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 #3

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-RC3, 2022

General comments

In this study, the authors use a cluster analysis of NAO, GBI, and column water vapor to derive a "North Atlantic influence on Greenland" (NAG) index. RACMO2 output is then used to investigate atmospheric and cryospheric conditions across different NAG phases and their changes across a 1991 break point in summer surface mass loss. Results describe a large array of seasonal anomalies in atmospheric conditions and surface energy balance components across the NAG phases for each season during the pre- and post-1991 periods.

I found this paper difficult to follow due to the large number of figures and sub-panels within figures and the organization of the paper, as it lacks a clear statement of the research questions or summary of what important new information was learned in this study. I also agree with the editor that there is insufficient originality, at least with how the results are presented in current form. However, there do not appear to be any technical flaws in the methods employed, and I do think there is potential for some of the results to form a nice study if they are better organized. I encourage the authors to think about what they consider to be the most important and novel findings contained within their many analyses and distill these findings into a focused message for readers to take from the paper. As an example, the contrast between moistening in northern Greenland and drying / clearing in southern Greenland under +NAG conditions is an interesting finding. In addition to the specific comments and technical corrections below, I would recommend that the authors simplify the figures, and restructure the discussion so that a large part of the findings in the main paper are not describing figures found in the supplement.

We thank Referee #3 for the challenging remarks and appreciate the overall potential they see in our study. We acknowledge that there was indeed an obviously too unclear aim of the study which was similarly pointed out by Referee #1 and we will implement this very thoroughly in the revised version. We also take up the reviewer's recommendation and will strengthen the organization of the discussion in the revised version. This will significantly improve the reading of the paper. For now, we would point to the amendments made and the following major research questions that we will state at the end of the revised introduction:

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).

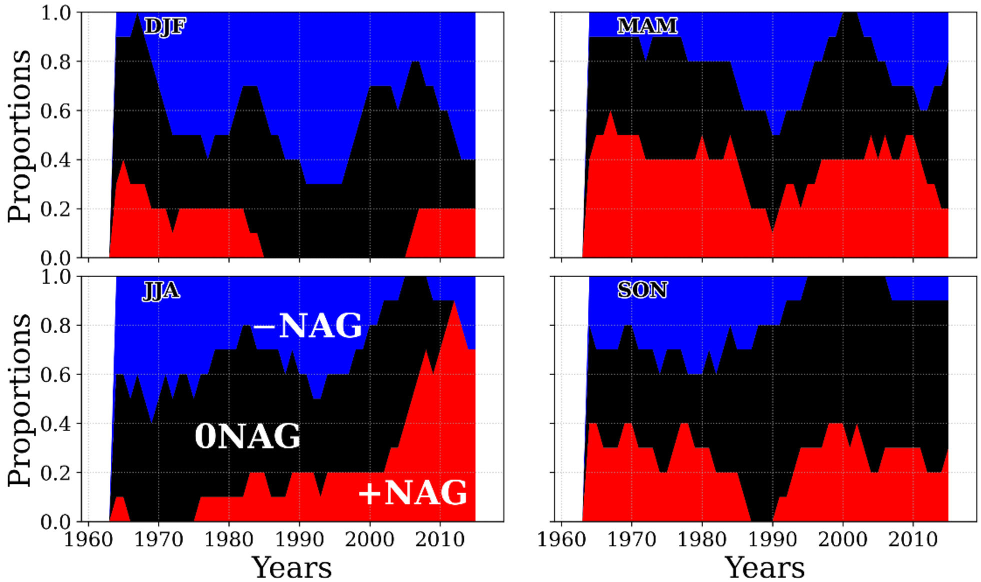
…

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

Furthermore, we will simplify the figures whenever appropriate.

Specific comments

Did the authors examine trends in the frequency of NAG phases, or did they only look at changes in atmospheric conditions over time during each NAG phase?



We made a brief trend analysis in the frequency of the NAG phases. We collected decadal-moving proportions as dependent on the NAG phase (Figure R1). However, we solely focused on spatio-temporal changes of the atmospheric conditions within NAG phases overtime. The NAG development over time is found in Figure 2.

L18–45: The opening paragraph of the Introduction is quite long and does not provide a compelling introduction to the research topic that the authors investigate. I think it would make more sense to first introduce the problem of Greenland surface melt and its atmospheric drivers (the second paragraph), before moving on to the indices that are used to help quantify these atmospheric drivers (first paragraph).

We acknowledge the referee's comment, which was also mentioned by Referee #1. We will reformulate the Introduction by moving the first paragraph and breaking it into two parts in the revised version.

L21: Liu and Barnes (2015) is a good reference on the relationship between Rossby wave breaking and poleward moisture transport in the vicinity of Greenland.

Thanks for pointing us towards this reference which we will implement both in the introduction and in the discussion in a revised version.

L29: I'm not sure it's correct to say that the NAO phase "explains most of the heat and moisture transported poleward". It's more accurate to say that the NAO phase affects the location and magnitude of poleward heat and moisture transport, and provide a reference on this.

Indeed, the formulation was misleading, and we adopt the formulation suggested by the referee. At the same time, we add the following references (e.g., Bjørk et al., 2018, Papritz et al, 2020).

L32: GBI simply quantifies the mean 500 hPa geopotential height over a Greenland centered domain, as the authors state in the previous sentence. It does not directly quantify the strength and moisture transported over the Greenland domain although it is correlated with these quantities (see the Barrett et al. 2020 paper the authors already cite). See Wachowicz et al. 2020 for a more nuanced discussion of the GBI and comparison with other blocking metrics.

To our understanding, GBI provides insight on blocking-like conditions in the vicinity of Greenland. We agree that "quantify the strength" was not the best wording. Nevertheless, positive GBI conditions can regionally block heat and moisture transport towards the interior of the GrIS. We reformulate the sentence as: Its index denotes the predominant atmospheric circulation pattern in the vicinity of Greenland, and it regionally controls the heat and moisture transported towards the interior of the GrIS.

L120 and Figs. 5, S9–S11: It is not clear how the method of dividing the adjacent seas into four areas is actually used to assess potential sources of moisture. I am having trouble understanding what the numbers in the corners of Figs. 5 and S9–S11 (the "differences in composites between adjacent seas") represent.

We were interested to know if changes in atmospheric variables over land were similar to the changes over the adjacent seas, as moisture and heat are advected from there towards the ice sheet. In order to simplify the visualization, instead of showing the spatial anomalies over the adjacent seas we preferred to show the temporal change in one value, which is displayed in the corners of each subpanel. We acknowledge the complexity of the figure, but at the same time we value its contribution to the discussion. We will move the 0NAG to supplementary and improve the caption description to: Seasonal and spatial anomalies for (a) integrated water vapor, (b) incoming longwave radiation reaching the surface, (c) near-surface specific humidity, and (d) skin temperature between 1959-1990 and 1991-2020 as dependent on the NAG phase from RACMO2.3.p2. The percentage (f) of the NAG phase in each period is indicated for each season. For reference, Summit and South Dome are marked as big and small triangles, respectively. Stippled regions indicate areas with a confidence level greater than 90% (based on the Wilcoxon rank-sum statistic test for unpaired sets). Temporal anomalies between composites over the adjacent seas are also shown as colored numbers (Baffin Bay: upper left; Greenland Sea: upper right; Irminger Sea (lower right) and Labrador Sea (lower left). See Figure S1 to discern the extension overseas and, Figure Sx to examine spatio-temporal anomalies under 0NAG.

L123: It should be stated explicitly at the beginning of section 2.3 that the reason for the break point detection is to form the basis for subsequent analyses of atmospheric and glaciological conditions before and after the break point. As it stands now, this section reads like it is reporting research findings, rather than describing a method that will be used to produce the results of the study.

We fully agree with the comment. Also, taking into consideration the comment from Referee #1, we reformulated Section 2.3 to:

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.

L172–180: State up front that you are using a k-means clustering method (rather than first describing the method and naming it as k-means clustering at the end of the description).

Thanks, we will name the clustering method before its description.

L181: I don't think the "influence of the North Atlantic over Greenland" is an accurate description of what the NAG index produced by the cluster classification provides. Maybe describe as the "influence of regional climate" on Greenland instead. (The AMV index, which specifically quantifies oceanic conditions, is discussed in the Introduction and in L159 in the Data and Methods, but doesn't appear to be included as an input to the NAG index.)

We name NAG as such given the importance of the North Atlantic Oscillation in setting the storm track and atmosphere-ocean interactions feeding large-scale weather systems along the North Atlantic. As mentioned in the Introduction, the AMV index was negative until the early 1990's and it has been positive since. Given the strong relationship in summer between AMV and GBI (and GrIS IWV), the inclusion of AMV alongside NAO, GBI and GrIS IWV in the 62 years of cluster analysis does not contribute with new information and it does not change the summer classification. However, in the remaining seasons (e.g. spring), positively high AMV in recent years adds noise to the classification by making GBI<0 and NAO>0 as +NAG, which is contradicting with the rest of the cluster.

L226, 232–236, 311–315, and 368–370: The authors should consider that the stronger wind speeds during the +NAG phase are not strictly katabatic but are enhanced by the interaction of a strengthened synoptic-scale pressure gradient with the Greenland ice sheet's orography. I would suspect this is especially true for the winter cases where the authors find that increased wind speeds and SHF occur during +NAG. Previous studies have described this synoptically-driven wind enhancement as the Greenland "barrier jet" or "plateau jet" – see e.g. Meesters 1994, van den Broeke and Gallée 1996, Moore et al. 2013, Mattingly et al. 2020.

We will improve our discussion regarding the coupling of the katabatic winds with upper air winds whenever appropriate.

L255, Figs. 4–6: I assume all the results in Figs. 4–6 (e.g. the increasing trend in TCWV in northern Greenland described in L255) are produced from RACMO2 data? If so this should be explicitly stated in the figure captions and the text.

We add to the figure caption that these results are based on the RACMO2.3p2 output, and convenient figure reference along the text.

L282–284: This statement about the seasonal preconditioning effect of skin temperature warming appears to contract the finding in L166–168 that there is no relevant time-lag response between seasonal GrIS surface mass fluxes and the predominant atmospheric circulation pattern prevailing in the preceding seasons.

The cross-correlation in L166–168 was applied to the overall GrIS SMB with isolated climate oscillations. In L282–284, we discuss that the skin temperature in winter during the period 1991-2020 is warmer than in 1959-1990 independently of the NAG phase. Hence, we do not attribute the impact of changing Tskin during individual subsequent seasons, which is why a direct comparison among the statements is not possible. We could add a clarification as "Note, that Fig. 5 compares general conditions among different periods and cannot be used in order to deduce subsequent season's cause and effect". If the Referee does not find this answer satisfactory, we kindly ask you to reformulate how can these statements be contradicting.

L314: How would decreasing ice in neighboring seas contribute to an increase in summer wind speed? Please explain in more detail.

A direct attribution to individual components of such a complex system is indeed very challenging. However, in general, more open waters promote more convection, and consequently, generate a low surface pressure in the neighboring seas that will enhance the regional surface pressure gradient leading to higher wind speeds. Detailed modelling studies may shed light on such relevant connections. They do, however, go beyond the scope of the current study. We will address this point in a revised version discussing the potential of testing such hypotheses with an RCM on regional to local scales.

Technical corrections

L2: The word "fluxes" is not needed since "advection" already describes the horizontal flow of heat and moisture.

Thanks, we changed this as suggested.

L2: surface mass balance of what? (state definitively that it's the SMB of the Greenland Ice Sheet)

Thanks, we changed this as suggested.

L2: "pattern" --> "patterns"

Thanks, we changed this as suggested.

L14: "optical" --> "optically"

Thanks, we changed this as suggested.

L14–16: Run-on sentence. Consider splitting into two sentences.

We follow the advice and split up the sentence in two:

In the southern part of Greenland, the atmosphere has gotten optically thinner, thus allowing more incoming shortwave radiation to reach the surface. In the northern part, the incoming shortwave radiation has changed little with respect to the reference period, but the surface albedo decreased due to the expansion of the bare ice area.

L15: "shortwave radiation flux" should be "shortwave radiation" or "shortwave radiative flux"

Thanks, we changed this as suggested.

L18: north of the *climatological location of* the jet stream

Thanks, we clarify this ambiguity by changing the sentence to:

The GrIS is most commonly found north of the jet stream

L63: "largest" --> "most intense"?

Thanks, we follow this advice and reword accordingly

L91: ERA5 is the most recent reanalysis product from ECMWF (it's not an "earlier product")

Thanks, we agree with the Referee and reword to: The ECMWF reanalyses products - ERA40 (Uppala et al., 2005) (1959-1978); ERA-I (1979-1989); and ERA5 (1990-2020) - are used to laterally force…

L211: The abbreviation "0NAG" is used repeatedly from this point forward without previously being defined in the text. It appears to be defined in the caption for Figure 4, but its meaning should be explicitly stated in the text at first use.

Thanks, we add its meaning to the beginning of Section 3.2: Spatial and inter-seasonal anomalies under contrasting NAG (+/-) phases with respect to the neutral phase (0NAG) are illustrated in Figure 4…

L331: Delete the word "or" at the end of this line.

Thanks, we deleted "of" at the end of this line.

L335: Accumulation zone has been decreasing *in area*?

Yes, in area, we add this at the respective line in order to clarify.

L337: Insert the word "zone" after "accumulation"

Thanks, we changed this as suggested.

L366-367: "vertically distributed changes" --> "vertical distribution of changes"

Thanks, we changed this as suggested.

References

Liu, C. and Barnes, E. A.: Extreme moisture transport into the Arctic linked to Rossby wave breaking, J. Geophys. Res. Atmos., 120, 3774–3788, https://doi.org/10.1002/2014JD022796, 2015.

Mattingly, K. S., Mote, T. L., Fettweis, X., van As, D., Van Tricht, K., Lhermitte, S., Pettersen, C., and Fausto, R. S.: Strong Summer Atmospheric Trigger Greenland Ice Sheet Melt through Spatially Varying Surface Energy Balance and Cloud Regimes, J. Climate, 33, 6809–6832, https://doi.org/10.1175/JCLI-D-19-0835.1, 2020.

Meesters, A.: Dependence of the energy balance of the Greenland ice sheet on climate change: Influence of katabatic wind and tundra, Q.J Royal Met. Soc., 120, 491–517, https://doi.org/10.1002/qj.49712051702, 1994.

Moore, G. W. K., Renfrew, I. A., and Cassano, J. J.: Greenland plateau jets, Tellus A: Dynamic Meteorology and Oceanography, 65, 17468, https://doi.org/10.3402/tellusa.v65i0.17468, 2013.

van den Broeke, M. R. and Gallée, H.: Observation and simulation of barrier winds at the western margin of the Greenland ice sheet, Q.J Royal Met. Soc., 122, 1365–1383, https://doi.org/10.1002/qj.49712253407, 1996.

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.