Response to reviewer comment #1. Note reviewers' text is shown in **blue**, with responses in **black**

Review of "Cloud forcing of surface energy balance from in-situ measurements in diverse mountain glacier environments" by Jonathan Conway et al. #tc-2022-24

General comments:

The authors presented a study on how cloud cover influences the glacier surface energy balance (SEB) in diverse climate settings across the globe based on observed meteorological data from 16 mountain glacier sites. They have compared the results and discussed the differences among 16 sites in terms of cloud's role in controlling local meteorology and SEB and thus glacier surface melt. First, the influence of cloud on the glacier mass balance is an extremely important topic to grow our understanding about physical glacier-atmosphere interactions where the existing community knowledge is poor. Second, this comparative study based on in-situ data from 16 diverse glacier sites is highly welcoming and has potential to increase our knowledge significantly. Finally, such understanding is also helpful to improve the SEB-based regional-wide glacier mass balance models and regional climate models. Based on my knowledge, the work is timely. Dataset selection/filtration steps are well-justified and standard, also methodology section is with strong physical background of the cloud cover estimation equations, etc. Figures are high quality and the statements and conclusions are well supported by the results/figures. Analysis of cloud effects on SEB across 16 sites is one of the unique part and gives a greater knowledge of spatial distribution of such understanding based on observed datasets. Also, I would like to commend the authors for this work which brought together several authors with similar interest and used the unique glacier SEB dataset in a common framework for better understanding the mountain glacier-atmosphere interactions. Also, they have nicely highlighted the future work needed and a need for a common repository of crucial AWS/SEB datasets.

I feel this is an interesting contribution to TC and valuable for the cryosphere community across the globe. The paper is interesting, concise and clearly written, therefore, I do not have many comments/suggestions for the authors as the manuscript is in already good shape. Below you will find some general and minor comments and suggestions that you might find helpful to improve the quality of the manuscript.

We thank the reviewer for their helpful and positive review. The suggested changes have helped clarify many points.

Specific comments:

1. L164: I understand the data scarcity of such high-quality glacier AWS datasets, but don't you think data of 10-days from a month is a bit under-represented the monthly features/statistics? Or how about half a month (15-days) considering limited data for each site, also could be better-justified? If you agree, I do not think it would take much time to consider.

Filtering using a lower limit of 15 days in a month would remove 3 additional site months, being June at CABL (12 days) and CACC (14 days), and November at MERA (14 days). At the Conrad Glacier sites (CABL and CACC) these extra records are in the melt season, so we prefer to retain them to increase the applicability of statistics calculated over the full melt season (e.g. Figures 6 to 13). For reference, only two site months were filtered by the 10-day criterion (being September at CABL (5 days) and CHHO (4 days)), with the other missing site months having no valid data.

2. In Figure 5, I am a bit surprised to see the overcast cloud fraction in July for CHHO/Chhota Shigri Glacier. It's very small, compared to other Himalayan glaciers (Yala, Mera etc.). However, I am aware that Chhota Shigri area is a monsoon-arid transition zone, where monsoon clouds don't penetrate much (Azam et al., 2014), but such small overcast cloud fraction days are surprising. Or is it due to not having complete-month data in July, as I see in Azam et al. 2014 it starts from 8 July 2013? In that case I believe it is quite under-represented. Otherwise, it is worth putting a small note on the figure caption about this.

The lower fraction of overcast periods at Chhota Shigri Glacier in Figure 5 is due to the use of daily average cloudiness and due the poor monsoon reach at Chhota Shigri Glacier compared to Mera and Yala glaciers, as pointed out by the reviewer. Mera and Yala glaciers (central Himalaya) are located in typical monsoon-dominated climate while Chhota Shigri Glacier (western Himalaya) is in Alpine climate (Azam et al., 2021, Science https://www.science.org/doi/10.1126/science.abf3668) and thus receives monsoonal precipitation occasionally. In our present analysis, we estimated the cloudiness at hourly scale and then estimated the mean daily values to reduce the noise, limit the influence of sub-daily variability and focus on synoptic scale (daily) variability in cloud-SEB analysis. On an hourly basis (Figure A4, there is a much higher fraction of overcast periods in July (25%) and August (40%).

We don't think the low cloud factor in July 2013 is because of short data (23 days). For instance, in Azam et al. (2014) the daily mean cloud factor was 0.34 for July 2013 (23 days) while it was 0.38 for August 2013 (complete month) and the mean of 60 days (selected period = 8 July to 5 Sept 2013) was 0.36.

We have amended the text to in section 3.1.2 to explain the reasons for fewer overcast periods at Chhota Shigri compared to other Himalayan Glaciers.

3. Section 3.4: How the melt pattern (frequency/amount etc.) gets influenced due to positive QL during summer in the Himalayan sites, for example, in Chhota Shigri, Yala, Mera, you get positive QL during summer, though it is not a significant amount. Is there any impact of clear-sky/overcast conditions in QL overall? Is it worth explaining briefly here?

Figure 11 shows the variation of QL with cloudiness confirming QL becomes positive or close to 0 during overcast periods at Chhota Shigri, Yala and Naulek. At Mera, QL is still negative, but less so than in clear-skies. Without a doubt this has an influence on the SEB and helps create increased QM in overcast conditions alongside increased LWin. We comment on this feature at lines 354 and 374.

4. Section 4.2: Although the authors choose to say that there is no relationship or not easy relationship between melt energy (QM) CE and latitude/air temperature, but from Figure 12, I think that the relationships are a bit clearer than with altitude or RH or SWin CE. In that case it is worth discussing briefly why there could be a bit clear relation between melt energy (QM) CE and latitude/air temperature? Or is it due to the higher latitude sites or maritime influence? Can you comment on this! This brings me to another important point: you should mention which glaciers are maritime/very high-altitude in Table 1, you can create a new column and mark them or find an easy

way. This will give a quick idea to the readers and they can correlate better among the diverse climate/sites.

We have added a column to table 1 to describe the regional grouping of glaciers. In Figure 12 we have added a legend to allow readers to identify the sites as well as linear correlation coefficients to each panel to aid in the interpretation. These show air temperature has a moderate and statistically significant association (r=-0.54,p=0.03) while latitude and altitude shows only weak and insignificant associations (r=-0.25,p=0.32 and r=0.27, p=35, respectively). We have also added further variables and discuss these relationships further in a new section 3.5 (see response to reviewer comment 2 for full text)

Figure and Table:

Figure 1: Here authors may cite the RGI 6.0 (RGI Consortium, 2017) in the caption, as they have used it in this figure, but I did not see any citation in the reference list. Also, you could mention the background image of this map (Natural Earth?).

Thanks. References have been added.

Table 1: Latitudes and Longitudes digits/decimals are not consistent, some with three decimals and some two. I would have made them two decimals for all sites.

The coordinates were supplied in a variety of formats (some very precise), so we have rounded to three decimals (~100 m) to make these more concise yet still precise enough to place the AWS within the general vicinity of the glacier. We would prefer to keep the precision where possible.

Figure 3: Does the colors mean anything? If yes, you can briefly mention in the caption, else you may remove the colors.

The colors align with the sections (2.2, 2.3, 2.4, 2.5) that are relevant. The figure has been updated with annotations and caption updated to "Steps used to process and analyse data, annotated with relevant sections of the methods."

Minor/technical comments:

L57: You could put Ts ≥ 0 °C or > -0.1 °C in parenthesis.

Changed to "When the surface is at the melting point (i.e. surface temperature (T_s) = 0 °C),"

L58: Please expand: w.e. (water equivalent) within the parenthesis, I see it first appears here in the manuscript.

Replaced with water equivalent

L70: What do you mean by highly reflective glacier surfaces? Do you mean fresh snow? You may mention a few as e.g.

Added 'clean snow' as an example

L71-73: Although the paper by Mandal et al. (preprint in TCD) is still in discussion stage, they showed that sublimation is also considerably reduced (about 2-3 times) due to clouds in the Chhota Shigri Glacier area-one of the sites in your present study.

Very interesting paper. We have added a reference to it in the introduction.

L99: I think you should expand the abbreviation of AWS here, because it first appears here and removes it from L107.

Done

L105: surface energy balance —> SEB

Done

L107-109: Remove 'balance' after radiation.

We have kept balance here to distinguish these components from other differentiations of radiation (e.g. diffuse, direct)

L124-125: NORD and CHHO are not expanded here, so it is a bit hard to follow, or can you cite Table 1 somewhere here, so that readers can quickly go to Table 1 and see what these short names refer.

Added to line 126 "(See Table 1 for site name abbreviations)."

L170: In equation 3, you have not mentioned about the sigma (σ)/ Stefan–Boltzmann constant. As you have mentioned details about all other variables/parameters, I would have mentioned for a bit easy read.

Added "where σ is the Stefan–Boltzmann constant (5.67×10^{8})."

L195: For partly cloudy, isn't it should be 0.2 > Nε < 0.8? Please correct.

Yes – corrected now $0.2 < N_\varepsilon < 0.8$

L204: Is it important to keep the last part of the sentence 'SWin does not provide meaningful values during the night time'? I would have deleted it because it is relatively understood that SWin is up only during daytime.

Good point. Have reworked sentence "In addition, cloudiness cannot be derived from *SWin* during the night time and terrain shading of *SWin* introduces further uncertainty, especially in winter."

L221: Can you cite someone here, as you say 'In studies of net radiation', where they defined CE as the difference between average and clear-sky conditions.

Citation added

L250: Partial cloud —> partly-cloudy, and elsewhere (e.g., L255, L265 and elsewhere).

Updated definition at line 197 to "partial-cloud as $0.2 < N_\varepsilon < 0.8$"

L244: In caption, add comma after εcs

added

L289: W m-2 —> W m-2

fixed

L289-291: Which three sites? It is difficult to identify them easily from 16 sites/legends, can you mention them in parenthesis?

Added to line 293 “(MIDT, MORT, CHHO)”

L303: Here you write melt-season, elsewhere it is melt season.

‘melt-season’ is used where the term is used as a compound adjective to define the period of measurement (e.g. melt-season air temperature), whereas ‘melt season’ is used when the term is used a noun (e.g. cloud conditions during the melt season. We have updated the text to ensure this is consistent.

L308: wind climate or wind system?

We use wind climate to describe the typical conditions, rather than a specific weather system.

L341: I would have written clearly: In contrast to the percentage of hours with surface melt. Otherwise, for the general readers it is a bit rethinking what is fraction of time with melt.

Thanks, good suggestion. Changed to “In contrast to the percentage of hours with surface melt,”

L355: Evaporation because of Ts ≥ 0 °C or > -0.1 °C? You can quickly mention within the parenthesis for easy read for other/general readers.

Changed to “(indicating evaporation as T_s = 0°C)”

L403-405: Here I think you should mention the colder and warmer sites, at least a few, in parenthesis. Else, until here the readers have already forgotten which sites are colder/warmer because there are 16 sites across the globe.

Examples of colder and warmer sites are now given in the text

L406-407: Is it proper to say it as correlation here? Or would you go with relationship, but again then relationship comes two times. You may find some other words. Cite Figure 12h after the albedo part.

Changed to “association”

L490: Conclusion does not have any section number. Maybe some formatting issue.

We have followed the journal template, which has no section number for the conclusion.

L491: How about, …. and surface energy balance over glaciers from very different...?

good suggestion. Changed to “surface energy balance over glaciers in very different climate settings”

L504: Clear-skies.

Changed to “cloudy compared to clear-sky conditions.”

L515: This sentence is similar to L480. Or you may remove it from L480 and combine it here in the Conclusion.

At the risk of being repetitive, it is worth restating this key result in both locations.

References:

Azam, M. F., Wagnon, P., Vincent, C., Ramanathan, AL., Favier, V., Mandal, A., and Pottakkal, J. G.: Processes governing the mass balance of Chhota Shigri Glacier (western Himalaya, India) assessed by point-scale surface energy balance measurements, The Cryosphere, 8, 2195–2217, https://doi.org/10.5194/tc-8-2195-2014, 2014.

Mandal, A., Angchuk, T., Azam, M. F., Ramanathan, A., Wagnon, P., Soheb, M., and Singh, C.: 11-year record of wintertime snow surface energy balance and sublimation at 4863 m a.s.l. on Chhota Shigri Glacier moraine (western Himalaya, India), The Cryosphere Discuss. [preprint], https://doi.org/10.5194/tc-2021-386, in review, 2022.

RGI Consortium (2017). Randolph Glacier Inventory – A Dataset of Global Glacier Outlines: Version 6.0: Technical Report, Global Land Ice Measurements from Space, Colorado, USA. Digital Media. DOI: https://doi.org/10.7265/N5-RGI-60

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