Gross underestimation of decadal atmospheric circulation signals in climate models

Huge uncertainty in projected 30 year trends

Opposite sign of NAO trends for 2016-2045

Projections use the same climate model differing by tiny perturbations to initial state

Irreducible uncertainty due to unpredictable internal variability (?)
Huge uncertainty in decadal predictions?

CMIP5 and CMIP6 decadal predictions
14 models, 169 ensemble members (>77,000 years!)
Huge uncertainty if models taken at face value
BUT this can be tested…

Observed temperature anomaly
Forecast member 3
Forecast member 149
Forecast signal is much too weak

NAO: Forecast years 2 to 9

Raw model output

Variance adjusted

Ensemble mean is highly correlated with obs ($r = 0.79$)

Should explain 62% of observed variability

Magnitude of ensemble mean variability is inconsistent with correlation

Smith et al (submitted)
Signal to noise paradox

Paradox: models predict the real world better than themselves despite perfectly representing themselves

Members NOT alternate realisations of obs

Need a very large ensemble to extract the predictable signal

Undermines the basis of ensemble prediction

Signal

North Atlantic Oscillation

Time

\( \sigma_s^2 \)
Signal + noise

Eade et al 2014, Scaife and Smith 2018
A simple interpretation

Climate models have the right amount of variability

**BUT**

The *proportion* of variability that is predictable is too small
Predictable component

Predictable component (PC)

\[ \sigma^2 = \frac{\text{signal}}{\text{total}} \]

\[ \sigma_s^2 = \frac{\sigma_s}{\sigma} \]
Ratio of predictable components

Observations: $PC \geq r$ (anomaly correlation)

Models: $PC = \frac{\sigma_{ens\,mean}}{\sigma_{ens\,members}}$

Ratio of predictable components (RPC) $\geq \frac{r}{\sigma_{ens\,mean}/\sigma_{ens\,members}}$

Ratio of predictable signals $= \frac{\sigma_{s,obs}}{\sigma_{s,models}} = RPC \approx \frac{\sigma_{s,obs}}{\sigma_{models}}$
Forecast signal is MUCH too weak

NAO : Forecast years 2 to 9

Ratio of predictable components RPC = 11

Signal is an order of magnitude too weak in climate model ensemble

Need 100 times the number of ensemble members to extract the signal
A widespread issue

RPC > 1 in many regions
- Especially for precipitation and pressure
- Atmospheric circulation signals too weak
Why worry about this?

Probabilistic and error based skill measures will give inaccurate estimates of the forecast skill that is potentially available.

Ensemble forecasts of are sometimes overconfident and their statistical properties may be improved by techniques such as stochastic physics which often increase ensemble spread. However, such techniques could potentially exacerbate this problem where the signal-to-noise ratio is too small and models are underconfident.

Upper limits on predictability are sometimes estimated from model ensembles but this is not the case here.

Event attribution will give inaccurate estimates of the probability of extremes, especially in the North Atlantic sector, where the signal-to-noise ratio is too small.

Estimates of unpredictable internal variability in regional climate change over the coming decades may be too large and forced signals may be too weak.

Resolving the paradox would allow reduced ensemble sizes and increase prediction skill.

Scaife and Smith, npj Clim. Atm. Sci., 2018
Impacts of the NAO

In reality NAO dominates over other factors (GHGs)

NAO too weak in ensemble mean → GHGs dominate (but small impact)
Impacts of extreme NAO

- Extreme positive NAO in late 1980s to 1990s
- Clear quadrupole impact seen in observations
- Not captured in raw model data

Smith et al (submitted)
Impacts of extreme NAO

NAO captured by ensemble mean (standardised)
Other impacts not captured (especially temperature)
Impacts of the NAO

In reality NAO dominates over other factors (GHGs)

NAO too weak in ensemble mean → GHGs dominate

Chose ensemble members with the correct NAO magnitude
NAO-matching

In reality NAO dominates over other factors (GHGs)

NAO too weak in ensemble mean → GHGs dominate

Chooses ensemble members with the correct NAO magnitude:

Compute ensemble mean NAO adjusted for underestimated signal

Compute NAO for each ensemble member

Select ensemble members whose NAO is close to adjusted ensemble mean NAO
Impacts of extreme NAO

Temperature (a) Observations

Precipitation (b) Observations

Pressure (c) Observations

(j) NAO-matched

(k) NAO-matched

(l) NAO-matched

Impacts captured very well by 20 ensemble members with correct NAO magnitude

“NAO-matching”
Impacts of the NAO on Atlantic ocean

NAO-matching clearly improves AMV predictions

AMV not the sole driver of the NAO
Internal variability or external forcing?

Significant skill using a large ensemble

Precipitation and pressure as well as temperature

Patterns of skill are captured by uninitialized simulations

Initialisation mainly improving the response to external forcings?

Smith et al, 2019
Summary

The good news:
Climate is *much* more predictable than previously thought
NAO correlation skill = 0.8 in decadal predictions

The bad news:
There is a serious deficiency in climate models
Predictable signal is an order of magnitude too small
What is the cause?
Does it affect projections beyond 10 years?
Need to understand the role of external forcings
Signal to noise paradox: hypotheses

Paradox: models predict the real world better than themselves despite perfectly representing themselves

Members NOT alternate realisations of obs

Need a very large ensemble to extract the predictable signal

Undermines the basis of ensemble prediction


Null hypothesis: it’s just noise

QBO teleconnections too weak

Lack of persistence

Errors in transitions between regimes
Eddy feedback too weak?

Eddy driven jet too weak
Eddy momentum flux convergence too weak

Eddy feedback weaker in models than reanalysis
Strengthens at higher resolution
May need 10km or higher resolution

\( F_y = - \frac{\partial (u'v')}{\partial y} \)
Signal to noise paradox in external drivers?

Volcanoes

Observations

Solar

Models

Note different colour scales!

Observations

Model response is too weak, and not lagged

Driscoll et al 2013; Gray et al 2013
Not just a trend

- Significant skill in many regions after detrending
- Highlights importance of non-GHG forcings
  - Anthropogenic aerosols
  - Volcanoes
  - Solar
  - Ozone
A widespread issue

**Seasonal NAO**

**Sahel rainfall**

Years 2-5, RPC=1.2

Years 3-7, RPC=1.6

RPC > 1 in multiple seasonal forecasting systems

**European summer rainfall**

Seasonal, RPC=5