

Supplementary Materials for

Anthropogenic Climate Change Leads to a Pronounced Reorganisation of Wintertime North Atlantic Atmospheric Circulation Regimes

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Supplementary Text

Supplementary Figs. S1 to S12

Supplementary Text

Validation of Streamfunction at 500 hPa and Surface temperature from CESM2-LE with ERA5

To validate CESM2-LE with ERA5 over the North Atlantic region, we show some key statistical measures in Fig. S1. We observe that the ERA5 distributions for the 500 hPa streamfunction and surface temperature closely align with those simulated from CESM2-LE, with nearly identical means and comparable spread (Fig. S1(a-b)). This suggests that the CESM2-LE effectively captures the statistical structure of the large-scale atmospheric circulation over the North Atlantic region.

Further, we notice that the time series of streamfunction at 500 hPa and surface temperature over the North Atlantic region from ERA5 reanalysis lie well within the ensemble spread of CESM2-LE (Fig. S1(c and f)), showing the model's ability to capture the amplitude and temporal evolution of the observed variability, i.e., ERA5. Moreover, on comparing the variance across the ensemble members of CESM2-LE with that of ERA5, we find that the variance of ERA5 for both streamfunction at 500 hPa and surface temperature lies within the ensemble spread, indicating that the CESM2-LE's representation of internal variability amplitude is consistent with that of ERA5 (Fig. S1(d-e)).

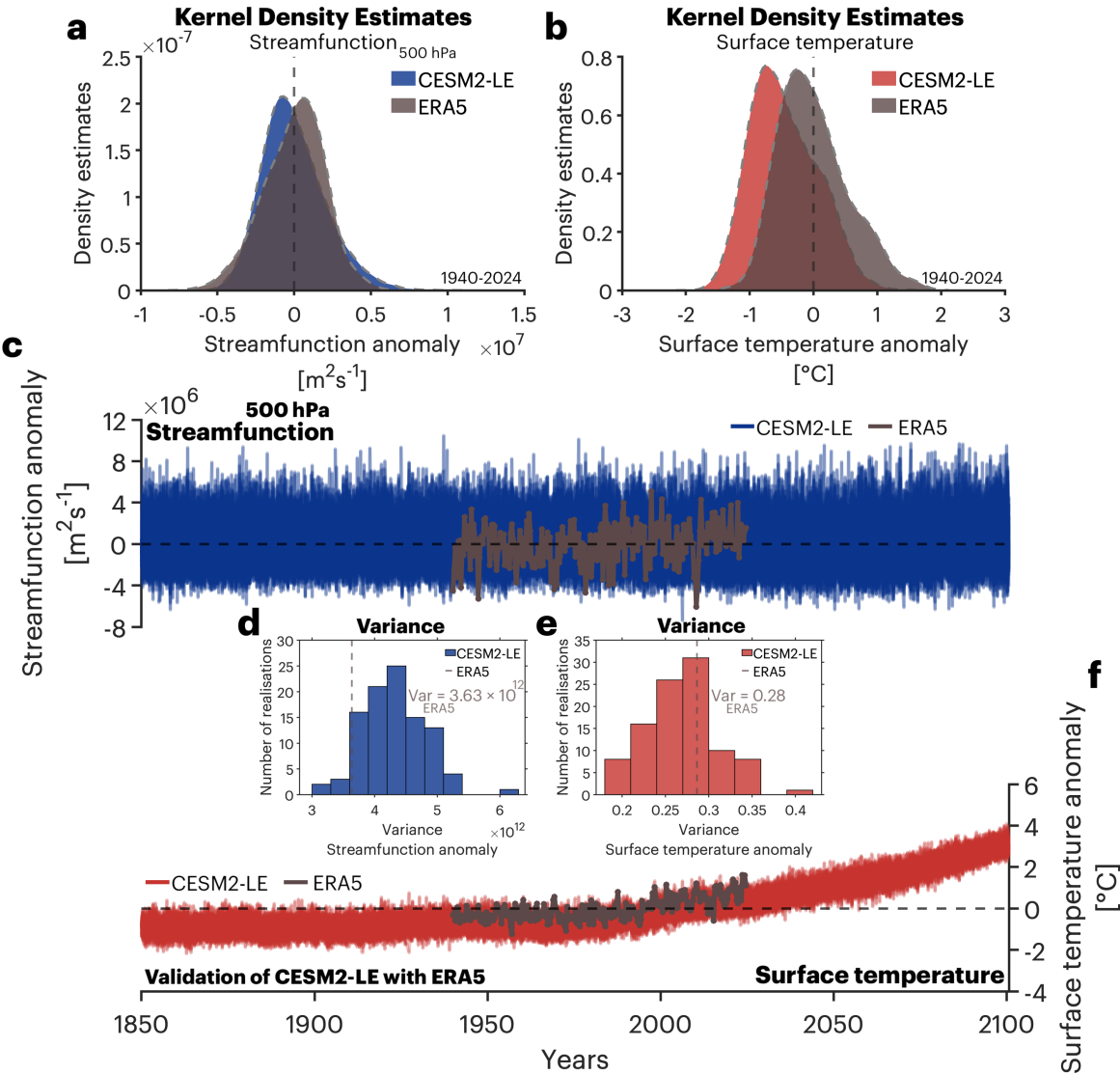
Coupled Singular Value Decomposition Patterns for the Full and Internal Variability Flow Fields

In Fig. S2, we present the spatial patterns associated with the first two SVD modes (left and right singular vectors), i.e., SVD1 and SVD2, along with the corresponding principal component time series, i.e., PC1 and PC2 of the full flow field (FF) and internal variability (IV) in Figs. S3 and S4, respectively. The coupled SVD analysis of streamfunction at 500 hPa and surface temperature allows us to address the key question of how atmospheric circulation patterns over the North Atlantic respond to ongoing anthropogenic warming. More specifically, the coupled analysis identifies changes in atmospheric circulation patterns over the North Atlantic that co-vary with surface warming. The first SVD mode (SVD1), representing the coupled variability between the 500 hPa streamfunction and surface temperature, captures the global warming signal, explaining 68% of the shared covariance (Fig. S2(a-b)). Likewise, the associated principal components of streamfunction at 500 hPa and surface temperature (PC1) show an increasing trend observed across the ensemble members from their ensemble mean

from CESM2-LE (Fig. S3(a and c)). SVD1, therefore, corroborates the dominance of the anthropogenic climate change signal in the FF, as expected. Whereas, the SVD2 spatial pattern for the FF presents a tripolar-like structure over the subpolar North Atlantic (Fig. S2(c-d)), featuring a cyclonic circulation centred over the North Atlantic Warming hole (NAWH) region¹⁻⁷, associated with negative surface temperature anomalies. We utilise the ensemble mean of the first two principal components (Fig. S3(a-b)) for the streamfunction at 500 hPa later in Fig. 1 to highlight anthropogenic warming's impact on North Atlantic atmospheric circulation.

Additionally, we note that the circulation response of the streamfunction SVD1 pattern in the FF is opposite to that in the IV, with notable differences in the centres of cyclonic and anticyclonic circulation regions (Fig. S2(a and e)). The SVD1 for the IV captures a NAO-positive-like dipole pattern in the mid-tropospheric circulation (Fig. S2(e)) along with its associated surface temperature variability (Fig. S2(f)). A comparison of the SVD2 patterns for the streamfunction at 500 hPa between FF (Fig. S2(c)) and IV (Fig. S2(g)) shows a northward and eastward displacement in the location of the cyclonic circulation. In the FF, the cyclonic circulation is positioned over the NAWH, whereas for the IV, it is displaced south-westwards over the subtropical Atlantic. These reorganisations in the centres of circulation patterns highlight the impact of external forcing in the positioning of large-scale circulation patterns over the North Atlantic.

51 **Supplementary Figures with captions**



52
53 **Fig. S1. Validation of streamfunction at 500 hPa and surface temperature from CESM2-**
54 **LE with ERA5:**

55 The panel a illustrates the individual ensemble members of the streamfunction anomalies at 500 hPa over the
56 North Atlantic for the winter season (DJF) from 1850 to 2100, overlaid with ERA5 reanalysis. Panel b displays
57 the surface temperature anomalies from the CESM2-LE ensemble members, also overlaid with ERA5 realisation,
58 demonstrating that the reanalysis remains within the ensemble spread.

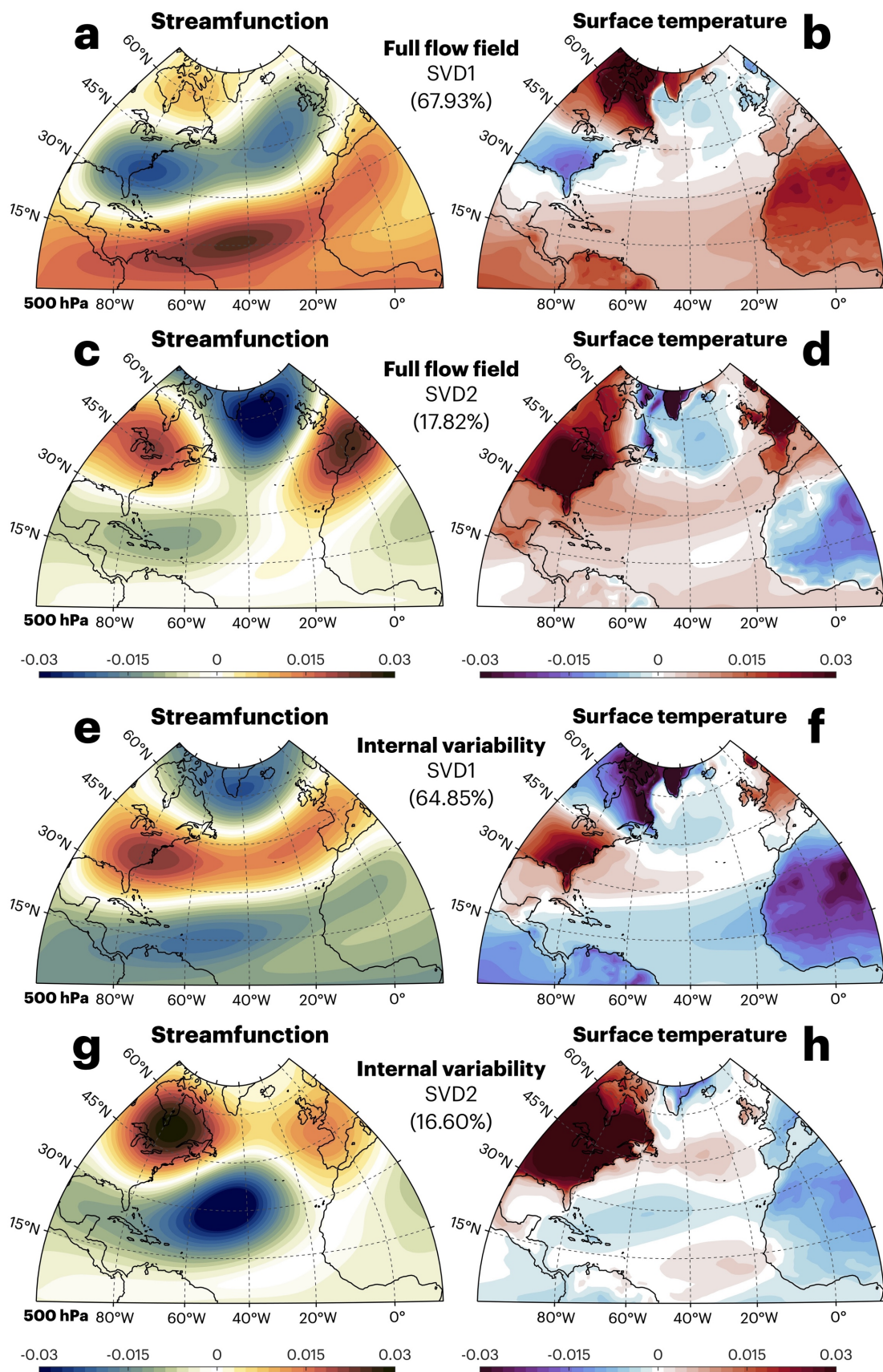


Fig. S2. First two SVD patterns for FF and IV:

61 The left panel (**a, c, e, and g**) shows the coupled SVD spatial patterns of the mid-tropospheric streamfunction
62 from 1850 to 2100. Whereas, the right panel (**b, d, f, and h**) illustrates the coupled SVD spatial patterns of the
63 surface temperature. The top two panels (**a-d**) represent the full flow field (FF), i.e., the combination of the internal
64 variability (IV) and forced response. The bottom two panels (**e-h**) are for IV.

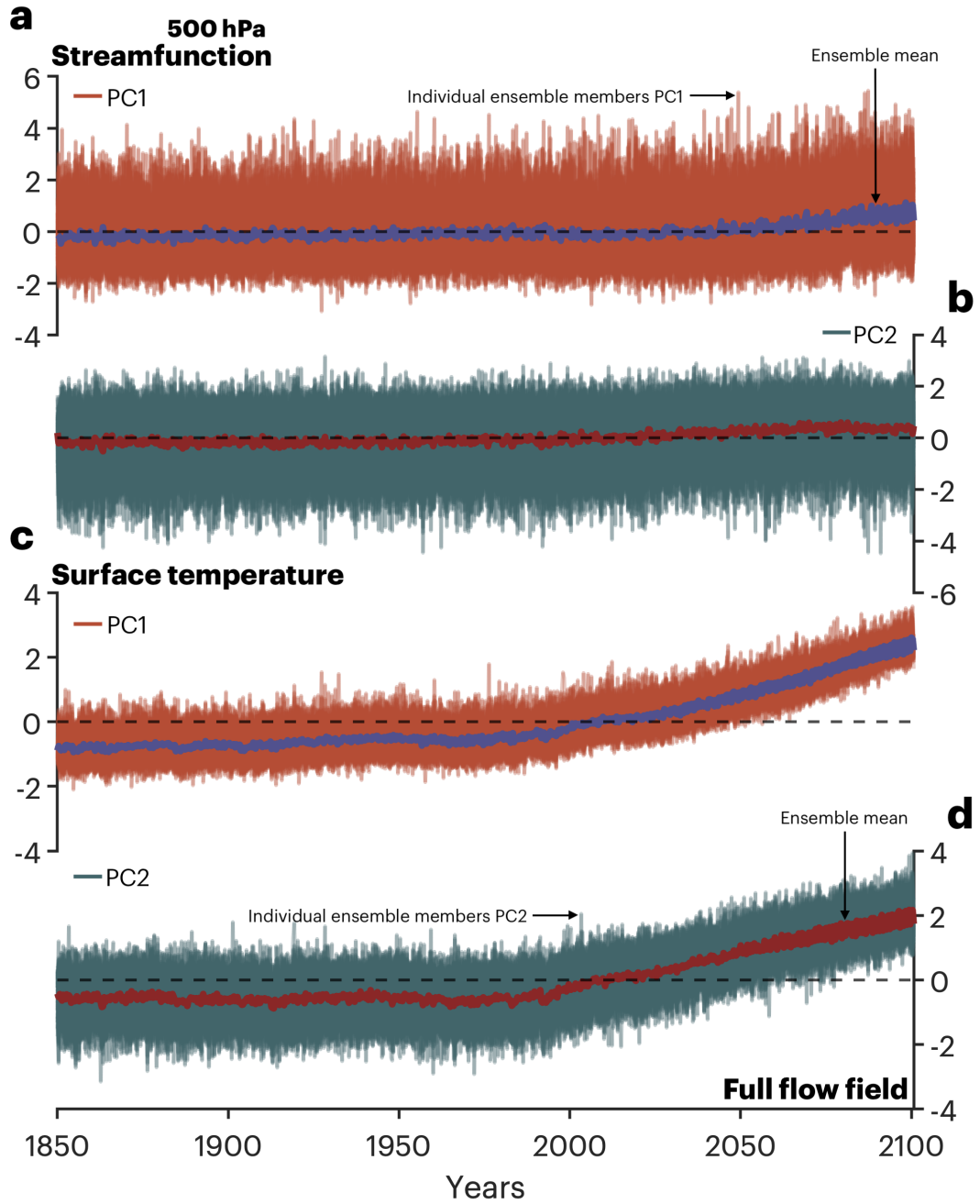


Fig. S3. Coupled SVD principal components of streamfunction at 500 hPa and surface temperature for the FF:

The panels **a and b** illustrate the individual PC1 and PC2 ensemble members along with the ensemble mean of the streamfunction anomalies at 500 hPa, while panels **c and d** display the PC1 and PC2 of the surface temperature anomalies from the CESM2-LE ensemble members over the North Atlantic for the winter season (DJF) from 1850 to 2100. These associated PCs are for the full flow field (FF), i.e., the combination of internal variability (IV) and the forced response.

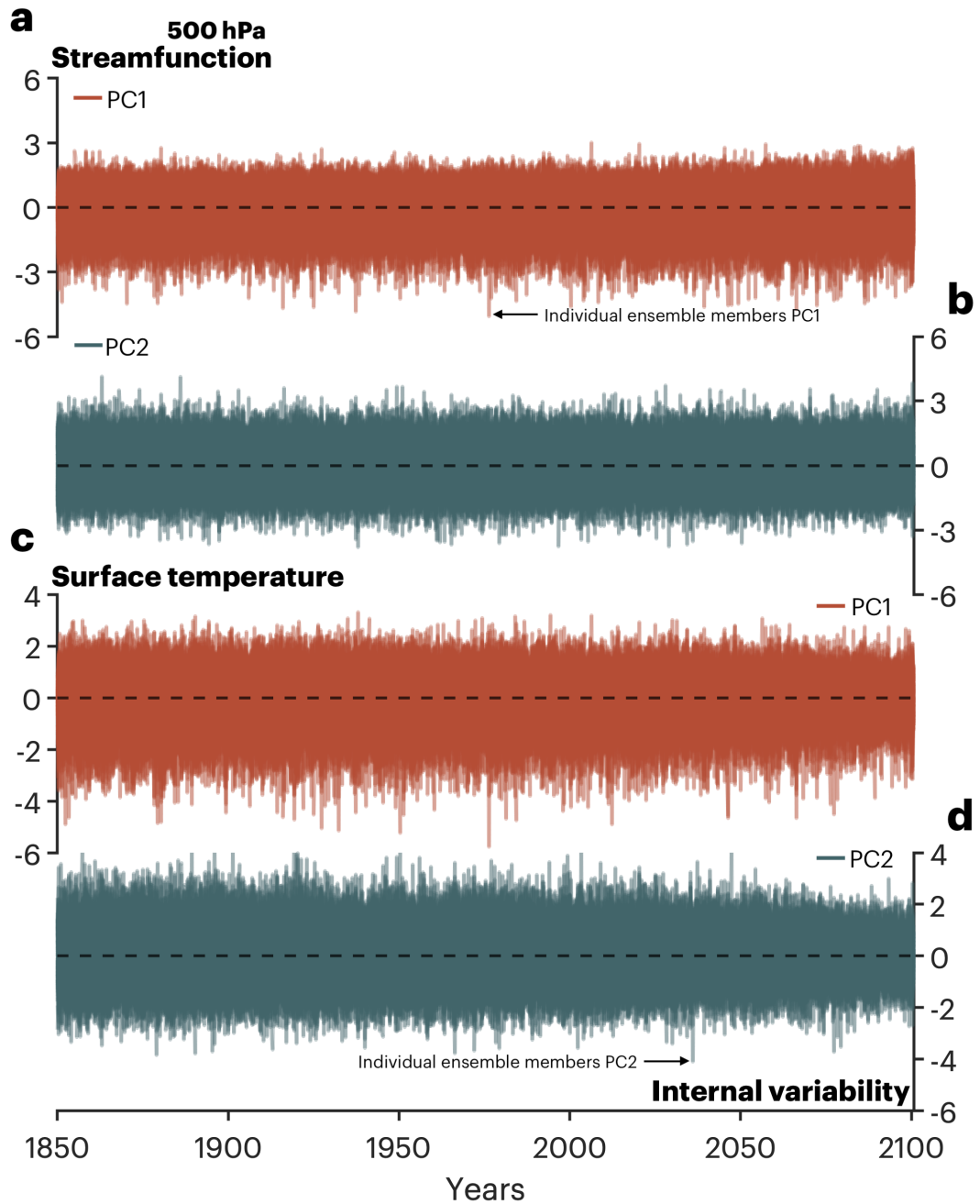


Fig. S4. Coupled SVD principal components of streamfunction at 500 hPa and surface temperature for IV:

The panels **a and b** illustrate the individual PC1 and PC2 ensemble members of the streamfunction anomalies at 500 hPa, while panels **c and d** display the PC1 and PC2 of the surface temperature anomalies from the CESM2-LE ensemble members over the North Atlantic for the winter season (DJF) from 1850 to 2100. These associated PCs are for the internal variability (IV) flow field.

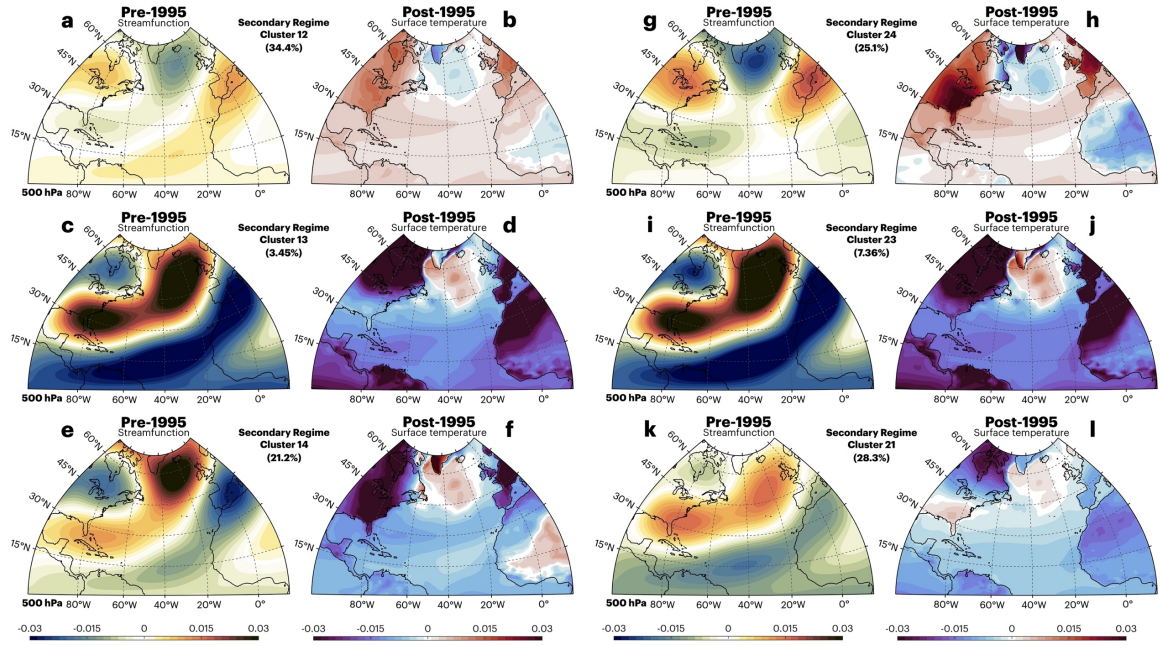


Fig. S5. Secondary Regimes across Pre and Post-1995 periods for the FF:

The upper row (a-f) shows the spatial patterns of the Secondary Regimes (SR) centroids of the mid-tropospheric streamfunction and the corresponding spatial patterns of the surface temperature across the Pre-1995 period. Whereas, the row below (g-l) illustrates the same for the Post-1995 period. The spatial patterns are associated with the full flow field (FF), i.e., the combination of the internal variability (IV) and forced response. Moreover, the spatial patterns are computed by projecting the centroids in the phase space on the first two eigenvectors, and hence are unitless.

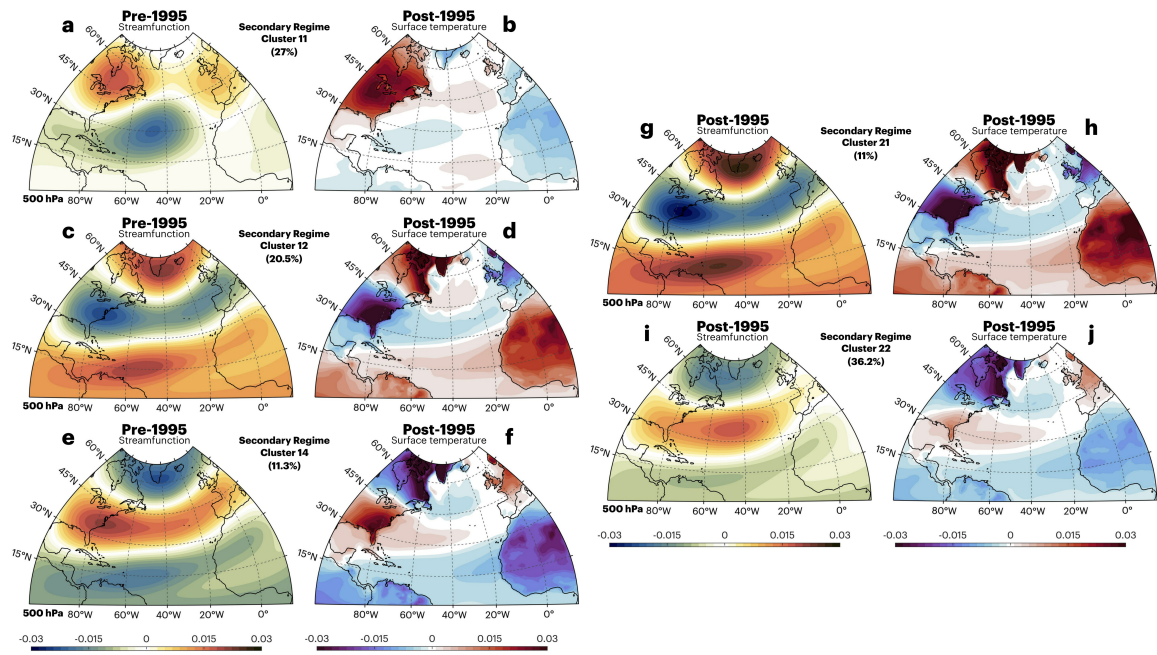


Fig. S6. Secondary Regimes Across Pre and Post-1995 periods for the IV:

Similar to Fig. S5, but only for the internal variability flow field (IV), i.e., departures of the hundred ensemble members from the ensemble mean and showcasing the spatial patterns of the secondary regimes (SR).

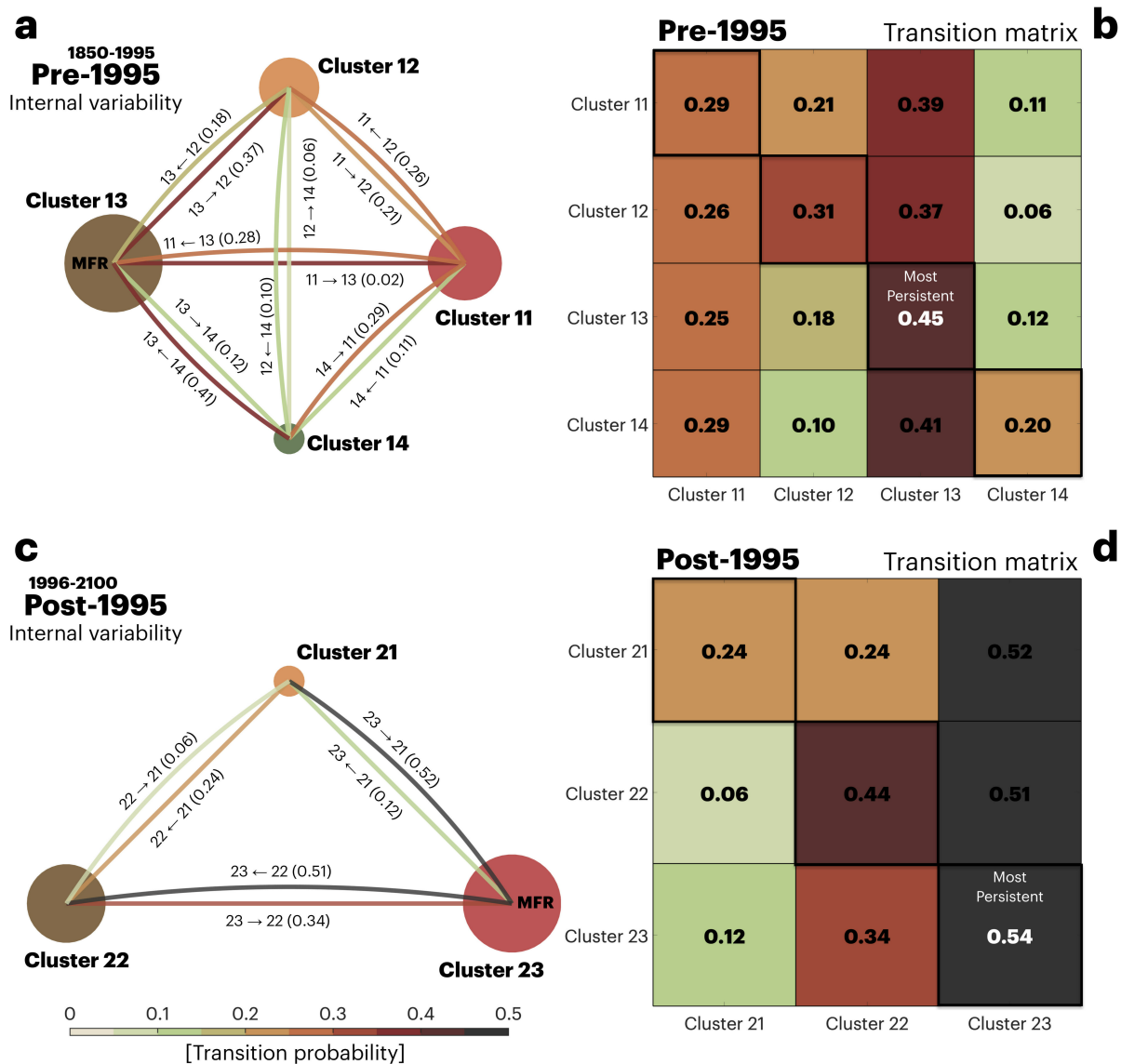


Fig. S7. Inter-Regime Transition and Persistence across Pre and Post-1995 periods for the IV:

Similar to **Fig. 5**, but for the internal variability flow field (IV), i.e., departures of the hundred ensemble members from the ensemble mean.

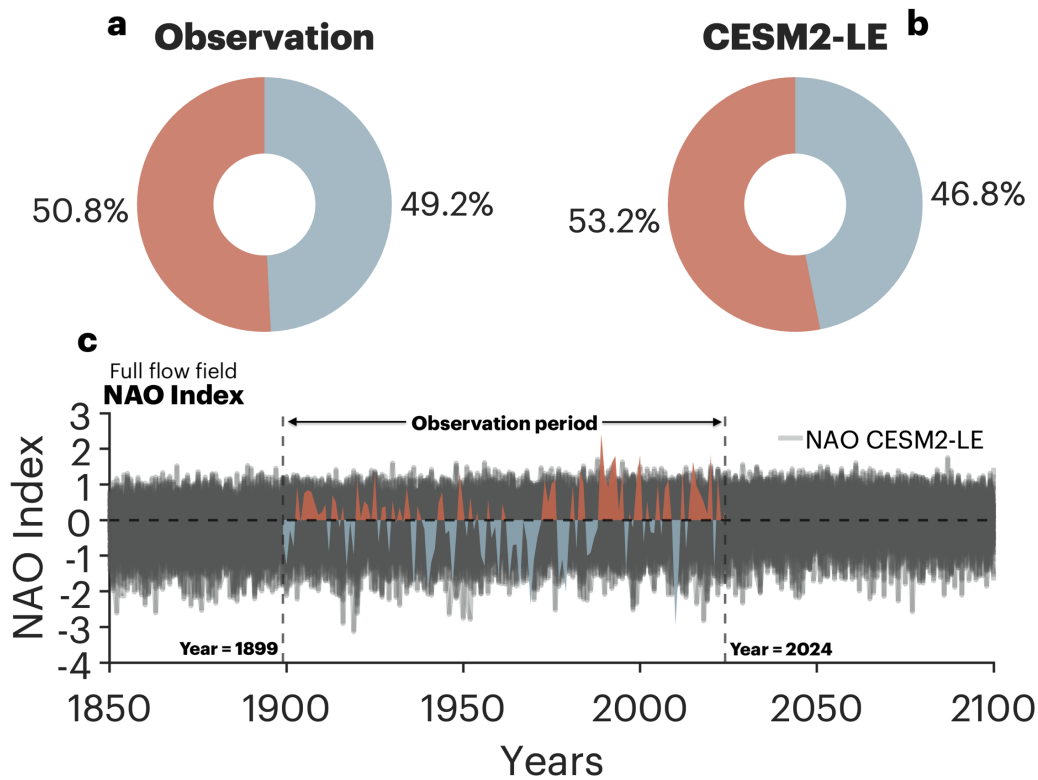


Fig. S8. Validation of NAO index from CESM2-LE with Observation:

The upper panel **a** and **b** show the distribution of NAO positive (+ve) and negative (-ve) phases during the observation period, i.e., 1899 to 2024, comparing the CESM2-LE ensembles with the Observation PC-based index (<https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-pc-based>). Panel **c** demonstrates that the observational index falls within the ensemble spread of the CESM2-LE, with minor deviations.

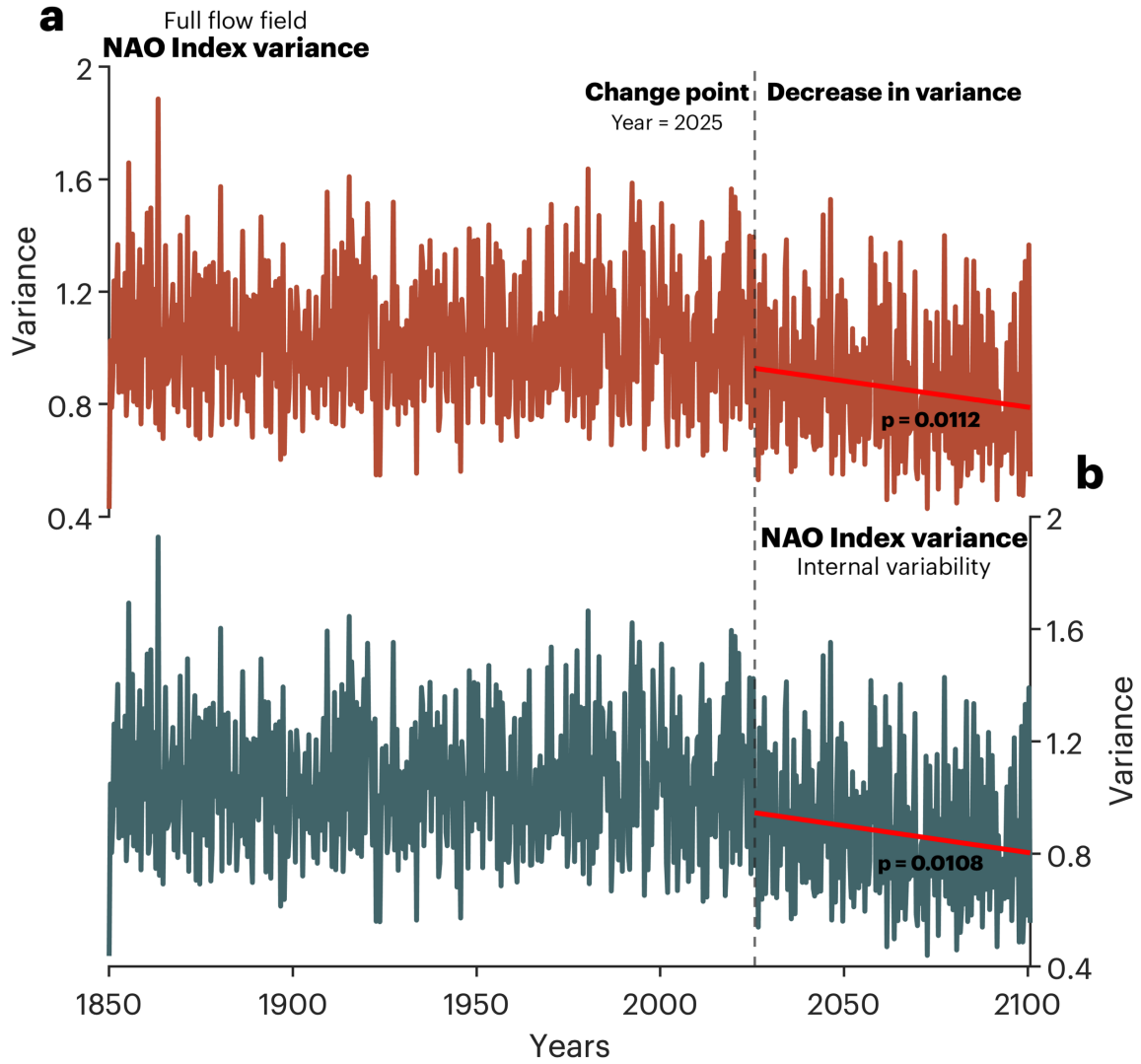


Fig. S9. Weakening NAO variance for the FF and IV:

The top and bottom panels display the time-evolving variance of the NAO Index along the hundred realisations of the CESM2-LE from 1850 to 2100 for the full (FF) and internal variability (IV) flow fields. The change point in the declining variance of the NAO index is identified based on the shifts in slope, with the key transition occurring in 2025. The change point for both the FF and IV is identified to be 2025. Further, the declining trend in the variance is also accompanied by a statistically significant p-value, i.e., $p_{\text{Full}} = 0.0112$ and $p_{\text{Internal}} = 0.0108$.

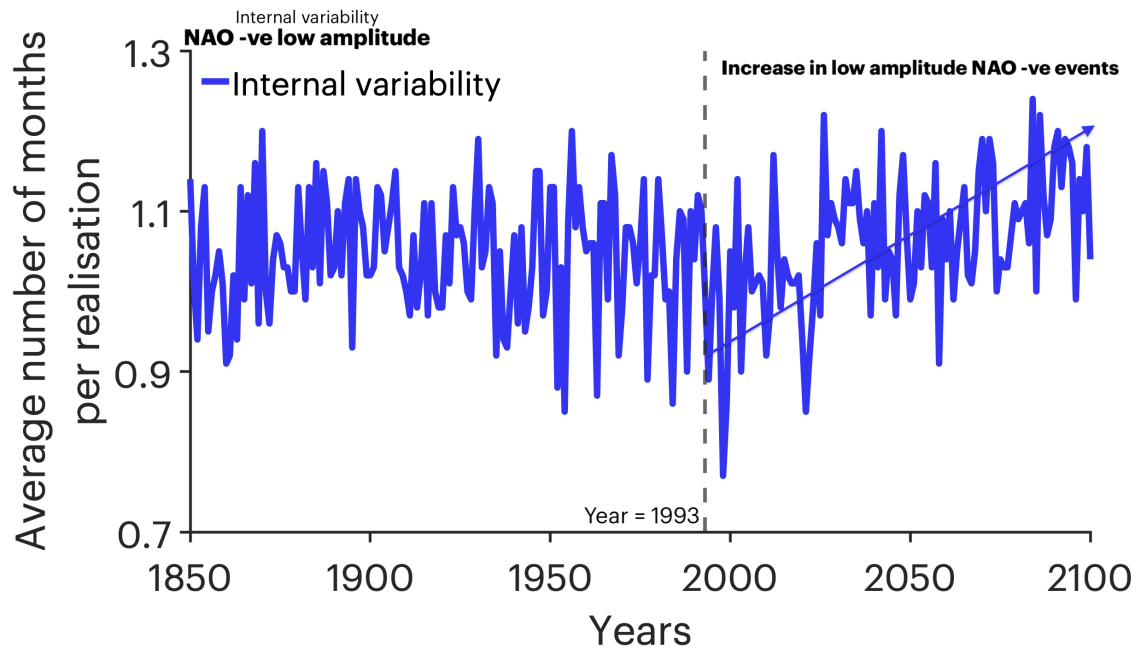


Fig. S10. Count of low-amplitude NAO -ve events for the IV:

The schematic diagram shows the average number of months per ensemble for the internal variability (IV) flow field associated with the low-amplitude NAO-negative phases across 1850 to 2100. The low-amplitude NAO-negative phases are defined for the NAO values between -1 and 0. The vertical line denotes the year, i.e., 1993, where we note an increase in the number of low-amplitude NAO-negative events for the IV.

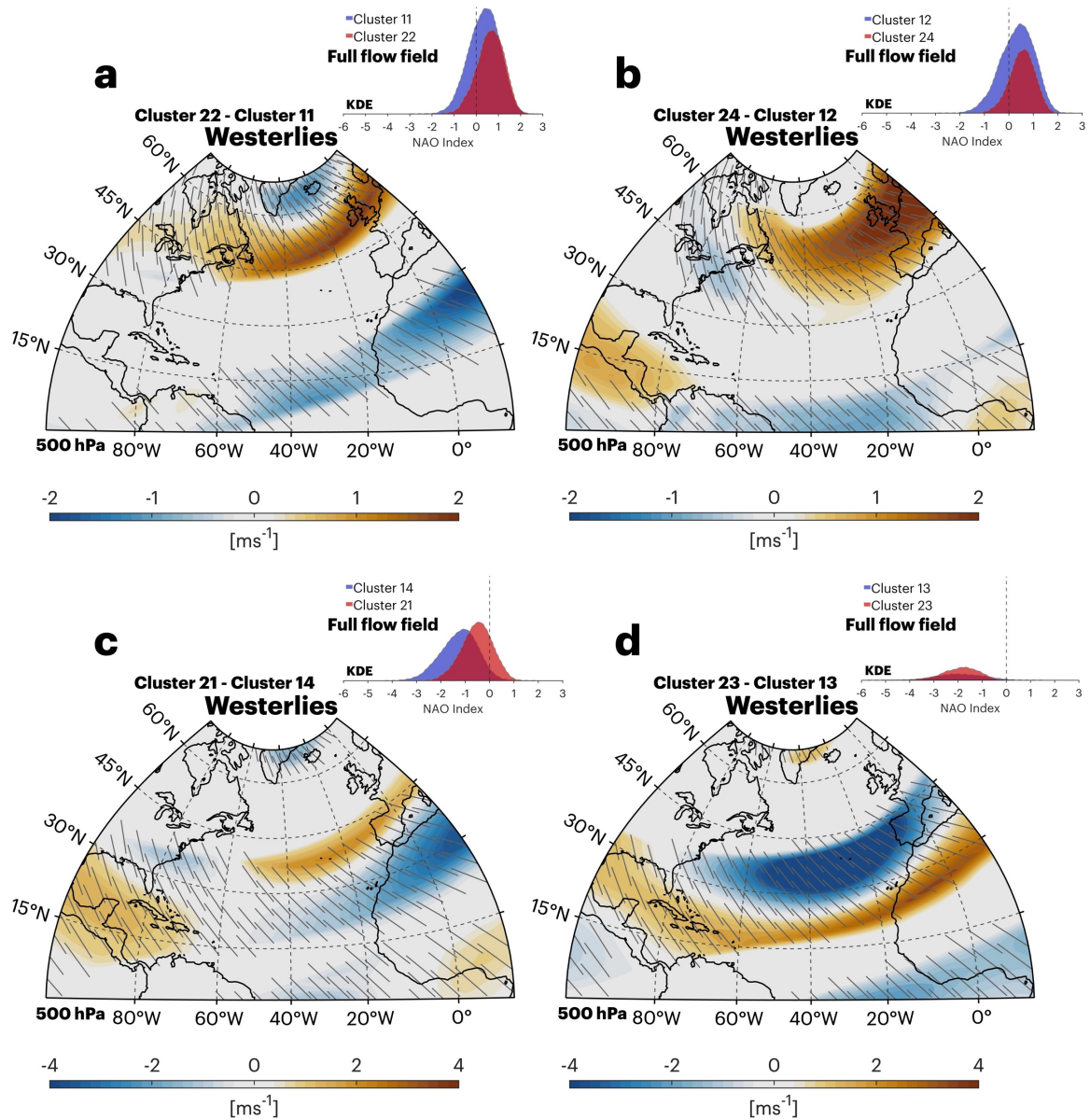


Fig. S11. Westerlies difference among recurrent atmospheric regime states for FF:

The left and the right panels show the significant spatial difference of the mid-tropospheric westerlies among the recurrent atmospheric regime states across the Pre and Post-1995 periods for the full flow field (FF), i.e., the combination of internal variability (IV) and forced response. Hatched areas indicate regions where the differences are statistically significant at the 95% confidence level ($p < 0.05$) using a two-sample t-test at each grid point. The density estimate of the NAO index associated with each cluster or the regime state is shown adjacent to the spatial patterns. The density estimates reveal the association of that particular cluster with the NAO +ve or NAO -ve phases.

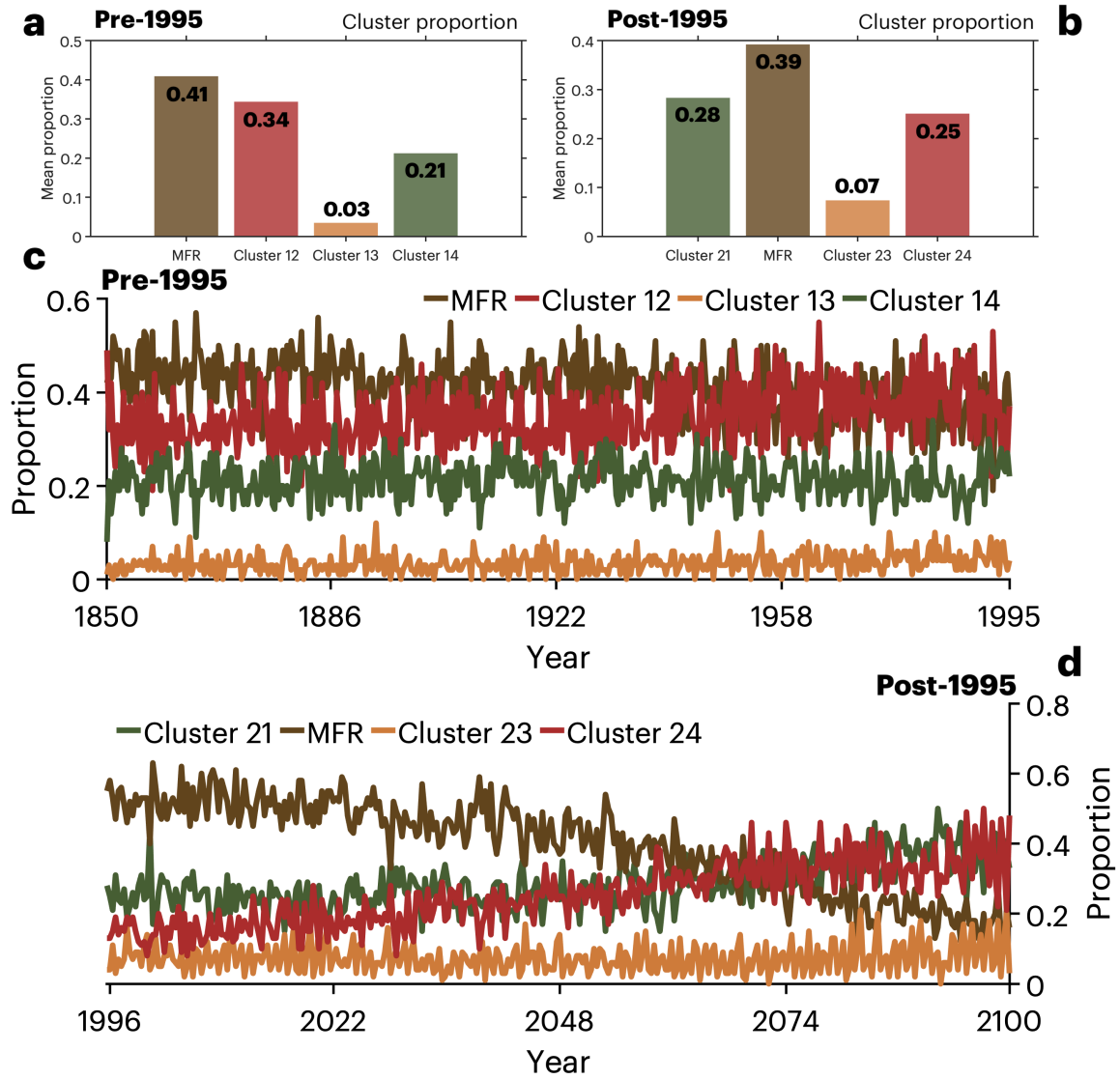


Fig. S12. Temporal evolution of cluster proportions for the FF across Pre- and Post-1995 periods:

The panels **a** and **b** illustrate the time evolution of the cluster proportions for the full flow field (FF) during the Pre- and Post-1995 periods, respectively. Clusters exhibiting similar spatial patterns across the two periods are considered recurrent and are shown in identical colours. In panel **a**, the clusters remain relatively stable, supporting the stationarity assumption of the GMM framework. Panel **b** reveals that the stationarity assumption is violated for the cluster regimes, as the anthropogenic warming trend induces non-stationarity characteristics to the atmospheric circulation regime states.

Supplementary References

1. Gervais, M., Shaman, J. & Kushnir, Y. Mechanisms Governing the Development of the North Atlantic Warming Hole in the CESM-LE Future Climate Simulations. *Journal of Climate* **31**, 5927–5946 (2018).
2. Gervais, M., Shaman, J. & Kushnir, Y. Impacts of the North Atlantic Warming Hole in Future Climate Projections: Mean Atmospheric Circulation and the North Atlantic Jet. *Journal of Climate* **32**, 2673–2689 (2019).
3. Chemke, R., Zanna, L. & Polvani, L. M. Identifying a human signal in the North Atlantic warming hole. *Nat Commun* **11**, 1540 (2020).
4. He, C. *et al.* A North Atlantic Warming Hole Without Ocean Circulation. *Geophysical Research Letters* **49**, e2022GL100420 (2022).
5. Park, I.-H. & Yeh, S.-W. Projections of the North Atlantic warming hole can be constrained using ocean surface density as an emergent constraint. *Commun Earth Environ* **5**, 98 (2024).
6. Kramer, S. M., Karnauskas, K. B., Zhang, L., Heede, U. K. & Liu, H. A positive atmospheric feedback on the North Atlantic warming hole. *Sci Rep* **14**, 29829 (2024).
7. Yu, H. *et al.* Seasonal phase change of the North Atlantic Tripole Sea surface temperature predicted by air-sea coupling. *npj Clim Atmos Sci* **7**, 322 (2024).