Response to reviewer comment #2. Note reviewers' text is shown in **blue**, with responses in **black**

Review of Conway et al. Cloud forcing of surface energy balance from in-situ measurements in diverse mountain glacier environments

Conway et al. use a global selection of on-glacier AWS data to determine the effect of clouds on the surface energy balance. They investigate the influence of clouds on the near-surface meteorology, individual energy fluxes and the frequency and magnitude of melt. They found an increase in the frequency of melt during cloudy conditions but the effect of clouds on the energy available for melt varied spatially.

Overall, I think the purpose of the paper is a very good one, and it is certainly an interesting approach to look at the impacts of clouds across a range of sites, since often energy balance studies are confined to one site or a region, so the global aspect is appealing. The paper is also clearly written throughout, and the methodology followed is sensible. However, I do have a couple more significant concerns which I highlight in the major comments below:

We thank the reviewer for their thorough and insightful review, which has helped us improve the manuscript. As well as addressing the minor comments, we have added two sections to the manuscript that address the main concerns listed below.

Major comments

1. Depth of analysis and understanding of global trends

In the main results section the variation in the results (in terms of the cloud effect on the meteorology, surface fluxes and melt) caused by the different location, climate and elevation of the sites is mentioned (certainly when the effect is quite clear). However, I don't think the authors really make the best use of their dataset to fully interrogate the spatial variation in the results. The relationship between the cloud effect and station and energy balance characteristics is not investigated fully (with scatter graphs) until section 4.2 (which anyway should be a result section). Although the figures earlier in the results section are clear as they are they are not well suited to investigating the spatial differences and improving these figures to make the station characteristics clearer and including scatter graphs earlier in the results would be a good idea. Furthermore, the analysis in section 4.2 is not robust, the authors need to calculate the correlation and regression (if appropriate) coefficients and report them in the paper. Currently assessments are made only on a visual assessment. In general, I think the paper needs an extra stage of analysis yet to give its findings more credibility, and this may also allow clearer findings on why the effect of clouds on melt energy varies in sign spatially.

We have moved the previous section 4.2 into the results section (now section 3.5) and expanded the analysis to include an objective assessment of correlation and statistical significance, as well as analysing further variables for their relationship to cloud effects on melt energy in Figure 12. We have also added a legend to Figure 12 that allows readers to identify the station characteristics of each site, as well as regional climate groupings to Table 1. Together this presents a more thorough assessment of the spatial variations of cloud effects.

New section 3.5:

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3.5 Relationships between Q_M cloud effect and site characteristics

While the average change in Q_M with cloudiness is small at some sites, it is instructive to assess whether the melt-season average Q_M cloud effect (CE) at the various sites can be related to geographic or climatic parameters. Figure 12a,b shows the average relationship between cloudiness and melt at the various sites does not follow easy relationships with latitude or altitude. Average near-surface air temperature is moderately correlated to Q_M CE (Figure 12c). Sites with lower T_a (e.g. MERA, KERS) generally have smaller Q_M CE than sites with higher high T_a (NORD, CABL, MORT), but with some notable exceptions (e.g. LANG has positive Q_M CE with relatively high T_a). Average cloudiness shows some association to Q_M CE with clearer sites tending to have more negative Q_M CE (Figure 12e), with the exception of Tropical sites with predominately clear-skies (KERS, GUAN) that show neutral Q_M CE. Neither, average wind speed or relative humidity show a clear relationships with the Q_M CE (Figure 12d,f). Average turbulent heat fluxes and *LWin* are moderately correlated Q_M CE (Figure 12g,h,j), largely following the pattern of sites shown for T_a, while average *SWin* is not significantly correlated (Figure 12i).

Considering the association of radiative and melt cloud effects, average incoming radiation cloud effects explain some of the variance of Q_M CE*,* with *LWin* (Figure 12l) showing a stronger association than *SWin* CE (Figure 12k). Combined, the incoming radiation cloud effects can explain over half (53%) of the variation in Q_M CE (Figure 12m). Surface albedo has a similar correlation to Q_M CE (Figure 12n) as the incoming radiation cloud effects together. The combination of these into the *Rnet* CE shows the clearest relationship to Q_M CE (Figure 12o). In general, sites that experience a radiation paradox (LANG, ZONG, MERA) also experience greater melt in cloudy conditions (positive Q_M CE), while sites with negative *Rnet* CE experience less melt in cloudy conditions (Figure 12o).

Turbulent flux cloud effects are also moderately correlated to melt-season average Q_M CE (Figure 12p,q) and when combined explain a 44% of the variance in Q_M CE (Figure 12r). Thus, sites where Q_S decreases with cloudiness show more negative Q_M CE. Sites where Q_S varies little with cloudiness and/or Q_L becomes less negative/more positive during cloudy periods show neutral or positive Q_M CE. Interestingly, the radiative and turbulent heat cloud effects show a moderate association, with sites with large negative *Rnet* CE also having a negative net turbulent flux cloud effect, and vice versa (Figure 12s).

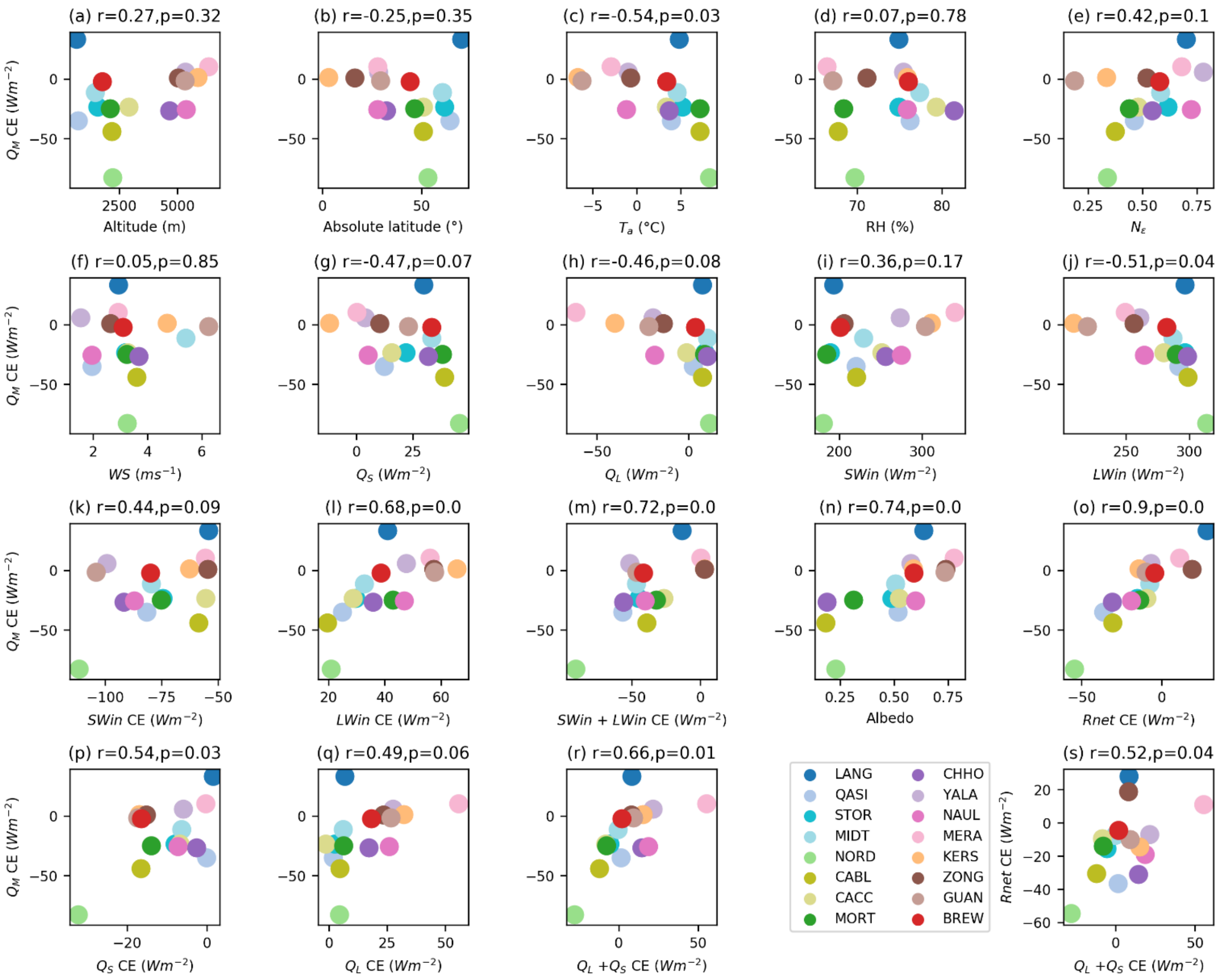

Figure 12: The variation of average melt-season Q_M cloud effect (CE) with (a) station altitude, (b) absolute station latitude, average melt-season (c) T_a, (d) *RH*, (e) N_ε, (f) wind speed (*WS*), (g) Q_S, (h) Q_L, (i) *SWin*, (j) *LWin*, (k) *SWin* CE, (l) *LWin* CE, (m) *SWin*+*LWin* CE, (n) albedo, (o) *Rnet* CE, (p) Q_S CE, (q) Q_L CE, (r) $Q_S + Q_L$ CE. (s) is variation of *Rnet* CE with $Q_S + Q_L$ CE. See Section 2.5 for definition of CE. Average melt-season values are calculated by averaging values from the 5 cloudiness bins equally. The Pearson correlation coefficient (r) and associated p-value are given above each panel.

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The aim of the present paper is to describe the relationships between cloud, meteorology, SEB and melt at different sites and discuss what features are common or unique across the sites. A deeper assessment of why these relationships differ between sites requires further analysis that is beyond the scope of the present paper i.e. it would require an investigation of how regional climatology impacts cloud characteristics and the co-variance between cloud radiative forcing and changes in near-surface meteorology during cloudy conditions at each site – analysis that would be better suited to a separate paper.

2. Discussion

The first two sections of the discussion are really still results, and then there are only the limitations and implications sections, with the latter section really missing references. I miss here a proper in-depth discussion which brings together the understanding alongside other studies. Consider answering some questions, e.g. Why do clouds influence the near surface meteorology in the ways you found? (explain the physical mechanisms) What factors cause changes in the impact of clouds on melt? You touch on this in sections 4.1 and 4.2 and also in your limitations, but I feel you need to set this out more as a clear discussion with each of the factors and their influence. There is also a need to bring in other energy balance studies which have looked at the cloud effect (or even seasonal differences where cloud cover likely varies markedly), especially in regions not covered by your analysis.

We have added a section to the discussion “4.3 Mechanisms influencing SEB changes with cloud” in which we discuss the physical processes leading to changes in SEB due to cloud as well as linking this work to other studies:

“””

4.3 Mechanisms influencing SEB changes with cloud

In addition to the key role that surface albedo plays in determining *Rnet*, there are three key mechanisms that drive temporal changes in SEB with cloudiness

i) direct forcing of incoming radiation (decreased *SWin* and increased *LWin*),

ii) changes to near-surface meteorology that alter turbulent heat fluxes

iii) surface and subsurface temperature feedbacks that alter net radiative and turbulent fluxes

Here we demonstrate that direct forcing of incoming radiation and surface albedo explains much of the net effect of clouds on Q_M across sites. The high correlation between melt-season average *Rnet* CE and Q_M CE between sites (Figure 12), along with the sensitivity of these averages to the length of the melt season (Figure 10 vs Figure 12) underlines the primary control of direct and indirect radiative mechanisms on determining the sign of melt response to cloud. It is likely that substantial seasonal variations of *Rnet* CE exert the primary control on the effect of clouds on glacier melt.

Changes in turbulent heat flues with cloudiness tend to be smaller in magnitude than changes in *Rnet* (Figure A5), except for the more extreme cases where air temperature changes greatly with cloudiness, e.g. NORD, where Q_S markedly decreases with cloud and MERA, where Q_L becomes far less negative during cloud. Despite this, net turbulent heat flux cloud effects show moderate correlation to Q_M CE, and thus changes in near-surface meteorology play a significant role in determining the net response of melt to cloud. These findings echo those of Liu et al. (2021) who show increased melting during cloudy periods on Mt Everest are due to increased *Rnet* as well as lower wind speeds that drive smaller losses to Q_L, and Conway et al. (2016) who found changes to Q_L contributed to increased melt during cloudy periods. Future work should assess the mechanisms driving the observed covariance between cloudiness and near-surface meteorology at different sites, e.g. Do large-scale changes in airmass or local/meso-scale processes drive changes in T_a with cloud? How well are these processes represented in the datasets used to force glacier melt models on regional scales? Seasonal changes in the relative magnitudes of turbulent and radiative cloud effects also deserve further scrutiny.

Surface temperature responds quickly to changes in SEB, and here we show that during cloudy periods, a melting state is observed more frequently, in line with previous research on maritime glaciers (Conway et al., 2016). We have not attempted to analyse further surface and sub-surface temperature feedbacks here as not all datasets contain these variables and a detailed analysis is more suited to sensitivity experiments that allow the transient response of sub-surface temperature, humidity and refreezing to the resolved.

The increased frequency of melt during cloudy conditions, especially at higher elevations, raises the question of how glacier-wide melt is altered by clouds, along with how glacier-wide surface mass balance is altered by refreezing. Van Tricht et al., (2016) show increased runoff from the Greenland Ice Sheet during cloudy periods due to increased melt extent and decreased refreezing of melt water, while Niwano et al. (2019) found clouds increase melt extent but reduce total melt due to feedbacks between cloudiness and near-surface humidity. These studies are in line with the findings here – that clouds enhance the possibility of melt at a given site, by removing large negative *LWnet* and Q_L fluxes to precondition the surface to melt, but do not necessarily cause greater melt unless albedo is high enough to cause a radiation paradox or unless increased near-surface air temperature, humidity and/or wind speed causes an increase in net turbulent fluxes.

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Minor comments

L56: To me the subsurface is more the material under the glacier, I think Qc is the conductive heat flux into the surface.

Changed to "Q_C is the heat flux at the surface from conduction within the glacier"

L57: Are all the fluxes in W m-2 (they usually are but just state this)?

Yes, and now noted in text

L86-88: It might be worth expanding on some of these methods to derive cloudiness and their main assumptions/difficulties.

We expand on the methods to derive cloudiness in Section 2.3.

L99: Define AWS here.

done

In methods: Maybe it would be useful to have a simple idea of the climate type/seasonality of each site? It seems that the overall broader climatology will drive the differences in the cloudiness patterns and how they relate to the melt seasons, so having this context early on would be useful.

We have introduced the broad climatology at the end of Section 2.1

"Figures A1 and A2 show monthly average meteorology and SEB fluxes for each site used in the analysis. A few broad groupings of sites (listed in Table 1) can be identified through seasonal trends in near-surface air-temperature (T_a; °C) or relative humidity (*RH*) in Figure A1: mid- and high- latitude maritime and continental sites with strong seasonal cycles of T_a but small variations in *RH*; Himalayan sites with strong cycles of T_a, and distinct wet and dry seasons; Tropical sites with small variations in T_a and distinct wet and dry seasons; and a mid-latitude arid site (GUAN) with low *RH*."

L110: Due to the different methods of the calculation of the turbulent fluxes consider including a table with how the non-radiative fluxes were calculated for each site (in the appendix/SI would be fine).

We have clarified that the turbulent fluxes were all calculated using bulk aerodynamic methods. We list the papers corresponding to each dataset, so the reader can find extra details if they require.

Figure 1: Maybe include insets where you have several sites relatively close by in a region. Also use a different symbol to label colour for readability.

Thanks for the suggestion, but we prefer to keep the figure as is.

Sections 2.3, 2.4 and 2.5 – if these are all within 'data processing' then it might make sense for these sections to be 2.2.1, 2.2.2, 2.2.3 (so sub-sections of 2.2)

Thanks for the suggestion but we prefer to keep the original sections

Figure 3 caption: 'Steps'

done

L149-162: Honestly, I think this could go into an appendix or SI. But I am wondering, if you had to do these quality checks then how do you know that the SEB fluxes were also calculated post these quality checks - I thought you were using the published data (which hopefully would already be checked?) Can you clarify this please. Calculating Ts from LWout works quite well but not always, give the reference for how you did this.

The quality control step was mainly to ensure the datasets were homogenous in terms of temporal coverage and the variables included. Because the full time series data from each site was provided, and in some cases this included periods that different variables were not available, these periods had to be removed. We have given a clarified we use the Stefan-Boltzmann law and *LWout* to calculate surface temperature if it is not available.

L172: Also define sigma as the Stefan Boltzmann constant, and give a reference for this equation.

Done

Section 2.4 could probably be shortened.

For the sake of completeness we have retained the text.

Figure A2, A4: Please add a legend so the reader knows that the colours are used to define the melt season.

Consistent with Figure 5, a note has been added to the caption of Figure A4 and A6: "Months defined as within the 'melt season' are shaded blue."

L224: Why only look at the cloud effects versus the radiative fluxes? You do look in Figure 11 at the importance the turbulent fluxes for melt and how that varies with cloudiness, but why not also include them as for the radiative fluxes in Figure 7. Furthermore, is there not some circularity in looking at the LWnet differences given that LWin is used to calculate the cloudiness?

We have followed previous research that has analysed the direct effects (radiative) of clouds separate from the indirect effects (through temperature/humidity/wind etc). In Figure 11/A5 we analysis the variation of the turbulent fluxes with cloudiness.

We agree there is some unavoidable degree of circularity in analysing radiative fluxes that have been used to derive cloudiness. However, as LWin does not solely depend on cloudiness, but also the variation of temperature and humidity, the circularity is not complete. For instance, at Brewster Glacier, the increase in LWin between clear-sky and overcast conditions is approximately the same as the change in clear-sky LWin due to seasonal variations in air temperature. The method used to calculate cloudiness removes the effect of temperature/humidity on LWin, so the effect of these variations in near-surface meteorology on LWin is retained in the analyses in Figures 6 and 7.

Figure 4 caption: It would be useful to have a legend, or at least to explain what the darker via lighter colours represent. From the text it seems like darker colours = greater frequency of conditions, but this should also be clear from the figure/legend on its own. Consider outer boxes (or other methods) showing the splits between regions.

The caption has been updated to make it clear the plot shows the frequency of different conditions along with the meaning of different colors.

L258: 'between monsoon and arid regions although it still shows an increase in partially cloudy conditions in the melt season' Or something similar, just for clarity.

Agreed – changed to "between monsoon and arid regions, though the fraction of partial-cloud conditions still increases in July and August."

Figure 5: This is nice way to show the cloudiness at the sites, but it might be useful to have some overall metrics so its slightly quicker to compare sites, e.g. the mean and range of melt season monthly cloudiness? It might also be useful to group by region (Himalayan, European etc.) Even though I know most of these sites and where they are its not so easy to see trends, and I imagine it would be harder if you didn't know inherently the site locations.

The sites are ordered by latitude in this and other figures, so naturally fall into regional groupings. We now show average melt-season cloudiness against cloud effects in Figure 12.

Figure 6: Maybe it would be helpful to take this a step further, for instance can you relate the gradients of these lines to the site lat/long/elevation, e.g. in a scatter graph? It's easy to see that KERS, MERA and ZONG are different but harder to know what is causing the variation in the other sites. You do attempt this in the discussion but I think this analysis could be more thorough and come earlier in the paper.

We did investigate analysis of gradients of relationships as suggested but settled on the overall cloud effects. An analysis of gradients could be undertaken in future work.

L289: 'cloud effect is small and negative' It would be useful also to scatter this overall change in Rnet against the sites to see if there are regional clusters.

This is done in Figure 12.

L293: 'more positive response to' - do you mean in terms of an increase in Rnet here?

'more positive and/or less negative *Rnet* cloud effect'

L307: 'relationship is weak and non-linear' - Quantifying the strengths of these relationships and their gradients (for all the variables in Figure 8) would be a good idea.

We have clarified the patterns displayed at these sites in Figure 8 "…, QASI, which shows no large change cloudiness and CACC, which shows peak wind speed at moderate cloudiness."

L323: 'at all study sites' - this doesn't appear to be the case for GUAN.

Have added "with the exception of GUAN, which experiences very infrequent melt in all conditions."

L329 – 331 ‘While…..day and night’ – Add a reference to this effect if you don't show the analysis yourself.

We have modified the sentence to read, “the higher percentage of hours with melt during overcast conditions indicates that night time melt is more frequent during overcast periods.”

L331- 334: This sentence might be better earlier in the paragraph.

Thanks, but we prefer to keep the original position

Figure 9: Here and in other similar figures, it might be a good idea to use different line styles as well as colours to indicate different regions? It might also allow you to use fewer colours, and have a palette which is more colour blind friendly. The strength of this paper is the wide range of sites and yet you need to show better the regional/climate/elevation differences in your plots.

Thanks for the suggestion, but we prefer to retain consistent line style and not pre-determine the expected groupings in the results too much. As the sites are grouped by latitude, the groupings of colors do follow this.

L337: ‘indicating sublimation’ Since we are going from ice to vapour.

Because this analysis in Figure 11 is limited to timesteps where the surface is melting, QL results in evaporation of melt water. We have clarified in the text “(indicating evaporation as T_s = 0°C)”

Section 4.1 In this section in general you could do with better links (references to) your results section, so for instance refer back to the figures or sections where these results which you are bringing together are first mentioned. I also think this section could also be rather in the results section still.

Thanks. We have added references to the appropriate figures but have kept this section in the discussion as it does not introduce new results but rather attempts to synthesize the results.

L388: ‘At all of these sites,’

corrected

L392: ‘and QL’ Usually increased QL (sublimation) would decrease melt? Or do you mean increased in terms of less negative? But I would expect the opposite if its windier.

Here we define QL as a positive flux towards the surface, so increased means less negative or more positive. The text has been clarified.

Section 4.2: Again, to me this section is still results. You need to do the statistics here and show them - are these relationships significant at a given p-value? What are the R2 values? Just showing the scatters on their own in Fig 12 is not enough. Also consider looking at only the sites in the ablation zone or those in different regions separately.

Correlation statistics (r and p values) have now been added to the figure, to objectively assess which relationships are statistically significant.

L403: ‘with latitude or altitude’ - There does look to be a relationship with latitude, perhaps with an outlier? Do the stats to check.

QM cloud effect has a linear correlation of r = -0.25 to latitude and r = 0.27 to altitude, so neither variable explains much. Figure updated with correlations.

L404: ‘Neither average near-surface air temperature’ - Again, Ta does look to relate to the cloud effect, but you need to do the stats to know!

Yes, air temperature is indeed moderately correlated with QM cloud effect (r = -0.54). Figure and text updated.

Figure 12: Here it would really help (similar to in the line graphs above) to somehow differentiate (maybe using symbols) the different regions. You should also include a legend for this figure so the reader can understand it on its own. Also why not include also the influence of the turbulent fluxes and wind speed?

Figure has been updated with legend, as well as wind speed and the turbulent fluxes.

L435: Zongo’s large seasonal variations in climate. Perhaps make it clear that the precipitation and cloudiness are the key variables which change seasonally here, rather than Ta.

Modified to “large seasonal variations in precipitation and cloudiness”

L441-442: Is this reference to Chen et al. (2021) also referring to the site at BREW?

No, this is for a Laohugou Glacier No. 12 in China – now clarified in the text.

L458: ’in the first partial’

corrected

L470-473: You need to cite the studies you refer to here. Are you sure there are no studies that include changes in cloud in future glacier change?

References added. To our knowledge, the only global study to include changes in radiation is Shannon et al., 2019.

Shannon, S., Smith, R., Wiltshire, A., Payne, T., Huss, M., Betts, R., Caesar, J., Koutroulis, A., Jones, D., and Harrison, S.: Global glacier volume projections under high-end climate change scenarios, The Cryosphere, 13, 325-350, 10.5194/tc-13-325-2019, 2019.

L474-475: Reference here to your results figures/sections.

Sentence removed as largely repeated sentences on either side.

L476: ‘during marginal melt seasons and especially at high elevations.’

Thanks, and modified

L483 and 484 ‘metadata’

Corrected

L488-489: ‘As many…’ You need to cite studies here, also I'm less sure what you mean, usually Swin is influenced strongly by topography whereas Lwin is less so (aside from cloud forming processes but they are not related to Swin). There are parameterisations of Lwin from Swin (e.g. Juszak and Pellicciotti, 2013), if that is what you mean?

Yes, these are the sorts of parameterisations referred to. Glacier mass balance models use these to compute LW/SW at specific elevations, or to calculate LW/SW from near-surface meteorology (i.e. air temperature, humidity). Now clarified in the text:

"As many glacier SEB models rely on empirical relationships between *SWin* and *LWin* to modify these variables to account for local-scale changes in near-surface meteorology (e.g. Mölg et al., 2009a; Conway et al., 2015),"

L506: When mentioning the turbulent heat fluxes be clear about how the latent heat flux changes, since it is often negative.

Have added 'Less negative and/or more positive' in front of 'turbulent latent heat fluxes'

L509-511: 'The association….' I think you could have pulled this apart in more detail, it feels like you have the data to understand this, but it needs more in-depth analysis than you have shown.

We have clarified the associations of clouds and melt energy in an expanded results section 3.5 and discussion section 4.3. We agree there is scope for further analysis, but it is beyond the scope of this manuscript.

Data availability: Given your point in the limitations it would be much better if these data were made available together (with your analysis code) in a repository. Of course, it depends on the agreement of individual data providers, but you should aim for this.

We prefer to work towards a common repository in the future, rather than publish the collated dataset now. In the interim, the collated dataset could be made available for analysis to individuals on request (and agreement of the providers). The code to read in and analyse individual datasets will be made available online.

Figure A1: Tidy up the labels here to use correct notation, also add units for the left hand variables.

done

Figure A2: Tidy up the labels and legend to use superscript (for units) and proper notation for the fluxes.

done

Figure A4/A6: Missing a legend, its not clear what the colours represent.

Figure captions have been updated to clarify the meaning of colours and shading.

References

Juszak, I. and Pellicciotti, F. (2013) A comparison of parameterizations of incoming longwave radiation over melting glaciers: Model robustness and seasonal variability, Journal of Geophysical Research: Atmospheres, 118, 3066-3084, doi:10.1002/jgrd.50277