Met Office Hadley Centre

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Quantifying the rarity of extreme multi-decadal trends: how unusual was the late twentieth century trend in the North Atlantic Oscillation?

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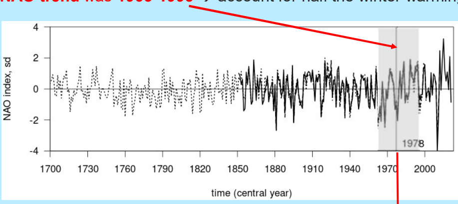
(1) Background

- **Extreme NAO trends:** maximum (or minimum) in a moving window trend series.
  → large impact on regional winter climate change in Northern extra-tropics.
- **Winter NAO index**: standardised pressure difference Azores minus Reykjavík.
- **Max 31-year NAO trend was 1963-1993** → account for half the winter warming in N extra-tropics. (1-3)



NAO Observations

The standardised DJF mean NAO index for observation datasets: HadSLP2r (black solid line), 20th century reanalysis (black dashed line), Luterbacher reconstruction (black dotted line). Max 31-year trend centred on 1978.

- **CMIP5 & 6 models underestimate** extreme NAO trends. (4-9)

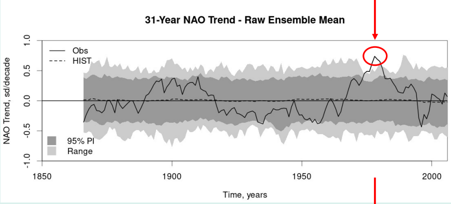
(2) Question: How unusual was the Max winter NAO 31-year trend?

$q(z) = Pr(Max\ Trend \geq z)$ $z = 0.737$ sd/decade (historical period 1862-2005)

(2a) CMIP6 Models of Extreme NAO Trends

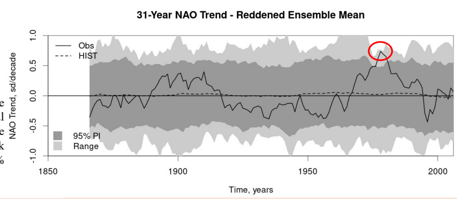
q(0.737) = 0.4%   **~ "1 in 200" event**

- Only 1 simulation out of 258 (9)
  - Similar results for CMIP6 & 5 combined (4,5,8) e.g. 2/538 (8)
- Obs. outside model envelope at that timestep (1963-1993).



Moving window 31-year trends
For raw (left) and reddened (right) models

Dashed black curves show CMIP6 multi-model ensemble mean NAO 31-year trend series using historical experiments (and SSP585 beyond 2014) alongside HadSLP2r observations (black solid curve). Light and dark grey shading shows the ensemble range and empirical 95% prediction interval respectively.



(2b) Fitted Stochastic Models of Extreme NAO Trends

AR(1) with ρ_{obs} = 0.17
***q(0.737)* = 3.5%**

FD with d_{obs} = 0.15
***q(0.737)* = 6.1%**

~ "1 in 20" event

- First order auto-regressive processes (AR(1)) and fractional difference (FD) processes chosen as:
  - Model the winter NAO index fairly well. (10)
  - Only have one parameter to estimate from observations (lag-1 autocorrelation ρ or difference d).
- Generated 5000 random simulations of length matching 1862-2005.

- Average lag 1 autocorrelation estimate for **CMIP6 models: ρ_{cmip} = 0.0**
- Using AR(1) process with **ρ = 0.0**: ***q(0.737)* = 0.6%**   **~ "1 in 200" event**

(2c) Key points

CMIP6 models underestimate the likelihood of extreme 31-year NAO trends by a factor of 10

- CMIP6 models underestimate the likelihood of max and min multi-decadal NAO trends on a range of timescales (tested 1 to 8 decades relative to stochastic models).

This is consistent with a lack of autocorrelation in the CMIP6 models compared to observations.

- Reason for lack of autocorrelation is unknown but consistent with signal to noise paradox.
- CMIP6 models lack important aspects of the mechanisms for low frequency variability of the NAO.

(3) New recalibration method: "Reddening"

- Redden the CMIP6 NAO simulations (Y) by applying a smoothing filter based on the stochastic processes from Section (2b) to improve the autocorrelation structure (→ Y^R)

AR(1)
$Y^R = \gamma(1-\rho B)^{-1} Y$
i.e. $Y^R[t] = \gamma(Y[t] + \rho Y^R[t-1])$

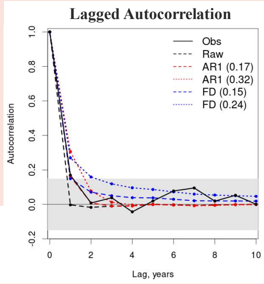
FD
$Y^R = \gamma(1-B)^{-d} Y$
i.e. $Y^R[t] = \gamma\left(Y[t] + \sum_{j=1}^{t-1} Y_j \Pi_j\right)$

- ρ and d represent level of reddening, γ scales to retain original variance (Π_j FD coefficients (8,9)).
- It is assumed that the original CMIP6 NAO simulations have no autocorrelation (ρ = 0).

(3a) Recalibration improves NAO autocorrelation structure

- Fitted (ρ = 0.17; d = 0.15) and upper (ρ = 0.32; d = 0.24) levels of reddening parameters are considered (based on Bartlett's 95% confidence interval) $\rho \pm 1.96\sqrt{(1-\rho^2)/n}$

- Reddening recalibrates CMIP6 NAO simulations to have autocorrelation structure better matching that observed.
- FD (d = 0.24) best captures the longer-term memory.



The average lag autocorrelation value across all individual CMIP6 ensemble members for lags zero to ten years for the raw and reddened output using stochastic models in key. The observed estimates are shown by the thick black solid line. Gray shading represents the 95% confidence interval for a white noise process using the Bartlett formula with ρ = 0.

(3b) Recalibration improves distribution of extreme NAO trends

- Leads to CMIP6 exceedance probabilities better matching the stochastic models in Section (2b).

AR(1) with ρ = 0.17
***q(0.737)* = 2.7%**

FD with d = 0.15
***q(0.737)* = 6.6%**

~ "1 in 20" event

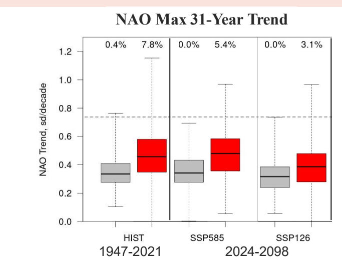
- Widens the CMIP6 distribution of moving window trends.

- Strong reddening needed for CMIP6 envelope to capture 1963-1993 trend at that time (d = 0.24).
  - Inflates total variance of moving window trends by 46% (boosts internal variability).
  - Inflates variance of the ensemble mean by 52% (boosts response to external forcing).

(3c) CMIP6 models also likely underestimate multi-decadal NAO trends in the future

- Reddening shifts and widens distribution of max trends.

- Reddening shows clearer distinction between future scenarios



Effect of reddening on Max NAO trends.
The distribution of *maximum* 31-year trends in the 75-year historical (HIST) and future periods using high (SSP585) and low (SSP126) radiative forcing scenarios (HIST uses SSP585 beyond 2014). CMIP6 distributions are shown using raw (grey) and reddened (red, FD with d=0.24) output (median centre line, 25 to 75 percentile box, total range whiskers). The percentage of model members above the observed max (dashed line) are displayed.

(3d) Key points

Reddening is a useful recalibration tool to increase the magnitude of CMIP6 NAO trends.

- Inflates multi-decadal variability → extreme trend probabilities match fitted stochastic models.
- Alternative approach constructs synthetic simulations based on spectral characteristics of Obs (11)
- Advantage over stochastic/synthetic simulations is that the reddening method retains the influence of model dynamics and external forcings.

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