The Subpolar North Atlantic (SPNA) stands out for its high decadal predictability of heat content variability. At the same time, climate models exhibit oscillatory behaviour on decadal to multi-decadal time scales in that region. We show that a damped harmonic oscillator model driven by North Atlantic Oscillation (NAO) variability successfully mimics the behaviour of more complex climate prediction models and exhibits similar hindcast performance during the period 1980 to present. In line with previous work that emphasises the role of ocean dynamics, the performance of the analytical model drops if the ocean heat transport – represented as SPNA heat content tendency – is utilised. The model’s resonance characteristic further suggests that the amount of predictable internal variability is considerably stronger in the recent frequency history of the atmospheric forcing. It is therefore likely that the extended period of predominantly positive NAO prior 1995 led to enhanced SPNA predictability in subsequent years and decades. The simulated variability during the period of interest is not very sensitive to the spin-up length and synchronisation rather quickly – within few decades – when NAO forcing is applied. This confirms the utility of using atmospheric re-analysis products to synchronise the ocean in prediction models. Amongst other applications, the damped harmonic oscillator framework may help to investigate the limits of SPNA decadal predictability under the assumption that the atmospheric forcing being itself is not predictable and to better understand inter-model prediction differences.

1. Introduction

SPNA (Fig. 1) climate is characterised by 1. decadal-scale climate variability driven by atmospheric NAO variability; 2. prediction models show large benefit from initialisation; 3. initiation of meridional transports thought to be key (Fig. 2); 4. ESIs show quasi-bi-decadal oscillatory behaviour (Fig. 3).

2. Damped Oscillator Model (DOM) – cont.

Analytical solution – underdamped case
\[ y(t) = A_0 e^{\alpha t} \cos(\omega t + \phi) \]
where \( A_0 \) is the initial amplitude, \( \alpha \) is the damping coefficient, and \( \omega \) is the angular frequency.

2.1. Spectral Transform of NAO forcing

To be able to analytically integrate the model, we perform a spectral transformation of the NAO time-series using the discrete cosine series (DCT). The DCT is defined as:
\[ \text{DCT}(n) = \sum_{k=0}^{N-1} x_k \cos \left( \frac{\pi}{N} (k+1/2) n \right) \]
where \( x_k \) is the original time-series, \( N \) is the number of data points, and \( \phi \) is the phase shift.

3. Thermal Inertia Model (AR1)

Differential equation
\[ \frac{dy}{dt} + \beta y = \alpha N(t) \]
where \( \beta \) is the damping coefficient, \( \alpha \) is the forcing coefficient, and \( N(t) \) is the NAO index.

4. Results

The damped oscillator model (DOM) forced with historical NAO variability successfully captures inter-decadal variations in observed SPNA temperature (Fig. 6a vs. 6b, bars). DOM produces hindcasts results (Fig. 6c, solid lines) that largely resemble the results from a dynamical prediction model (Fig. 6d) and compare favourably to the observed variability (Fig. 6e).

They hypothesize that the improved hindcast performance of DOM over ESIs is due to: 1) the ability of ESIs to capture the dominant oscillatory modes; 2) the use of stochastic or predicted NAO forcing in DOM predictions.

5. Summary

Good agreement with a dynamical model suggests the idea that SPNA climate variability behaves primarily like a damped harmonic oscillator forced by NAO variability. Rapid shifts are not well captured, hinting that there is more to SPNA variability than the damped oscillator dynamics investigated here.

6. Future work

• use of stochastic or predicted NAO forcing in DOM predictions to model prediction spread/uncertainty
• characterise resonance behaviour of ESIs with idealised ocean runs
• investigate transient resonance behaviour using NAO wavelet analysis
• perturbed parameter ensemble with multiple resonance frequencies
• address failure of DOM to capture rapid shifts