

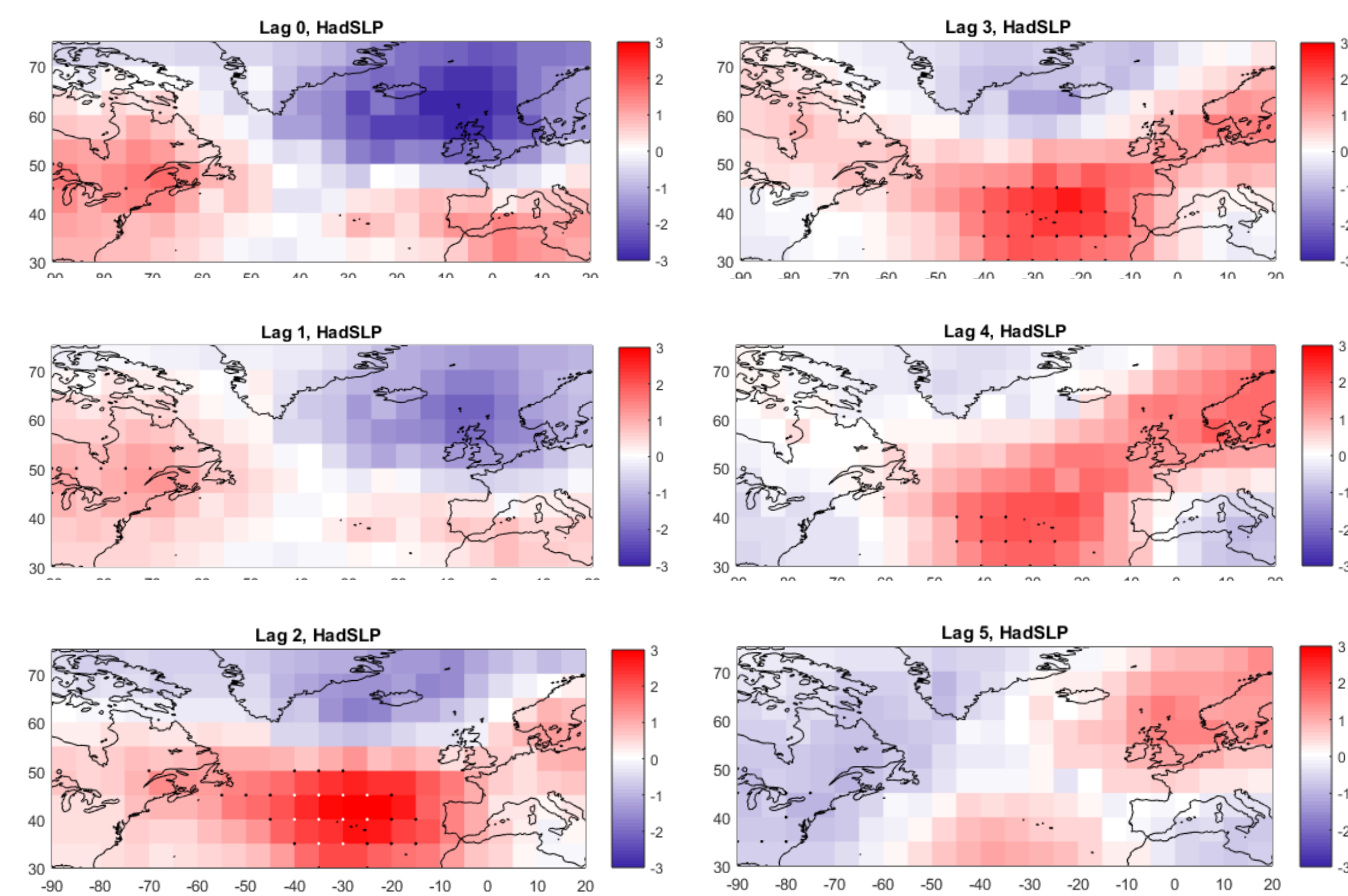
# Lagged Correlations Between the NAO and the 11-Year Solar Cycle: Forced Response or Internal Variability?

## Proposed Solar/NAO Relationship

The North Atlantic Oscillation (NAO) has been suggested to respond to the 11-year solar cycle with a lag of 2-4 years (Gray et al. (2013); Scaife et al. (2013)). The solar/NAO relationship provides a potential pathway for solar activity to modulate surface climate. However, a short observational record paired with strong NAO internal variability raises questions about the robustness of the claimed relationship.

## Correlations in Reanalysis

We first studied this relationship in reanalyses (HadSLP, HadISST, NOAA, ERA-20C, 20th Century Reanalysis) (Allan and Ansell (2006); Smith and Reynolds (2004); Poli et al. (2016); Compo et al. (2011)). We regressed onto DJF sea level pressure or sea surface temperature anomalies with trend, Niño 3.4, aerosol optical depth, and sunspot number as predictors. For the solar index, we performed regressions at lags of 0-11 years and found positive NAO-like patterns for lags 2-4 years. This pattern was robust across reanalyses for SLP and SSTs.

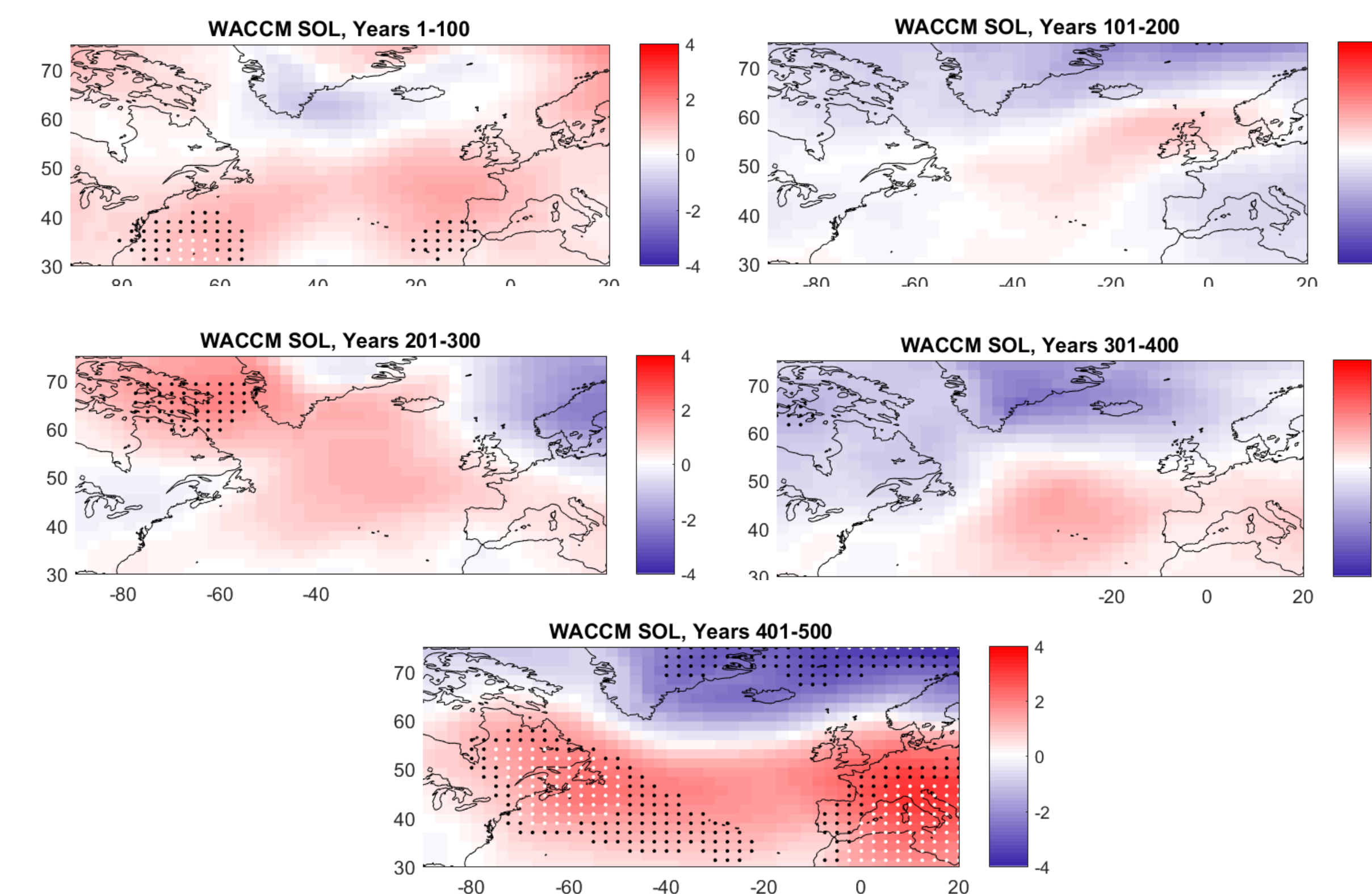


**Figure 1:** HadSLP 1870-2004 DJF solar regression coefficients on SLP anomalies at lags 0-5 years. Positive lags correspond to SLP changes after peaks in solar irradiance.

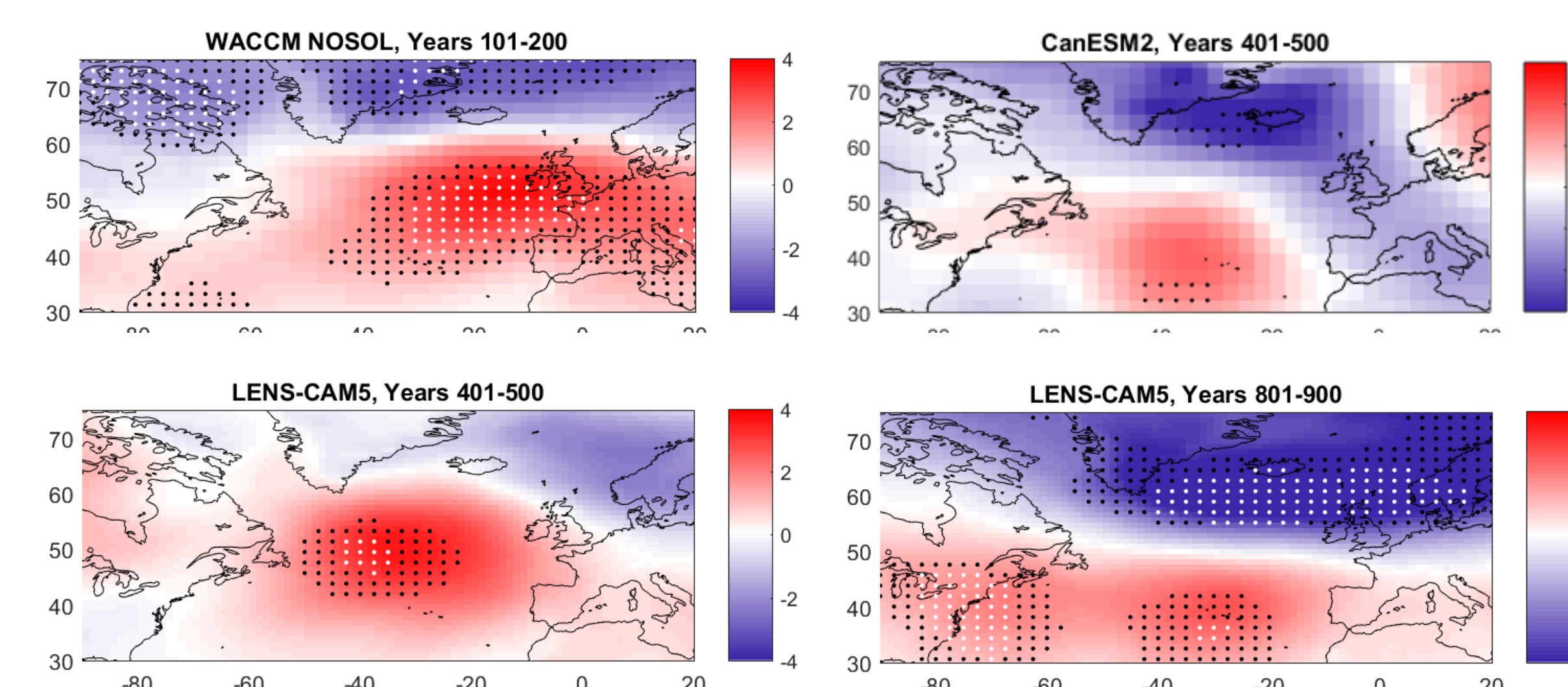
## SOL and NoSOL Simulations

We used WACCM runs to establish the robustness of this signal, using simulations over a longer period than reanalysis. We used two 500 year runs, one with an 11-year solar cycle (SOL) and one without (NoSOL). We also used 1000 year NoSOL runs from LENS-CAM5 and CanESM2. We performed regressions at lag 2 with trend, Niño 3.4, a QBO index (30 mb  $u$ ), and down-

welling solar flux at the top of the atmosphere as predictors for SLP anomalies. The solar index for the NoSOL regressions was a shifted version of that from the SOL model.



**Figure 2:** 100 year windows of solar regression coefficients on SLP at lag 2 in WACCM SOL. In years 401-500 the NAO-like signal is strong, and in years 201-300 it does not exist.

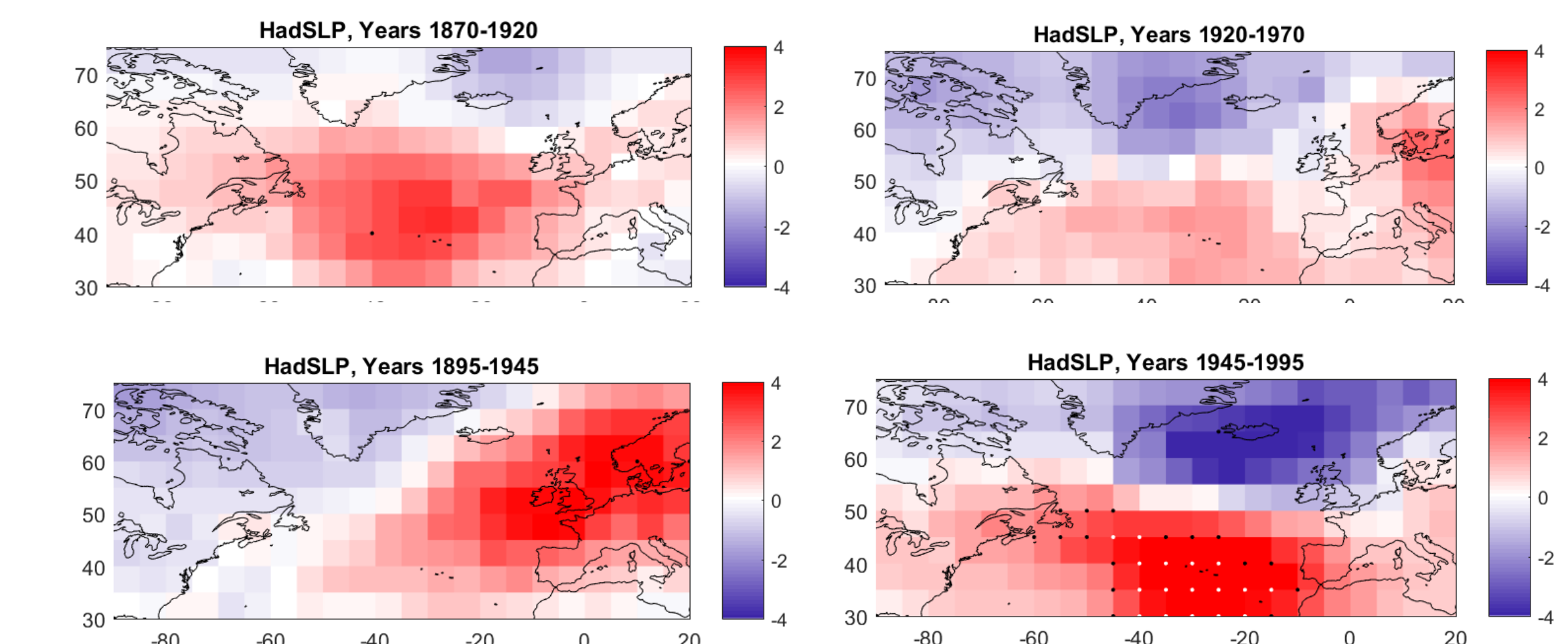


**Figure 3:** 100 year windows of solar regression coefficients on SLP at lag 2 in WACCM NoSOL, LENS-CAM5, and CanESM2 showing strong positive NAO-like patterns.

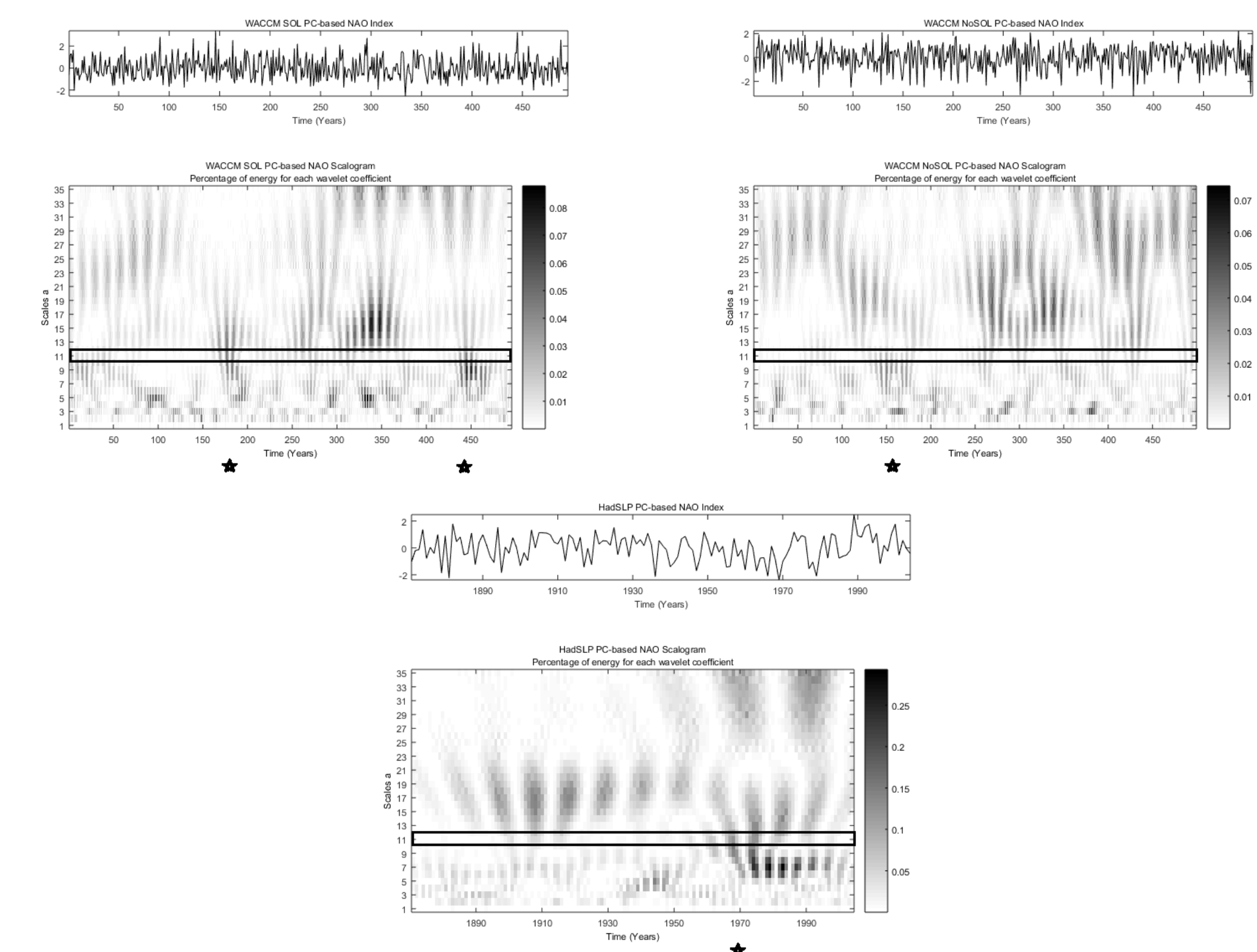
Only some windows in the SOL model show the lagged signal. Further, we observe significant signals in some windows of the NoSOL models. This transience and reproducibility in models without a solar cycle indicates that the relationship is not forced.

## Non-Stationarity

To determine whether this transience appears in observations, we considered 50 year windows in HadSLP. The signal varies significantly across windows. To investigate this further, we performed a wavelet transform on PC-based NAO indices from WACCM SOL and NoSOL and HadSLP.



**Figure 4:** 50 year windows of HadSLP DJF solar regression coefficients at lag 2. The NAO-like signal in the correlation is transient.



**Figure 5:** Continuous wavelet transforms of NAO indices from WACCM SOL, WACCM NoSOL, and HadSLP. Black rectangles indicate the peak period of the solar index. Stars indicate years where the transform of the NAO index shows power at that period.

## Conclusions

The proposed solar/NAO relationship is robust across reanalyses but can be replicated in models with no 11-year solar cycle. This suggests that the observed correlation is due to internal NAO variability, not a response to the solar cycle. This is further supported by the non-stationarity seen in shorter windows and wavelet transforms of NAO indices in reanalyses and models.

## References

- Allan, R., and T. Ansell. 2006. A new globally complete monthly historical gridded mean sea level pressure dataset (HadSLP2): 1850-2004. *J Climate* 19:5816-5842.
- Compo, et al. 2011. The twentieth century reanalysis project. *Quarterly J Roy Meteorol Soc* 137:1-28.
- Gray, L., et al. 2013. A lagged response to the 11 year solar cycle in observed winter Atlantic/European weather patterns. *J Geophysical Research: Atmospheres* 118(13):405-413.
- Poli, et al. 2016. Era-20c: An atmospheric reanalysis of the twentieth century. *J Climate* 29:4083-4097.
- Scaife, A., et al. 2013. A mechanism for lagged North Atlantic climate response to solar variability. *GRL* 40:434-439.
- Smith, T.M., and R.W. Reynolds. 2004. Reconstruction of monthly mean oceanic sea level pressure based on COADS and station data (1854-1997). *J Oceanic Atmos Tech* 21:1272-1282.