamline the text to emphasize the numbers that lead to our interpretations and conclusions. For example, instead of going through each energy flux individually in a systematic but dense manner in the section *Impact of the monsoon*, we now discuss the monsoon impacts in a more integrated way: We will start from the change in melt between pre-monsoon and monsoon (old Figure 6, old Table 5), then present the changes in the radiative budget before addressing the role of the turbulent fluxes and their changes. We will link each statement and number to the respective figure and/or table.

To further improve the readability of the *Results*, we will adopt a more intuitive language and terminology. For example, instead of using “sources” and “sinks”, we will use “contributing to melt” or “reducing melt”, in order to reduce confusion around the direction of the fluxes and their changes.

We hope that this new structure and writing style will allow us to explicitly draw together the distinct numerical results to answer our research questions in an easily understandable way. As an excerpt from the revised results section *4.4. Impact of the monsoon* (Note that the Figure numbers do not correspond to the original submitted version and that *M* will replace *dQ* as the energy available for melt):

4.4.3 Impact of the monsoon on a thinly debris-covered glacier

In contrast to the glaciers with thick debris, during the monsoon, the melt energy M increases considerably at the thinly debris covered Hailuogou glacier. Although SW_{net} contributes less energy for melt during monsoon and LW_{net} remains overall small at this site (Figure 5), M increased by 28.7 $W\,m^{-2}$ on average (Table A2), and mostly during the nights (Figure A10). The increase in melt energy is mostly driven by the turbulent energy fluxes: H increases by 15.6 $W\,m^{-2}$ and LE increases by 24.5 $W\,m^{-2}$ (Figure 5 and Table A2), with higher increases during the nighttime than during the daytime (Figure A10). While they acted to reduce melt at the glaciers with thick debris cover, here the turbulent fluxes drive additional melt during the monsoon.

Discussion:

We will restructure the *Discussion* in subsections that answer the new research questions and link the revised sections, figures and tables in the *Results* to the *Discussion* clearly.

As the *Limitations* and *Future work* sections might have distracted from the main outcomes, we will remove both sections and move some key elements of *Limitations (*i.e. on the debris parameters and moisture interception), to the *Methods*. We will also remove the *Implications* section but keep the most important messages on the possible climate change impacts for the *Conclusion*. A snippet from the *Discussion* section *5.3. How does the monsoon change the glacier surface energy balance*:

5.3.3 Glacier with thin debris

At the site with thin debris, we observe a melt-enhancing effect: the dark debris surface absorbs almost 90% of $SW_{\downarrow}$ in the case of Hailuogou (Table A2). With a short conduction length ($1\,cm$), the energy influx goes almost entirely to melt. Melt additionally increases during monsoon: higher wind speeds enhance turbulence resulting in an increase in H (Section 4.5 and Table A3). Warmer and more humid air increases LE inputs from condensation at the cold surface (Table A3 and Figure A8). Both turbulent fluxes thus become potent sources of melt energy (Section 4.4.3). This adds detail to prior observations and modelling results, that thin debris causes higher melt rates than at both clean-ice sites and sites with thicker debris cover (Östrem, 1959; Reznichenko et al., 2010; Reid and Brock, 2010; Fyffe et al., 2020), especially in humid environments (Evatt et al., 2015), e.g. the location of Hailuogou glacier.

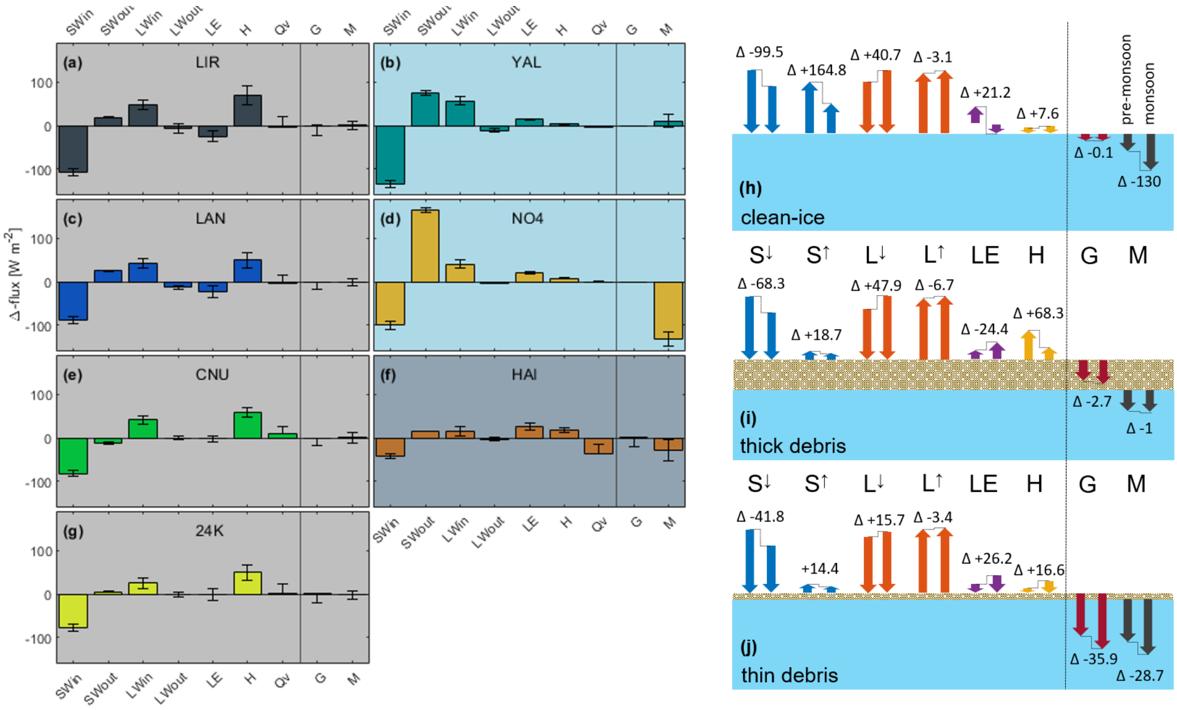
Conclusions

We will rewrite the *Conclusion* so that it provides structured answers to the research questions.

Most of the figures themselves are overwhelmingly complex and the main points are not supported by them. Perhaps the manuscript can be more logically structured and extensive work can be done to give the reader a thread to follow.

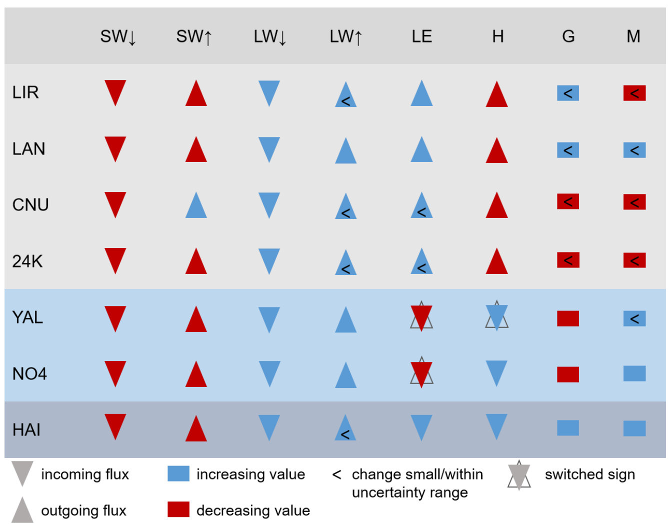
To address the referee comment, we have restructured the manuscript in the way described above and introduced important changes to the main figures or removed some of them:

1) After careful consideration of the referee's comments we will modify the original Figure 6: we will add to the original figure panels (h)-(j) below, which depict the pre-monsoonal and monsoonal fluxes, their actual direction, their magnitude and their changes from one season to the other with the actual values from one site. The new panels will support the interpretation of panels (a)-(g), and should avoid confusion around the direction and magnitude of flux changes. We have made a panel for each surface type, and the numbers used are from one site for each of those surface types.



New results figure. ***(a)-(g)*** *Differences in energy balance components from pre-monsoon to monsoon at each site including their uncertainties (error bars). The direction of change is to be considered relative to the sign of the original flux (x-axis). For example, a positive change in a negative flux means a reduction in the flux, and can also lead to a change in sign. Background indicates the surface type of the site: grey indicates debris-covered, light blue indicates clean-ice sites, and grey-blue indicates thin-debris.;* ***(h)-(j)*** *Alternative depiction of the changes from (a)-(f), summarizing surface types; Example Δ-flux numbers in [W m*$^{-2}$*] refer to (g) Parlung No.4, (h) Lirung and (i) Hailuogou; Numbers for the other glaciers can be looked up in Table 5.*

2) To link the discussion on the *Impacts of the monsoon* to the respective results, we will introduce a new figure in the *Discussion*. The idea of this figure is to summarize the flux changes between the different surface types in a visually more straightforward manner.



New discussion figure. *Triangles pointing down/up indicate a positive/negative flux with regards to our sign-convention, where positive/negative means a flux towards/away from the surface. Red/blue indicate an increasing/decreasing value of the flux when moving from pre-monsoon to monsoon. When signs switch, the underlying, empty triangles indicate the pre-monsoonal direction of the flux, while the overlying, colored ones indicate the monsoonal flux.*

3) We will move Figure 9 with the corresponding text (originally in section 5.2 *Sensitivity of seasonal flux changes to elevation and debris thickness)* to the supplementary material. These numerical experiments were intended to demonstrate that the seasonal flux changes are robust and do not depend on the actual elevation or debris thickness of the AWSs, but may have interrupted the flow of the results and discussion.

To this point I found that the most compelling explanation of the role of differences in local climate came from the ERA-5 output and figure 3. But I must ask: What do the in situ station data tell us that the ERA-5 output do not already inform us about? There is quite a lot of scatter between the in situ site data (the data is from different years, elevations, surfaces, and aspects) unlike the patterns shown in the ERA-5 output.

We thank the reviewer for their perspective. Reanalysis data are extremely useful for many purposes, including catchment-scale hydrological modelling or even for the forcing of glacier-scale energy balance models of large glaciers. Here, we examined the ERA5-Land outputs to put our AWS records (which span only individual years) into their long-term context, as explained later in this answer. In fact, as shown for our study site Langtang, the reanalysis data captures the seasonal cycle of most variables reasonably well (Figure below). However, if we are interested in the monsoon impacts on the glacier surface energy balance and in the detailed processes behind them, we do not think that the accuracy of the reanalysis data is sufficient to reach our research objectives. The figure below makes evident that there are considerable local biases in each meteorological variable at our Langtang glacier site. Indeed, a few °C of air temperature bias (here, 4°C) or different wind speeds (>100% bias) particularly affect, and can even change the direction of the turbulent fluxes, which are key fluxes in the seasonal transition. These biases exist because first, a 9km grid element over high mountain terrain can integrate an altitudinal range of several thousand meters, as well as glaciers, snow cover, vegetation, surface water, and bare rock. Second, there are glacier-atmosphere interactions that create non-average conditions over the glacier surface, e.g. a colder boundary layer and katabatic winds. Those processes cannot be represented in sufficient detail by current climate models and reanalysis products. Third, climate models are known to not perform well in regions with complex topography and where local observations are scarce.

The AWS data, on the other hand, allow us to reproduce the glacier surface energy balance accurately, make inferences about the surface (debris) properties, and evaluate the model performance. The referee makes a valid point that our study site records have different duration and refer to different years, which might complicate their comparison. However, very few on-glacier datasets are available in High Mountain Asia because they are very difficult to collect, and therefore they rarely overlap spatially and temporally. Importantly, the major result of our analyses is that, despite the differences between sites, there are common patterns in the seasonal changes in energy fluxes. To make sure that we do not accidentally compare exceptional years, and draw the wrong conclusions from that, we indeed put our records into the context of average conditions by comparing them to the ERA5-Land data. This showed that the seasonal variability is greater than the interannual variability for all variables and across study sites, and that the years of our records represent typical conditions.

In response to the reviewer's comment, and to avoid ambiguity as to what we use the ERA5-Land data for, we will move most of the description of the reanalysis data, including the corresponding Figure 3, to the supplementary information, and make clear in the main text that we use those data and figure only to show that our selected years are representative of the multi-annual patterns.

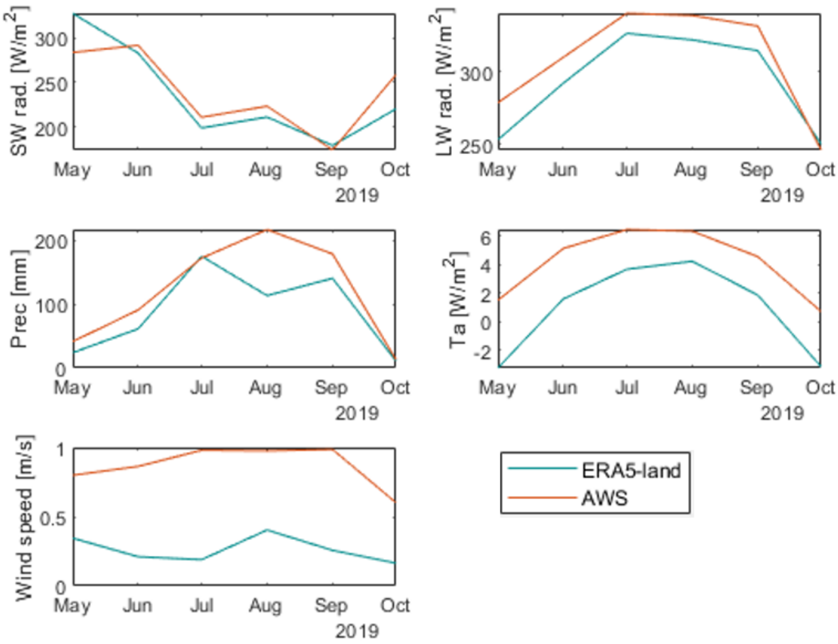


Figure. *Monthly sums (precipitation) and mean (all other variables) of ERA5-Land vs. Langtang on-glacier weather station data;*

Perhaps the figures and text can more clearly show the take homes from the station data and support the more general take homes?

To link the key outcomes better to our analysis and figures, we will restructure and modify our manuscript and some of the figures in the ways described above.

My sense is that this could be an interesting, valuable study for TC but as it stands I am not sure if the analyses actually support the conclusions and if using in situ station data is better suited for this question than atmospheric reanalysis output.

We thank the referee again for appreciating the potential value of our study. We tried to respond to the referee's concerns in the best way possible, and will revise the manuscript considerably based on the comments. We will link our conclusions to our results more explicitly in the text, and have made it clear in an answer above why it was necessary to use station data rather than reanalysis data for our study.

More specific comments:
Line 30-32 dates on Mölg should be 2012,2014 and the references should be in order of date in line 33 with the oldest first. Should be corrected throughout.

Thank you for these suggestions, we will revisit this citation and sort citations throughout the manuscript by date.

Line 99. too may uses of ‘extensive’ in this paragraph.

We will fix this issue and revise a part of this paragraph in order to streamline it.

Figure 1. I cannot see the RGI glaciers in panel A. Please change the color of the glaciers. The arrows in panel A seem a bit inaccurate considering that the Indian summer monsoon certainty affects easter Nepal and too the west as well.

We will revise this figure based on these suggestions. We will give the RGI glaciers a more visible blue shade. We will change the arrows to represent the influence of the Indian Summer Monsoon more accurately. We will also rearrange panels b and c slightly and add a few elements that are missing: North arrow and coordinates with tick marks for panels b and c.

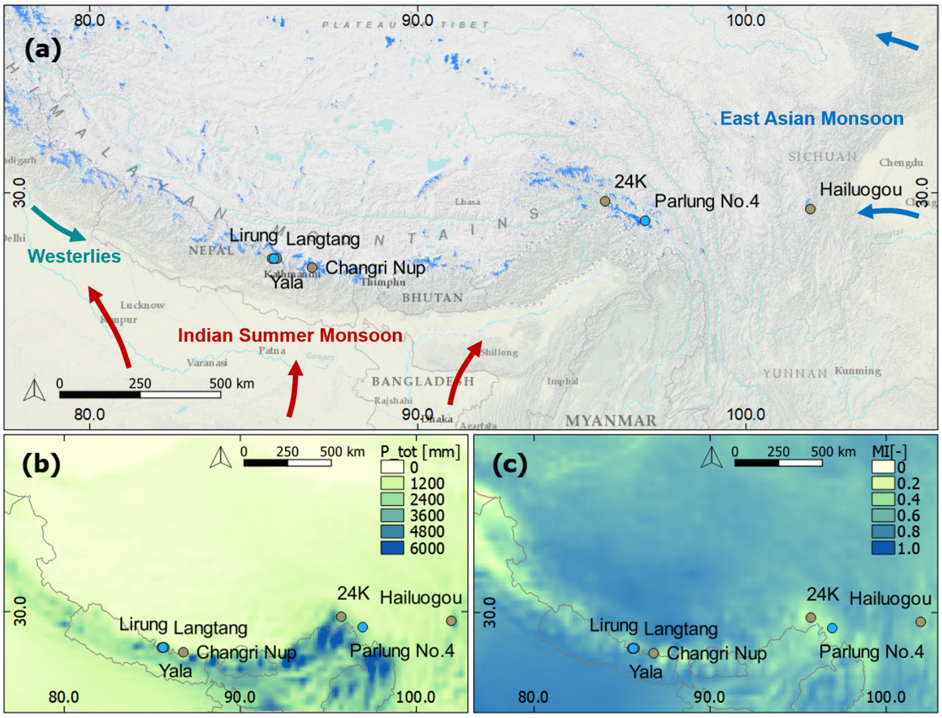


Figure 1 (a) revised glacier color, monsoon influence, guides for glaciers; (b) and (c) scale bars and north arrows;

Tables 5 and 6. Perhaps these should be in the supplement? They are rather overhelming to try to pull anything away from them.

We will move these two tables to the supplementary information

Section 5.1.1 Here many of these points are expected and reproduced by other studies. It seems to me those other studies should be cited here.

This is a good suggestion and we will add additional references. For example:
The importance of the radiative fluxes and their changes through monsoon were discussed at individual sites in a number of studies (e.g. Kayashta et al., 1999, Aizen et al. 2002, Yang et

al., 2011, Mölg et al., 2012). In studies comparing different sites, Zhu et al. (2018) and Bonekamp et al. (2019) identify the timing and quantity of snowfalls as major controls on the glacier mass balance through the albedo effect. Mölg et al. (2012) discuss in particular the role of spring snow accumulation and the importance of monsoon onset timing in controlling the seasonal mass losses. Fujita et al. (2000) highlight the important role of monsoonal summer accumulation, which we called 'ephemeral snow cover from monsoonal precipitation', in protecting the glacier through the albedo effect.

Aizen, V. B., Aizen, E. M., & Nikitin, S. A. (2002). Glacier regime on the northern slope of the Himalaya (Xixibangma glaciers). *Quaternary International*, *97*, 27-39.

Bonekamp, P. N., de Kok, R. J., Collier, E., & Immerzeel, W. W. (2019). Contrasting meteorological drivers of the glacier mass balance between the Karakoram and central Himalaya. *Frontiers in Earth Science*, *7*, 107.

Kayastha, R. B., Ohata, T., & Ageta, Y. (1999). Application of a mass-balance model to a Himalayan glacier. *Journal of Glaciology*, *45*(151), 559-567.

Mölg, T., Maussion, F., Yang, W., & Scherer, D. (2012). The footprint of Asian monsoon dynamics in the mass and energy balance of a Tibetan glacier. *The Cryosphere*, *6*(6), 1445-1461.

Yang, W., Guo, X., Yao, T., Yang, K., Zhao, L., Li, S., & Zhu, M. (2011). Summertime surface energy budget and ablation modeling in the ablation zone of a maritime Tibetan glacier. *Journal of Geophysical Research: Atmospheres*, *116*(D14).

Zhu, M., Yao, T., Yang, W., Xu, B., Wu, G., & Wang, X. (2018). Differences in mass balance behavior for three glaciers from different climatic regions on the Tibetan Plateau. *Climate Dynamics*, *50*(9), 3457-3484.