We would like to thank the editor and the three anonymous referees for their thorough evaluations with constructive comments that certainly will improve the manuscript. In the following, we will address the referees' comments point by point. We mark red the comments given by the referee, give our answers and comments in black and indicate how we addressed the amendments in the manuscript in green.

Comment on tc-2021-388

Anonymous Referee #1

Referee comment on "The impact of climate oscillations on the surface energy budget over the Greenland Ice Sheet in a changing climate" by Tiago Silva et al., The Cryosphere Discuss., https://doi.org/10.5194/tc-2021-388-RC1, 2022

Silva et al. examines the influence of the North Atlantic Oscillation (NAO), Greenland Blocking Index (GBI), and a cluster-aggregation of the aforementioned indices along with integrated water vapor (IWV) over the Greenland Ice Sheet (GrIS) on regional surface energy budget (SEB) changes, derived from the polar-adapted Regional Atmospheric Climate Model (i.e., RACMO2), between the 1959-1990 and 1991-2020 periods. In addition to deconstructing the GrIS-wide and regional SEB and thermodynamic variables (e.g., skin temperature, IWV, and near-surface specific humidity) by phase of these raw and clustered climate indices, the authors also correlate the accumulation and ablation zone rates of change associated with the indices' phases to each of these variables individually for winter and summer seasons. Mesoscale processes forcing SEB changes (e.g., loss of local sea ice increases in wind speeds due to strengthening surface pressure gradients) are also discussed in the context of results. Main conclusions include that GrIS surface warming is most pronounced during winter (following the strongest period of Arctic Amplification), but the associated magnitude and spatial pattern of temperature changes depend on the prevailing atmospheric pattern and presumably its frequency. Meanwhile, sensible heat flux increases in the summer ablation zone are found regardless of the atmospheric circulation pattern, further signaling the importance of mesoscale controls (e.g. katabatic wind strengthening due to land-sea temperature and pressure changes) on low-elevation melt. The level of detail provided in linking the climate indices/oscillations to the SEB and thermodynamic variables is commendable and presents a more detailed picture of atmosphere-GrIS surface forcing than is typically presented in comparable studies.

However, this amount of detail also presents challenges with regards to clearly distilling key results. As such, the main findings could be more clearly stated in the abstract and especially in the conclusions. If key takeaways and related points could be more clearly stated through the manuscript, this study could be a valuable addition to the literature.

My comments are provided by line number (LN) or specific figure below. While most are minor in nature, the total number of comments may tilt the paper toward the category of major revision.

We thank Referee #1 for the overall positive assessment. We acknowledge the main concern that also resonates in other reviewers' comments: the fact that we need to state our main findings more clearly. We will integrate this in a revised version as suggested to condense our findings into clear take-home messages. In this way we should be able to address the main criticism appropriately. Below, we list and comment issues of minor nature from Reviewer #1 point by point.

LN14: Do you mean clouds have become optically thinner? Please clarify.

We state that the atmospheric optical thickness has decreased in the southern parts of Greenland. Aside from the cloud's physical state, we do not explore to which extent the decreasing optical thickness is related to other changes in cloud's microphysics properties. What we can add, though, is due to the decrease in water vapor abundance, cloud's formation becomes improbable in the region.

LN43: Can you clarify what is intended and ultimately hypothesized by "tilt within largescale structures may have an impact at different locations"? Work by Woollings et al. (2008) J. Climate and Hanna et al. (2018) Int. J. Climatol. has shown that that the setup of Greenland blocks tends to precede by a couple of days downstream positive North Atlantic SLP anomalies in the vicinity of the Icelandic Low (i.e., -NAO conditions). Perhaps referencing this work may help clarify the large-scale structural reference?

The references suggested are indeed relevant for the description of the large-scale systems in the North Atlantic and we will include them once we submit a revised version. We will also reformulate the paragraph addressing the hypothesis mentioned by the Referee. The vertical tilt (of temperature and geopotential) within large-scale systems exists due to baroclinicity and recently has been pointed out by Martineau et al. (2020) as an essential mechanism in the North Atlantic for large-scale system development. Therefore, we hypothesize that the tilt within large-scale structures plays a role when calculating climate oscillations, which rely on one parameter at one specific atmospheric level (only at 500 hPa or only at the surface). We thus suggest various spatiotemporal effects on the near-surface impacts dependent on the climate oscillation in use. Particularly in the cold season and under strong cyclonic influence, the usage of a classification that combines NAO and GBI rather than select one of these climate oscillations in isolation may help to account for processes in different atmospheric levels as the air mass properties are distinct (e.g., frontal systems).

In fact, the seasonal composites made for each NAG (Fig. S4) show that the location of the maxima of geopotential height at 925 and 500 hPa, respectively, are typically hundreds of kilometers apart. These distances are likely to be larger for analysis in higher temporal resolutions.

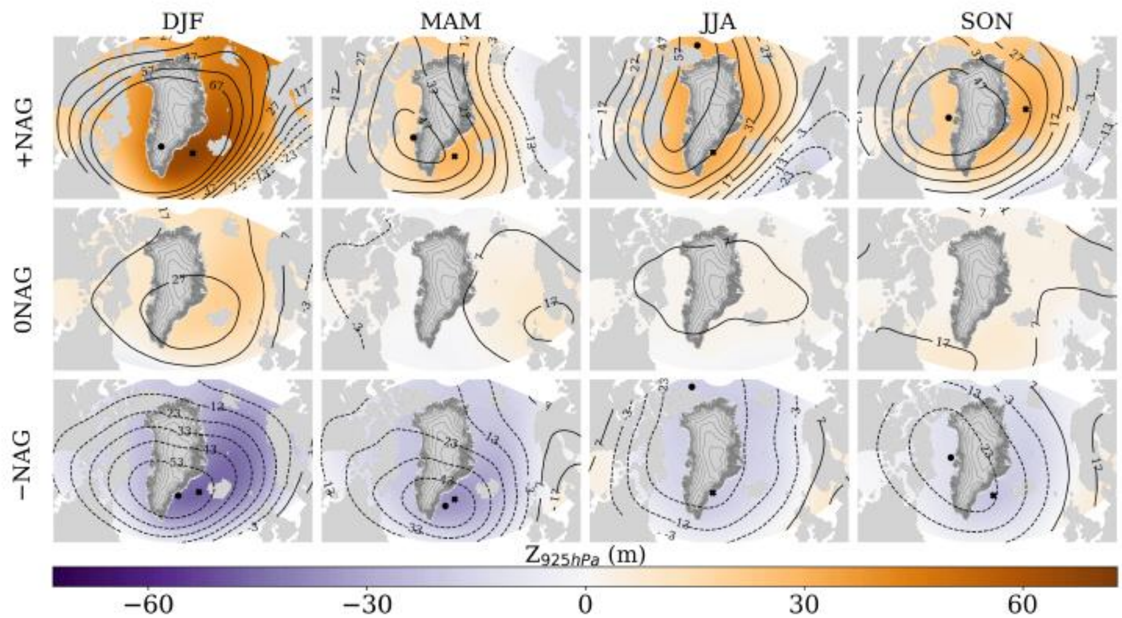

Figure S4. Inter-seasonal 500 hPa geopotential height anomaly (contour lines; positive: solid and negative:dashed; spaced in 10 m intervals), and 925 hPa geopotential height anomaly for each NAG phase with respect to climatology (1959-2000). The ridge (trough) at 925 and 500-hPa geopotential height anomaly is indicated as dot and cross, respectively, for +NAG(−NAG).

LN76: It would be good to emphasize around this point in the introduction the explicit goal and primary research questions of the study. These would help build upon some previously mentioned hypotheses (e.g., LN 74-75) by adding more structure and thus guidance for the reader toward analyses that lie ahead.

Thanks, we changed this as suggested. We initially had decided to state each of our hypotheses next to the respective literature review paragraph (1st hypothesis in LN 43 and 2nd hypothesis in LN 74) instead of a paragraph explicitly dedicated to our research goals. We will follow the referee's suggestion to emphasize at the beginning of the last introductory paragraph our research aims.

Here, we explore a cluster method that links the role of the North Atlantic Oscillation (NAO) with the prevailing mid-troposphere circulation pattern over Greenland, commonly known as Greenland Blocking Index (GBI), along with the atmospheric water vapor over the GrIS. Additionally, we investigate the regional impact on the surface energy budget (SEB) of contrasting atmospheric circulation clusters, and finally, we examine changes on SEB components within clusters by comparing recent decades (1991-2020) to a historical period (1959-1990).

…

Section 2 describes the data analyzed, explains the clustering method, and justifies 1991 as the period breakpoint. The Results and Discussion is broken into three subsections. In Section 3.1 we show the inter-annual variability of the newly cluster-derived classification and compare it with NAO and GBI alone; in Section 3.2 we describe the inter-seasonal and regional variability of the cluster classification; in Section 3.3 we present spatio-temporal anomalies within the same atmospheric circulation cluster, and finally, we focus our discussion on the regional changes in the summer ablation zone.

LN 117: List the flux terms units, W/m^2?

Thanks, we include the flux terms units as suggested.

LN126-127: I think you could move this sentence (beginning with "Using the 62 years…") to L131 and explicitly list the sub-periods that were the result of equally dividing the total years in the dataset.

Thanks, we took into consideration the Referee's input! Since Referee #3, recommended to make this particular section clearer in the manuscript, we reformulated the paragraph. This improved paragraph contains an explanation of trends in sub-periods, a definition of the trend ratio, an example of one period ratio and most importantly we explicitly state the reason for the breakpoint detection.

Most studies agree that the pronounced Greenland summer mass loss started in the 1990s (e.g. Mouginot et al. 2019, Hanna et al. 2021, Shepherd et al. 2020). However, the onset of a clear negative trend varies depending on the time period of each study and on the dataset used. In order to determine the breakpoint of the marked summer mass loss in RACMO2, we divided the GrIS into its main seven drainage basins (see Fig. S1) and run regional trends for multiple periods with multiple sizes for the 62 years of data. This will allow the investigation of atmospheric and glaciological conditions prior and post the breakpoint. The breakpoint was formed on the most regionally frequent and the largest absolute trend ratios. One trend ratio (RT) is based upon two slopes from equally-sized sub-periods that are split in a common central year. The division of the slope after the central year (s2) by the slope before the central year (s1) produces one RT. For instance, s1 between 1977 and 1995 and s2 between 1995 and 2013, whose central year is 1995 (Fig. 1) gives RT > 1. This means that s2 is more pronounced than s1. The length of each sub-period varied from 15 to 32 years.

The non-parametric Mann-Kendall (M-K) trend test is used to assess trend monotonicity and significance on summer surface ablation rates (c.f. Section 2.2). The slope corresponds to the Theil-Sen (T-S) estimator. The T-S estimator is a robust regression method that does not require the data to be normally distributed and is hence less vulnerable to outliers. One specific period is considered significant only when the confidence level from the M-K test is higher than (or equal to) 90% in both sub-periods. Trends in periods exhibiting confidence levels lower than 90% may still be identical to those exhibiting greater significance levels but given their high variability they were not considered.

As we analyzed 612 trends for equally-sized sub-periods, we consider it unfeasible to explicitly list them. Nevertheless, we show to the Referee in the figure below the distribution of sub-periods used.

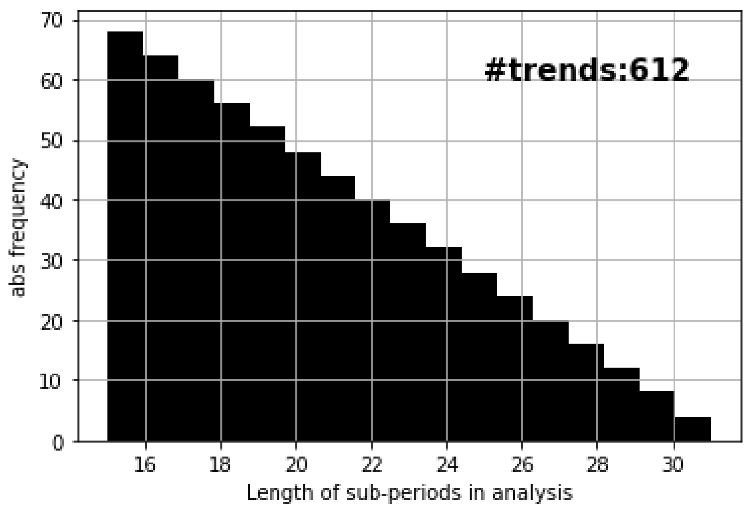

Figure R1-Distribution of sub-periods used for the trend analysis in Section 2.3

L155: Both the NAO and GBI indices should be defined here (e.g., domains, methods, papers defining such, etc). Moreover, both atmospheric indices are derived at z500, did you look at the surface NAO (i.e., Hurrell PCA or weather station-based NAO)? In this context, I recommend in the paper that you address why only z500 indices are used or why NAO from SLP data is not used. This discussion would seem appropriate since you are exploring through cluster analysis how co-varying characteristics of these atmospheric patterns (along with IWV) may impact GrIS surface conditions.

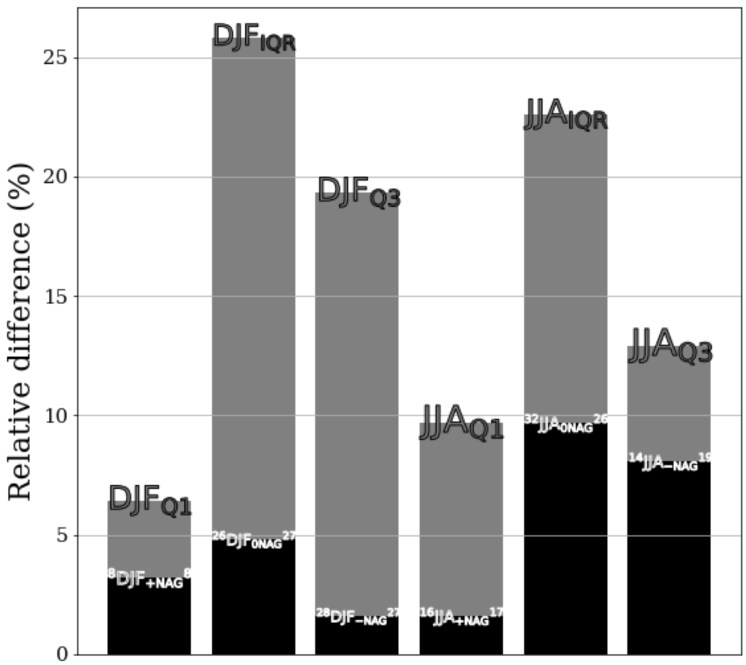

Figure R2- Relative differences on NAO percentile (gray) and NAG (black) classifications dependent on the NAO used. The first (last) three bars correspond to winter (summer) phases.

Thanks, this indeed is a crucial remark to highlight in the methods and discussion, as the NAO can be calculated with different methods (e.g., weather stations, PCA and clustering) at different pressure levels (e.g. surface and 500 hPa).
We follow up on this by statistically comparing two datasets using PCA: the surface (Hurrel) NAO (from NCAR) and the 500 hPa NAO (from NCEP/CPC). Relative differences on NAO percentile and NAG classifications dependent on the NAO used are shown in Figure 2. The NAO as derived from different levels is highly and positively correlated. However, the NAG clustering and the NAO percentile classification are sensitive to the dataset used. Relative differences in the NAG classification are lower than 10% and are essentially related to the separation with the neutral phase. Typical NAO classifications using the 1st and 3rd quartile to respectively categorize negative and positive phases show (up to 10 times) larger disagreements than the NAG classification. The disagreement between the NAO from different levels roses from variations at the 500 hPa geopotential height anomalies that are not resembling with surface anomalies.
The NAG results from Figures 4 and 5 are dependent little on the NAO definition used as all spatial anomalies remain. In general, the spatial anomalies using surface NAO are larger and more significant than for 500hPa NAO. However, spatial anomalies based on the percentile classification depend greatly on the pressure level used for deriving NAO, as the spatial anomalies for surface and 500hPa are different (occasionally, with opposite signals) in some cases.
Once again, we appreciate the referee's remark that will make our study more comparable and applicable. We will hence adapt our results using the definition of NAO by Hurrel (PCA based). In addition, we will briefly highlight differences between both NAO methods.

LN167-168: To clarify the sentence, I recommend substituting "predominant" with "prevailing" then remove "prevailing" in LN168.

Thanks, we changed this as suggested.

LN172: The clustering approach could use more description. Why did you pick 3 clusters? Did you select these based on subjective or objective criteria? Are the results sensitive to the number of clusters selected and analyzed?

The selection of 3 clusters (negative, neutral, and positive) is based on the number of climate oscillation phases commonly used in many studies (e.g. Croci-Maspoli et al. (2007), Gimeno, et al. (2002), Wu and Zhang (2015)). We believe that the inclusion of more clusters is not useful, as they become abstract and objectively challenging to physically interpret them. As shown above, the results are sensitive to the selected variables (NAO, GBI, GrIS IWV) in the cluster, as well as the number of clusters set.

LN179: Be more specific on what data is shown in the Figure S3 scatterplots. This is very vague as currently written.

Thanks, we will improve Figure S3 caption to:

Seasonal NAG phases based on the k-means clustering: positive (red cluster); neutral (black cluster); and negative (blue cluster) phase.
NAO and GBI phases are categorized based on the seasonal 25th (blue line) and 75th (red line) percentile. The Spearman correlation coefficient (rS) is shown for clusters with significance higher than 90%.

The third-dimension correspondent to GrIS IWV is omitted. The dark circle indicates years whose seasonal GrIS IWV is greater than the 95th percentile.

LN183: "The positive phase of NAG is connected…" Is this "connection" illustrated somewhere either graphically or statistically? This would be helpful to show the reader to see what +NAG entails.

We show the NAG and its relations in Figure 2, S3 and S4:

Figure 2 illustrates the development of NAO and GBI over time. Figure S3 shows the relationship between NAO and GBI and the respective NAG clusters/phases. Figure S4 characterizes the anomalies of geopotential height at 500 hPa with respect to the climatology dependent on season and NAG phase.

We complete the sentence with: Based on resulting clustering (Fig. S3) and the involved large-scale structures (Fig. S4), the positive phase of NAG is connected to the …

Figure 2 caption: The last sentence is unclear. I suggest mentioning that data from 1991 onward is found to the right of the gray vertical line.

We expand this and add:

For reference, 1991 is highlighted to illustrate GBI, NAO and NAG phases, as well as seasonal accumulated SMB in the time-series.

L192: Why show the 925 hPa height anomaly rather than SLP, a field typically used in defining surface pressure characteristics of the NAO.

For practical reasons, model pressure levels were preferred, but for clarity we can easily replace 925 hPa by surface pressure in a future version.

L193: "vertical tilting structure" meaning what? Please clarify.

We expand this definition stating:

Under strong baroclinicity, the minimum/maximum in geopotential (Fig. S4) and temperature are vertically titled within large-scale structures.

L199: Do you mean "winter" instead of "spring" is when the equator-to-pole air temperature contrast is maximized?

On average, the strongest equator-to-pole temperature gradient coincides with the end of winter. Depending on the year, the maximum equator-to-pole air temperature contrast takes place between February and March, and therefore coincides either in the meteorological late winter or early spring. In order to avoid misinterpretations, we drop the clause ("when the equator-to-pole temperature is the strongest") out of the sentence.

Figure 3: Should the colorbar label r_s(Seasonal ablation…) be r^2 as it is in the caption?

While the figure colors are representative of the Spearman correlation (r_S) and vary from -1 to 1, the noted number (r_S^2) indicates the proportion of shared variance among ranked variables and ranges between 0 and 1. We reformulate the second sentence of the figure caption to: The Spearman correlation coefficient (r_S) is color-coded and the determination coefficient (r_S^2) is displayed.

Figure 4: "The percentage of each NAG phase used..." can you please clarify what this means? As I interpret it, it sounds like some +/-NAG days were composited and some were not without explanation as to why since f0 and f- percentages do not sum to 100% (as in Fig 5).

Thanks for pointing this out. This was indeed misleading. The relative frequency of seasonal NAG (0NAG, +NAG, -NAG) sums to 100%. However, as the 0NAG is the reference for +NAG and -NAO, we indicated its frequency at both instances. We improve the mentioned caption sentence to: The seasonal frequency (f in %) of each NAG phase (0NAG, +NAG, -NAG) used to produce composites is indicated as subtitle.

LN253: Remove "configuration."

Thanks, we removed this as suggested.

Also, since these surface temperature and radiative fields (i.e., Fig 5) increase regardless of atmospheric pattern, does that suggest that warming climate is the main culprit in driving these fluxes that impact SMB? What link is being made with adjacent marginal seas; they respond similarly to these fields as the GrIS?

Our results suggest warming climate and its spatial magnitude over the GrIS depending on the NAG phase. As we supposedly split internal climate variability into clusters, we point anthropogenic effects as the culprit in the Conclusions. However, a direct attribution to individual factors of such a complex system is indeed very challenging and beyond our study scope.

Temporal changes over the adjacent seas depending on season and NAG phase are described and compared to GrIS along the Results and Discussion (e.g., LN261, LN279 and LN305). However, we acknowledge that this point is a missing point in the Conclusions, and therefore, we will add it in a revised version.

LN 270-271: In comparing 1991-2020 against the reference period, do you mean "increased surface-based inversions…"

We simply adopt the hypothesis from other studies (e.g., Niwano et al. 2019) stating that surface-based inversions in combination with subsidence are the physical mechanism responsible of the elevated values of water vapor near the surface. To avoid confusion, we reformulate the sentence to: As a consequence of the surface-based inversions favored by subsidence and surface melt, the surface comprises more q2m for the period 1991-2020 than during the reference period.

LN272-273: This sentence is confusing; the IWV increase over the northern GrIS is not related to local cloud water content? Please clarify. Is this shown in the analysis and if so, then where?

The IWV increase is not only related to the local cloud water content changes, but also a result of the increasing near-surface water vapor. We do not attribute the increase in SWnet to cloud water content changes in the Northern regions because the SWin and cloud water content did not significantly change in comparison to the reference period (Fig. S12). We improve the sentence to: Despite the residual change in SWin (Fig. S12) and cloud water content, the SWnet (Fig. S14) has significantly increased over the northern regions. Thus, we attribute the increase in IWV to the widespread increased q2m.

LN293: “high summer GBI values…” –where is this analysis shown?

In order to reduce the number of supplementary figures, we removed seasonal GBI and NAO time-series. However, this statement is supported in Figure 2 as seen by the red shading enhancement and frequency of positive GBI greater than the third quartile (marked by diamonds). In addition, we will also add a few studies entirely focused on the recent extreme GBI (e.g., Barrett et al. 2020) and the Greenland Blocking (e.g., Wachowicz et al 2020).

LN 297: “crucial role of NAO advecting heat and moisture…” through storms/the storm track migrating poleward toward Greenland?

We complete the sentence taking into consideration the reviewer’s remark.

LN311-313: This sentence is a bit hard to follow. I recommend splitting it into two sentences.

We follow the reviewer’s advice and change this paragraph to: The near-surface temperature gradient is enhanced by the larger increase of the air temperature than the temperature of the melting snow/ice surface that is physically limited to 273.15 K. The melting snow/ice surface, in conjunction with steep slopes, promotes downslope winds. In addition, the migration of the snowline to higher elevations of the ice sheet enhances the surface pressure gradient and adds momentum to the flow contributing to the observed wind speed strengthening.

LN315: To clarify, is the suggestion that the summer wind speed increase over northern GrIS is due to the near-complete summer melt of Baffin (particularly) ice cover, a typical feature of its annual cycle? Atmospheric circulation patterns can accelerate the melt, but their intensity and orientation could also presumably affect the onset of such summer wind increases.

We agree with the reviewer: atmospheric circulation patterns can influence the onset of the regional sea ice melt. We will add the Referee’s thought as follows: The wind speed increase in the Northwest ablation zone is only significantly different from the reference period under 0NAG (Fig. S12 and S13). The seasonality of the almost sea-ice free Baffin Bay (Bi et al. 2019) can be one of the factors that impedes statistical evidence in wind speed increase in the region. This is in contrast with the North and Northeast zones, where coastal margins are almost permanently ice covered during the reference period and the wind speed has increased significantly regardless of the NAG phase. The increased wind speed may also form brash ice which promotes more convection, and consequently, generates a low surface pressure in the neighboring seas that will enhance the regional surface pressure gradient leading to higher wind speeds.

LN 322-324: It would be a good idea to direct the reader to this figure or analysis within the paper.

We follow the advice and add the figure (Fig. 6) in the main paper in the revised version.

LN382: Change “has” to “have”

Thanks, we changed this as suggested.

Supplemental Material:

Figure S8: Label seasons at the top of the graphic as with Figure S7, etc.

Thanks, we labeled this as suggested.

Figures S12-14: I am confused what these graphics actually show and what the units on each concentric circle represent. Please clarify.

Thanks, we expand their description in their caption stating:

Fig. S12. Changes in atmospheric variables contributing to SEB components between 1959-1990 and 1991-2020 in the summer ablation zone for each NAG phase (color-coded). Variables in the panel a) exhibit the variable name and the respective unit. All variables in the panel b) are fluxes in W m^{-2}. The spatial relative frequency of ablation is shown at the center. Negative changes are limited by the gray area. Hollow circles indicate significant mean differences based on the Wilcoxon rank-sum statistic test for unpaired sets with a confidence higher than 90%.

These charts come to support the analysis in Figure 6. The radar chart aspect is an alternative to the bar chart in Figure 6.

References:

- Barrett, B. S., Henderson, G. R., McDonnell, E., Henry, M., and Mote, T.: Extreme Greenland blocking and high-latitude moisture transport, Atmospheric Science Letters, 21, e1002, https://doi.org/10.1002/asl.1002, 2020.
- Bi, Haibo, et al. "Baffin Bay sea ice inflow and outflow: 1978–1979 to 2016–2017." The Cryosphere 13.3 (2019): 1025-1042.
- Croci-Maspoli, Mischa, Cornelia Schwierz, and Huw C. Davies. "Atmospheric blocking: Space-time links to the NAO and PNA." Climate Dynamics 29.7 (2007): 713-725.
- Gimeno, Luis, et al. "Identification of empirical relationships between indices of ENSO and NAO and agricultural yields in Spain." Climate research 21.2 (2002): 165-172.
- Niwano, Masashi, Akihiro Hashimoto, and Teruo Aoki. "Cloud-driven modulations of Greenland ice sheet surface melt." Scientific reports 9.1 (2019): 1-8.
- Wu, Zhiwei, and Peng Zhang. "Interdecadal variability of the mega-ENSO–NAO synchronization in winter." Climate dynamics 45.3 (2015): 1117-1128.
- Wachowicz, L. J., Preece, J. R., Mote, T. L., Barrett, B. S., and Henderson, G. R.: Historical Trends of Seasonal Greenland Blocking Under Different Blocking Metrics, Int J Climatol, 41, E3263–E3278, https://doi.org/10.1002/joc.6923, 2020.