Answer review comment #1

Dear reviewer,

We are very grateful for your very constructive review and appreciate the valuable time put into this. We will incorporate the suggested changes as follows and are confident that the adjustments will improve the manuscript.

Below, we present the review comments in **bold**, followed by our responses in *italic*. Any amendments we would make to a revised manuscript are highlighted in green. The line numbers indicated with [l.XXX] are based on the preprint.

We hope that the changes will convince both the reviewer and the editor and are looking forward to a decision.

Once again, many thanks for the valuable input and all the best – on behalf of the author team,

Florina Schalamon

Main comments

- It is unclear from the introduction and methods why the WEG_L site is chosen as study area for the AT anomaly analysis. Further motivation is needed in the introduction or methods to clarify why the authors choose to link this analysis with the dataset described in Abermann et al. (2023).

Thank you for this important comment to the need to explain the motivation for selection of study site. This study is part of the WEG_Re project, which investigates the influence of climate drivers on glacier changes since Alfred Wegener's last expedition to Greenland (1930/31). WEG_L is the position of an automated weather station implemented within WEG_Re, that coincides with the location of a weather station from Wegener's historic expedition.
The submitted article should be seen in the context of a number of studies such as Abermann et al. (2023) who give a general background of environmental changes, or Scher et al. (submitted), who demonstrate that even short observational periods can improve uncertainty estimates in reanalysis data.
Beyond project logics, our study also covers a scientifically relevant region where strong AT trends are present (see Fig. 2 (b) and (c)) in both WPs.
To address the reviewer's concern that this connection is unclear, we will add additional explanation in a revised manuscript.

Using the same location as Wegener's expedition allows for a direct comparison between past and present atmospheric conditions, enabling a better understanding of long-term changes and the role of large-scale atmospheric patterns (LSPs) in shaping regional climate variability. ~~This unique data trove triggered us to investigate the connection between of atmospheric large-scale pattern (LSPs) and WPs.~~ [l. 39]

From a climatological perspective, WEG_L is located in a region where AT changes are among the strongest during both WPs, as seen in Fig. 2 (b) and (c). The particular strong and significant warming in this area further supports WEG_L as a representative study site, making it a well-suited choice for this study. [l.208]

- Are the SOM results dependent on seasonality in the geopotential height field? Previous studies (e.g., Cassano et al., 2015) suggest that using spatial anomalies instead of absolute fields can remove seasonal signals, focusing SOM analysis on gradients in geopotential height that drive advection.

Thanks, this touches an interesting point. It would indeed be possible to compute the SOMs on spatial anomalies instead of absolute fields. If the anomalies were computed on a non-seasonal basis, then this would lead to exactly the same results, as differences would cancel out in the distance functions. If the anomalies were computed on a seasonal basis (e.g., with a running seasonality), then the results would potentially be different. While this would be a valid alternative approach for this type of analysis, this would answer a slightly different research question – namely "which large-scale anomalies drive regional warming?", in contrast to our analysis, which answers one of the research questions in our paper, namely "which large scale patterns drive regional warming?". In order to keep conciseness, we suggest keeping the focus with absolute fields. We address this point in the revised manuscript's discussion, adding:

[…] from 1900 to 2015. While alternative approaches using pressure anomalies could offer different insights into seasonality, we base our SOM analysis on absolute pressure fields to directly assess the influence of LSPs on regional warming. [l.142]

- It is interesting that in LSP3 both positive and negative anomalies occur. Could the small number of clusters have resulted into several patterns being averaged into the zonal pattern shown in LSP3? Have the authors tested the results by training a larger SOM and seeing if those positive and negative anomalies still occur from a zonal pattern?

This is a valid and interesting point. Given the high relative occurrence of LSP3 and its broad range of associated anomalies, it is likely that different conditions are grouped within this pattern. This is expected climatologically, as zonal airflow can result from various large-scale pressure configurations. Additionally, the SOM algorithm assigns more cluster centres where data density is higher, meaning that LSP3, containing a large number of days, likely represents multiple similar patterns in a less dense input space.
While increasing the number of SOM clusters could, in principle, help differentiate these patterns, it introduces challenges. Some LSPs would become too rare creating special cases rather than offering a streamlined interpretation of dominant large-scale patterns. Any SOM analysis involves some arbitrariness in parameter selection, including the choice of cluster numbers. Our selection aligns with previous studies (Preece et al., 2022; Schmid et al., 2023; Schuenemann & Cassano, 2009), ensuring comparability. As noted in l. 158, we aimed to avoid manually regrouping clusters after the analysis with SOM and opted for a manageable number of clusters.

We also tested configurations with more (9,10,15,20,25,30) and fewer (6,7) clusters. While this naturally altered the distribution, it did not improve interpretability. Specifically, increasing the number of clusters did not lead to a meaningful differentiation of AT anomalies within zonal LSPs. It needed 30 clusters to split the zonal flow LSP into two clusters and both showed similar AT anomalies associated with it.
Our goal was to maintain reproducibility, minimize manual intervention, and keep the number of patterns manageable. We found that our chosen number of clusters (8) provided a good balance.

- It would be valuable to add whether warming trends in WP1 and WP2 show seasonal variation. Are certain seasons contributing more than others to the observed trends?

Thank you for your helpful comment. We have indeed examined the seasonality of warming trends and will include this aspect in the revised manuscript. Figure R1 shows that winter AT trends are larger than in the other seasons in both WPs, highlighting the dominant role of winter variability. This finding aligns with Box et al. (2009), who demonstrated that positive annual temperature anomalies over Greenland are largely driven by winter temperature variations. To address this, we will add the following sentences in the introduction and the results part, as well as Fig. R1 as Fig.A1.1 in the appendix:

[...] from 1994 to 2007. Their study shows that these warming trends are not uniform across seasons, with winter temperatures exhibiting much greater variability than summer temperatures. [l. 28]

A seasonal analysis confirms the findings from Box et al. (2009), that the AT increase is strongest in winter (see Fig. A1.1), while the smaller anomalies are observed in summer and autumn. [l.208]

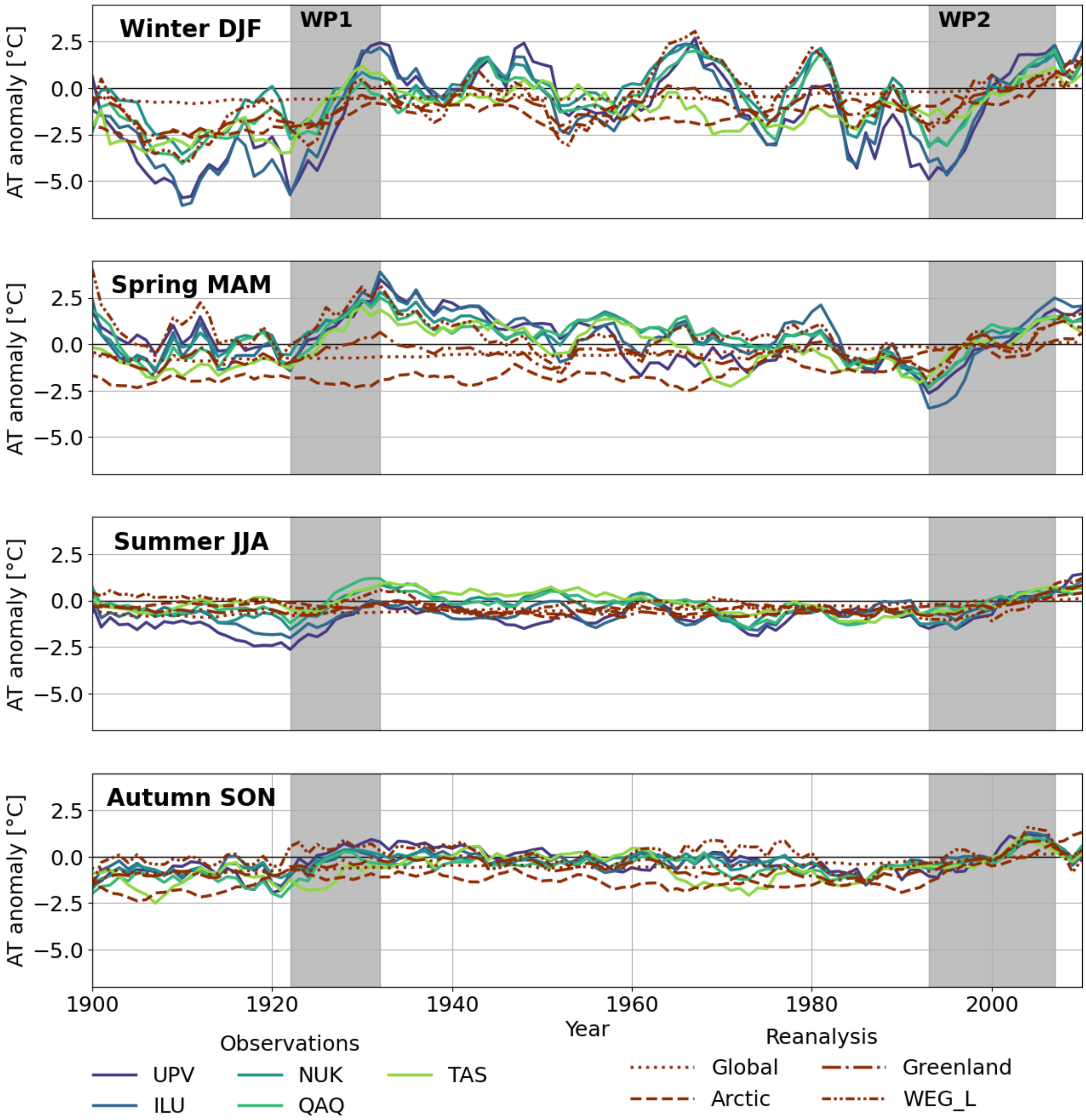

Figure R1: Seasonal annual AT anomaly with respect to the reference period 1986-2015 at weather stations (Upernavik (UPV), Illulisaat (ILU), Nuuk (NUK), Qaqortoq (QAQ), Tasiilaq (TAS)) and in addition the 20CRv3 as spatial AT anomaly average of the Arctic, Greenland, globally and interpolated to the study site WEG_L, smoothed with a 5-year window rolling mean. The two defined WPs are marked with the grey background.

- I would suggest to add an additional figure in which the LSP occurrence per year is given for the full study period. This could show potential shifts in LSP occurrence in the cold period before the WP versus the warm period after that could explain the WP patterns.

Thanks, this is of course another useful possibility to display the LSP occurrence per year and we investigated this aspect beforehand. Figure R2 (a) shows the relative occurrence per LSP over the years scaled to the average occurrence over the full period 1900-2015. A value above/below 1 means a higher/lower occurrence of that pattern compared to the average

occurrence of that pattern. Figure R2(b) shows the course of the relative occurrence of one specific LSP per year over the full study period.
Despite it giving an additional comprehensive perspective, we did not find a clear trend of specific LSPs over the whole study period. For instance, while LSP2 (a cold pattern) occurs more frequently than average during WP1, LSP7 also shows an increased occurrence, making it difficult to establish a direct link.
We aimed to observe changes as similar trends have been identified in other Arctic regions, such as the reported rise in cyclonic activity by Hanssen-Bauer et al. (2019) and Wickström et al. (2020).
We plan to include the shown figure in the appendix A2 of a revised manuscript to complete the analysis of the LSP occurrence. Additionally, we will include the following sentences.

[...] significant difference robust. We did not find clear evidence of trends in LSP distribution per year. Figure A2.1 in the appendix provides further details, illustrating the annual relative occurrence of each LSP compared to its average occurrence over the full period (1900–2015) (a), as well as the relative occurrence per year (b). [l.240]

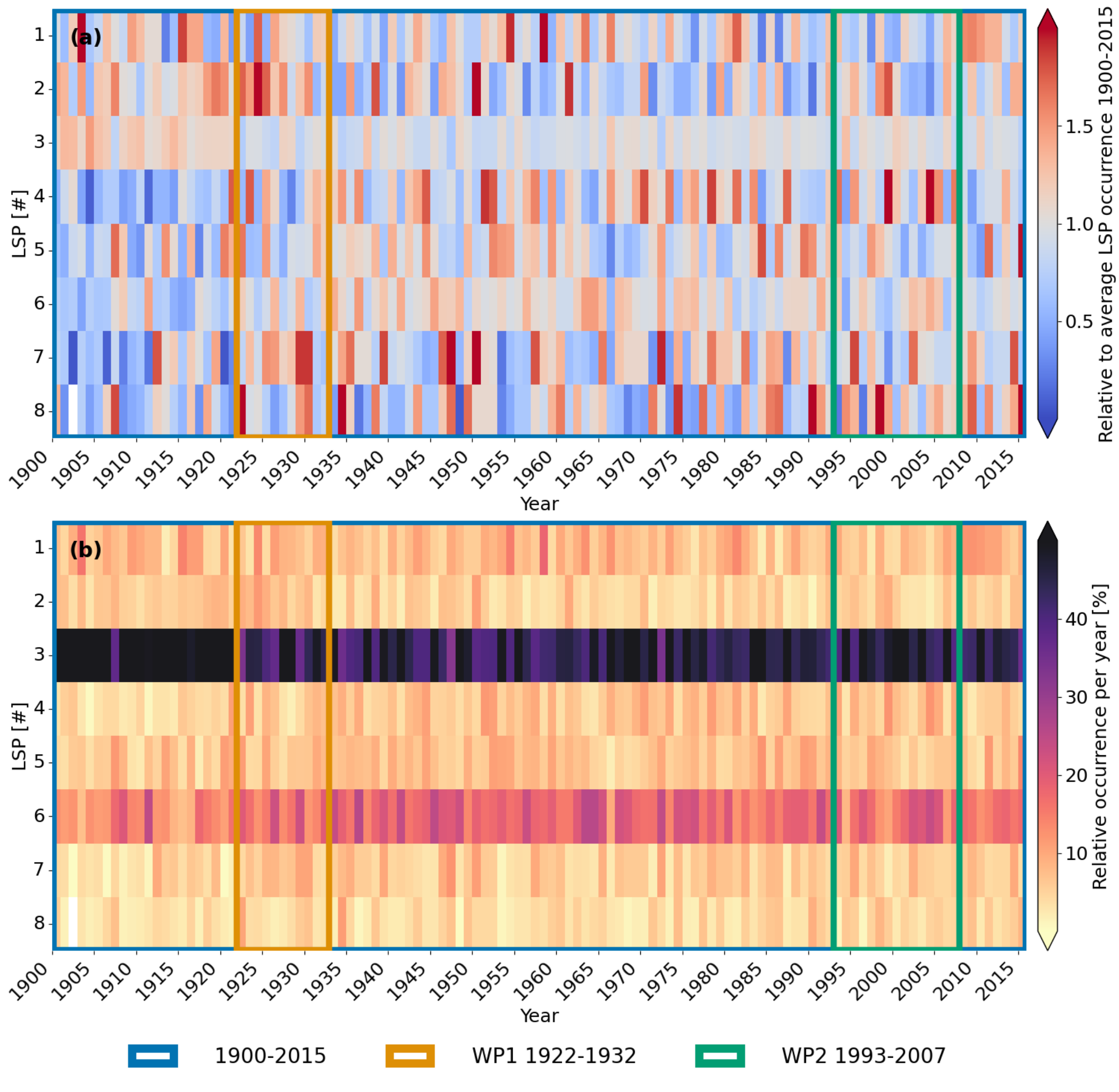

Figure R2:(a) the relative occurrence per LSP over the years scaled to the average occurrence over the full period 1900-2015. A value above/below 1 means a higher/lower occurrence of that pattern compared to the average occurrence of that pattern. (b) shows the course of the relative occurrence of one specific LSP per year over the full study period.

- Is there seasonality in LSP occurrence over the full period? In that case I would suggest instead of showing relative changes during WPs, Fig. 5 could show absolute occurrences of LSPs across both the overall as well as the warming periods.

We appreciate this point and show the relative occurrence of LSPs during WPs and FPs in Fig. R3. Our point on small but significant differences between the WPs and the full study period is further highlighted in Fig. 5, where we show it in relative terms – in principle containing the same information. To address the reviewer's point, we will include Fig. R3 as Fig. A2.2 in the appendix A2 and add the following explanation to the revised manuscript:

In a first step the relative occurrences were analysed seasonally, and the full overview is displayed in Fig. A2.2. To highlight the small but significant differences between the occurrence of the LSPs, Fig.5 shows the occurrence in the WPs relative to the occurrence in the entire study period 1900-2015. [l. 273]

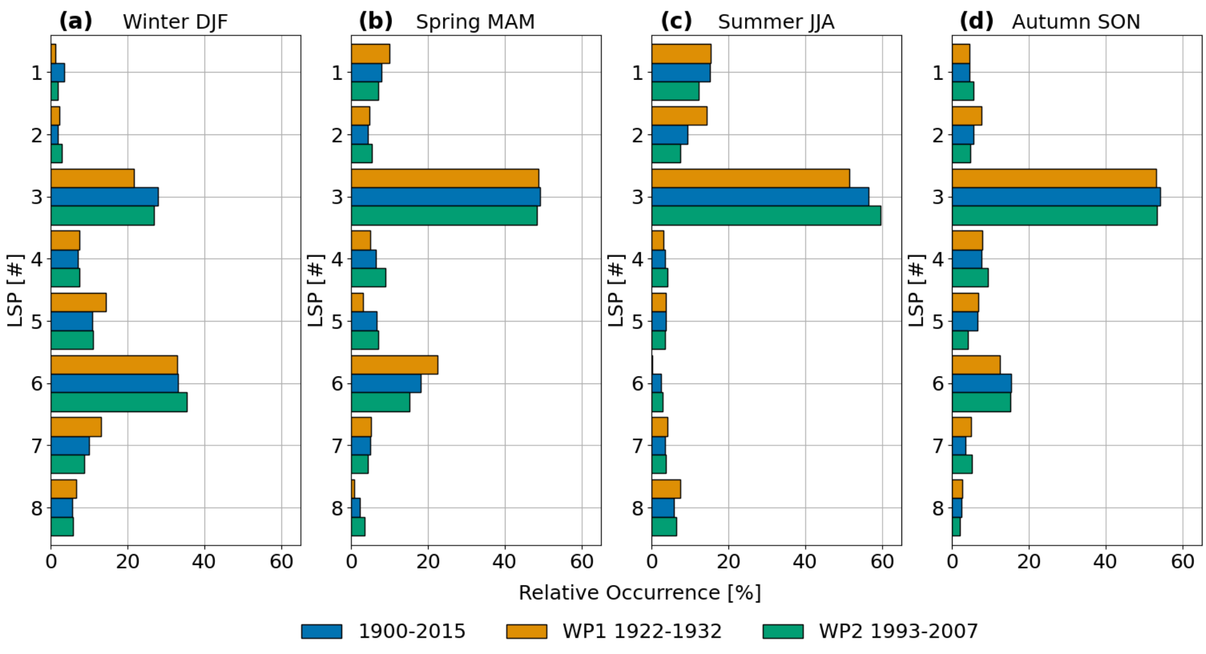

Figure R3: Seasonal relative occurrence of the LSPs in the WPs and in the entire study period 1900-2015.

- Looking at the similarity in relative occurrence of the LSPs between the different periods I am surprised the distribution of LSPs is significantly different. Can the authors explain why a Chi-Square test is used and if this result would be robust with other significance tests?

Indeed, subtle differences must be confirmed with appropriate statistical testing. To compare the occurrence of LSPs between the full study period and the WPs, we tested whether there was a significant difference between the expected occurrence (based on the full period) and the observed occurrence within each WP. We acknowledge that the differences in Fig. 4(a) appear small, which is why we highlighted the differences in Fig. 5. To ensure the robustness of our results, we repeated the significance test 1500 times.
The Chi-Square test is appropriate for comparing observed frequencies of categorical data in a contingency table against expected frequencies under the null hypothesis of no association between the two distributions. In our case, it assesses whether the observed frequency of LSPs in a WP deviates significantly from the expected frequency derived from the full study period. This test evaluates the overall difference in LSP distribution rather than individual deviations for specific LSPs.
To validate our results, we performed additional analyses with other significance tests for the independence of two categorical distributions. For this we performed the G-Test (log-likelihood ratio test) and Fisher's exact test. Additionally, we also applied the permutation-based and Monte Carlo methods as variation of the standard Chi-Square test. These variations account for small frequency of one category in the contingency table, which could cause the default asymptotic approximation of the standard Chi-Square test to be inaccurate.

Table R1: P-values from different significance tests comparing the periods, including the Chi-Square test, G-Test, Fisher's Exact Test, and permutation-based and Monte Carlo methods.

Method	*WP1 vs WP2*	*WP1 vs full period*	*WP2 vs full period*
Chi Square	*2.8e-07*	*6.2e-08*	*0.00097*
G-test	*3e-07*	*2.08e-07*	*0.0011*
Montecarlo variation	*0.0001*	*0.0001*	*0.0015*
Permutation variation	*0.0001*	*0.0001*	*0.0011*
Fisher Exact	*0.0001*	*0.0001*	*0.0013*

Tab. R1 gives an overview of the p-values obtained with the different tests and for the different periods that have been compared categorically. It shows that there is a significant difference between the LSP distribution in the WPs and the full period (threshold alpha = 0.05) for all tests and all periods.
We will add the following statement to the manuscript as an explanation for choosing the chi-square test:

[...] a Chi-square test was performed. The Chi-Square test is appropriate for comparing observed frequencies of categorical data in a contingency table against expected frequencies under the null hypothesis of no association between the two distributions. That means in our case that the observed frequency of LSPs in one WP is compared to the expected frequency of the LSPs in the full study period. [l. 173]

We will also include a sentence about the additional test results along:

However, statistical testing using a Chi-Square Test reveals a significant difference in the distribution of LSPs among WP1, WP2 and the full study period. This result is also supported by various other significance tests, including Fisher's Exact Test and the G-Test, as well as alternative approaches to the standard Chi-Square test, such as the Monte Carlo and permutation-based resampling methods. [l. 239]

- The manuscript could be strengthened by some further interpretation of the results from the SOM analysis and linking these with known modes of variability. For example, do the node occurrences correlate with the Arctic Oscillation or NAO? Could high occurrence of LSP3 reflect conditions of strong polar vortex with less meandering, in which the Arctic and Greenland are often colder (agrees with Fig. 6. which is often during the positive phase of AO). During opposite conditions the polar vortex is weaker and weavier patterns form in the geopotential height field, which might explain the patterns detected by the other LSPs.

Thank you for your insightful suggestion and for highlighting the potential connections between the LSPs and large-scale climate modes like the Arctic Oscillation (AO). We agree that the high occurrences of LSP3 could reflect conditions associated with a strong polar vortex, where a more zonal atmospheric circulation leads to colder conditions over Greenland, especially during the positive phase of the AO. This phase is characterized by a more stable and confined polar vortex, which typically results in less meandering of the jet stream and colder temperatures across the Arctic. Conversely, during the negative phase of the AO, the polar vortex weakens, allowing for increased meandering of the jet stream and the formation of more variable weather patterns, which could align with the LSPs observed in other periods.
While these connections are well-documented in the literature, our study primarily focuses on the variability of the distribution of LSPs during the warming periods (WPs), rather than exploring the mechanisms driving these patterns. The aim was to assess how different atmospheric circulation patterns contribute to temperature anomalies during these specific periods of warming, and linking LSP occurrences directly to indices such as the AO or NAO would require a more detailed analysis of these dynamics, which goes beyond the scope of the current manuscript. However, we do recognize the importance of these climate modes in shaping atmospheric conditions over Greenland, and this will certainly be an important consideration for future research as we further explore the role of large-scale circulation patterns in driving temperature variability.
In a revised manuscript we will add the following statement to strengthen the interpretation as the reviewer suggested.

[...] amplify warming trends. The variability of LSP occurrences may also reflect broader atmospheric circulation changes, potentially influenced by climate modes such as the Arctic Oscillation (AO). A strong polar vortex, often associated with a positive AO phase, can contribute to more stable, zonal airflow patterns, while a weaker vortex during a negative AO phase allows for increased meandering and variability in geopotential height fields. These large-scale influences provide additional context for understanding the observed shifts in LSP frequency and their role in shaping local AT anomalies. [l.345]

- The discussion could be strengthend by comparisons with studies linking extreme warming/melt events in Greenland to atmospheric conditions (e.g., Fettweis et. al 2013, Neff et. al, 2014, Hermann et. al, 2020)

Thank you for this valuable suggestion, which coincides with our research agenda very nicely. In the next phase of our project, we will investigate the historical and modern datasets at the study site, explicitly linking atmospheric conditions to recorded melt events. As part of this analysis, we will assess the role of the LSPs defined in this study as potential drivers of these events. Since this aspect is part of a new manuscript we are working on, we have not included it in this. However, we will add a sentence outlining this future research direction in the conclusion in a revised manuscript.

[...] under different warming scenarios. A further application of our research in the future will be to connect LSPs to measured and modelled surface mass balance of the glacier in the study area, as it is known that extreme melt events are closely linked to atmospheric circulations (Fettweis et al., 2013; Hermann et al., 2020; Neff et al., 2014). [l.409]

Specific comments

Title: Consider including the study period to highlight the long temporal scope of the study.

*We will change the title to: "*The role of atmospheric large-scale patterns for recent warming periods in Greenland from 1900-2015*".*

L. 37: Without reading Abermann et al. 2023, it is unclear from this section what is meant with 'high-resolution observations'.

*We will rephrase the expression to "*Observations with high temporal and spatial resolution*".* [l. 37]

L. 65: add 'summer' after 'from the west'.

This will be added in the revised manuscript. [l. 65]

L. 80: Can you add more information on the weather station data, such as measured variables and presence of data gaps, or refer to the source for these details.

Cappelen et al., (2021) gives the full background to the DMI Historical climate data collection used for this study. This reference is already included in the description of the weather stations in l.81. We will add the following sentence for clarification in a revised manuscript.

[...] station on the east coast. More detailed information can be found in Cappelen et al. (2021). [l.85]

Sect. 4.1: The warming periods are based on significant warming trends in the weather station data. Are the trends in reanalysis over the same periods significant as well? For example, in Fig 2b doesn't look significant at the study site location.

Thank you for the valuable suggestion, which led us to refine the representation of the data. To ensure consistency, we applied the smoothed AT anomaly trends in all panels of the figure

(see Fig. R4), providing a clearer depiction of the significant warming at the study site. Additionally, we verified all smoothed AT anomaly trends (Fig. 2a) during the WPs at the observation stations and in the reanalysis data for WEG_L, confirming that the trend remains statistically significant.
In a revised manuscript, we would include the following figure:

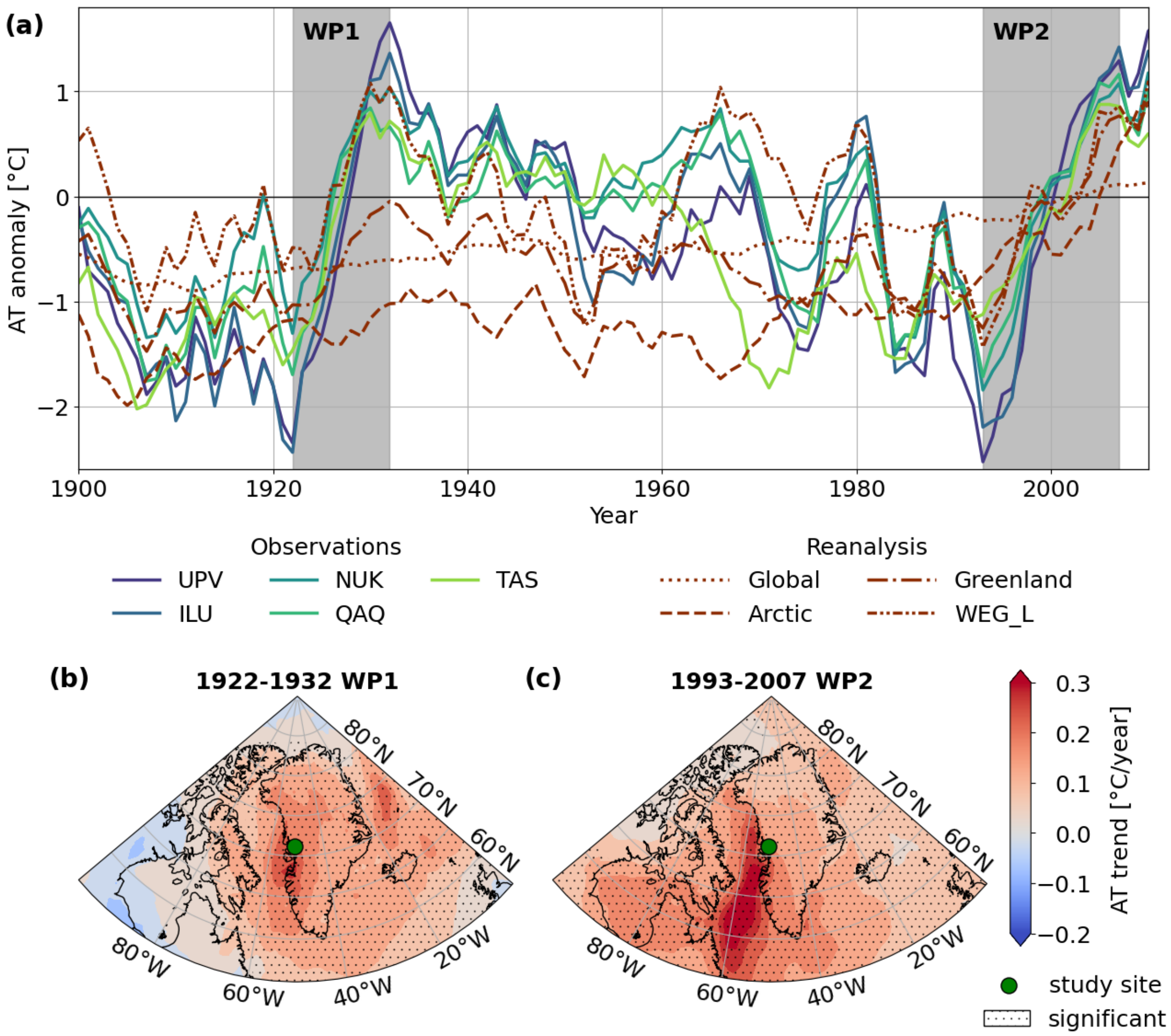

Figure R4: (a): Annual AT anomaly with respect to reference period 1986-2015 at weather stations (Upernavik (UPV), Illulisaat (ILU), Nuuk (NUK), Qaqortoq (QAQ), Tasiilaq (TAS)), of 20CRv3 as spatial average of the Arctic, Greenland, globally and interpolated to the study site WEG_L, smoothed with a 5-year window rolling mean. The two defined WPs are marked with the grey background. (b) and (c): spatial representation of the Sen’s slope estimator for the WPs. The colour shows the AT trend for one grid cell of 20CRv3, the “.” hashing indicates grid cells where the trend is significant (Mann-Kendall test).

Fig 2: Include the study site location also in Fig 2b.

This will be adjusted as we will include the Fig. R4 above in a revised manuscript.

L. 197: The Arctic doesn’t seem to warm during this period, so rephrase to

'concentrated over Greenland' to also agree with your following statements.

This will be corrected in a revised manuscript. [l. 197]

L. 225: Can you clarify this statement? Often SOMs are shown as matrix in which neighboring nodes are most similar and further away nodes most different. In case of atmospheric circulation patterns neighboring nodes could be transitional from one synoptic state to another.

This statement was meant for the naming convention. That LSP 1 is the first does not have any meaning as it is just the first cluster centre found during the training part of SOM with choosing random input. We will rephrase the sentence into:

Note that the numbering of LSPs (e.g., LSP 1, LSP 2) is arbitrary, as it is based on the first cluster identified during the SOM training process, which depends on randomly chosen initial input data. [l. 225]

L. 315 – 320. This section would fit better in Methods section 2.2

We will move l. 317-320 to the end of the suggested section. We left the comparison of the reanalysis at WEG_L and the observations at the weather stations in the discussion part, as this is discussed further in the following paragraph. The decision to choose 20CRv3 based on the prior study will be in the method part with minor adjustments to embed it in the text.

L. 367: The difference in warming through LSP6 (dominantly in winter) and LSP3 (dominantly in summer) is interesting and could have more discussion here. What is the role of advection from continental vs oceanic regions? This could explain why in winter there is more warming during LSP 6 (relative warm ocean) and in summer warming from continental sources (LSP3).

Thanks for the input. We will add the following sentences to include your argument.

[...] the effect on the local AT anomaly. Further the difference in warming between LSP6 (dominantly in winter) and LSP3 (dominantly in summer) can likely be attributed to the source of advection. During winter, LSP6 is associated with advection from warmer oceanic regions, while LSP3 in summer is influenced by advection from continental sources, which explains the seasonal variation in warming. [l.369]

Literature:

Abermann, J., Vandecrux, B., Scher, S., Löffler, K., Schalamon, F., Trügler, A., Fausto, R., & Schöner, W. (2023). Learning from Alfred Wegener's pioneering field observations in West Greenland after a century of climate change. *Scientific Reports*, *13*(1), 7583. https://doi.org/10.1038/s41598-023-33225-9

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Schuenemann, K. C., & Cassano, J. J. (2009). Changes in synoptic weather patterns and Greenland precipitation in the 20th and 21st centuries: 1. Evaluation of late 20th century simulations from IPCC models. *J. Geophys. Res. Atmos.*, *114*(D20), 20113. https://doi.org/10.1029/2009JD011705

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