

## General comments

In this manuscript, the authors present the surface energy balance throughout western Greenland over a long-term AWS recording period. The paper provides a nice, detailed process-based analysis of similarities and differences in the surface energy balance between sites, and the controls exerted by elevation and latitude on these observed differences. Another strength of this work is that it provides one of the first validation studies of the ERA5 reanalysis over the Greenland Ice Sheet, finding that this dataset improves upon ERA-Interim only in the representation of albedo and is still inferior to the RACMO model. Although the scientific results presented in the paper are generally timely and sound, it suffers from poor presentation quality in a number of instances, particularly related to the figures. In my opinion these issues, as detailed in the specific comments and technical corrections below, must be amended before I can recommend publication of this paper in *The Cryosphere*.

**Reply: We thank the reviewer for the comments, which have improved the paper.**

## Specific comments

L11-12: What constitutes “reasonable agreement” between modeled and observed melt? Be more specific with numbers here, as you were with the RMSEs for modeled versus observed surface temperatures.

**Reply: We added specific numbers with explanation.**

The uncertainty in daily ablation measurements owing to different error sources (differential ablation, density of ice, stake reading) can be as large as  $\pm 10\%$  (*Braithwaite et al., 1998*). *Van den Broeke et al., (2010)* report that constant systematic meteorological measurement errors, which can be interpreted as an upper bound on the modelled uncertainty range, result in model melt uncertainty of  $\pm 15\%$ . Given these uncertainty estimates, with an average difference of 6% between observed and modelled ice melt, the agreement is reasonable.

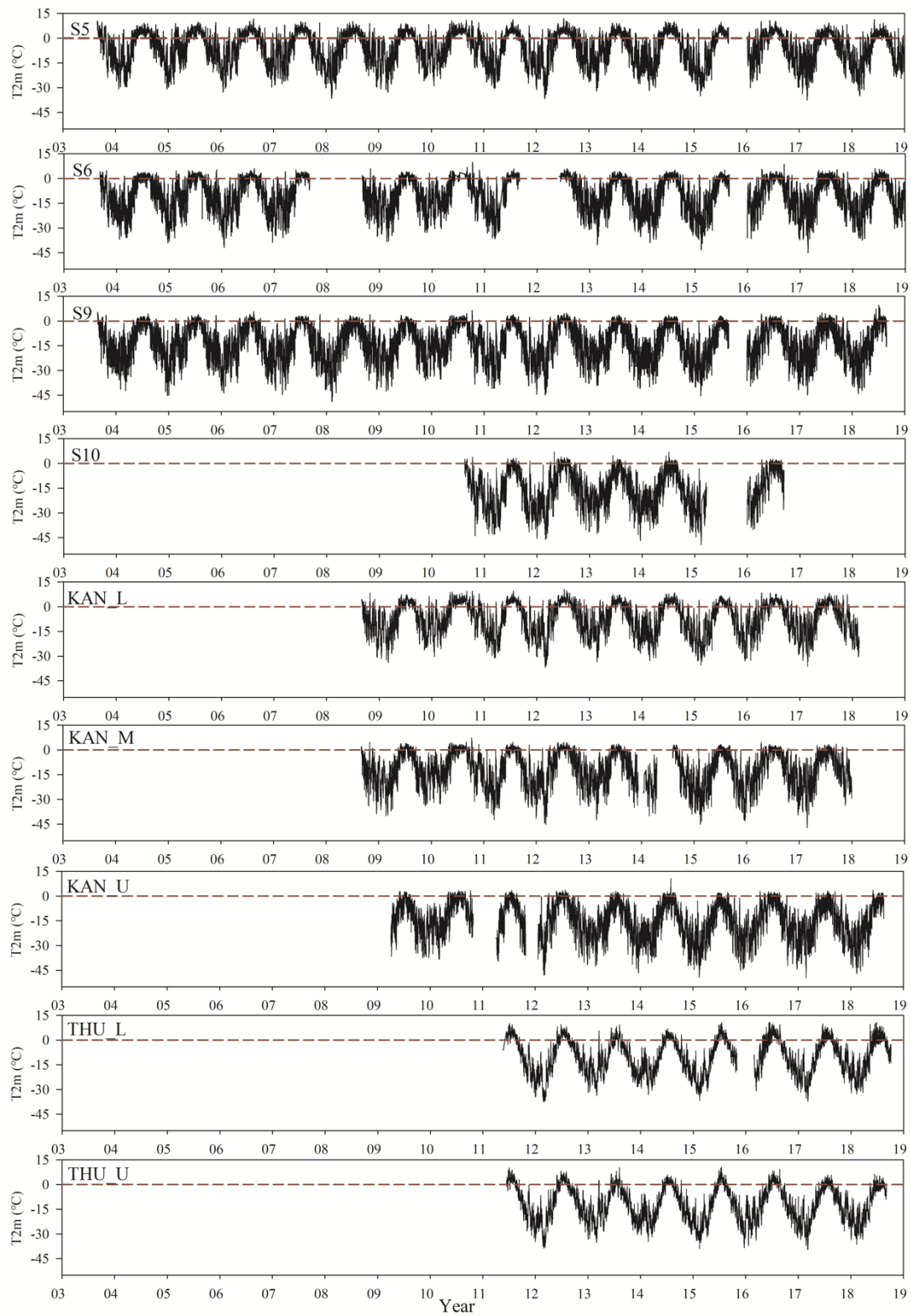
L138-139: This sentence requires a lot of work from the reader, forcing them to scroll up and down repeatedly to compare Figs. 2, 4, and 6. It would help to add short descriptions of each figure to the sentence, i.e. something like “Data points used in the model validation scatter plots (Figure 4) coincide with the time series of each variable in Figure 2, while the analysis of surface height changes in Figure 6 starts in 2008.”

**Reply: We followed the reviewer's advice and added:**

Data points used in the model validation scatter plots (Figure 4) coincide with the time series of 2 m temperature in Figure 2, while the analysis of surface height changes in Figure 6 starts in 2008.

Figure 2: This figure would be easier to read with tighter y-axis limits, particularly the lower limits. Temperatures appear to never exceed  $\sim 10\text{C}$  or drop below  $\sim -45\text{C}$  at any station, so the y-axis ranges can be made smaller.

**Reply: The new Figure 2 y-axis range has been made smaller with the best range of -55 °C~ 15 °C.**



**New Figure 2**

Figure 2: This figure would also be more effective if the x-axes on all panels covered

the same time period (i.e. ending all time series plots in 2019 instead of ending some in 2017 and others in 2019), even if the data at all stations is not available for the same record length. Why do the S5, S6, S9, and S10 records only extend through late 2016? The data gaps at S6 during 2008, 2010, 2012, and 2015 are addressed in the text, but I don't see anywhere in the text where the truncation of these records in 2016 is addressed.

**Reply: Thank you for pointing this out. We have now added the used end date in Table 1. According to the comments, we fixed Figure 2 as requested:**

- (1) We extend the data of S5, S6 and S9 stations to 2018, but S10 records only extend until 2016, as now indicated in Table 1.
- (2) We also update the results of S5, S6 and S9 for the year of 2017, 2018 in all the figures and tables, and text.
- (3) Regarding the data treatment and gaps, we give a detailed description in the third paragraph of "2.2.1 AWS data and processing". We indicate here that for annual or multi-year averages of SEB components, we only use complete years, therefore in the analysis of SEB, these gaps are not specifically addressed. Note that in Figures 6, 7 gaps occur for the same years, and we have added an explanation in the text.

L217-223: How are periods of ice- and snow-covered surface determined? Is this information derived from albedo calculations using the station data?

**Reply: Indeed, determining whether snow or ice is present at the surface is done by combining surface albedo and sonic height ranger data. This is now stated at Line 232-233.**

L259-260: It is again not entirely clear what "reasonable agreement" means in quantitative terms here. Is "reasonable agreement" a qualitative assessment of the percentage differences reported in the last sentence of the next paragraph?

**Reply: Please see reply to "L11-12" comments.**

L291-294: More recent references on the post-2012 slowdown in GrIS mass loss could be cited here and in L351-353, including Mouginot et al. (2019) and the Shepherd et al. (2019) paper already cited in the introduction.

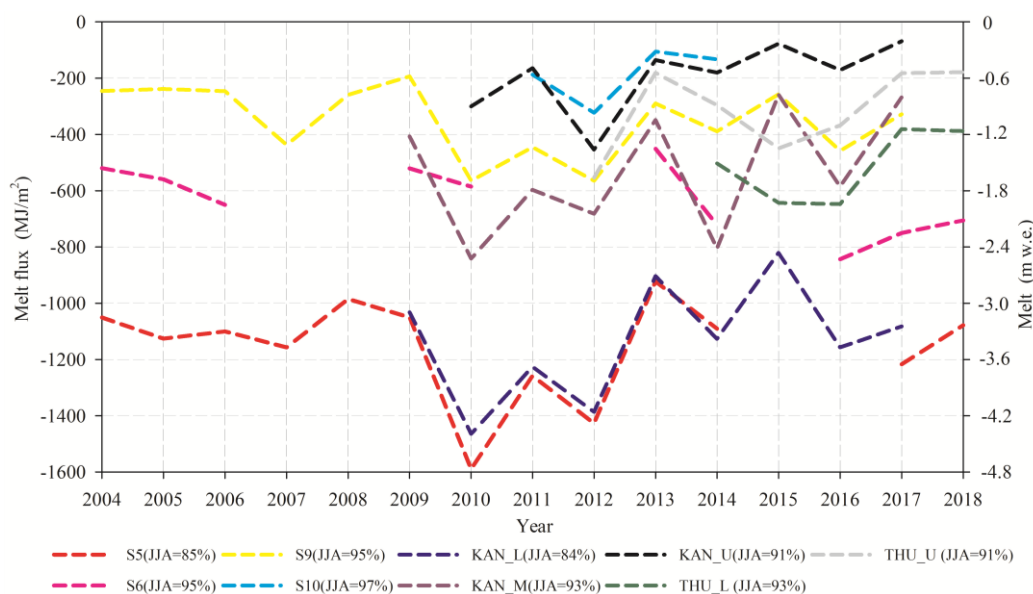
**Reply: Here we have cited these two papers.**

The strongest melt occurred in summer 2012, contributing to the largest annual ice-sheet mass loss on record (*Khan et al., 2015; Mouginot et al., 2019; Shepherd et al., 2019*), followed by a return to more average conditions in 2013 (*Nghiem et al., 2012; Kuipers Munneke et al., 2018*).

Figure 6 and Figure 7: The color-coding of lines in these figures should be matched so that the same stations are plotted with the same colors in each figure, unless there is a

compelling reason not to do this.

**Reply: We re-plotted Figure 7 in order to make the line colors of Figure 6 and Figure 7 consistent.**



**New Figure 7**

Figure 7: In my opinion, this figure would be easier to intuitively interpret if the y-axes were flipped so that more positive values indicate greater melt.

**Reply: We prefer to retain the negative value for melt energy to keep the SEB equation consistent and the SEB figures clear. We add the explanation as follows:**

In the Surface Energy Balance (SEB) equation:

$$M+S_{in}+S_{out}+L_{in}+L_{out}+Q_h+Q_l+G+Q_p=0 \quad (1)$$

all fluxes that are directed towards/away from the surface (surface gains/loses energy) are defined positive.

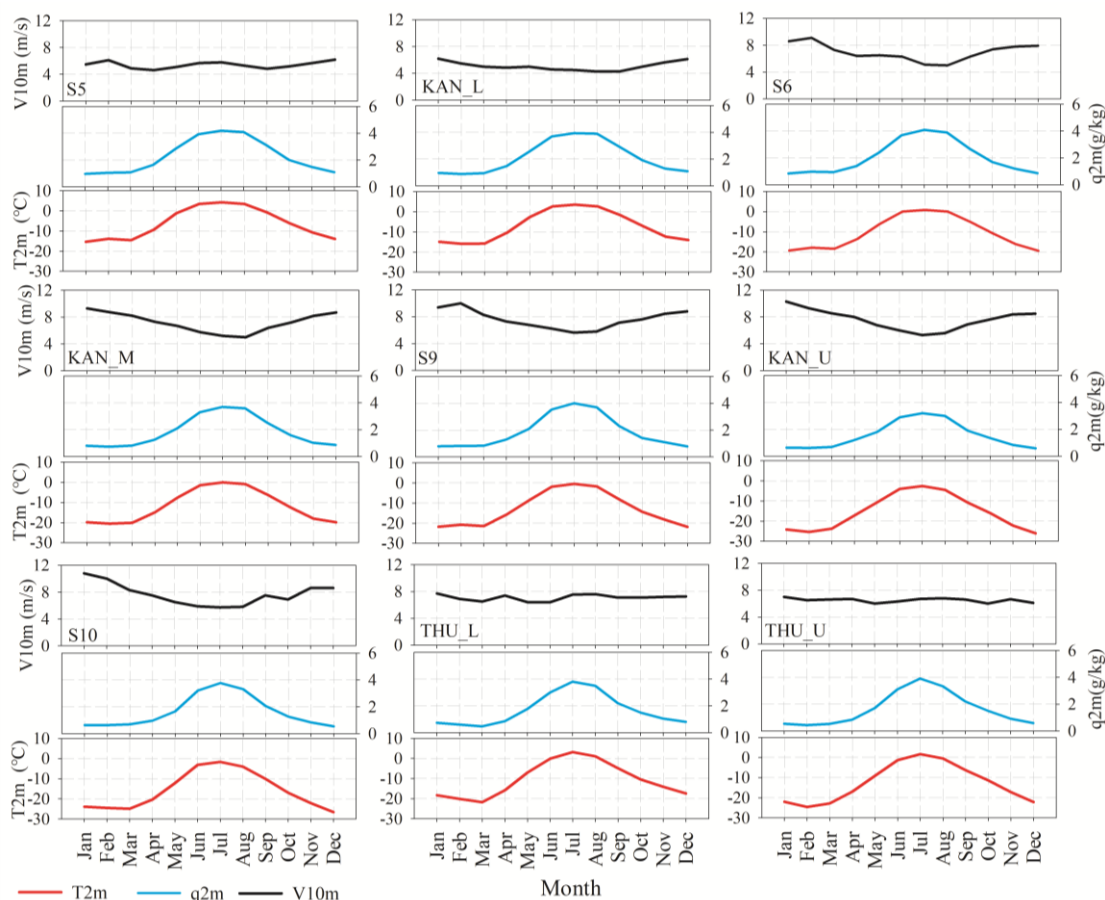
General comment on figures: Text size should be increased by a moderate amount on all figures to increase legibility. Text in Figures 8, 9, and 11 is particularly difficult to read at normal zoom levels for reading.

**Reply: We enlarged the font size in Figures 8, 9, and 11.**

Figure 8: Why are q2m and 10-m wind speed plotted on a shared y-axis? I understand the authors need to conserve the use of space in this multi-panel figure, but it seems more logical that q2m would be plotted on the same panels as t2m, as these two variables are measured at the same level and can be expected to be highly correlated due to Clausius-Clapeyron.

**Reply: Combining this suggestion with the suggestions from the second reviewer,**

we separated the three variables. If q2m and t2m are plotted on the same subplot, it is difficult to distinguish the amplitude of the seasonal cycle of q2m.



**New Figure 8**

L370-371: The meaning of the sentence “Specific humidity largely follows temperature” is not entirely clear. I assume it means that specific humidity increases alongside temperature due to the greater water vapor capacity of warmer air, but this should be stated clearly if so.

**Reply: We changed this sentence following the reviewer's suggestion.**

Specific humidity increases alongside temperature due to the greater water vapor capacity of warmer air, implying that specific humidity largely follows temperature.

Figure 9: Following the sign conventions of the SEB terms on this plot, should melt energy values be positive?

**Reply: Please see reply to “Figure 7” comments.**

L405-409: From examining Figure 9, it appears the summer Qh peak is as high or higher than the winter peak at S5, KAN\_L, and THU\_L. Consider rephrasing L406 to say that “\*Most\* stations show a maximum in winter..”

**Reply: Here we checked the value of Qh in summer, and then we fixed this sentence.**

Most stations show a maximum in winter, reflecting that  $Q_h$  is the main SEB component to balance  $L_{net}$ .

L460-462: Can the authors provide any reasoning as to why ERA5 improves on ERA Interim for albedo? Is there perhaps a revised surface scheme for ice sheets in ERA5?

**Reply: we add the explanation as follow:**

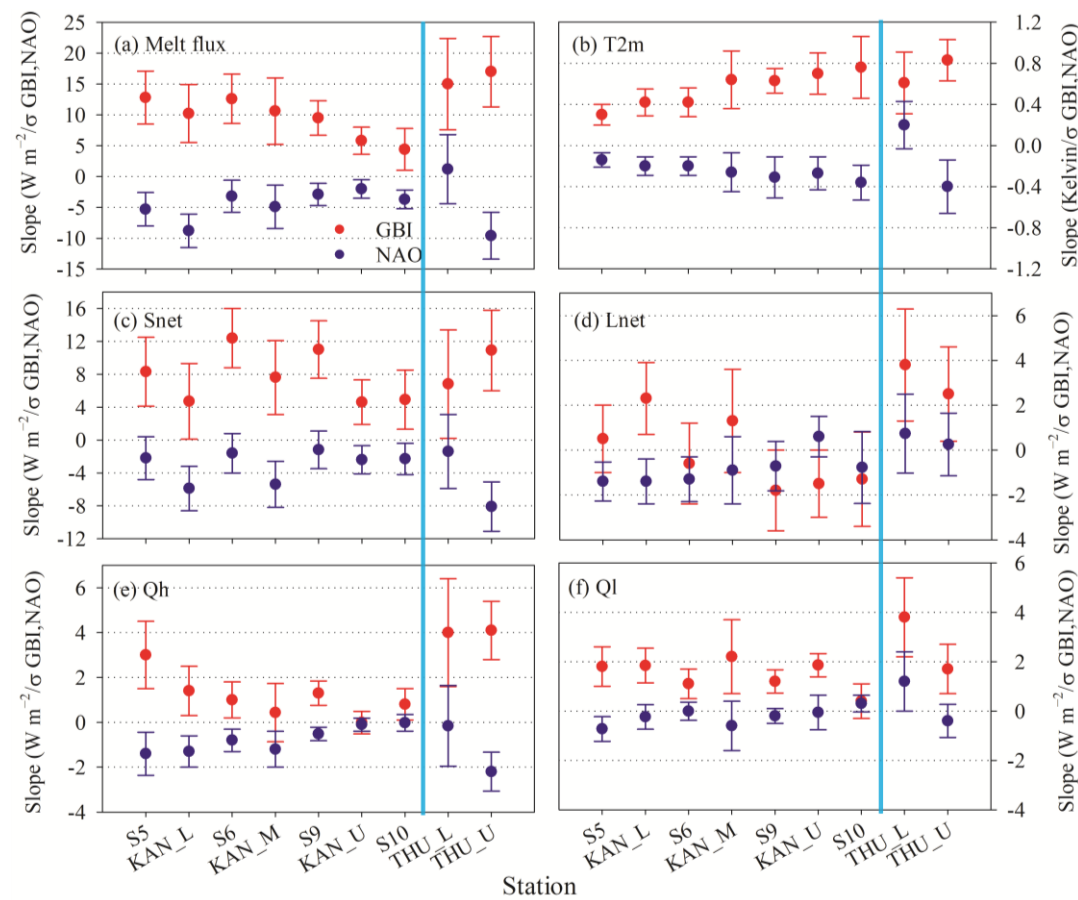
This is probably caused by the new snow albedo scheme, which changes exponentially with snow age in ERA5, and resets fresh snow albedo, while ERA-Interim set a maximum constant albedo for snow events (*ECMWF, 2016*).

L463: Why is this section called the “Discussion”? It seems to me to be a continuation of the reporting of the study results, and it doesn’t seem that there is a separate “discussion” section in this paper per se. I would recommend renaming this section.

**Reply: we re-named “4.3 Discussion” as “4.3 Relationships with large-scale circulation variability”.**

Figures 11-13: For clarity, units of the regression slope ( $W\ m^2/\sigma\ GBI,NAO$ ) should be included as labels of the y-axes in Figure 11 and the colorbars in Figures 12-13.

**Reply: we have added the slope units to Figure 11 and Figures 12-13.**

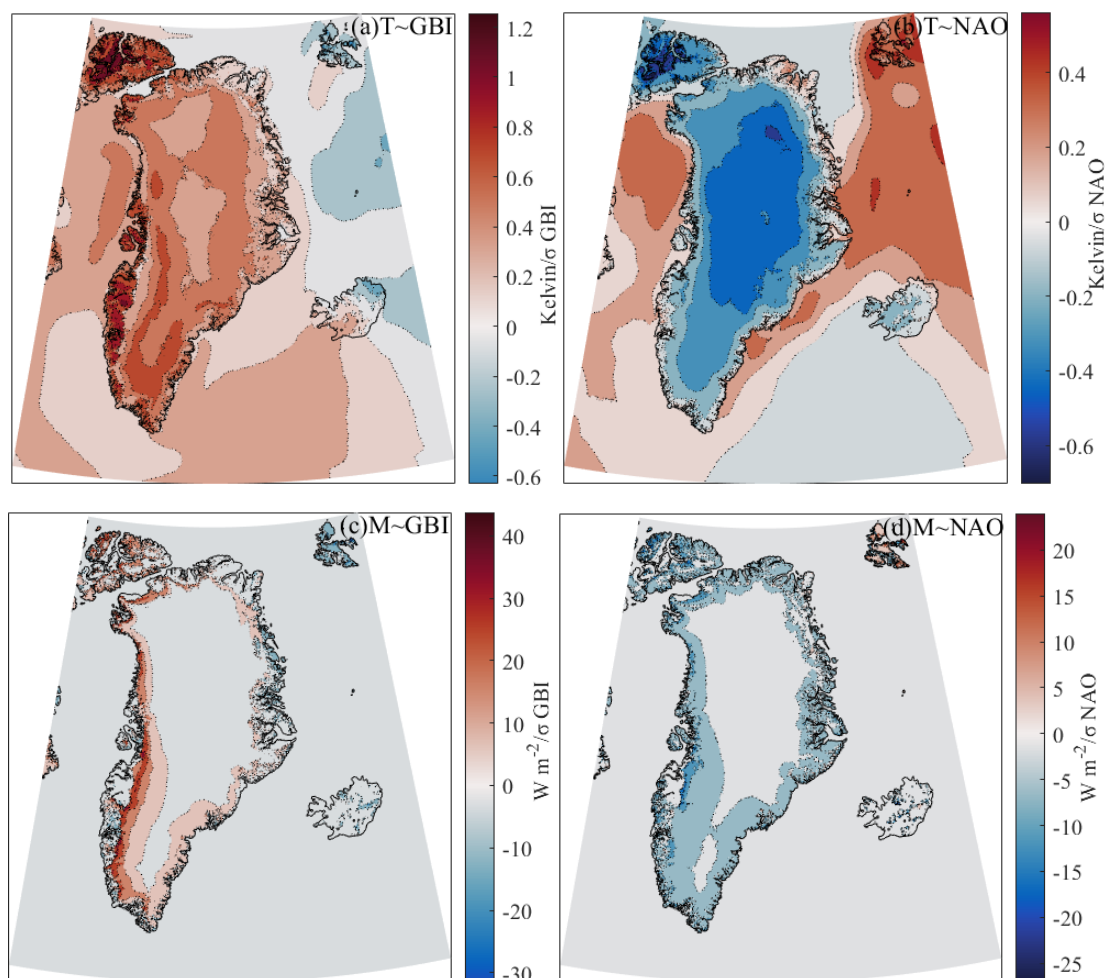


**New figure 11**

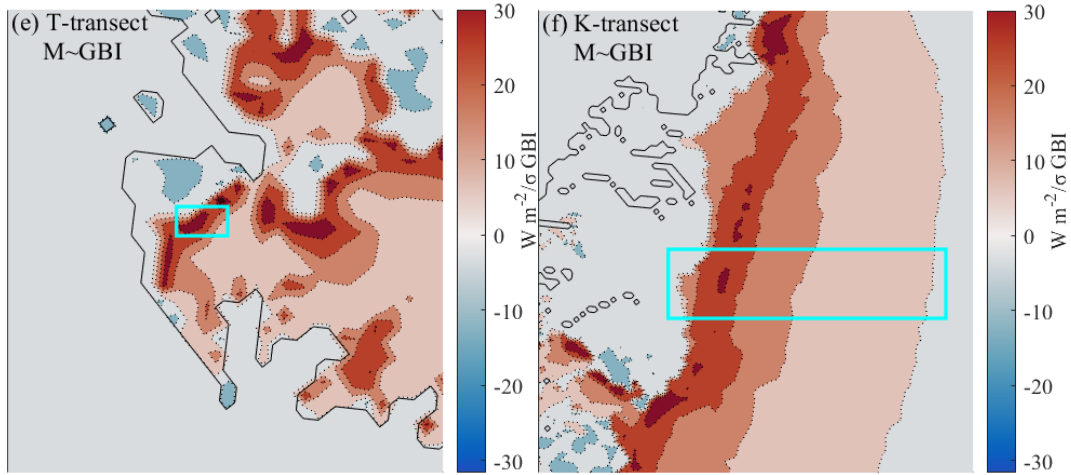
Figure 12 and Figure 13: The color ramps on these maps appear more suited for sequential rather than diverging data. To make it easier for the reader to discern areas of positive and negative regression slopes, a diverging color ramp should be used (for example the cmocean “balance” color map, for implementation in MATLAB see <https://www.mathworks.com/matlabcentral/fileexchange/57773cmocean-perceptually-uniform-colormaps>). Additionally, the color scale should be set with a midpoint at zero to ensure that warm colors show above-zero values and cool colors show below-zero values.

**Reply: Thank you for the suggestion to use toolbox “CMOcean Colormaps”.**

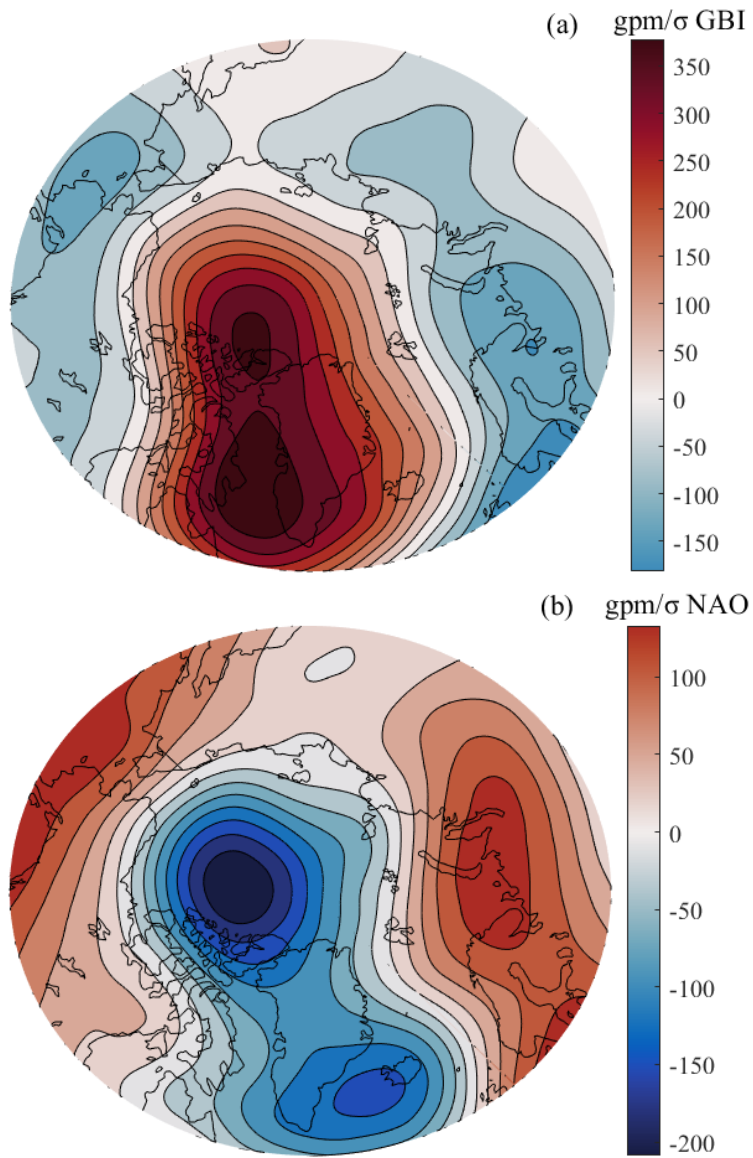
**We now use “cmocean ('balance', 'pivot', 0)” for the new Figure 12 and Figure 13.**







**New Figure 12**



**New Figure 13**



Figure 12: Coastlines should be included in panels e and f.

**Reply: We added coastlines to Figures 12 e and 12 f as shown above.**

L532-534: Figure 13 can be used to infer southwesterly advection of warm and humid air to NW Greenland given the spatial pattern of the regression slope. However, the maps do not show actual 500 hPa height contours or any wind vectors, so the figure does not directly show this phenomenon. This sentence should be amended to clearly indicate that this southwesterly advection has been inferred rather than directly shown.

**Reply: Here we changed the sentence as follows:**

Assuming geostrophy, the circulation anomalies in Fig. 13a imply anomalous southwesterly flow in northwest Greenland blocking conditions. Previous studies confirm that in the northwest, during blocking conditions anomalous southwesterly advection of warm and humid air results in higher temperatures and enhanced cloudiness, which explains the more important contributions made to the melt anomaly by  $L_{\text{net}}$ ,  $Q_h$  and  $Q_l$  (Noël et al., 2019).

## Technical corrections

Title, L6-7, and elsewhere: My personal preference is to capitalize “Ice Sheet” in the phrase “Greenland Ice Sheet”, since these letters are capitalized in the abbreviation “GrIS” throughout the paper. However I recognize that opinions differ on this and will leave it to the authors’ discretion.

**Reply: We changed as “Greenland Ice Sheet”.**

L14: “show” → “shows”

**Reply: Thank you, changed.**

The multi-year average seasonal cycle of SEB components shows that  $S_{\text{net}}$  and  $M$  peak in July at all AWS.

L19 and elsewhere: Capitalize the first “I” in “ERA-Interim”

**Reply: Changed.**

L23 and elsewhere: Be consistent with using a hyphen or no hyphen in the words “reanalysis” and “reanalyses” (i.e. L23 says “re-analyses” while L24 says “reanalyses”).

**Reply: Changed.**

L52: “described” → “have described”

**Reply: Changed.**

L68: This is a misquote of Rajewicz and Marshall (2014). The actual quote from this

paper is “... in Greenland” rather than “... in GrIS”.

**Reply: Changed.**

Table 2: There appear to be errors in text spacing and punctuation for the description of the wind speed and direction instruments. Are these sensors named “05103-5” and “05103-L” and manufactured by the same company (R. M. Young)?

**Reply: These sensors are from same company (R. M. Young05103).**

Table 2: “Kipp Zonen” → “Kipp & Zonen”

**Reply: Changed.**

L149: “time” → “temporal”

**Reply: Changed.**

L164: This sentence would be easier to interpret with a comma after the word “evaluation”.

**Reply: Changed.**

L198: “sites” → “site”

**Reply: Changed.**

L318: “ice sheet” → “ice sheet surface”

**Reply: Changed.**

L488: “clearsky” → “clear-sky”

**Reply: Changed.**

L506: “axis” → “axes”

**Reply: Changed.**

L522: “response” → “responses”

**Reply: Changed.**

L539-542: This sentence doesn’t make sense as written. Is the Hanna et al. 2013 reference supposed to be in the parentheses as an additional reference in support of the claim that “high summer GBI episodes are clearly linked to exceptional GrIS melt years”?

**Reply: We corrected this sentence to read:**

High summer GBI episodes are clearly linked to exceptional GrIS melt years (*Hanna et al., 2013; 2014*), but *Hanna et al. (2013)* as well as our results highlight the complexity of the response to variations in summer GBI.

L575, 583: “~” → “-“

**Reply: Changed.**

L592: “show” → “shows”

**Reply: Changed.**

L593: “similar” → “similarly”

**Reply: Changed.**

L601: “as” → “and”

**Reply: Changed.**

## **References**

**Reply:** We add these new references.

Mouginot, J., Rignot, E., Bjørk, A. A., van den Broeke, M., Millan, R., Morlighem, M., et al. (2019). Forty-six years of Greenland Ice Sheet mass balance from 1972 to 2018. *Proceedings of the National Academy of Sciences*, 116(19), 9239-9244. <https://doi.org/10.1073/pnas.1904242116>.

Braithwaite RJ, Konzelmann T, Marty C and Olesen OB (1998) Errors in daily ablation measurements in northern Greenland, 1993-94, and their implications for glacier climate studies. *J. Glaciol.*, 44(148), 583-588.

Van den Broeke, M. R., König-Langlo, G., Picard, G., Kuipers Munneke, P., and Lenaerts, J. T. M.: Surface energy balance, melt and sublimation at Neumayer Station, East Antarctica, *Antarct. Sci.*, 22, 87-96, <https://doi.org/10.1017/S0954102009990538>, 2010.