Answers to the reviewers

egusphere-2025-1373

“Summertime Arctic and North Atlantic-Eurasian Circulation Regimes under Climate Change”

By Johannes Müller, Oskar Landgren, and Dörthe Handorf

We are very grateful to the reviewers for their insightful feedback and constructive suggestions. Their suggestions have been highly valuable for refining our manuscript, and we have carefully considered and addressed each point below. As various issues were mentioned by both reviewers, we have provided the answers to their comments in one document.

In the document the reviewers' comments are written in black, and our responses in green.

Please note the following general comment, which affects the whole document: For the Arctic regimes, the East-West Dipole regime has been renamed to Cluster 5 due to the low similarity between the patterns obtained using the K-Means and SANDRA clustering methods after recalculating. Please, refer to Figure R15 and R16 for details.

Reviewer 1:

This study looks at the change of circulation regimes under climate change for an Arctic and Atlantic-Eurasian domain. It finds that the NAO+/AO- regimes will occur more often in the future, while the NAO-/AO+ regimes will occur less.
Overall, the study is a valuable addition to the scientific literature on weather regimes, presenting important results for the Arctic. However, the description and discussion of the methods and results needs to be substantially improved before I would find this ready for publication.
I have put comments in the pdf and summarise my main points here.

My major concerns are:
1.The authors use pseudo-PC’s to identify and assign regimes for the CMIP6 model data. While I think this is the most suitable approach for studying changes in regime occurrence, I question whether it is also suitable to study changes in the regime patterns. By projecting the CMIP6 data onto the ERA5 PC’s you introduce a bias of sorts and I wonder how different the results would be when using the model’s own PC’s?

In our study, we follow the projection method introduced e.g., in Fabiano et al. (2020) and Fabiano et al. (2021). Projection ensures that all calculations are done in the same reference space and allows comparison of regime patterns in a consistent way. On the other hand (see also comment 1 from reviewer 2) the projection method requires that the model sub-space is contained in the reference space. We agree that this has to be proven. To do this, we follow the suggestion of reviewer 2, and use the "quantization error" proposed by Quagraine et al. (2020) to quantify, if the model sub-space is contained in the reference space.

The "quantization error" is defined as the mean error of each day's pattern with respect to the reference cluster pattern to which it belongs (Quagraine et al., 2020). As explained in Quagraine et al. (2020), by comparing the error mapping of the GCMs to that of the ERA5 data, one can assess whether the GCM patterns have a greater error than the reanalysis. In this case, the GCM sub-space is not contained in the reference space spanned by the reanalysis data.

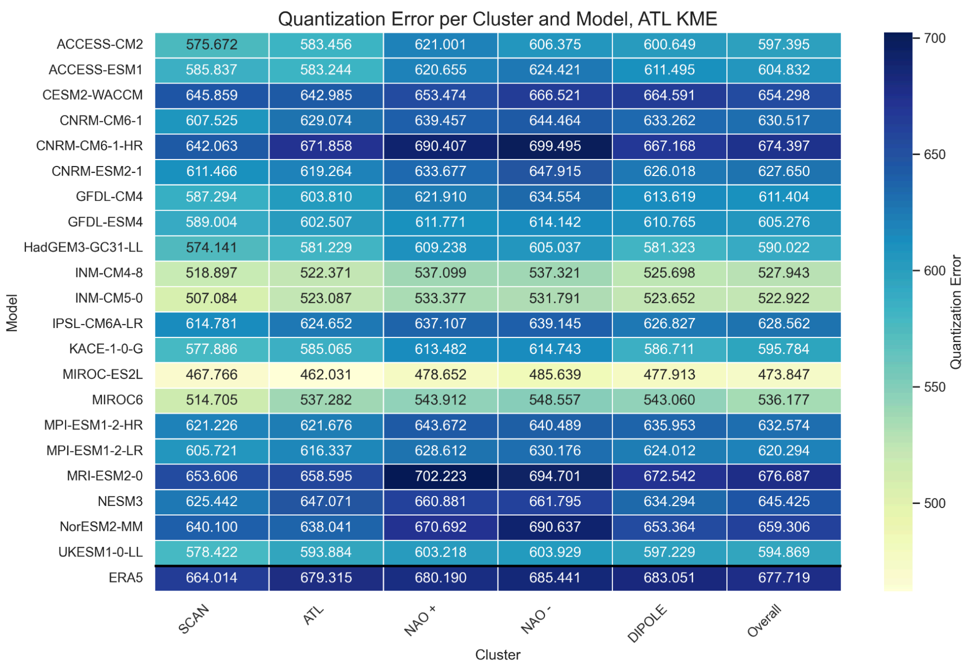


Figure R1: Quantization Error per regime and model, North-Atlantic-Eurasian region, KME method, historical period

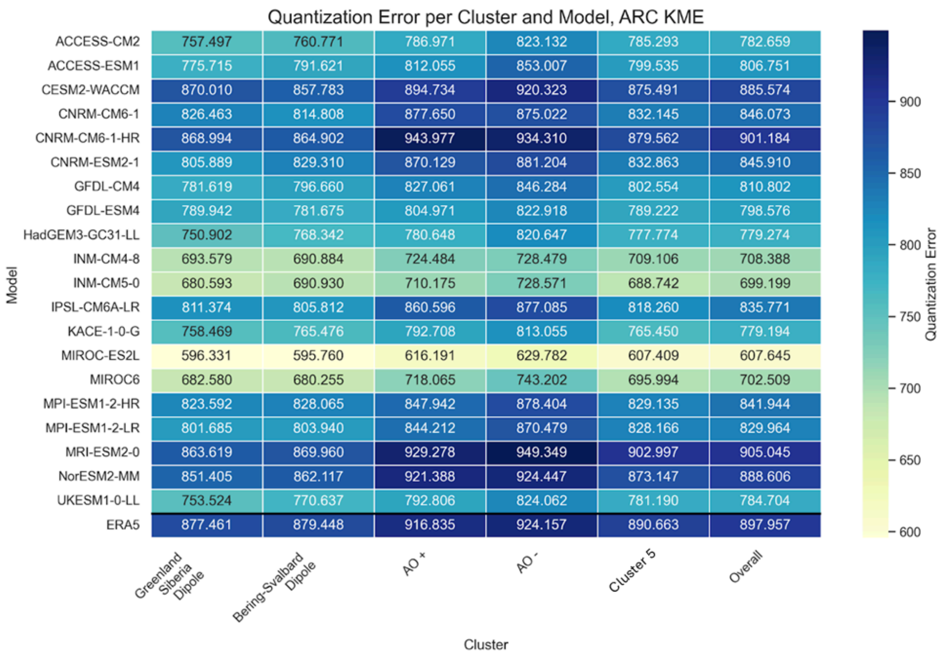


Figure R2: As Figure R2, but for the Arctic region.

Fig. R1 shows the quantization error for the North-Atlantic-Eurasian regimes for ERA5 (last row) and the historical simulations from 1985-2014, obtained with the K-Means (KME) clustering method. Except for NAO+ respectively NAO- for only 2 respectively 3 models the GCM patterns have smaller errors than the ERA5 daily patterns, which justifies the projection approach. A similar conclusion can be drawn for the Arctic regimes, see Fig. R2. The majority of the GCMs have smaller errors than the ERA5 daily patterns, except 3 models for the AO+ regime, 3 models for the AO- regime, and one model for the Cluster 5. We will include that justification into the revised manuscript's appendix. The Figures R1 and R2 are included in the Appendix A: Justification of Projection Approach in the revised manuscript after L430. The former Appendix sections (A,B,C) are shifted to Appendix section B,C, and D.

To underline the applicability of the projection approach for the calculation of the spatial regime structure (that is the simulated circulation regime framework in our terminology, Fig. 1 in the manuscript), we here show a comparison of joint regime patterns for the North-Atlantic Eurasian regimes for the extended summer season for the CMIP6 historical simulations 1985-2014.

In Fig. R3, upper row, we show the common simulated circulation regimes for the CMIP6 historical simulations 1985-2014. These are obtained by projecting the common climate model data onto the ten-dimensional ERA5 reference state space, and K-Means clustering of the resulting Pseudo-PCs. Fig. R3, lower row, displays the common circulation regimes, directly obtained by performing a common EOF analysis for the CMIP6 historical simulations 1985-2014 and subsequent K-Means clustering of the PCs. It is clearly visible that both approaches reveal similar patterns.

Please note that an improved explanation on the common simulated circulation regime framework will be given in the revised text for Method section, L122-L138 (compare answer to reviewer 2, comment 4). We will change the text from L122-L138 to:

"*The common simulated circulation regime framework enables the possibility to compare the spatial structure between reanalysis and the entire CMIP6 model ensemble. First the preprocessed data of each climate model are merged into a single data file along the temporal axis, either for the historical period 1985-2014 or the future period 2070-2099. Instead of performing a common EOF analysis and obtaining common PCs, (as described e.g. in Benestad et al., 2023), here the common climate model data are projected onto the ten-dimensional reference state space, determined from the ERA5 data, resulting in ten common Pseudo-PCs. The common Pseudo-PCs serve as input data for the K-Means clustering algorithm. Five common simulated circulation regimes are obtained for each time period, representing the joint regimes for the entire model ensemble*."

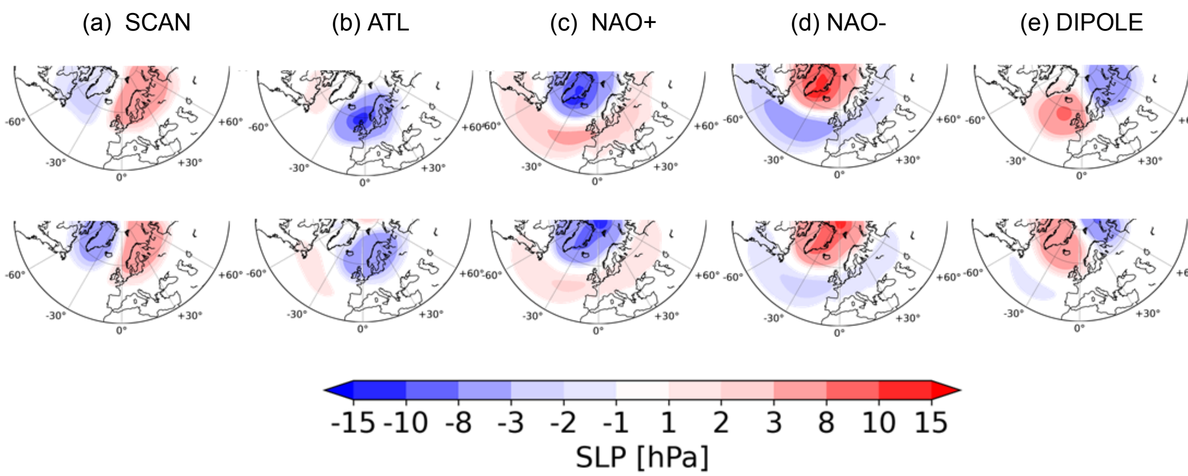


Figure R3: North-Atlantic Eurasian Circulation regime patterns in terms of SLP anomalies for MJJASO, for CMIP6 models in the historical period 1985-2014 obtained with K-Means clustering. Upper row: Common simulated circulation regime approach, with model data projected onto the ERA5 state space, lower row: Common regime approach with state space spanned by common EOFs from climate model data.

2.Also the other choices made in the method section are not in all case thoroughly argued for, for example the use of 10 PC's and not e.g. 15. I believe the paper would benefit significantly from rewriting and clarifying the arguments behind the choices made.

We included the following argument in the revised manuscript after L106 "*Many studies used the winter season and the North-Atlantic region, where 4 EOFs already explain more than 50% of the variance (Fabiano et al., 2021; Dawson and Palmer, 2015). Our own sensitivity tests for the extended summer season have shown that 4 EOFs explain about 40% of the variance for the North-Atlantic-Eurasian region and about 34% for the Arctic region. Moreover, we found a stable spatial structure of the regimes obtained with K-Means clustering (KME) based on ERA5 SLP data only when retaining 6 or more EOFs (explained variance larger than 52 and 45%, respectively) for the North Atlantic-Eurasian region and for the Arctic region. To ensure a sufficient amount of explained variance, we decided to consider the 10-dimensional state space* *consistently for both regions, explaining about 67% of variance for the North-Atlantic-Eurasian region and 61% of variance for the Arctic region*."

Please note: We would not include the Figures R4 and R5 in the revised manuscript's appendix but will mention the fractions of explained variance in the revised manuscript (added after L106).

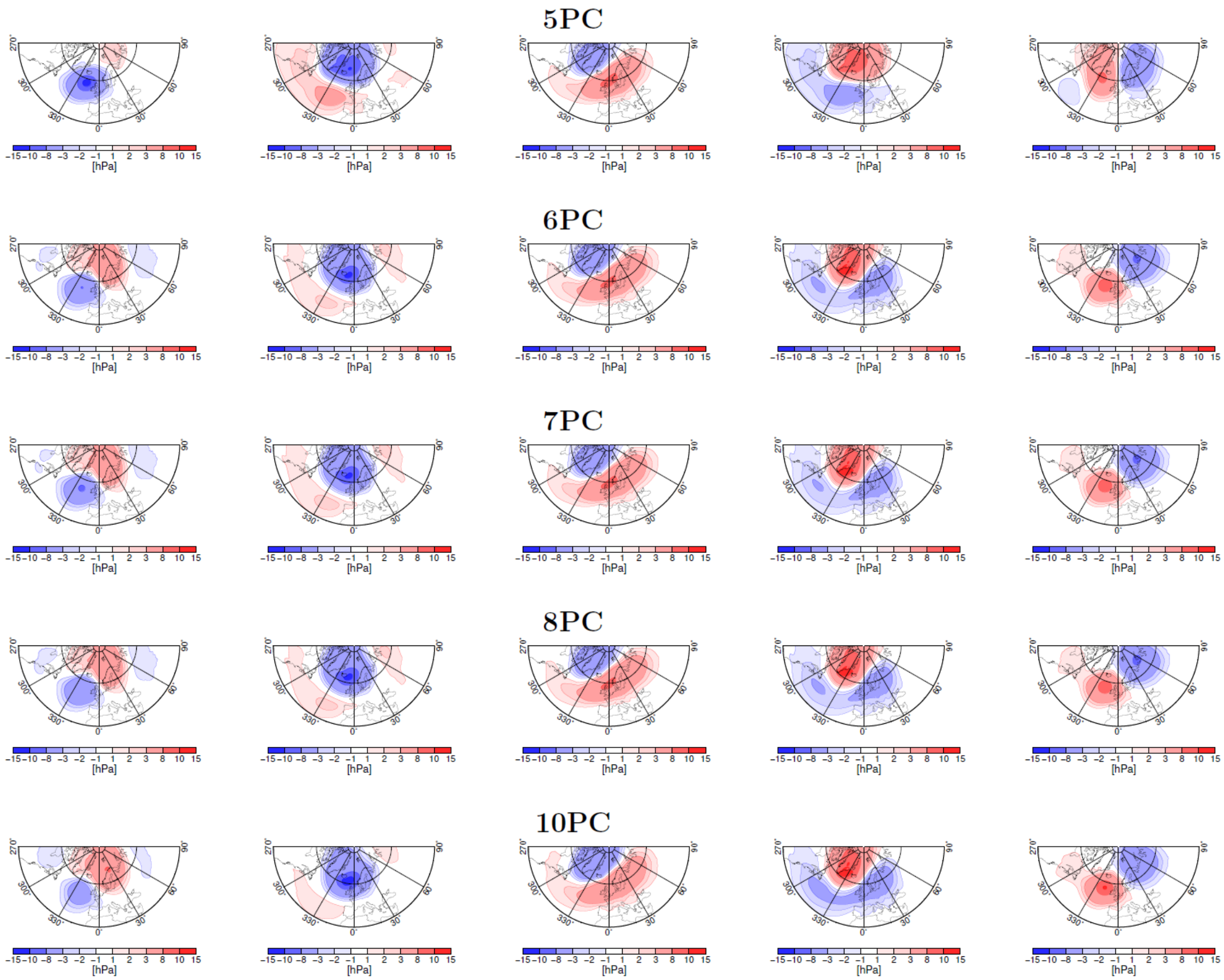


Figure R4: North-Atlantic Eurasian circulation regime patterns in terms of MSLP anomalies for MJJASO, for ERA5 data from 1985-2014 obtained with K-Means clustering in the state space spanned by 5, 6, 7, 8, 10 PCs.

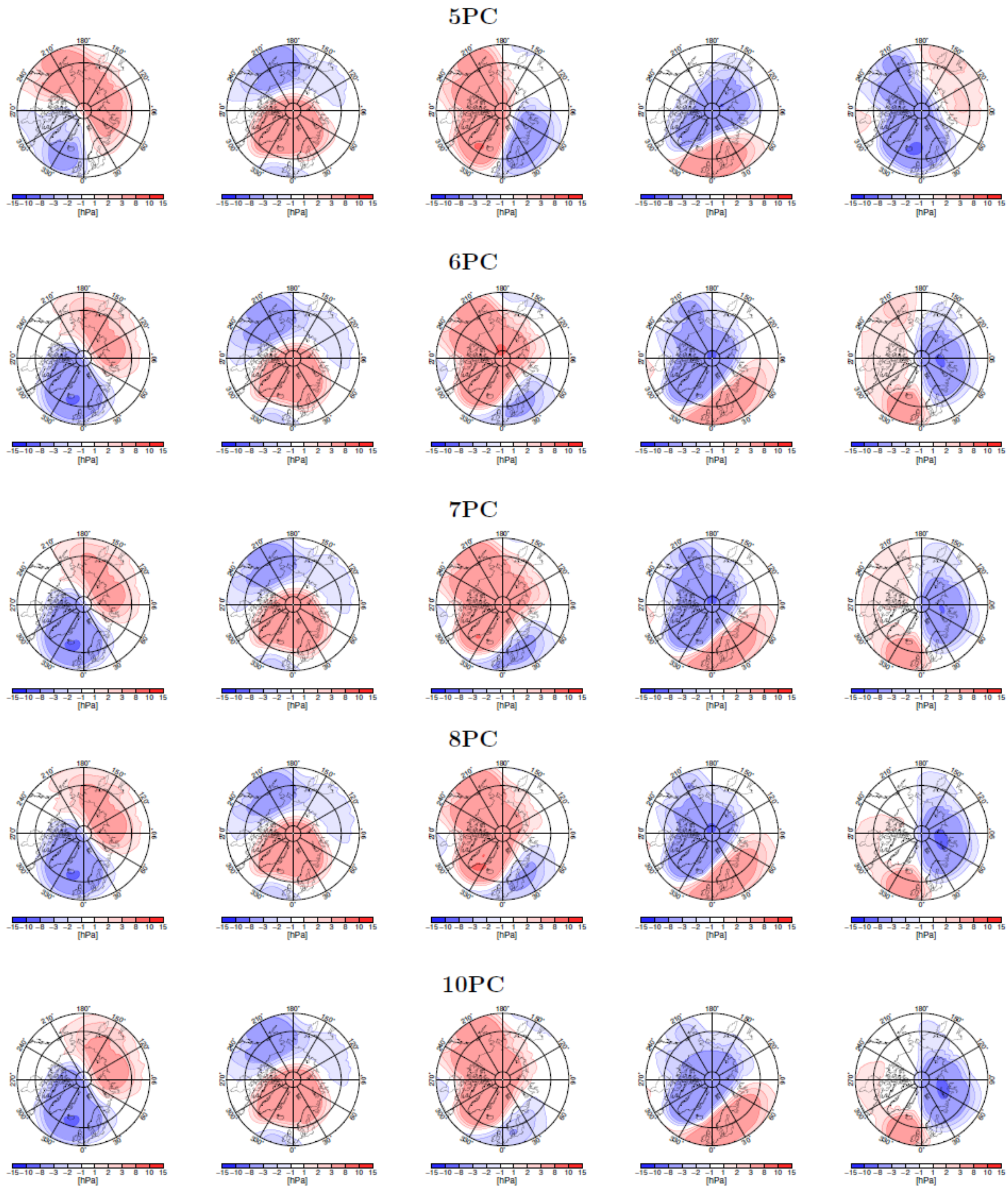


Figure R5: As Fig. R4, but for the Arctic region.

3.The authors study both a projected and simulated approach for k-means, but not for SANDRA. Could you clarify why? A similar question for arguing toward the best number of regimes.

In the SANDRA (SAN) method there is no equivalent of projecting onto the 10-dimensional state space of another dataset. We have now however included a separate calculation of circulation types for the future period from the CMIP models.

We have based the decision for a reasonable number of circulation regimes for the K-Means clustering on the silhouette score and elbow plot metrics described in the appendix. To further justify this choice for both methods, K-Means and SANDRA, here we add an additional metric, following Grams et al. (2017), a reference reviewer 1 suggested in comment 8. As suggested by Grams et al (2017) their metric to evaluate a suitable number of clusters is the Anomaly Correlation Coefficient ("*The optimal number of clusters is seven (Supplementary Fig. 1) based on the criterion that the anomaly correlation coefficient between the clusters is below 0.4*", Grams et al., 2017, Method section). In the following we show the results of the anomaly correlation coefficient calculated for the North Atlantic-Eurasian region in Figure R6 and for the Arctic region in Figure R7 for both methods, KME and SAN, based on ERA5 data 1985-2014. For both methods and both regions, the suggested criteria of Grams et al. (2017) is satisfied for 5 regimes each, which justifies our choices for the number of regimes.

We will include the description of this third metric and the respective discussion in the revised manuscript. This additional metric is added in the paragraph "Determining the Numbers of Clusters" at L157, in the discussion section at L427 and the Figures R6 and R7 are included in the Appendix "Number of Considered Circulation Regimes" from L435 to L450.Specifically we changed L157-L161 " Here, an elbow test (Olmo et al., 2024, see Appendix B) was conducted to ascertain whether it was feasible to identify an optimal number of centroids. According to this test and supported by the silhouette score (Rousseeuw, 1987, see Appendix B) the number of clusters is set to five for both regions. This is in agreement with cluster numbers in other studies, e.g. in Crasemann et al. (2017) a Monte-Carlo simulation was performed to determine the number of clusters in the winter season for the North Atlantic-Eurasian region, resulting in 5 clusters." to
Several methods have been applied to determine an optimal number of regimes, with most studies indicating a number of regimes between four and six for North-Atlantic winter regimes (Falkena et al., 2020). Here, we have based the decision for a reasonable number of circulation regimes on three metrics described in detail in the Appendix C: The anomaly correlation coefficient between the patterns of the clusters, following (Grams et al., 2017) have been applied for both methods, K-Means and SAN. In addition, the elbow test and the silhouette score has been applied for K-Means. The elbow test assesses the efficiency of allocation of centroids (Olmo et al., 2024) and the silhouette score measures the quality of clustering (Rousseeuw, 1987). All three metrics support a choice of k=5 clusters for both regions. This is also in agreement with cluster numbers used in other studies for winter North-Atlantic regimes, e.g. in Crasemann et al. (2017) and Dorrington and Strommen (2020).

Also we changed L427-L428 in the appendix " but also because of our performed analyses on two metrics, the Distortion score and the Silhouette score in Appendix B" to *but also because of our performed analyses on three metrics, the Anomaly Correlation coefficient, Distortion score and the Silhouette score in Appendix B.*

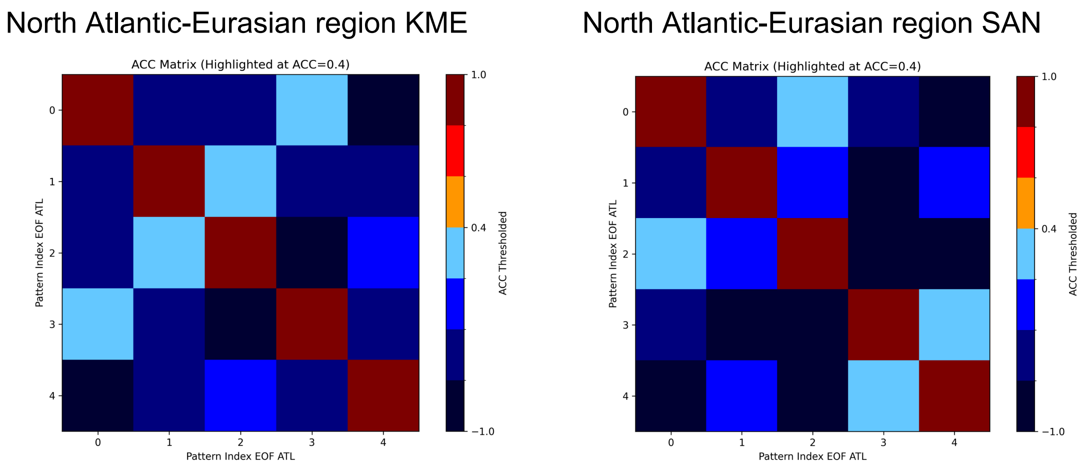


Figure R6: Anomaly correlation coefficient matrix for the North Atlantic-Eurasian regime patterns and both methods, KME on the left side and SAN on the right side. ERA5 data, MJJASO, 1985-2014

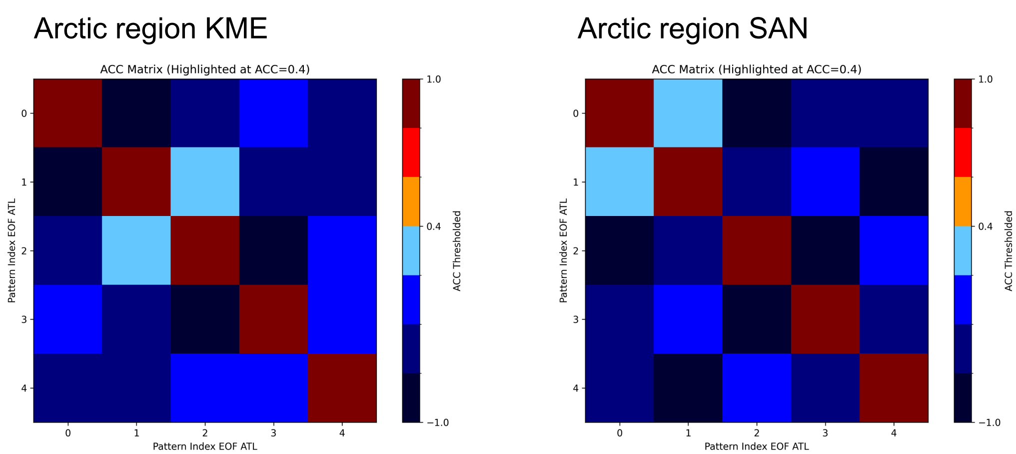


Figure R7: As Figure R6, but for the Arctic regimes.

4. In the results the authors argue for just using the projected approach because it is "more accurate", where to me it appears the smaller spread between models is by design. By that I

mean that the using each models own regimes by definition will create more variability in the frequency, as now also the regime patterns differ between the models. Can the authors elaborate on this and argue for their choice?

We would argue that while using the models' own regimes would result in a larger variety of the spatial patterns, it would actually lead to a reduction in the frequency bias, as the regimes would be more tailored to each model's circulation states, leading to fewer misclassifications.

However, we see the opposite in the results here, which is why we made the conclusion as we did. The phrasing "more accurate" is perhaps not the best, and will be re-written in the revised manuscript. The more precise phrasing should lean towards the fact that the average and median frequency bias for the projected regimes is smaller compared to the simulated regimes.

We will now try to argue mathematically why this is not by design. If it would be true that this is by design, then the projected approach should lead to smaller frequency biases for **every** model compared to the simulation approach. The frequency bias for every model is given below in Table R1 (for the North-Atlantic-Eurasian regimes obtained with K-Means) and Table R2 (for the Arctic regimes obtained with K-Means). For the ACCESS-ESM1 model (and ACCESS-CM2 for the Arctic) model, the absolute frequency bias for the projected approach is greater compared to the simulated approach. This suggests that the smaller frequency bias in the projected approach compared to the simulation approach is not by design.

Frequency Bias for North-Atlantic-Eurasian regimes, KME

Model	Projected Abs Bias (%)	Simulated Abs Bias (%)
ACCESS-CM2	0.652	1.041
ACCESS-ESM1	1.29	0.483
CESM2-WACCM	0.471	2.446
CNRM-CM6-1	0.442	0.758
CNRM-CM6-1-HR	0.725	1.294
CNRM-ESM2-1	0.239	2.475
GFDL-CM4	0.413	1.41
GFDL-ESM4	0.377	0.903
HadGEM3-GC31-LL	0.449	2.504
INM-CM4-8	0.326	0.823
INM-CM5-0	0.399	1.417
IPSL-CM6A-LR	0.572	2.222
MIROC6	0.406	1.925
MPI-ESM1-2-HR	0.514	2.62
MPI-ESM1-2-LR	0.109	2.381
MRI-ESM2-0	0.203	0.323
NorESM2-MM	1.283	2.345
UKESM1-0-LL	0.681	1.113

Table R1: Frequency bias of projected and simulated approach for North-Atlantic-Eurasian regimes, k-means clustering.

Frequency Bias for Arctic regimes, KME

Model	Projected Abs Bias (%)	Simulated Abs Bias (%)
ACCESS-CM2	1.138	1.028
ACCESS-ESM1	1.144	0.656
CESM2-WACCM	1.384	3.175
CNRM-CM6-1	0.753	2.377
CNRM-CM6-1-HR	0.998	2.514
CNRM-ESM2-1	0.927	3.492
GFDL-CM4	0.528	2.308
GFDL-ESM4	0.897	2.225
HadGEM3-GC31-LL	0.395	2.845
INM-CM4-8	0.567	3.685
INM-CM5-0	0.872	2.157
IPSL-CM6A-LR	0.684	4.607
MIROC6	0.805	5.351
MPI-ESM1-2-HR	0.521	3.836
MPI-ESM1-2-LR	0.815	5.805
MRI-ESM2-0	0.613	0.67
NorESM2-MM	1.496	2.308
UKESM1-0-LL	1.023	1.909

Table R2: Frequency bias of projected and simulated approach for Arctic regimes, k-means clustering.

5. The authors repeatedly mention the patterns being similar between the two methods considered (KME and SAN), where looking at the figures I do not think the differences are non-significant for all regimes. This is also indicated by the different response to climate change of some regimes. I do not have an intuition about how to interpret the SANDRA regimes with respect to those of k-means. It would be helpful if the authors could elaborate on the difference between the methods and its impact on the regime interpretation.

Our sincere apologies! We have discovered an error in our SANDRA (SAN) setup, and it turned out that area weighting was turned off. This gave an unproportionally large weight to the grid cells near the pole, which of course affects the patterns. We have now run SAN again with area weight turned on (by the cosine of the latitude, just as for the KME method) and the new results indeed look a lot more similar between KME and SAN.

Regarding interpretation, SAN, like any other optimization method, including KME, uses statistical measures to obtain a set of regimes that are the optimal representation of the dataset in terms of metrics such as minimum inter-cluster distance. There is no inherent feature in the methods that would suggest they favour certain patterns over others.

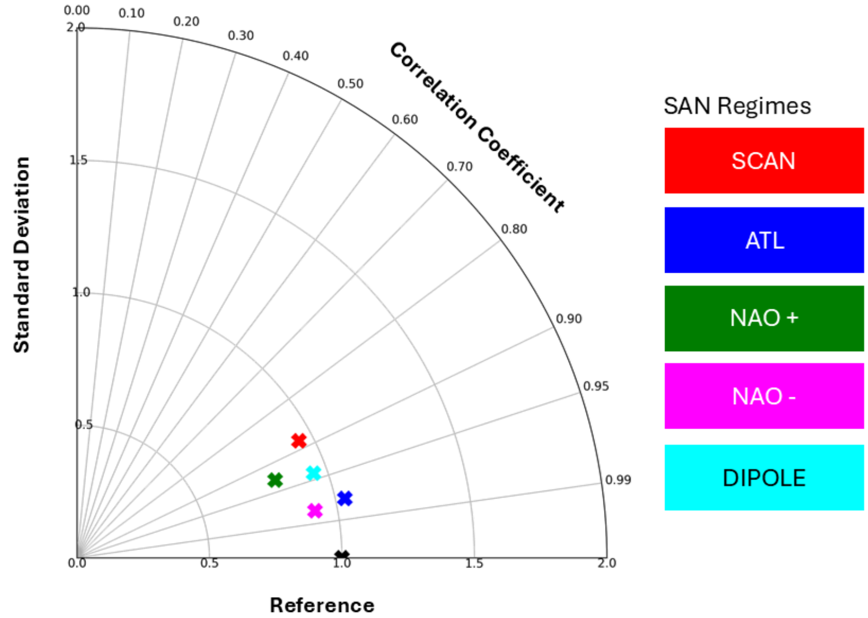


Figure R8: Taylor diagram analysis of circulation regimes computed by KME and SAN algorithms in the historical period for the North Atlantic-Eurasian region in extended boreal summer season from May to October. The reference circulation regimes computed from ERA5 reanalysis data with KME is marked as black cross, the colored crosses represent the SAN regimes.

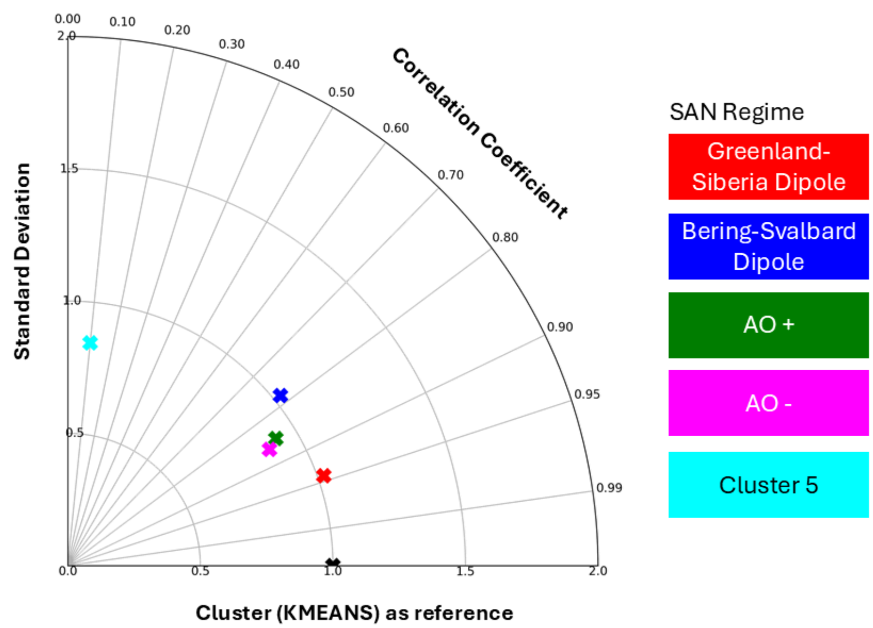


Figure R9: Taylor diagram analysis of circulation regimes computed by KME and SAN algorithms in the historical period for the Arctic region in extended boreal summer season from May to October. The reference circulation regimes computed from ERA5 reanalysis data with KME is marked as black cross, the colored crosses represent the SAN regimes.

A common result when applying different circulation type classification methods is that while some patterns appear very similar between different methods, but the small differences will lead to differences in which days will be assigned to which pattern, and in the end this often results in one of the patterns becoming more different. As an example, for the Arctic patterns (Fig. R15 and R16), *we note that the low pressure in the "Bering-Svalbard dipole" cluster is located over Alaska in KME, while it is more towards Kamtchatka in SAN. This is compensated for in SAN by grouping together days with low pressure over Alaska in cluster 5*. We will discuss this in the revised manuscript at the discussion of Cluster 5 after L308 in the original manuscript.

The updated circulation regimes for the Arctic region are added and discussed after L307. The rephrasing from “East-West Dipole” to “Cluster 5” affects the whole revised manuscript and all Figures regarding the Arctic region.

Including the updated results from SAN, Figure R8 and Figure R9 evaluate the spatial similarity between KME and SAN results in a Taylor diagram. For the North-Atlantic-Eurasian regimes (Figure R8), all pattern correlation coefficients are high (> 0.88 for all patterns) with similar spatial standard deviations, underlining that both methods revealed similar regimes. For the Arctic, 4 out of 5 regimes are detected similarly (pattern correlation >~0.8, similar spatial standard deviation). Cluster 5 is very different, as explained in the previous paragraph.

Accordingly, we updated the figures showing the changes in occurrence frequency under climate change (Figures 6 and 9 in the old manuscript, updates in Figures R17 and R18.)
With the updated SAN results, there is a strong agreement between changes in frequency for the North Atlantic domain, with all 5 regimes having the same sign of the ensemble median of frequency changes. For the Arctic however, only two of the regimes show robust results when comparing the methods (decrease of AO+ and increase of AO-).
Because of that changes, the description and analysis after original Manuscript Figs. 3,4,6 for the North Atlantic-Eurasian region and Figs. 7,8,9 for the Arctic region changed.

6.Figure 4. I do not know what is shown in this figure. Which regimes are compared to the reference? I would say each model has their own, whereas the authors refer to the common EOFs of CMIP6 models. I could not find anything in the methods section discussing this. I think it would be valuable to show the spread between models in a figure like this, also finding which models have a regime representation that is closer to reality.

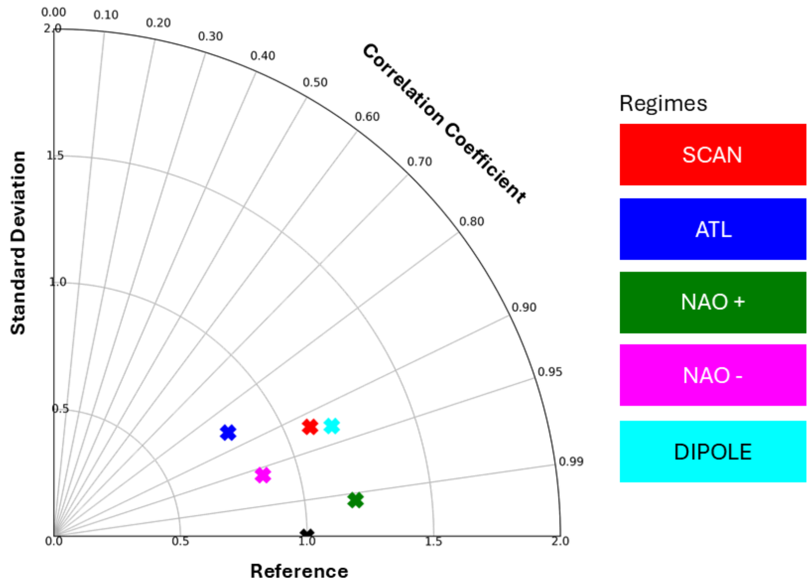


Figure R10 (Figure 4 in original manuscript): Taylor diagram comparing the future common simulated regimes for the CMIP6 ensemble for SSP5-8.5 and the period 2070–2099 to the corresponding reference regimes from ERA5 reanalysis in the historical period (1985–2014), for the North Atlantic-Eurasian region. Spatial regime patterns determined with K-Means clustering.

Using Figure R10 (Fig. 4 in the old manuscript) we evaluate the future changes in the spatial structure of the circulation regimes by comparing the future common simulated regimes for the CMIP6 ensemble for SSP5-8.5 and the period 2070–2099 with the ERA5 reference regimes for the historical period 1985-2014. for the North Atlantic-Eurasian region. The respective Taylor plot for the Arctic regimes is shown in Fig. R20 (and will be included in the revised manuscript).

Both Taylor plots, Fig. R10, R20, underline the similar spatial structure of the common simulated future CMIP6 regimes to that of the ERA5 regimes for the historical period 1985-2014, with all pattern correlation coefficients higher than 0.8 for the North Atlantic-Eurasian and higher than about 0.8 for the Arctic regimes. In our view this justifies the application of the "projected approach" (see our terminology described in Fig. 1 of the manuscript) for the calculation of future changes in regime occurrence frequency (and persistence).

Note: The description of the common approach (compare answer to Rev.1, comment 1) is improved from L122-L138 to:

"*The common simulated circulation regime framework enables the possibility to compare the spatial structure between reanalysis and the entire CMIP6 model ensemble. First the preprocessed data of each climate model are merged into a single data file along the temporal axis, either for the historical period 1985-2014 or the future period 2070-2099. Instead of performing a common EOF analysis and obtaining common PCs, (as described e.g. in Benestad et al., 2023), here the common climate model data are projected onto the ten-dimensional reference state space, determined from the ERA5 data, resulting in ten* *common Pseudo-PCs. The common Pseudo-PCs serve as input data for the K-Means clustering algorithm. Five common simulated circulation regimes are obtained for each time period, representing the joint regimes for the entire model ensemble*."

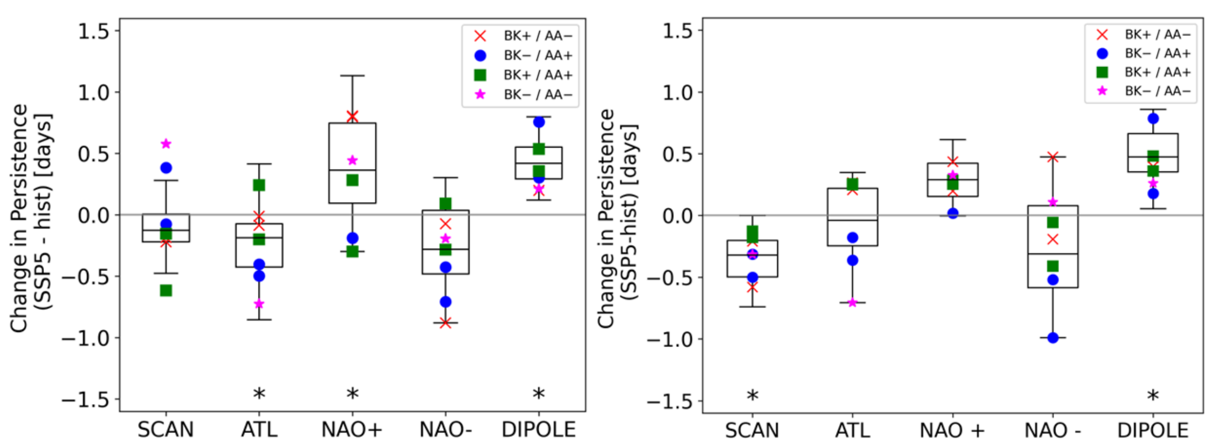
And the caption is improved from " Taylor Diagram of the simulated circulation regimes derived from the common EOFs of CMIP6 models in the future time period under GHG forcing, corresponding to the SSP5-8.5 scenario in the extended boreal summer season from May to October. These regimes are compared to those calculated from ERA5 reanalysis data, which serves as a reference point." to " *Taylor diagram comparing the future common simulated regimes for the CMIP6 ensemble for SSP5-8.5 and the period 2070–2099 to the corresponding reference regimes from ERA5 reanalysis in the historical period (1985–2014), for the North Atlantic-Eurasian region. Spatial regime patterns determined with K-Means clustering*"

7.The authors only look at changes in the regime occurrence. It would be valuable to also study changes in the persistence of the regimes, to get a more dynamical understanding of the effects of climate change, e.g. is a regime becoming more frequent because it becomes more persistent? I suggest adding results on persistence.

We thank reviewer 1 for this comment and we will add results on persistence in the revised manuscript. The new results for the North Atlantic-Eurasian regimes are shown in Figure R11, those for the Arctic regimes in Figure R12.

Indeed, most of the changes in the frequency of occurrence of the North Atlantic-Eurasian regimes (refer Figure R17) coincide with the changes in persistence. For KME and SAN, the projected changes under SSP5-8.5 scenario are similar for both metrics (persistence and frequency). But the changes are not significant for the projected persistence for SCAN and NAO- regimes regarding KME and not significant for NAO+ and NAO- regimes regarding SAN method.

KME SAN



(a) KME (b) SAN

Figure R11: Changes in the persistence for the North Atlantic-Eurasian region under global warming (SSP5-8.5 scenario) compared to the historical period, in the extended boreal summer season May to October. The boxes denote the first and third quartiles, the center black line indicates the ensemble median and the top and bottom whiskers represent the 10th and 90th percentiles. Stars indicate significant changes compared to the historical data at the 95% confidence level calculated with Welch's t-test. Markers state the models associated with storylines.

Analysing the Arctic regimes, the projected changes in persistence are not as aligned with the frequency in occurrence, refer to Figure R18 but still coincide with the results in the projected frequency changes under SSP5-8.5 scenario for some regimes. Regarding the KME method, both metrics show similar significant changes for AO+, AO- and Cluster 5. Comparing the shifts for the Greenland-Siberia Dipole and Bering-Svalbard Dipole, persistence and frequency show opposing results, those changes are not significant for persistence. For the SAN algorithm, the projected significant positive change in the frequency of occurrence for AO- pattern is confirmed by the projected persistence change. Other projected persistence changes are not significant but show a similar tendency compared to the frequency changes except for Cluster 5. Here the frequency of occurrence is simulated to decrease significantly under the SSP5-8.5 scenario but the persistence is increased.

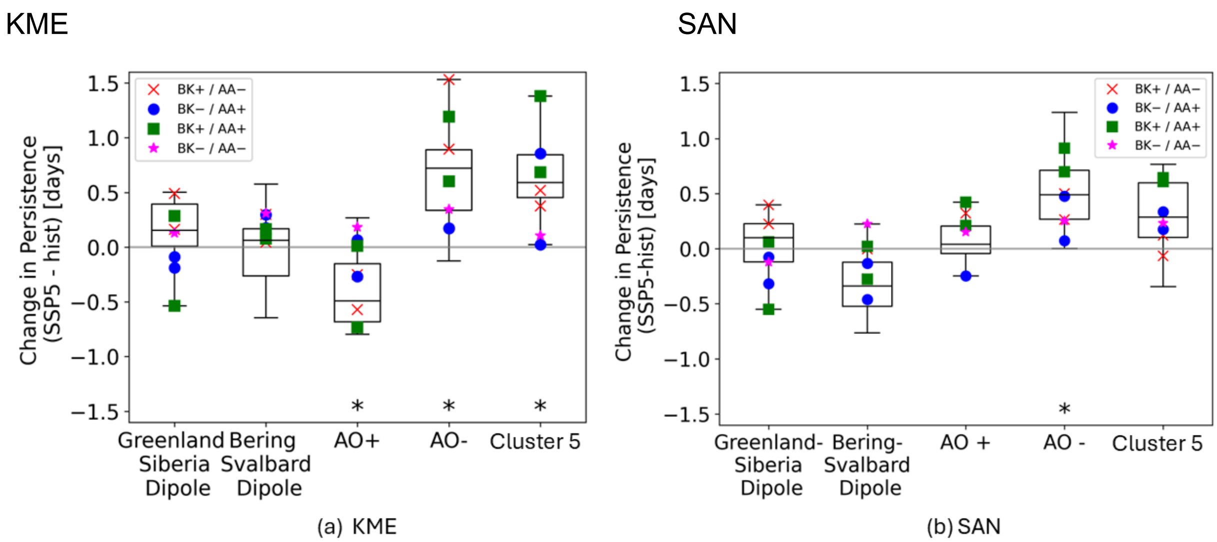


Figure R12: Changes in the persistence for the Arctic region under global warming (SSP5-8.5 scenario) compared to the historical period, in the extended boreal summer season May to October. The boxes denote the first and third quartiles, the center black line indicates the ensemble median and the top and bottom whiskers represent the 10th and 90th percentiles. Stars indicate significant changes compared to the historical data at the 95% confidence level calculated with Welch's t-test. Markers state the models associated with storylines.

The changes in persistence are included in the revised manuscript at L297 after Figure 6 for the North Atlantic-Eurasian region and at L359 after Figure 9 for the Arctic region and discussed from L316 in the revised manuscript for the North Atlantic-Eurasian, respective L416 in the revised manuscript for the Arctic region.

8.Many of the studies references for comparison study different domains, e.g. Europe in Boé (2019). It would be good to acknowledge that in the text, as it can impact the results. The same for studies used in comparison that study the winter season. Furthermore, I suggest adding some references on the different number of regimes:
https://www.nature.com/articles/nclimate3338 and
https://rmets.onlinelibrary.wiley.com/doi/pdfdirect/10.1002/qj.3818.

Both studies will be cited in the revised manuscript. Similar to Grams et al. (2017), we introduced the anomaly correlation coefficient to justify the chosen cluster number of 5 for both regions and both methods (see above our answer to comment 3). The second paper will also be included when discussing the general debate about an optimal cluster number.

In the revised manuscript we will be more accurate regarding seasonality and regionality.
In particular the text L193-209 will be changed to:

The reference circulation regimes for the ERA5 data 1985-2014 obtained with the K-Means clustering (KME, Fig.2, upper row) and the SANDRA (SAN, Fig. 2,center row) algorithm alongside with the zonal wind anomaly composites at 250 hPa for the KME regimes, lower row, are summarised here, the wind composites linked to the SAN regimes are shown in Appendix F

– The Scandinavian Blocking regime (SCAN), shown in Fig.2a, indicates a positive pressure anomaly centered above Scandinavia and a low pressure anomaly, centered over the North Atlantic Ocean westwards of the British Isles (refer to KME, Fig.2a, upper row). The regime pattern obtained by the SAN algorithm displays a slightly weaker positive pressure anomaly over Scandinavia and a slightly stronger low pressure anomaly over the North Atlantic (Fig.2a, center row). The SCAN is associated with a southward shifted Atlantic jet.

– TheAtlantic Trough regime (ATL) is characterized by a strong negative pressure anomaly centered between Iceland and the British Isles (Fig.2b), connected with a strengthening of the Atlantic jet exit.

– Fig. 2c displays the North Atlantic Oscillation, which is poleward shifted in summer, in its positive phase (NAO+). Here an elongated positive pressure anomaly extends from the Ural to Newfoundland accompanied by a negative pressure anomaly above Greenland. The NAO+ pattern is connected with a poleward shifted Atlantic jet. Dorrington and Strommen (2020) likewise identified a similar wind composite at 850 hPa, which they denoted as BLK / NAO +.

– Fig. 2d displays the North Atlantic Oscillation in its negative phase (NAO-), here the positive and negative pressure anomalies are swapped respectively to NAO+ as well as the wind anomalies, which indicate a southward shifted Atlantic jet.

– The Dipole Atlantic Blocking regime (DIPOLE, Fig. 2e) displays a positive pressure anomaly centered between Iceland and the British Isles. The accompanying negative pressure anomaly is located over the Ural region and Barents Sea. The DIPOLE pattern is linked to a weakening of the Atlantic jet exit and poleward shift of the jet structure

Riebold (2023) analysed circulation regimes over the same region for the summer season (JJA: June to August) and found similar MSLP anomaly patterns for each regime. Boe et al. (2009) and Cattiaux et al. (2013), on the other hand, analysed summer circulation regimes for JJA over a smaller North Atlantic region (20°–80°N, 90°W–30°E), using MSLP (Boe et al., 2009) and Z500 (Cattiaux et al., 2013) data, respectively. In both studies, four circulation regimes were detected. These four regimes comprise the negative and positive phases of the NAO (called NAO- and Blocking, BL), an Atlantic low (AL) and an Atlantic ridge (AR) regime, which bear many similarities with the NAO-, NAO+, Atl and SCAN regimes detected in our study. “

In addition, we checked our references to studies analysing winter regimes and found that we had properly referenced them as such.

9.I do not see the added value of discussing storylines for this paper. Since each storyline only contains two models, it is near-impossible to draw any robust conclusions. Can the authors clarify why they chose to also include the storylines in this work?

The main motivation behind adding the storyline perspective is to put the work in context with other ongoing work in the EU PolarRES project, which will also see more studies being published in the coming year. Regarding the circulation response to storylines, even with the small sample, there at least seems to be a tendency of the models of each storyline to be closer to each other in the same half of the box plots.

As shown in Levine et al. (2024, fig. 4), the CMIP6 multi-model mean (MMM) shows a poleward shifted N-Atlantic jet, but the strength of this poleward shift depends on the storyline, with a weaker poleward shift in storyline A and B and slightly stronger poleward shift in storyline C and D (compared to the MMM). Since the circulation regimes are related to specific patterns of jet anomalies, one might hypothesize that this is related to different future changes in the occurrence frequencies of in particular those regimes which are related to a northward shifted jet (NAO+, Dipole). We are aware that testing this hypothesis is limited because there are only a few models available which represent each storyline. (These paragraphs are also used as answer to reviewer 2, comment 2.)

We now consider models for all 4 storylines and will discuss this in the revised manuscript.The subsection 3.3 Storylines L182 to L183 “We therefore concentrate on the two storylines determined by the opposite signals in these two factors” will be updated to:

We consider all four storylines for a comprehensive analysis.

Additionally, Table 1 is updated to

BK+ PA−	BK− PA+	BK+ PA+	BK− PA−
CNRM-CM6-1 CNRM-ESM2-1	KACE-1-0-G NorESM2-MM	MIROC6 MIROC-ES2L	CESM2-WACCM

Caption: Table 1. Storyline and respective model selection.

and the Results section discussing the changes in frequency associated with storylines as well.

10.The conclusion and outlook section could benefit a lot from placing the work in the context of the wider literature. Are the finding in line with other studies, with what we expect linked to jet stream shifts, … As is, the outlook part is very brief and lacks context.

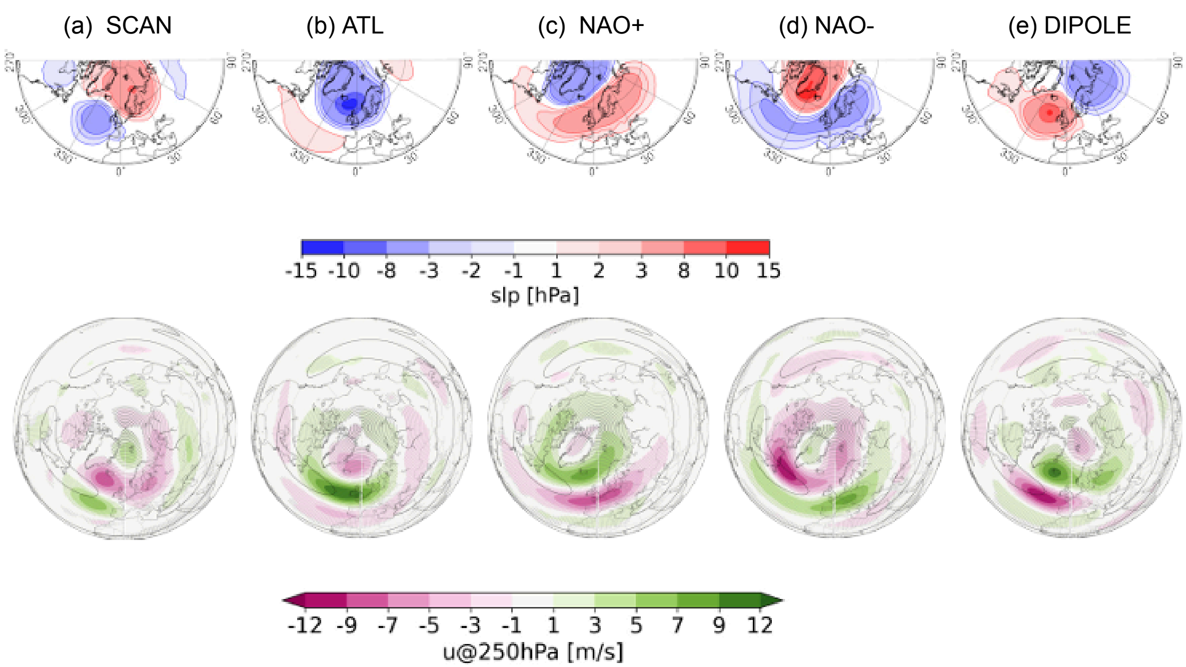


Figure R13: MSLP anomaly fields for North-Atlantic-Eurasian reference regimes (from ERA5) computed with KME method in upper row. Zonal wind composites @250hPa level in lower row. Climatology is plotted by black contour lines.

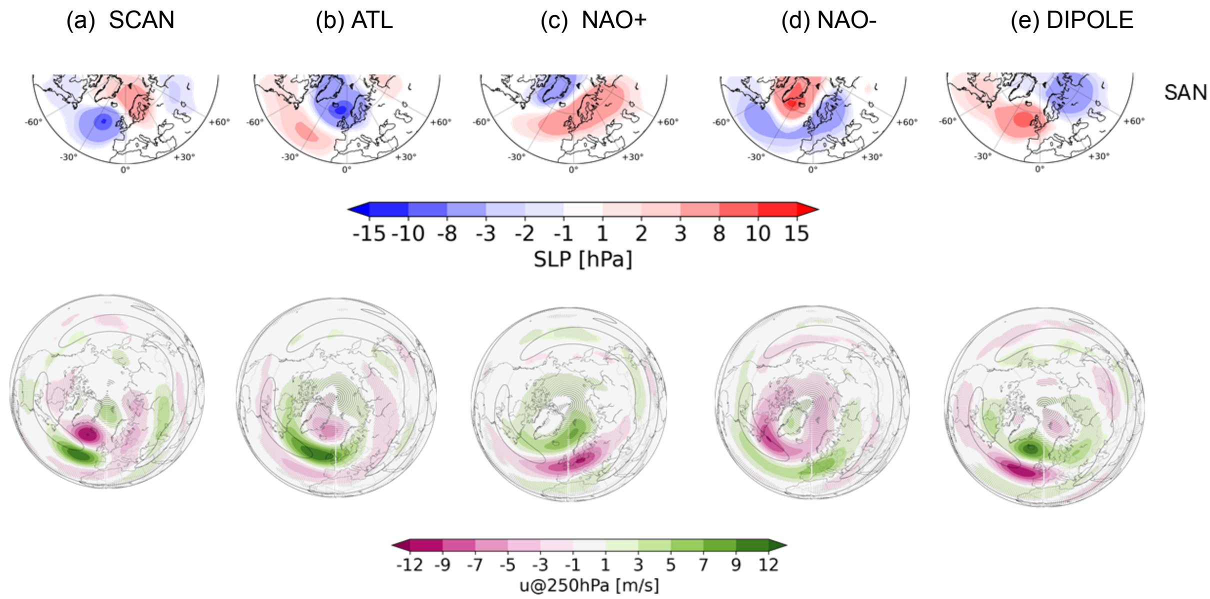


Figure R14: As R13, but for regimes obtained with SAN method.

We have done some analysis on the changes in the wind field, see below. We will add the following discussion as a new subsection to the results section which includes relations to existing literature on the subject.

To relate our results of regime changes changes in tropospheric jets, Figures R13 and R14 show composites of zonal wind anomalies at 250hPa (u@250hPa) for the North-Atlantic-Eurasian regimes determined with KME (Figure R13) and SAN (Figure R14). Due to the similar structure of the regimes obtained with both methods, the composites of u@250hPa display similar patterns, too. The SCAN and NAO- regimes are associated with a southward shifted jet above the Atlantic. NAO+ and Dipole are linked to a poleward shifted jetstream. The NAO+ regime is also connected to a slightly tilted jet exit. The Atl regime is associated with a strengthening of the jet exit. The predicted northward shift of the jet in the North Atlantic detected by Woollings & Blackburn (2012) (CMIP3) and Barnes & Polvan (2013) (CMIP5), Levine et al. (2024) (CMIP6) and Harvey et al. (2020) (CMIP3,5,6) is consistent with the increase in occurrence of the NAO+ and Dipole regimes under SSP5-8.5 scenario. In accordance, both regimes that are linked to a southward shifted jet (SCAN and NAO-) are simulated to occur significantly less frequently in the future. The future increasing tilt of the jet in the Atlantic region (Woollings & Blackburn, 2012) is in agreement with the detected increase in the frequency of occurrence of the NAO+ regime in our study. The description of the patterns are added as presented in Comment 8. And discussed when analysing the frequency of occurrences. For the summary of section 4.1 there is added: "*This can be also made for the wind composites changes: regimes associated with a northward shifted jet stream are simulated to occur more often and to be more persistent, while patterns linked to a southward shifted jet stream are projected to occur less often under strong global warming.*" after L296 in the original manuscript or L333 in the revised manuscript.

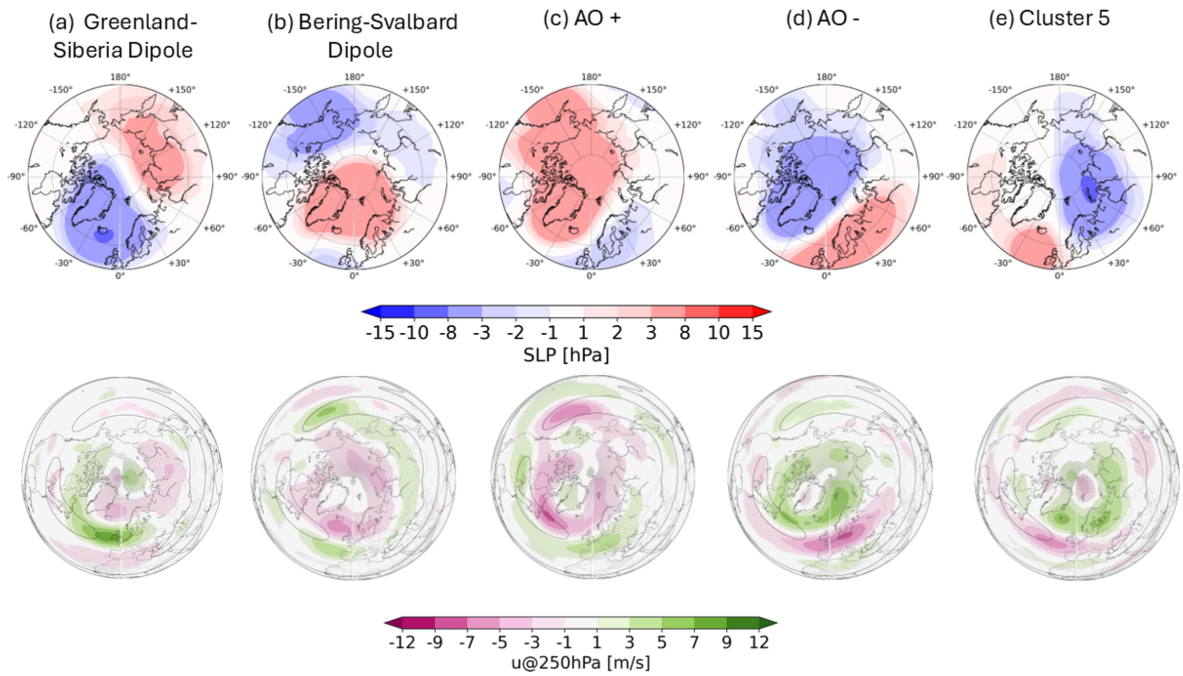


Figure R15: As R13, but for the Arctic regimes.

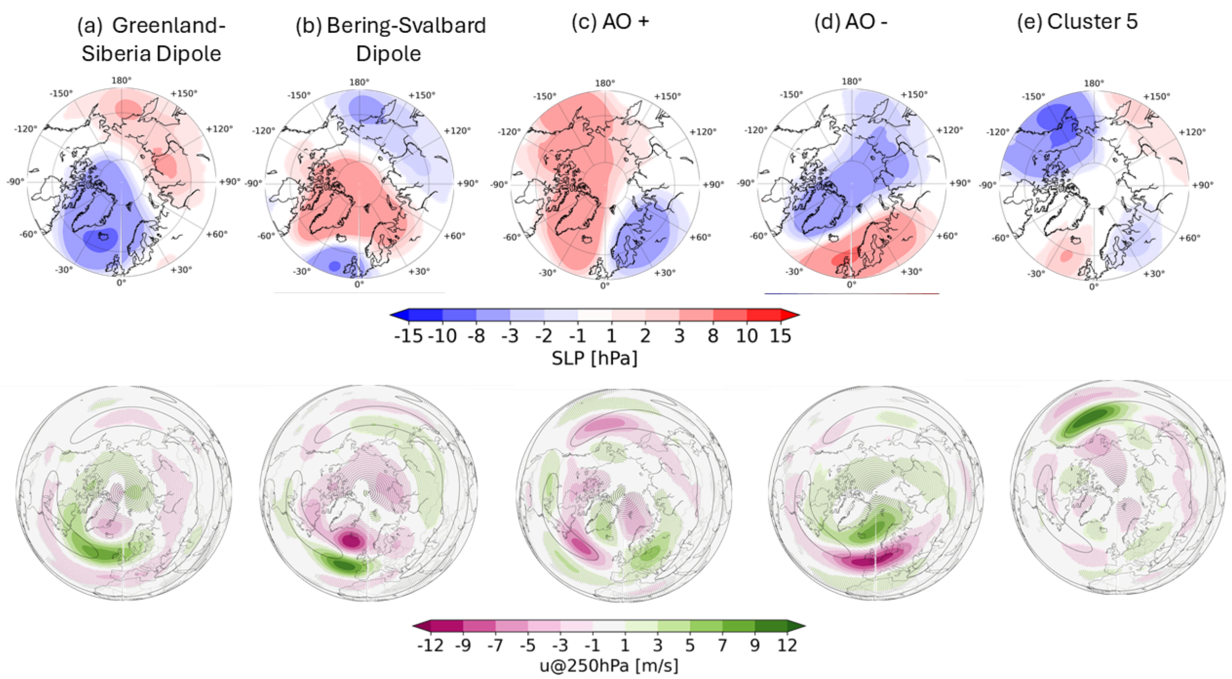


Figure R16: As R15, but for regimes obtained with SAN method.

The respective u@250hPa composites for the Arctic regimes are shown in Figure R15 for the KME method and in Figure R16 for the SAN method. These composites (Figure are again very similar for those 4 regimes with similar pattern structures in KME and SAN (Figures R15 (a)-(d) and R16(a) -(d)), but very different for cluster 5, compare Figures R15 (e) and R16(e).The u@250hPa composites show a strengthening of the Atlantic jet exit for Greenland-Siberia Dipole regime. The Bering Svalbard Dipole regime is associated with a southward shifted Atlantic jet, similar to the SCAN pattern. The AO+ regime is associated with a weakening of the Atlantic and Pacific jet exit, with a slight southward shift for the North Atlantic jet, similar to NAO-. In contrast, the AO- regime is associated with a northward shifted North Atlantic jet, similar to NAO+. The most robust change in the occurrence frequency we detected is the increase in occurrence of the AO- regime, i.e. a poleward shift of the North Atlantic jet, which is in accordance with the above cited studies. In accordance, the AO+ regime and the Bering Svalbard Dipole (for KME only) which are linked to a southward shifted North Atlantic jet, are simulated to occur significantly less frequently in the future.

The zonal wind anomalies at 250hPa will be added to Figure 2 and Figure 7.

The anomalies are discussed (see comment 8) in that Figures and added in revised manuscript at multiple Lines.

Regarding the discussion after L401 we add: “*The changes in frequency and persistence show that patterns, that are associated with a poleward shifted jet structure will be more prominent under global warming, while patterns linked to a southward shifted jet stream will occur less often and also be less persistent. This result is in agreement with Li et al. (2024); Osman et al. (2021), who likewise identify northward-displaced Atlantic jet structures linked to global warming. Similar trends have previously been reported in CMIP3 (Woollings and Black burn, 2012) and CMIP5 (Barnes and Polvani, 2013) simulations under strong global warming scenarios.”*

Comments from the PDF:

L1: “delves” and “that” has been changed to *explores* and *which*.

L8: "Specify which regimes".

We rewrite “ Despite slight differences between the SAN and KME methods in identifying spatial regime struc tures, the fundamental spatial configuration of these regimes remains largely unchanged under future climate scenarios” to *Despite slight differences between the SAN and KME methods in identifying spatial regime structures, the patterns remain~~s~~ largely unchanged under future climate scenarios*

L22: comment on “or” was changes into *or/and*

L24: "not change the spatial structure of the regime patterns" comment: "Needs a reference. It's the ones you give after, as there's not much, but which specifically do you refer to?"

We are adding Palmer (1993) and Corti (1999) already here.

L25: "strong"

We changed “a strong external forcing acting on the dynamical system can lead to significant changes in the spatial structure of the regime patterns or to the appearance of new regimes” To *On the other hand, an increasing strength of the external forcing acting on the dynamical system can lead to significant changes in the spatial structure of the regime patterns or to the appearance of new regimes. Then, the external forcing is regarded as strong forcing.*

See also response to reviewer 2, comment 4.

L29: changed “with” to *to*

L37 "storyline approaches", comment "describe in one sentence"

Moving from L58., *They provide plausible realizations of climate change and emerge from the range of climate projections found in a large ensemble of climate simulations*. is added as suggested in L58

L51: "Is this CMIP?", comment "Is this CMIP?"

We add *for CMIP3* after Citation.

L58: "They provide" -> "Mention where you first mention storylines"

Thank you for the suggestion. We are moving this to L37.

L66: "projected future changes", comment "Be more specific. Changes in what?"

We are adding *with focus on frequency of occurrence and persistence*.

L68: "the results", comment "Which results?"

We are adding *in frequency of occurrence as well as persistence*.

L73: "Only SSP5-8.5?"

We clarify and shorten by rewriting "In examining the simulation of future time periods, the SSP5-8.5 emission scenario is of particular interest. As the highest emission scenario, it is characterised by a large increase in Greenhouse Gas (GHG) emissions, impinging a strong external forcing upon the atmosphere. Thus, a response of characteristics of circulation regimes is expected." to "For the future period we use the highest emission scenario SSP5-8.5 as it is expected to give the most statistically robust response to climate change."

L78: what are these characteristics?

Rephrased the sentence to *For the future period we use the highest emission scenario SSP5-8.5 as it is expected to give the most statistically robust response to climate change.*

L79: "Why SLP and not Z500?"

Atmospheric circulation regimes are generally computed by performing clustering algorithms on a circulation variable such as the geopotential height at 700 or 500 hPa or mean sea level pressure MSLP). We agree that the majority of studies on atmospheric circulation regimes is based on analyses of the the geopotential height field at 500hPa, but there are also many studies analyzing geopotential height field at 700hPa (e.g. Michelangeli et al., 1995, Vautard 1990) or mean sea-level pressure (MSLP) fields (e.g. Philipp et al., 2007, Boe et al., 2009, Crasemann et al., 2017, Skific et al., 2009) .

Here, we chose to use MSLP instead of geopotential height as the future trend is much smaller in the MSLP fields.

We changed in L79:

"To analyse the characteristics of circulation regimes, the daily averaged sea level pressure (\,SLP\,) data are used." to "*To analyse the characteristics of circulation regimes, the daily averaged sea level pressure (\,SLP\,) data are used as a representative circulation variable*."

L80: "(30◦ N-90◦ N, 90◦ E-90◦ W)", comment "This is larger than in most other studies on regimes in the Euro-Atlantic sector".

We will reformulate " since the circulation regimes in this area are well-known" to "*Given that the circulation regimes in this area have been studied before (Crasemann et al., 2017, Riebold et al., 2023) during winter, here we study this area in the extended summer season*."

L85: "Is 30 years sufficient data?"

This is commonly used in multiple climate studies.

L85: "Sentence too long and difficult to follow."

We split the sentence after 2070-2099.

L93: "To the seasonal cycle?"

Yes. We clarify by reformulating "Averaging the data day by day at each grid point yield the mean seasonal cycle. Additionally, a 21-day running mean is applied to remove higher-frequency fluctuations." as "*The mean seasonal cycle is obtained by computing the daily climatology and then applying a 21-day moving average to this.*"

L94: "influenced by GHG forcing", comment "I understand that, but that does not fully answer the question as to why you use the historical one also for the future. It'd mean you consider the changes in the seasonal cycle as a part of the changes in regime dynamics."

We clarify by changing

"This difference is taken into account by subtracting the historical seasonal cycle from both the historical and future time periods of climate model simulations as presented in Fabiano et al. (2021)" to "*To keep this dynamically induced change in the future seasonal cycle, we subtract the same historical seasonal cycle from both the historical and the future periods, in line with the approach taken in Fabiano et al. (2021).*"

L97: "interpolated onto the identical 1.125x1.125 grid", comment: "Why? As this is not necessarily a requirement for the PC/EOF computation, that will work fine for any grid. Not sure about SANDRA. Do you think it could introduce an additional bias?"

The CMIP6 models have different resolutions, so for the common EOF part of the methodology, they need to be interpolated to a common grid. The choice of 1.125x1.125 was rather arbitrary and taken from previous studies, but as also shown, the results are not sensitive to using the 2.5x2.5 degree grid.

L104: "the ten-dimensional reference state space", comment "What do you mean by this?"

We rephrase “and span the ten-dimensional reference state space” as "*Moreover, the first ten EOFs computed from the ERA5 reference dataset constitute the basis vectors for our ten-dimensional reference state space*."

L111: "anomalies were projected onto the ten-dimensional reference state space", comment "Why? Provide some reasoning"

Refer to reviewer 1, comment 1 and reviewer 2, comment 1.

L115: "projected approach", comment "So in summary, you assign the model data to the ERA5 regimes, in a nuanced way."

Yes, to clarify we add "*In other words, we assign the data from the CMIP models to the regimes from ERA5 by using the pseudo-PCs.*" in L116.

L139: "How do you interpret the patterns that come out of SANDRA?"

See our answer to comment 5.

L148: "projected approach for SANDRA", comment "Why?"

See our answer to comment 3.

L153: "coarser resolution", comment "Ok, but then you might as well also use this for the EOF/PC computation, as there I wouldn't expect much difference either,."

The choice of 1.125x1.125 was rather arbitrary and taken from previous studies, but as also shown, the results are not sensitive to using the 2.5x2.5 degree grid. In our SANDRA setup we had previously mostly used 2.5x2.5, so we also ran tests with both resolutions to verify that there was no significant difference in the results.

L156: comment: "Add Falkena et al. (2020)"

We will add this reference at original manuscript L156 , revised manuscript L 178 and 179.

L158: "The same for both KME and SAN?"

See comment 3.

L162: "Further Methods", comment "Be specific in the heading what this is for."

We will change this heading to "Statistical Evaluation Methods".

L177: "Add references".

We added the storyline references (Trenberth et al., 2015; Shepherd, 2016; Shepherd et al., 2018) mentioned in the introduction also here. This can be found in revised manuscript L 200.

L183: "Why determined by opposite signals, and not also ++ or --?"

We are adding the other two storylines too, see reviewer 2, comment 2.

L186: For section 4.1, "Subsections in here would help the reader."

We agree. We added "Spatial regime patterns for the present day" and "Future changes".

Fig 2: Capital letters

For the North Atlantic-Eurasian region the DIPOLE pattern than would be stated as Dipole, that is not distinguishable from the word Dipole of opposing poles with different variable's signs. For the Arctic region, the rephrasing for the 2 different Dipoles (Greenland-Siberia / Bering-Svalbard) is not necessary since they are already clearly defined as such.

L195: "What do you mean by centre of action?"

We replaced this with "pressure anomaly centres".

The whole paragraph L193-209 was changed to:

"*TThe reference circulation regimes for the ERA5 data 1985-2014 obtained with the K-Means clustering (KME, Fig.2, upper row) and the SANDRA (SAN, Fig. 2,center row) algorithm alongside with the zonal wind anomaly composites at 250 hPa for the KME regimes, lower row, are summarised here, the wind composites linked to the SAN regimes are shown in Appendix F.:*

– The Scandinavian Blocking regime (SCAN), shown in Fig.2a, indicates a positive pressure anomaly centered above Scandinavia and a low pressure anomaly, centered over the North Atlantic Ocean westwards of the British Isles (refer to KME, Fig.2a, upper row). The regime pattern obtained by the SAN algorithm displays a slightly weaker positive pressure anomaly over Scandinavia and a slightly stronger low pressure anomaly over the North Atlantic (Fig.2a, center row). The SCAN is associated with a southward shifted Atlantic jet.

– TheAtlantic Trough regime (ATL) is characterized by a strong negative pressure anomaly centered between Iceland and the British Isles (Fig.2b), connected with a strengthening of the Atlantic jet exit.

– Fig.2c displays the North Atlantic Oscillation, which is poleward shifted in summer, in its positive phase (NAO+). Here an elongated positive pressure anomaly extends from the Ural to Newfoundland accompanied by a negative pressure anomaly above Greenland. The NAO+ pattern is connected with a poleward shifted and slightly tilted Atlantic jet

– Fig.2d displays the North Atlantic Oscillation in its negative phase (NAO−), here the positive and negative pressure anomalies are swapped respectively to NAO+ as well as the wind anomalies, which indicate a southward shifted Atlantic jet.

– TheDipole Atlantic Blocking regime (DIPOLE, Fig.2e) displays a positive pressure anomaly centered between Iceland and the British Isles. The accompanying negative pressure anomaly is located over the Ural region and the Barents Sea. The DIPOLE pattern is linked to a weakening of the Atlantic jet exit and poleward shift of the jet structure.

Riebold (2023) analysed circulation regimes over the same region for the summer season June to August (JJA) and found similar MSLP anomaly patterns for each regime. Boe et al. (2009) and Cattiaux et al. (2013), on the other hand, analysed summer circulation regimes for JJA over a smaller North Atlantic region (20°–80°N, 90°W–30°E), using MSLP (Boe et al., 2009) and Z500 (Cattiaux et al., 2013) data, respectively. In both studies, four circulation regimes were detected. These four regimes comprise the negative and positive phases of the NAO (called NAO- and Blocking, BL), an Atlantic low (AL) and an Atlantic ridge (AR) regime, which bear many similarities with the NAO-, NAO+, ATL and SCAN regimes detected in our study. "

L202: "Change brackets."

See above, Paragraph L193-202 changed in the revised manuscript.

L230 and comment on Fig. 2

See our response to comment 5.

L241: "common simulated circulation regimes", comment "What are these?", and comments to Fig. 4.

We will try to describe this better in the revised methods section. The common approach is to compute one set of EOFs for all CMIP models taken together as one dataset.

L247: "How would this be different if you use the model PC's instead of pseudo-PC's?"

See our answer to comment 1.

L251: "I find this too strong a statement because of the use of pseudo-PC's in the methods."

See our answer to comment 1.

L255: "more accurately", comment "What do you mean by more accurately? It's a different approach, and I would expect this difference given that for the simulated approach the regimes differ between models whereas for the projected they don't..."

See our answer to comment 4.

L280: "I struggle to see the value of the storylines if you only have two models for each."

See our answer to comment 9.

L286: "diverging future changes", comment "Because the patterns are different would be my hypothesis, elaborate a bit."

We agree, in the redone calculations (comment 5) and new Figure, see Fig.17, these observations of diverging results are not apparent anymore.

L289: "small differences", comment "Not always that small."

Results are updated and the differences are smaller, see our answer to comment 5.

L295: "tendency of models associated with BK+/AA− storyline to occur even more often" comment "One is on the median, so you're basing this on one model, which I think is a too strong statement."

We agree, and wording will be updated in light of the new results.

Fig. 6, comment "Difference for DIPOLE, also larger spread for SAN"

Figures are updated (see Fig. R17, R18) and text will be as well.

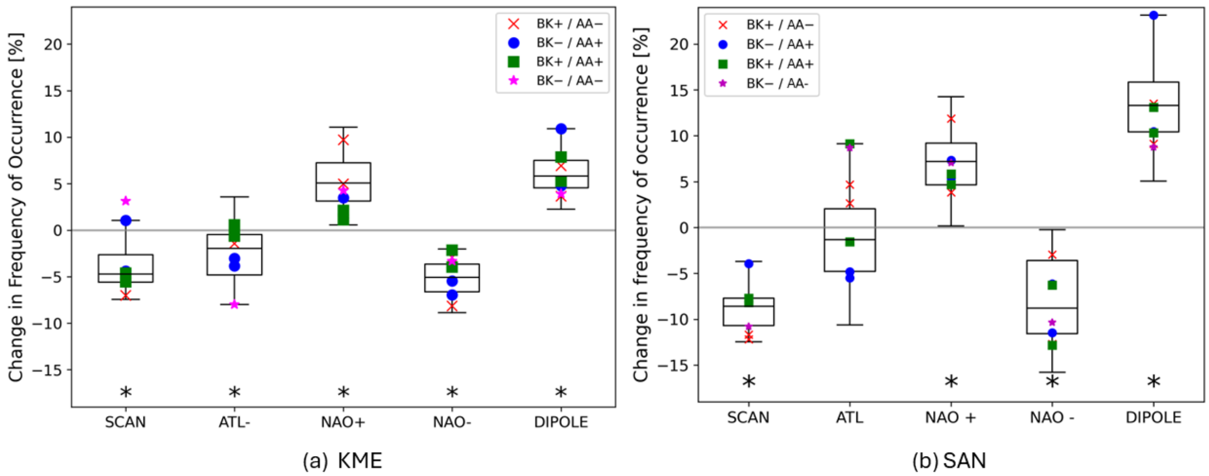
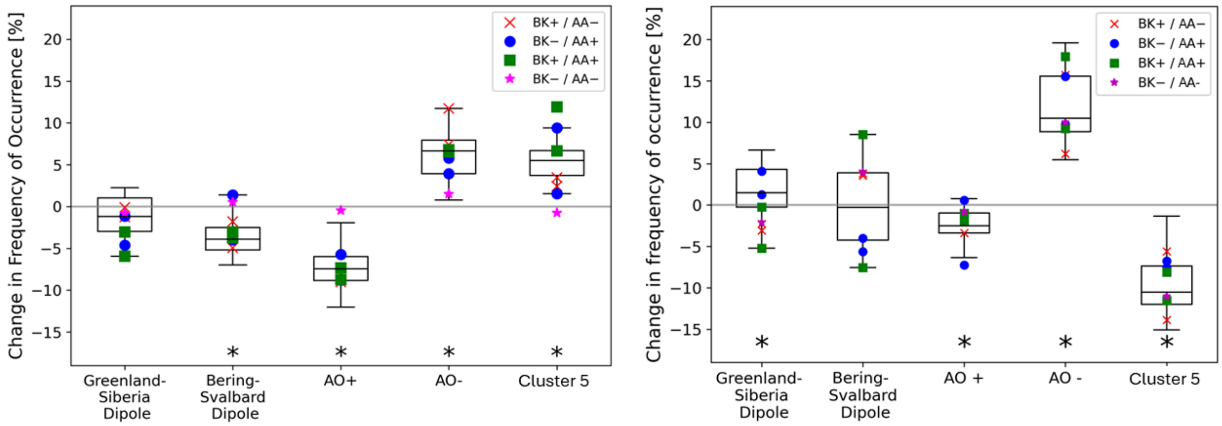


Figure R17: (Updated Fig. 6 original manuscript): Changes in the frequency of occurrence for the North Atlantic-Eurasian regimes under global warming compared to the historical period, SSP5-8.5 scenario in the extended summer season May to October. The boxes denote the first and third quartiles, the center black line indicates the ensemble median and the top and bottom whiskers represent the 10th and 90th percentiles. The star indicated significant changes compared to the historical data at the 95% confidence level calculated with Welch's t-test.The markers represent models attributed to the respective storylines.



(a) KME (b) SAN

Figure R18: (Updated Fig. 9 original manuscript) As Figure R17 for the Arctic regimes.

Fig. 7, comment "Also, AO+/- are very different in it's extent. And E-W Dipole is substantially different as well",
L318, "Again I find this too strong a conclusion, even more so than in the other domain.",
and L365: "similar in their spatial structure", comment "Questionable".

We agree. The patterns have changed and the discussion will be adapted accordingly. See comment 5.

L320: "No analysis of pattern change in the future?" and L377: "You haven't shown this for the arctic regimes."

Thank you for this comment. We had done this analysis as well, and we will include the respective Taylor plot Figure R20 and its description in the revised manuscript. Figure R20 reveals the similar spatial structure of the common simulated future CMIP6 regimes to that of the ERA5 regimes for the historical period 1985-2014, with all pattern correlation coefficients higher than about 0.8 for the Arctic regimes. In addition, here we show the respective Arctic regime pattern for the ERA5 regimes for the historical period 1985-2014 (Fig. R19, upper row) and the common simulated CMIP6 regimes for the future. Also the visual inspection reveals the similarity of the patterns, with some changes in the strength of the MSLP anomaly centers (as for AO+ and Greenland-Siberia Dipole) or in the position of the MSLP anomaly centers (as for Cluster 5).

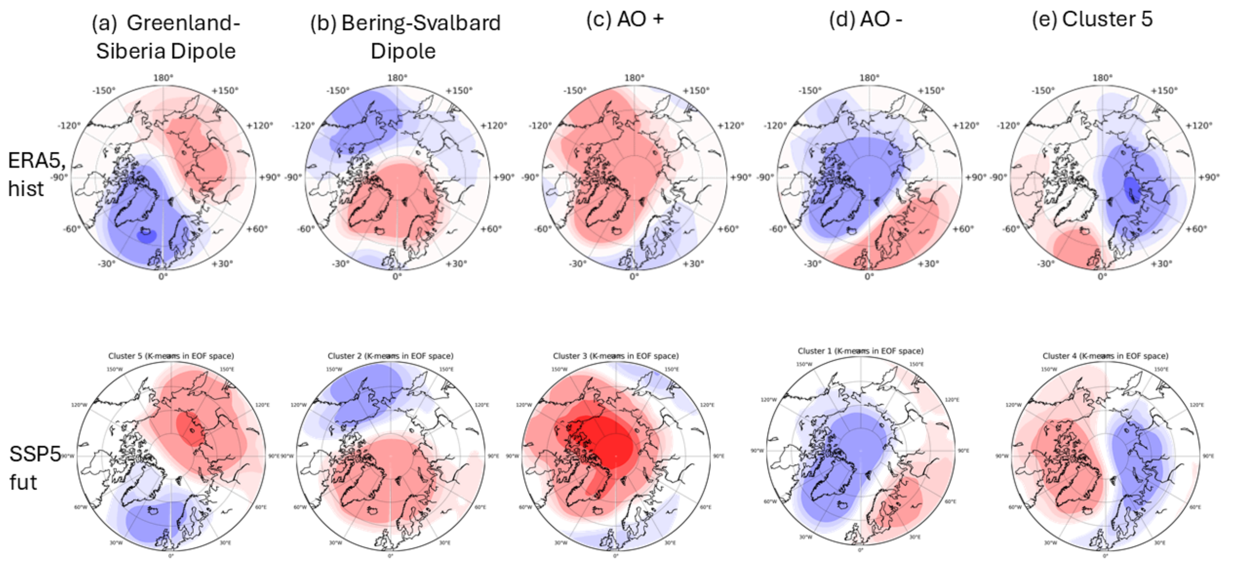


Figure R19: MSLP patterns computed by KME method for ERA5, historical time period in the upper row and common circulation regimes derived from CMIP6 models in the future period (SSP5-8.5, 2070–2099) in the lower row, Arctic region.

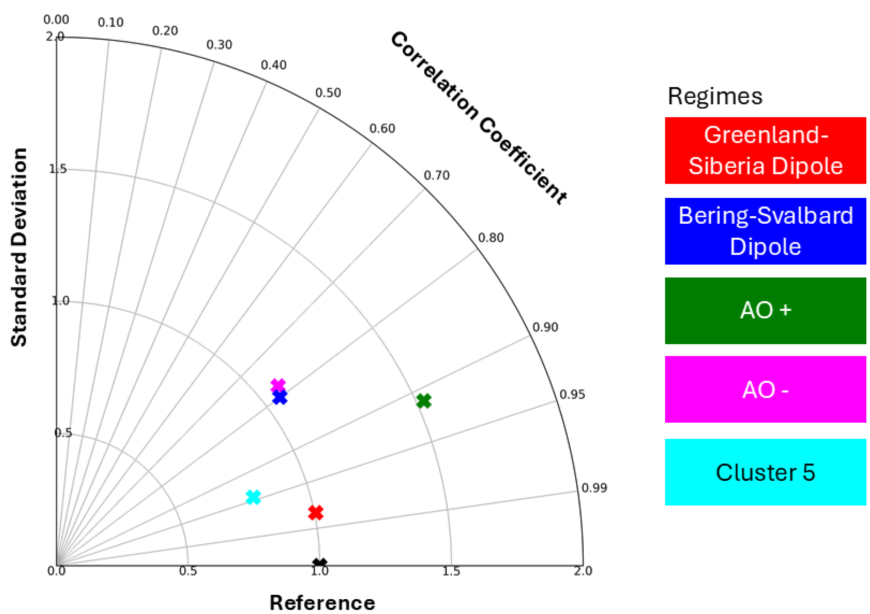


Figure R20: Taylor diagram comparing the future common simulated regimes, determined with K-Means clustering, for the CMIP6 ensemble for SSP5-8.5 and the period 2070–2099 to the corresponding reference regimes from ERA5 reanalysis in the historical period (1985–2014), for the Arctic region.Spatial regime patterns determined with K-Means clustering.

L329: "shifted positive pressure anomaly", comment "Can we learn something from this difference?"

The discussion is updated in light of the new results. See updated section 4.2. This affects Fig. 7, and Fig.8 in the revised manuscript.

Fig. 8: "I would say here there is less of a match."

Yes, this will be updated.

Fig. 10, "Storylines", comment "This is the average over two model? Can you show them separately?"

We previously used this figure to back up one claim which is no longer valid in the new and updated results. Therefore we will remove this figure. Since we also include all four storylines we can now refer to the full figures in Levine et al. instead.

L372: "Considered also looking at persistence?"

We have added analysis of persistence. See our answer to comment 7.

L386: "limited influence of localized drivers", comment "I think it's hard to conclude this based on two models per storyline." and multiple comments from L417 to L420.

See discussion in answer to comment 9.

L406: "now always...." (probably meant to be "not always...."

See our answer to comment 5.

L425: "many different considerations", comment "Add references"

We will add more references to this.

L429: "previously not so well-studied" -> "not often studied"

We used this suggestion in the updated manuscript.

Fig. B1: "By eye, this really isn't too clear."

Correct, but that is the point of the tool, to be able to assist in finding such a point when it is not easy to find by eye.

L460: "smallest area", comment "Why smallest?"

We want to have an area focused on the Arctic that is not constrained by geometry (due to too small area). If we would extend further south a larger fraction of the domain would be in the mid-latitudes. We will improve this formulation in the revised manuscript.

L460: "The patterns look different in ways, so what is the information that you ate after?"

At the centre of the domains, the patterns are very similar.

Reviewer 2:

If I were convinced that indeed the projected approach is valid in this case, the article is very well presented and presents a significant contribution to the field. The authors provide an explanaition to why the cluster frequency changes under one storyline and the other, which is a significant contrubution to understanding the impacts of large scale ciruclation changes and the model uncertainty. However, the article would highly benefit from carefully confirming that the regimes for which the frequencies are studied are indeed representative of how the circulation is organized in models and in the future. I recommend major revisions but I highly encourage the authors to address and resubmit.

Major comments:
1. The projected approach to weather regimes is an established methodology. However, the paper would be a much more valuable contribution if the authors were able to provide a more robust validation to justify the approach.
- The pseudo-PCs are already a projection of the data onto the EOFs from ERA5, which is already an great assumption. I would suggest that the projected approach was compared with the complete clustering approach performed with the models. To my understanding, only if the circulation in the model can be considered as representative of the reference, the two can be comparable. Formally, this means that the model sub-space is contained in the reference space. One way of quantifying this is the "quantization error" proposed by Quagraine et al. (2020).
- Currently the evaluation is performed using Taylor diagrams and the statistical significance of the changes in the frequency of occurrence under the influence of GHG is performed with a Welch's test. However, these metrics are valid once the above has been tested (i.e. that the model subspace is contained in the reference subspace).

We follow the suggestion of reviewer 2, and use the "quantization error" proposed by Quagraine et al. (2020) to quantify, if the model sub-space is contained in the reference space. The "quantization error" is defined as the mean error of each day's pattern with respect to the reference cluster pattern to which it belongs (Quagraine et al., 2020). As explained in Quagraine et al. (2020), by comparing the error mapping of the GCMs to that of the ERA5 data, one can assess whether the GCM patterns have a greater error than the reanalysis. In this case, the GCM sub-space is not contained in the reference space spanned by the reanalysis data. We also use this argumentation in our answer to reviewer 1, comment 1.

Figure R21 shows the quantization error for the North-Atlantic-Eurasian regimes for ERA5 (last row) and the historical simulations from 1985-2014. Except for NAO+ respectively NAO- for only 2 respectively 3 models the GCM patterns have smaller errors than the ERA5 daily patterns, which justifies the projection approach. A similar conclusion can be drawn for the Arctic regimes. The majority of the GCMs have smaller errors than the ERA5 daily patterns, except 3 models for the AO+ regime, 3 models for the AO- regime, and one model for the Cluster 5 regime, refer to Figure R22.

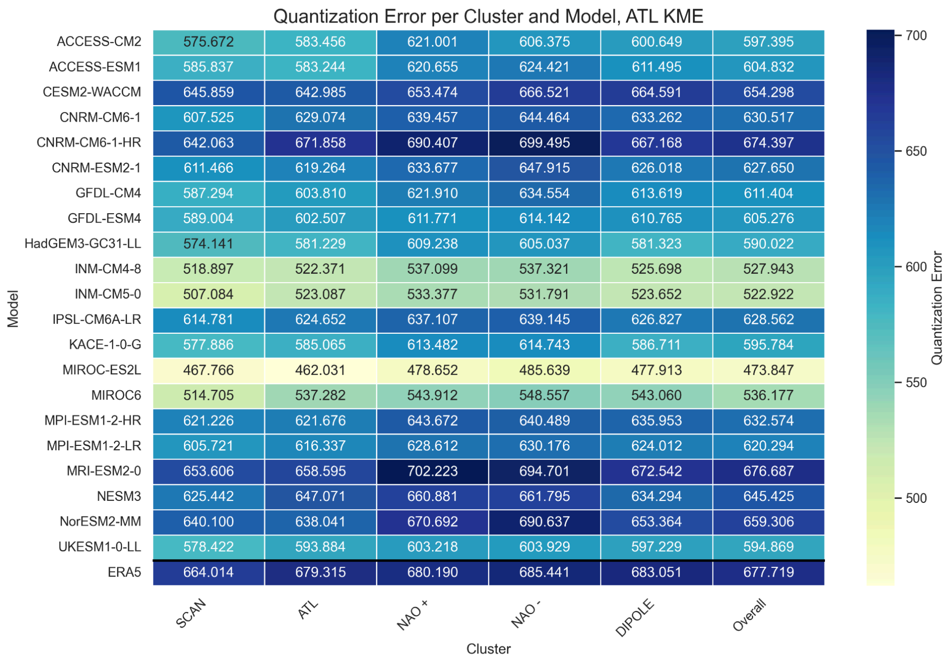


Figure R21 (same as Figure R1): Figure R1: Quantization error per regime and model, North-Atlantic-Eurasian region, KME method, historical period

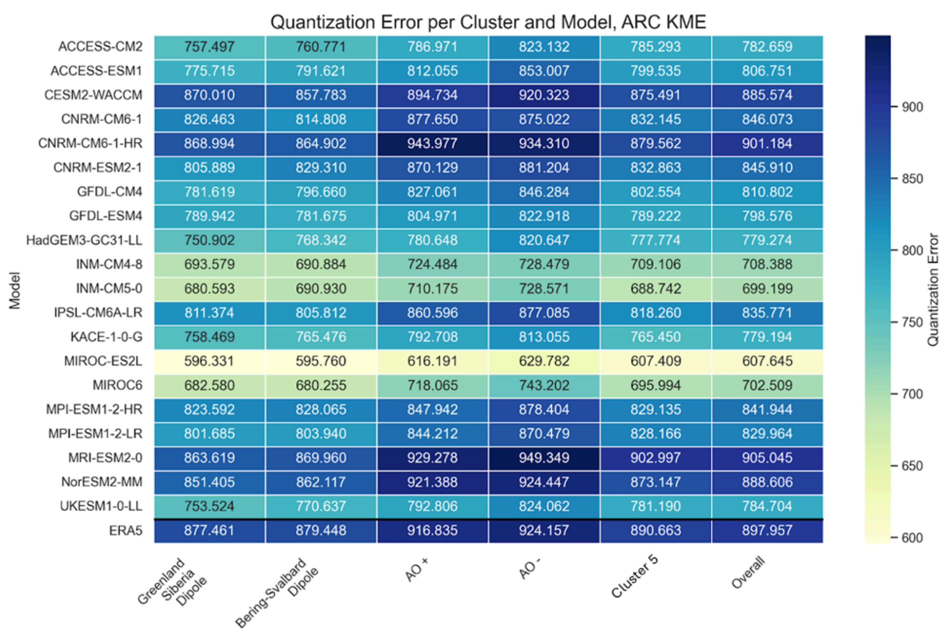


Figure R22 (same as Figure R2): As Figure R20, but for the Arctic region

We will include that justification into the revised manuscript's appendix. The Figures R1 and R2 are included in the Appendix A: Justification of Projection Approach in the revised manuscript after L430. The former Appendix sections (A,B,C) are shifted to Appendix section B,C, and D.

2. Storylines:

- Why didn't you consider the strong ArcAmp and strong Barents-Kara-Sea warming storyline and the opposite? I can appreciate from Lavine et al. that depending on the target variable, the change under each storyline is different, why use these two only?

As the reviewer mentioned, Levine et al. (2024) produced four Arctic climate change storylines: ArcAmp−/BKWarm+ (A), ArcAmp+/BKWarm+ (B), ArcAmp−/BKWarm− (C), and ArcAmp+/BKWarm− (D) using the regression approach of Zappa and Shepherd (2017). These storylines show noticeably different paths for Arctic climate change, which deviate substantially from the multi-model ensemble mean (MMM). Analysing these storylines of climate change for different target variables like 2m temperature, u@850hPa, precipitation or sea ice cover in Levine et al (2024) revealed that the storylines A and D are the most contrasting storylines. That's why we considered only these two in the previous version of the manuscript. In the revised version, we consider all 4 storylines. This is introduced in L182/183 from "We therefore concentrate on the two storylines determined by the opposite signals in these two factors." to "*We consider all four storylines for a comprehensive analysis*".

- Can you show that the circulation in the models undergoes the circulation changes that you consider relevant to your regime changes?

Our circulation regimes are related to specific patterns of jet anomalies (see Figures R15, R16). The CMIP6 multi-model ensemble shows a poleward shifted North Atlantic jet (e.g. Levine et al, 2024,Figure 4, Harvey et al., 2020). Since NAO+ and Dipole are related to northward shifted North Atlantic jet, and NAO- to a southward shifted North Atlantic jet, the robust more frequent occurrence of the NAO+ and Dipole and the less frequent occurrence of NAO- in the future (Fig. R17) are in line with the projected jet changes.

Please refer also to our more in-depth response to reviewer 1, comment 10 or multiple Lines in the results section as well as in the discussion part we add after L401:

"*The changes in frequency and persistence show that patterns, that are associated with a poleward shifted jet structure will be more prominent under global warming, while patterns linked to a southward shifted jet stream will occur less often and also be less persistent. This result is in agreement with Li et al. (2024); Osman et al. (2021), who likewise identify northward-displaced Atlantic jet structures linked to global warming. Similar trends have previously been reported in CMIP3 (Woollings and Blackburn, 2012) and CMIP5 (Barnes and Polvani, 2013) simulations under strong global warming scenarios.*"

- I think that the assumptions behind using the storylines should be justified. Why can the authors expect to find different regimes of regime frequency under these two storylines?

As shown in Levine et al. (2024, fig. 4), the CMIP6 MMM shows a poleward shifted North Atlantic jet, but the strength of this poleward shift depends on the storyline, with a weaker poleward shift in storyline A and B and slightly stronger poleward shift in storyline C and D (compared to the MMM). Since the circulation regimes are related to specific jet anomaly patterns, one might hypothesize that this is related to future changes in the frequency of occurrence of these regimes, particularly those related to a northward-shifted jet (NAO+, Dipole). We are aware that testing this hypothesis is limited because there are only a few models available which represent each storyline. Please refer also to our response to reviewer 1, comment 9.)

We now consider models for all 4 storylines and will discuss this in the revised manuscript.The subsection 3.3 Storylines L175 to L184 including Table.

3. Different clustering algorithms. I would move the evaluation of regimes using SAN to the Supporting Information or further exploring the results that are obtained when using SAN for the complete analysis. The authors claim that these is not much different between one method or the other, however, I find this questionable: First, the correlations in Figure 3 are not impressive and second, the SCAN and DIPOLE regimes are very different from a dynamical perspective. Low slp and high slp over the British Isles respectively can lead to very different weather conditions. What is relevant related to the weather regimes are the regional impacts. At least this is what is claimed in the introduction. Can you show that the precipitaiton and temperature impacts associated with these regimes are comparable?

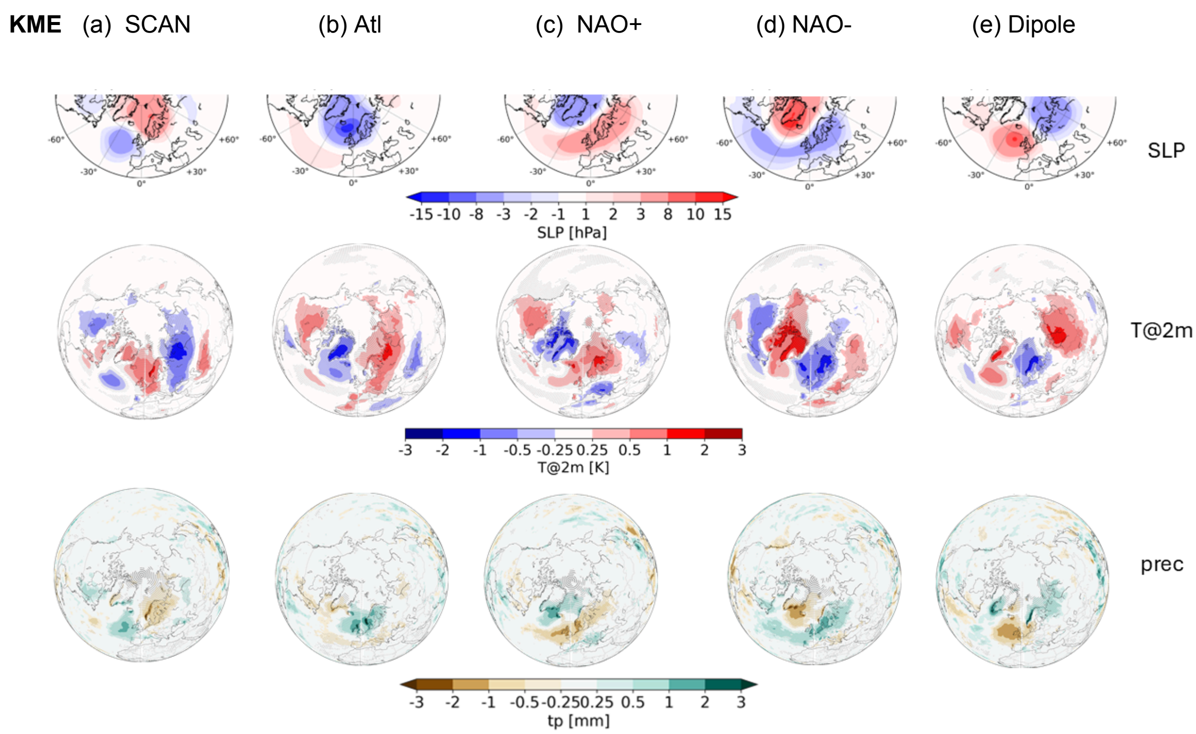
We argue that it is a strength to have both methods in the paper, as it increases the robustness of the results, so we would prefer to keep it in the main text rather than in an appendix.

As written above, we have updated the results as we discovered an error in our SANDRA setup, improving the agreement between the two methods, justifying that the results are more similar (except Cluster 5 for the Arctic region). This is resembled by the respective composites of other variables like the zonal wind at 250hPa shown in Figures R13-R16 and the composites for 2m air temperature and precipitation shown here in Figures R23 and R24. The zonal wind composites as well as the temperature and precipitation composites are very similar for the two methods, except for Arctic Cluster 5, which has a different circulation, as discussed earlier.

For the composites, we will include the zonal wind composites in the main text for KME and in Appendix F for the SAN method. The temperature and precipitation composites in the appendix and are discussed as follows:

“ Just like with the zonal wind anomalies, the composites of temperature at 2 meters and total precipitation anomaly (after preprocessing) composites are shown in Figs. E1–E4. It is evident that temperature, total precipitation, and wind patterns show strong similarities between the

KME and SAN regimes in the North Atlantic–Eurasian region, as well as among the four regimes in the Arctic region. Moreover, an analysis of the respective anomalies, combined with the results on frequency of occurrence, reveals that the NAO+, DIPOLE, and AO− patterns are consistently associated with positive temperature anomalies over western North America. The feature has been also identified in CMIP3 data by Ray et al. (2008); McWethy et al. (2010). Furthermore, NAO+ and AO− are linked to dry (negative precipitation anomalies) and warm (positive temperature anomalies) conditions above Scandinavia and central Europe, and are projected to be more persistent under global warming. This predicted long-lasting dry and warm spells are also reported in (Pfleiderer et al., 2019).”



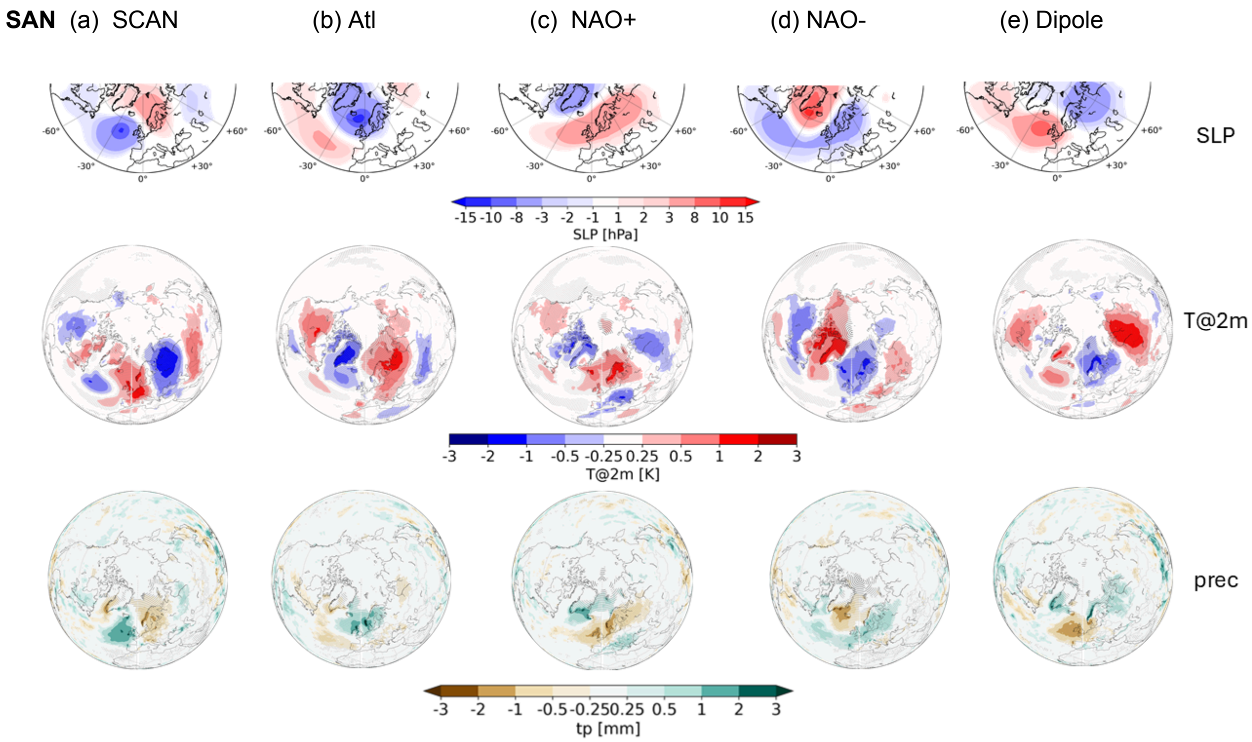
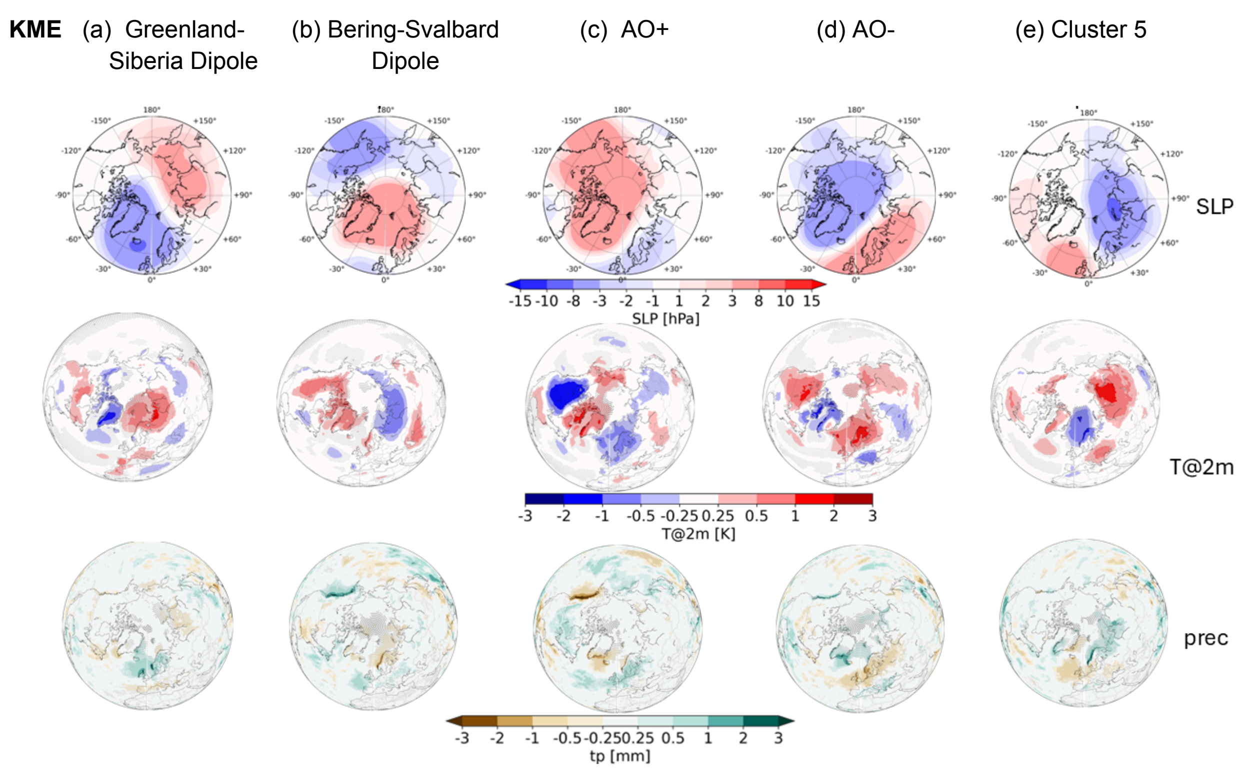


Figure R23: 2m air temperature and total precipitation anomalies associated with the respective regimes for KME and SAN in the North Atlantic-Eurasian region.



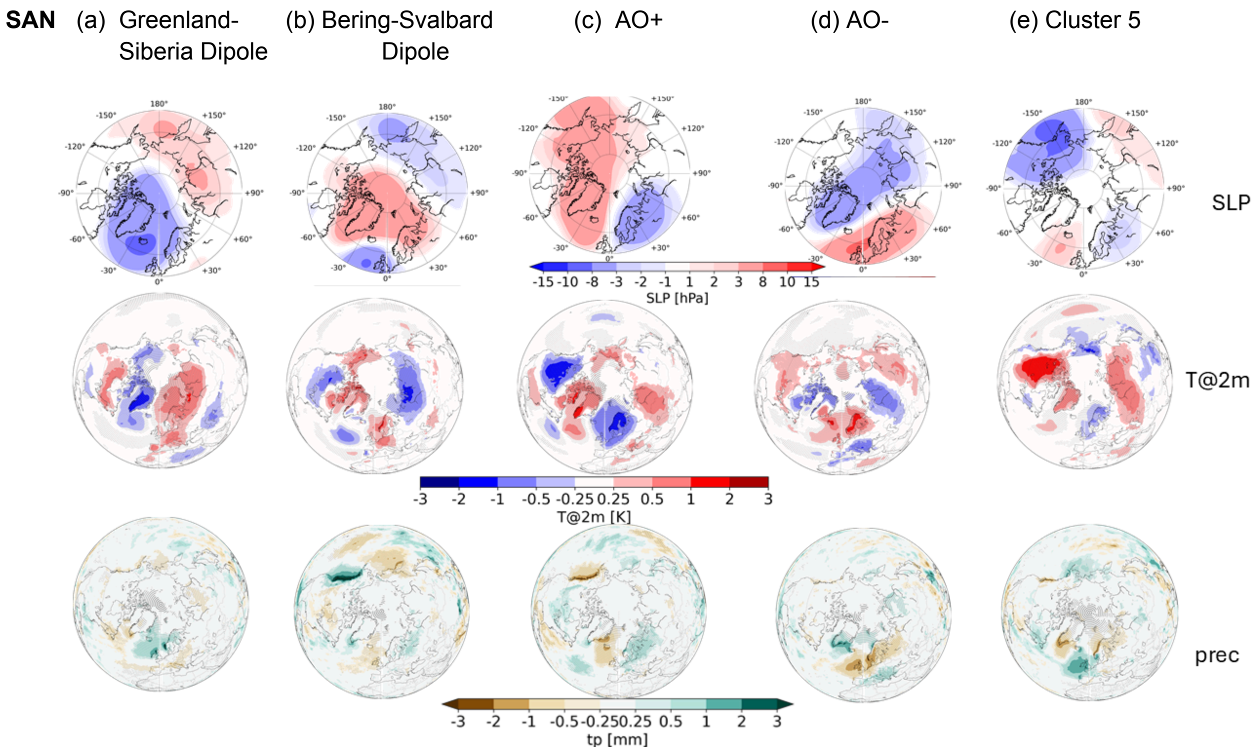


Fig R24: same as R23 but for the Arctic region.

Figures R21-R24 will be added to the revised manuscript to Appendix E after L461.

4. I am not convinced by the claim "Thus, the spatial structure of the summer circulation regimes does not change significantly under the influence of rising GHG emission in the future time period compared to the historical time period". Referring to my comment above, I would consider that evaluating the regimes independently for the future and the historical period would be a first step to ensure that projecting the forced simulations is a valid assumption.

We have argued in our answers to reviewer 1, comments 1 & 2 and reviewer 2 comment 1 that the projected approach is justified. Therefore, we kept the projected approach. To evaluate the future changes in the spatial structure of the circulation regimes we compare the future common simulated regimes for the CMIP6 ensemble with the ERA5 reference regimes for the historical period 1985-2014.

The respective Taylor plots are shown in Fig. R10 (Fig. 4 in the old manuscript) for the North Atlantic-Eurasian regimes and Fig. R20 (new figure in revised Manuscript) for the Arctic regimes. These Taylor plots underline the similar spatial structure of the common future CMIP6 regimes for SSP5-8.5 and the period 2070–2099 to that of the ERA5 regimes for the historical period 1985-2014, with all pattern correlation coefficients >~0.8. In our view this justifies the application of the “projected approach” (see our terminology described in Fig. 1 of the manuscript) for the calculation of future changes in regime occurrence frequency (and persistence).

To better describe the calculation of the common simulated regimes we will change the text in the revised manuscript (L122-138) to:

"*The common simulated circulation regime framework enables the possibility to compare the spatial structure between reanalysis and the entire CMIP6 model ensemble. First the preprocessed data of each climate model are merged into a single data file along the temporal axis, either for the historical period 1985-2014 or the future period 2070-2099. Instead of performing a common EOF analysis and obtaining common PCs (as described e.g. in Benestad et al., 2023), here the common climate model data are projected onto the ten-dimensional reference state space, determined from the ERA5 data, resulting in ten common Pseudo-PCs. The common Pseudo-PCs serve as input data for the K-Means clustering algorithm. Five common simulated circulation regimes are obtained for each time period, representing the joint regimes for the entire model ensemble*."

If this is the case, then one can claim that the spatial structure of the regimes does not change in the models. I also consider that this is not a "weak external forcing". Given that SSP5-8.5 is used and the authors refer to this as a strong forcing in a previous pragraph.

We agree that there is a bit of confusion about weak and strong forcing in the manuscript which we clarify here:

In the conceptual framework of circulation regimes, Palmer (1993, 1999) introduced a dynamical paradigm for climate change. According to this paradigm, a not too strong external forcing does not change the structure and number of atmospheric regimes, but instead changes the frequency of occurrence of the regimes. This determines, at least partly, the time-mean response of the atmospheric flow to the external forcing. On the other hand, very strong external forcing factors can lead to changes in the number and structure of circulation regimes as proven in several studies, e.g. by Kageyama et al. (1999) and Handorf et al. (2009).

To clarify we changed "a strong external forcing acting on the dynamical system can lead to significant changes in the spatial structure of the regime patterns or to the appearance of new regimes" (L25-L26 in the old manuscript) to "*an increasing strength of the external forcing acting on the dynamical system can lead to significant changes in the spatial structure of the regime patterns or to the appearance of new regimes. Then, the external forcing is regarded as strong forcing*."

Since we have proven that the structure of the joint model circulation regimes is not changing under SSP5-8.5, we call this a weak forcing in the conceptual regime framework and the above mentioned paradigm for climate change.

In the revised manuscript, we will clarify this and avoid the confusion. We will reformulate text beginning L73 (see also L73, reviewer 1 comment) from "In examining the simulation of future time periods, the SSP5-8.5 emission scenario is of particular interest. As the highest emission scenario, it is characterised by a large increase in Greenhouse Gas (GHG) emissions, impinging a strong external forcing upon the atmosphere. Thus, a response of characteristics of circulation regimes is expected." to "*For the future period we use the highest emission scenario SSP5-8.5 as it is expected to give the most statistically robust response to climate change*."

Moreover, we will reformulate text from L250-254 from “These results support the hypothesis put forth in Section 1, namely that a weak external forcing acting on the dynamical system—in this case, the external forcing on the atmosphere—does not alter the spatial structure of the regime patterns. Thus, the spatial structure of the summer circulation regimes does not change significantly under the influence of rising GHG emission in the future time period compared to the historical time period.” to “*These results support the hypothesis of Palmer (1993) and Corti et al. (1999) introduced in Section 1, namely that a rather weak external forcing acting on the dynamical system atmosphere does not alter the spatial structure of the regime patterns. In our case, even under the high emission scenario SSP5-8.5 the spatial structure of the joint summer circulation regimes does not change significantly in the future time period*.”

Line 280: This first sentence is not clear. Do you mean that "In the models representing the BK+ and AA- storylines the NAO+ occurs significantly more?

We are aware of the limitation of the low number of models per storyline, and we cannot prove a consistent response. Nevertheless, it may still be useful to keep the labeling just to indicate that models within the same storyline may actually exhibit quite different frequency responses. In relation to the changes in jet structure (Figures R13-R16), it can for example be that while there is a clear response in the mean jet shift, individual models among storylines project these changes on different clusters.

Line 295: The immediate above paragraphs were describing the results in Figure 6, while the paragraph starting in l288 refers to the KAN and SAN comparison. I don't follow the logic.

L295 is also part of the summary (starting with L288) and refers to results from both KME and SAN.

Caption Figure 6: The markers associated with the storylines are not described.

Label descriptions will be added to the figure caption. (See updated Figures R11 & R12 for persistence or R17 & R18 for frequency of occurrence.)

Overall the silhouette and elbow results are not impressive, 6 or 7 could have been a perfectly reasonable number of clusters. Line 440 says "The KElbow Visualizer suggests that five clusters represent an optimal number of clusters for both regions." No description of what is seen in the figure is provided. Why is this suggested by the figure?

We agree, that "optimal" number of clusters is an overstatement. We will reformulate from optimal to reasonable/suitable number in the revised manuscript. In addition, we will improve the description of the results from the elbow plots shown in the appendix. The elbow plot displays the distortion score, which describes the within-cluster sum of squared distances, in dependence of the number of clusters. The point of greatest curvature of that curve, the so-called "elbow" point suggests a reasonable number of clusters. As we agree that the change in the curvature is not very strong from k=4 to k=6 clusters, we justify our choice of 5 clusters with two other metrics (in the appendix). This is the silhouette score (already included in the old manuscript) and an additional metric, following Grams et al. (2017), a reference reviewer 1 suggested in comment 8. As suggested by Grams et al (2017) their metric to evaluate a suitable number of clusters is the Anomaly Correlation Coefficient ("*The optimal number of clusters is seven (Supplementary Fig. 1) based on the criterion that the anomaly correlation coefficient between the clusters is below 0.4*", Grams et al., 2017, Method section). In the answer to reviewer 1, comment 3 we show the results of the anomaly correlation coefficient calculated for the North Atlantic-Eurasian region in Figure R6 and for the Arctic region in Figure R7 for both methods, KME and SAN, based on ERA5 data 1985-2014. For both methods and both regions, the suggested criteria of Grams et al. (2017) is satisfied for 5 regimes each, which justifies our choices for the number of regimes.

Comments from the PDF:

L40: This paragraph, and in particular the second sentence are not. The logic is not clear. First sentence says that detection of circulation *changes* is challenge due to signal-to-noise problem. How is this related to evaluating state-of-the-art simulation of present day regimes?

We will reformulate L39-43 into:

"*A reliable detection of circulation changes in climate model simulations is often limited by a large uncertainty and low signal-to-noise ratios (Scaife and Smith, 2018; Smith et al., 2022). However, the concept of atmospheric circulation regimes has been successfully applied to characterise future circulation changes (e.g. Fabiano et al. 2021). A first step is to evaluate the ability of the models to reproduce observed circulation Regimes. To get robust results for future changes in circulation regimes, one needs to consider multi-model ensembles of climate projections such as the Coupled Model Intercomparison Project (CMIP).*"

L69: "physically based" -> "dynamical"?

The derivation in Levine et al. 2024 is based not on dynamical changes but on physical criteria (target variables relevant for climate change risks), so we would prefer to keep this formulation.

L77: "strong external forcing" "below you say it is a weak external forcing... are you referring to a different forcing?"

We will remove "strong" from this sentence. It was originally meaning "strong" as it is a high emission scenario, but we see that it can be confusing. We changed L75-L78 to "*For the future period we use the highest emission scenario SSP5-8.5 as it is expected to give the most statistically robust response to climate change*."

Also refer to our answer to reviewer 2, comment 4, second part.

L80: Regarding "since the circulation regimes in this area are well-known." comment: "Can you provide a reference for this? I think that I understand what you mean with "well known", but if the reference to previous research is going to be the only justification for the choice of region you should at least state it formally" "Given that the circulation regimes in this area have been extensively studied (provide corresponding references), and [the a reason to why this is enough to select a region...]."

> We take the reviewer's suggestion and use:
> "Given that the circulation regimes in this area have been studied before (Crasemann et al. 2017, Riebold et al., 2023) during winter, here we study this area in the extended summer season."

L82: "this" -> "region selection"

> We have changed this in the updated manuscript., L84 in revised manuscript.

L92: Comment on "Averaging the data day by day at each grid point yield the mean seasonal cycle.": "Isn't this the definition of a daily climatologu? Why not just say that you substract the daily climatology".

> Yes, it is, but we wanted to be explicit.

L92-93: Comment on "Additionally, a 21-day running mean is applied to remove higher-frequency fluctuations": "If daily weather regimes are the focus of the study, wouldn't this filter remote part of the signal under study?"

> We are sorry for the misunderstanding. We only perform the running mean on the climatology that we subtract. This keeps the high frequency changes in the resulting data. We will rewrite this to make this clear in the updated manuscript. We have replaced text from L92-L93 "Averaging the data day by day at each grid point yield the mean seasonal cycle. Additionally, a 21-day running mean is applied to remove higher-frequency fluctuations" by "*The mean seasonal cycle is obtained by computing the daily climatology and then applying a 21-day moving average to this.*".

L122 and L148 on the methodology:

> These comments are covered by previous answers. Please refer to Reviewer 2, comment 1, and Reviewer 1, comment 3.

Table 1: "I found it confusing that you call it Polar Amplification and they call it Arctic Amplification. It is a detail but it is still confusing to me. "

> We will call it Arctic Amplification (AA for short) in the revised manuscript.

Multiple comments on L230

> These comments are answered in our replies to Reviewer 1, comment 5 & 10, and Reviewer 2, comment 3.

Fig. 4 caption: "Clarify period".

We will clarify the time period.

L250: "Are you referring to the anthropogenic CO2 forcing? I don't know if I would call this a weak forcing, given the significant circulation changes associated with this forcing."

Please, refer to Reviewer 2 comment 4.

Comments on L251 and L254:

Please, refer to Reviewer 1, comment 1 and reviewer 2, comment 1.

L258: "I don't understand. The regimes could be different and therefore the frequency could be different. If by construction you force the regime centroids to be different to what the true centroids are in the models, how can you be sure that these frequencies are representative of how the actual circulation states?."

Please, refer to Reviewer 1, comment 4.

New references:

*Barnes, E. A., and L. Polvani, 2013: Response of the Midlatitude Jets, and of Their Variability, to Increased Greenhouse Gases in the CMIP5 Models. J. Climate, **26**, 7117–7135, https://doi.org/10.1175/JCLI-D-12-00536.1.*

Dawson A, Palmer T (2015) Simulating weather regimes: Impact of model resolution and stochastic parameterization. Clim Dyn 44(7–8):2177–2193. https://doi.org/10.1007/s00382-014-2238-x

Fabiano, F., Christensen, H. M., Strommen, K., Athanasiadis, P., Baker, A., Schiemann, R., & Corti, S. (2020). Euro-Atlantic weather Regimes in the PRIMAVERA coupled climate simulations: impact of resolution and mean state biases on model performance. Climate Dynamics, 54(11), 5031-5048. https://doi.org/10.1007/s00382-020-05271-w

Falkena SK, de Wiljes J, Weisheimer A, Shepherd TG. Revisiting the identification of wintertime atmospheric circulation regimes in the Euro-Atlantic sector. Q J R Meteorol Soc. 2020; 146: 2801–2814. https://doi.org/10.1002/qj.3818

Grams, C., Beerli, R., Pfenninger, S. et al. Balancing Europe's wind-power output through spatial deployment informed by weather regimes. Nature Clim Change 7, 557–562 (2017). https://doi.org/10.1038/nclimate3338

Harvey, B. J., Cook, P., Shaffrey, L. C., & Schiemann, R. (2020). The response of the Northern Hemisphere storm tracks and jet streams to climate change in the CMIP3, CMIP5, and CMIP6 climate models. Journal of Geophysical Research: Atmospheres, 125(23), e2020JD032701. https://doi.org/10.1029/2020JD032701

Li, X., Zheng, J., Wang, C., Lin, X., and Yao, Z.: Unraveling the roles of jet streams on the unprecedented hot July in Western Europe in 2022, npj Climate and Atmospheric Science, 7, 323, https://doi.org/10.1038/s41612-024-00880-2, 2024

McWethy, D., Gray, S., Higuera, P., Littell, J., Pederson, G., Ray, A., and Whitlock, C.: Climate and terrestrial ecosystem change in the U.S. Rocky Mountains and Upper Columbia Basin: Historical and future perspectives for natural resource management., 2010

Michelangeli, P. A., Vautard, R., & Legras, B. (1995). Weather regimes: Recurrence and quasi stationarity. Journal of Atmospheric Sciences, 52(8), 1237-1256. https://doi.org/10.1175/1520-0469(1995)052<1237:WRRAQS>2.0.CO;2

Osman, M. B., Coats, S., Das, S. B., McConnell, J. R., and Chellman, N.: North Atlantic jet stream projections in the context of the past 1,250 years, Proceedings of the National Academy of Sciences, 118, e2104105118, https://doi.org/10.1073/pnas.2104105118, 2021

Pfleiderer, P., Schleussner, C.-F., Kornhuber, K., and Coumou, D.: Summer weather becomes more persistent in a 2°C world, Nature Climate Change, 9, 666–671, https://doi.org/10.1038/s41558-019-0555-0, 2019.

Quagraine, K. A., Nkrumah, F., Klein, C., Klutse, N. A. B., & Quagraine, K. T. (2020). West African Summer Monsoon Precipitation Variability as Represented by Reanalysis Datasets. Climate, 8, Article 111. https://doi.org/10.3390/cli8100111

Ray, A., Barsugli, J., Averyt, K., Deheza, V., and Udall, B.: Climate Change in Colorado: Developing a Synthesis of the Science to Support Water Resources Management and Adaptation, AGU Fall Meeting Abstracts, 2008.

Riebold, J., Richling, A., Ulbrich, U., Rust, H., Semmler, T., and Handorf, D.: On the linkage between future Arctic sea ice retreat, Euro-Atlantic circulation regimes and temperature extremes over Europe, Weather and Climate Dynamics, 4, 663–682, https://doi.org/10.5194/wcd-4-663-2023, 2023.

Woollings, T., and M. Blackburn, 2012: The North Atlantic Jet Stream under Climate Change and Its Relation to the NAO and EA Patterns. J. Climate, **25**, 886–902, https://doi.org/10.1175/JCLI-D-11-00087.1.

Cited here but not used in the manuscript:

Skific, N., Francis, J. A., & Cassano, J. J. (2009). Attribution of projected changes in atmospheric moisture transport in the Arctic: A self-organizing map perspective. Journal of Climate, 22(15), 4135-4153. https://doi.org/10.1175/2009JCLI2645.1

Vautard R. 1990. Multiple weather regimes over the North Atlantic: Analysis of precursors and successors. Mon. Weather Rev. 118: 2056–2080. https://doi.org/10.1175/1520-0493(1990)118<2056:MWROTN>2.0.CO;2