

The need to account for **model error** in prediction, projection and attribution

Doug Smith



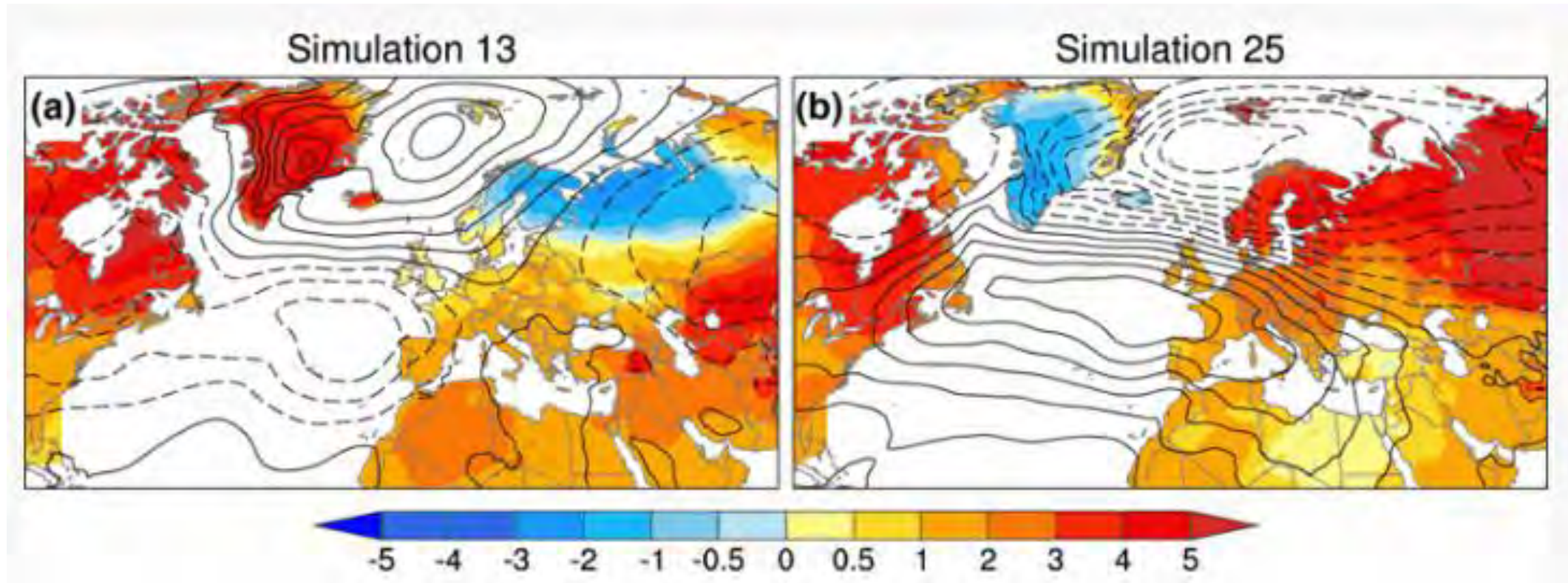
Key messages

Climate models can have **opposite** responses to the same forcings → **they can't all be right!**

Climate models may **underestimate** the true **forced response**

Not accounting for **model errors** could leave **society unprepared** for impending **extremes**

Irreducible internal variability?



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 (?)

Models fail to capture North Atlantic trends

Trends 1951-2020

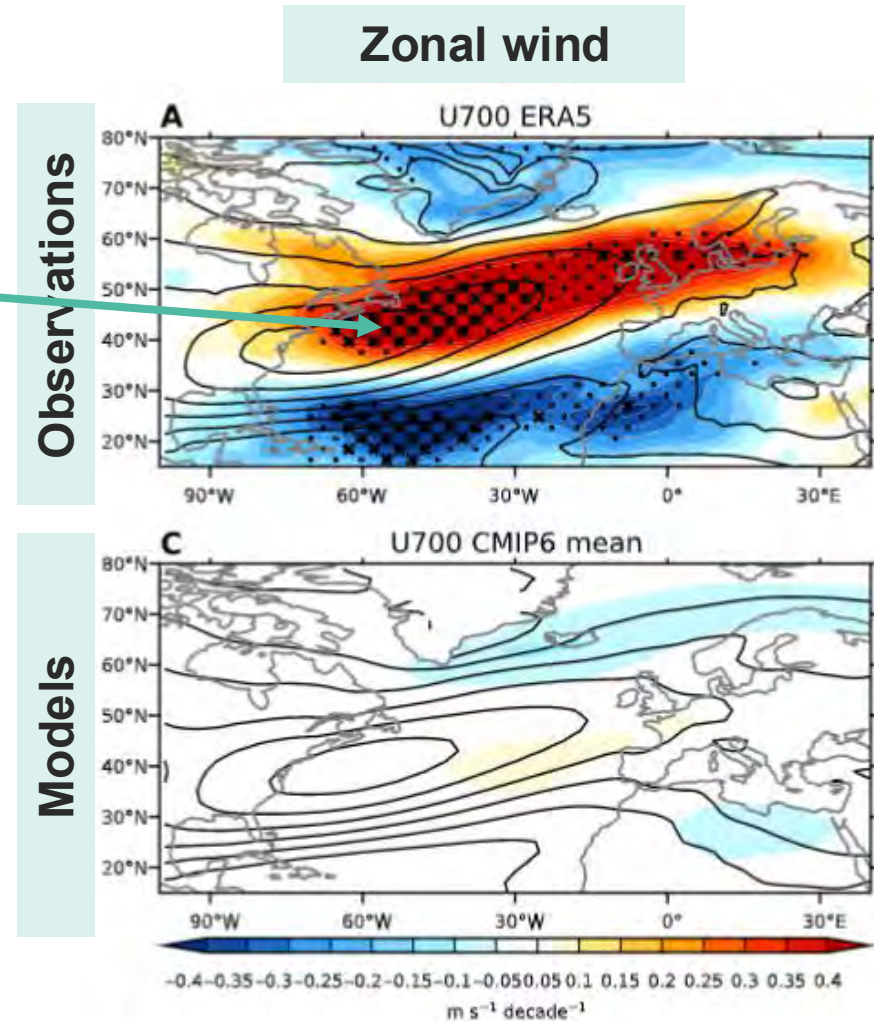
Obs outside model range (303 members)

Similar **patterns** but **obs** much **stronger**

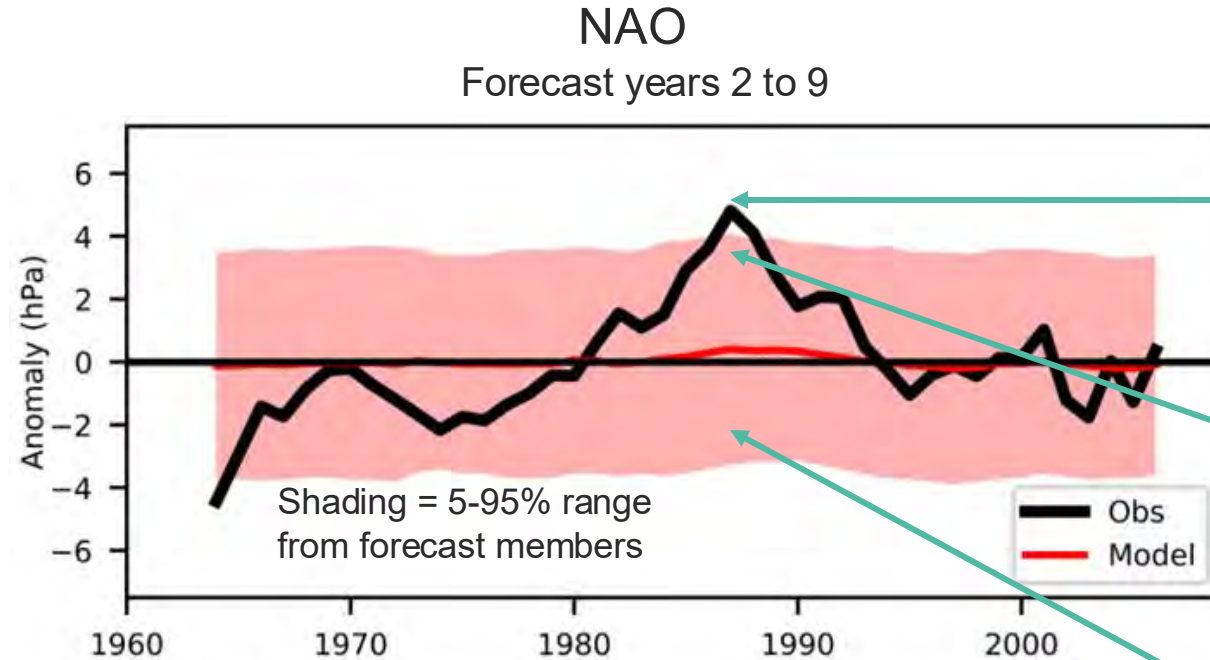
Models may have **errors!**

→ possible **underestimation** of **forced response?**

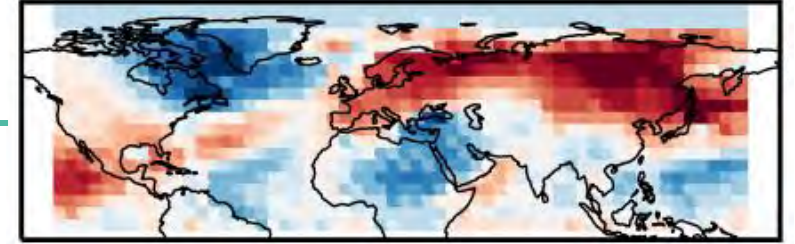
Taking models at **face value** might not be the best approach...



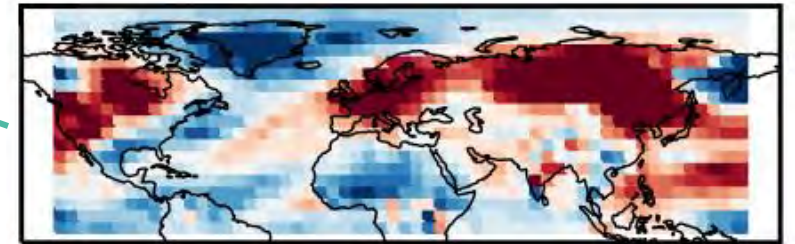
Irreducible internal variability?



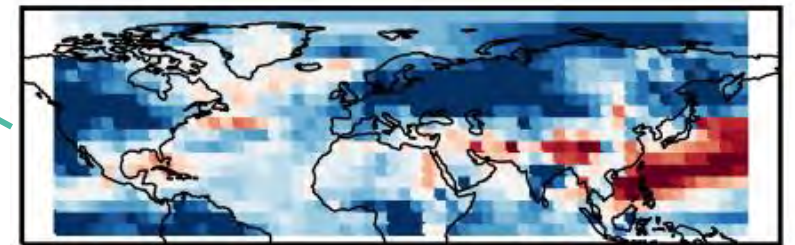
Observed temperature anomaly



Forecast member 3



Forecast member 670



CMIP5 + CMIP6 decadal predictions

Almost no signal in ensemble mean (red curve)

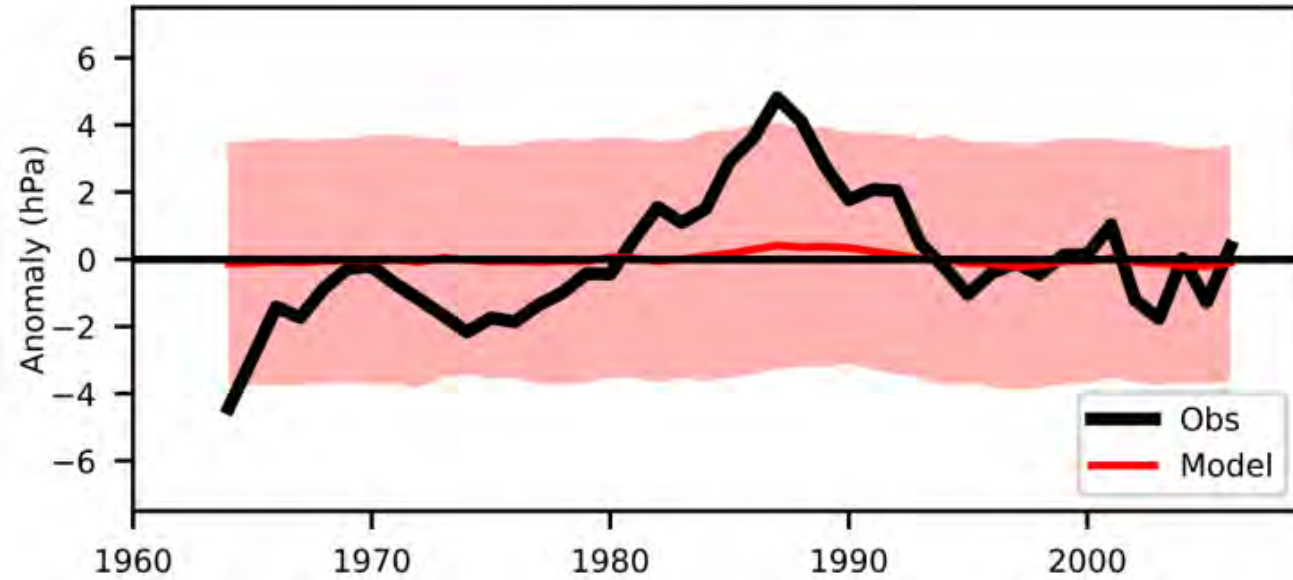
Irreducible internal variability if models taken at **face value**

BUT this can be tested...

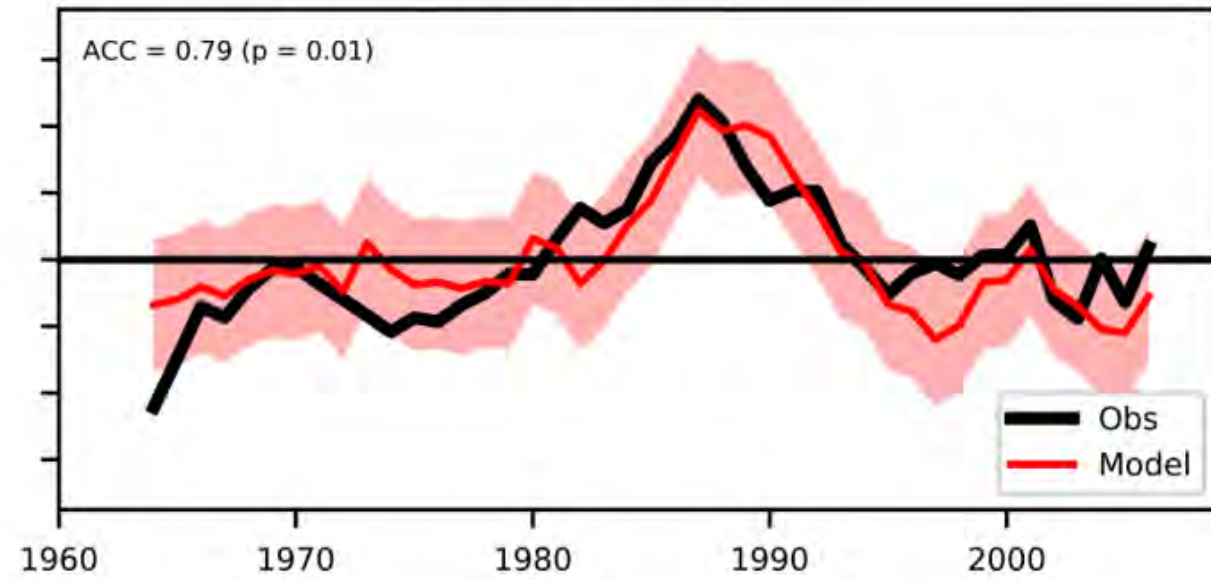
Forecast signal is much too weak

NAO : Forecast years 2 to 9

Raw model output



Variance adjusted

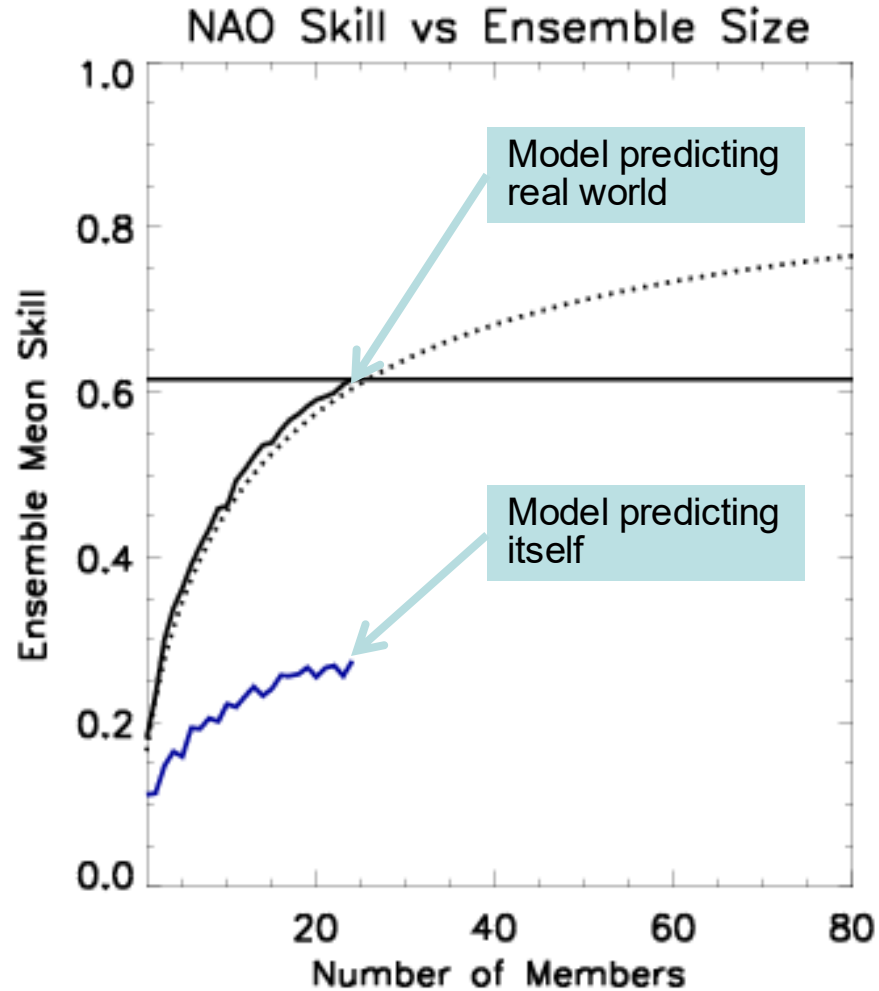


Ensemble mean is highly correlated with obs ($r = 0.79$)

Should explain 62% of observed variability

Magnitude of ensemble mean variability is **inconsistent with correlation**

Signal to noise paradox



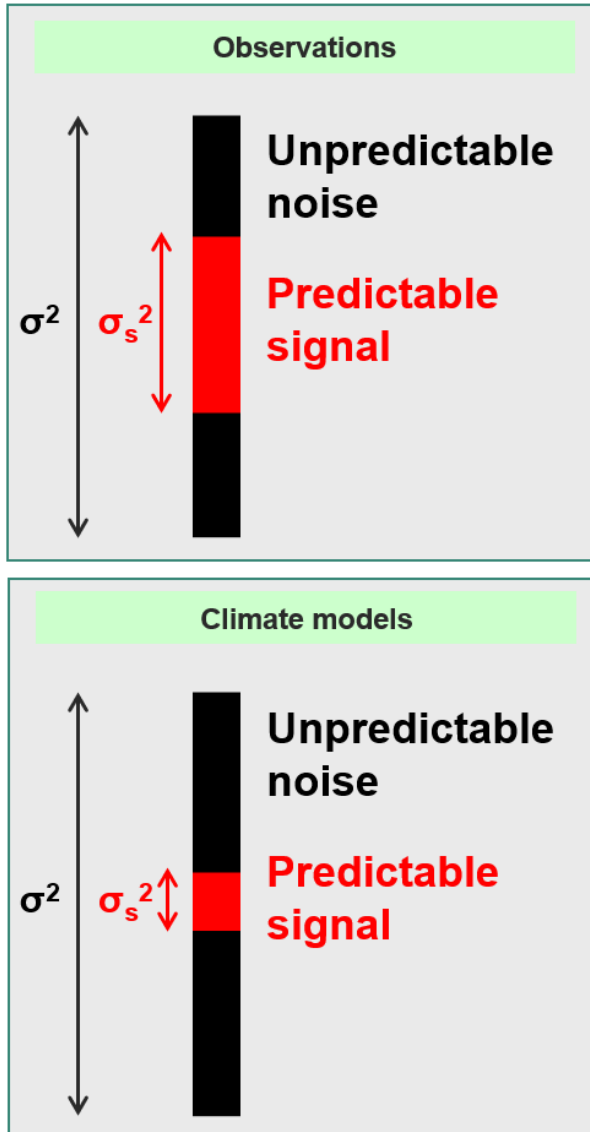
Paradox: models predict the real world better than themselves despite perfectly representing themselves

Members NOT alternate realisations of obs

Need a very large ensemble to extract the predictable signal

Undermines the basis of ensembles

Quantifying the error



Ratio of predictable components (RPC)

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

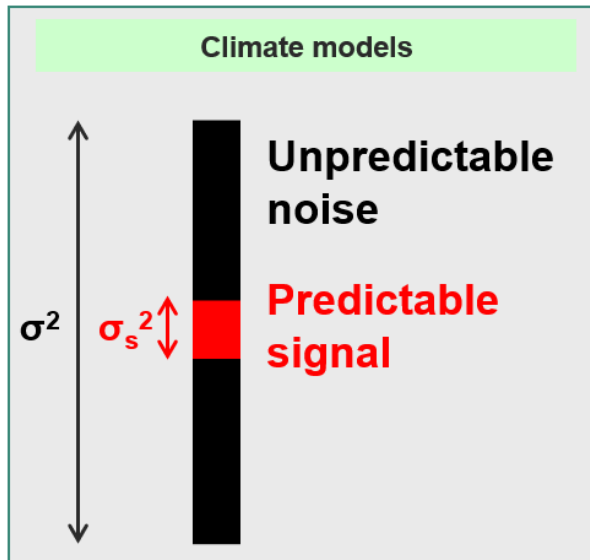
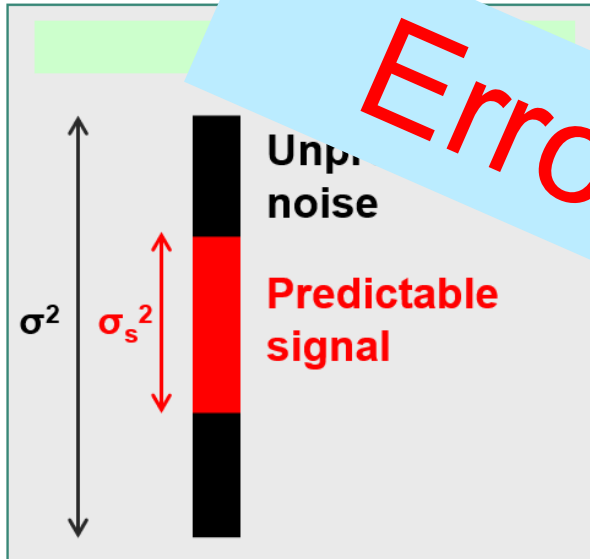
$$\text{Models: } PC = \frac{\sigma_{ensemble\ mean}}{\sigma_{ensemble\ members}}$$

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

RPC should be one

RPC > 1 shows the signal to noise error

Quantifying the error



Ratio of predictable components (RPC)

Predictable Component $PC \geq r$ (anomaly correlation)

$\sigma_{ensemble\ mean}$

ensemble members

Ratio of predictable components (RPC)

r
ensemble members

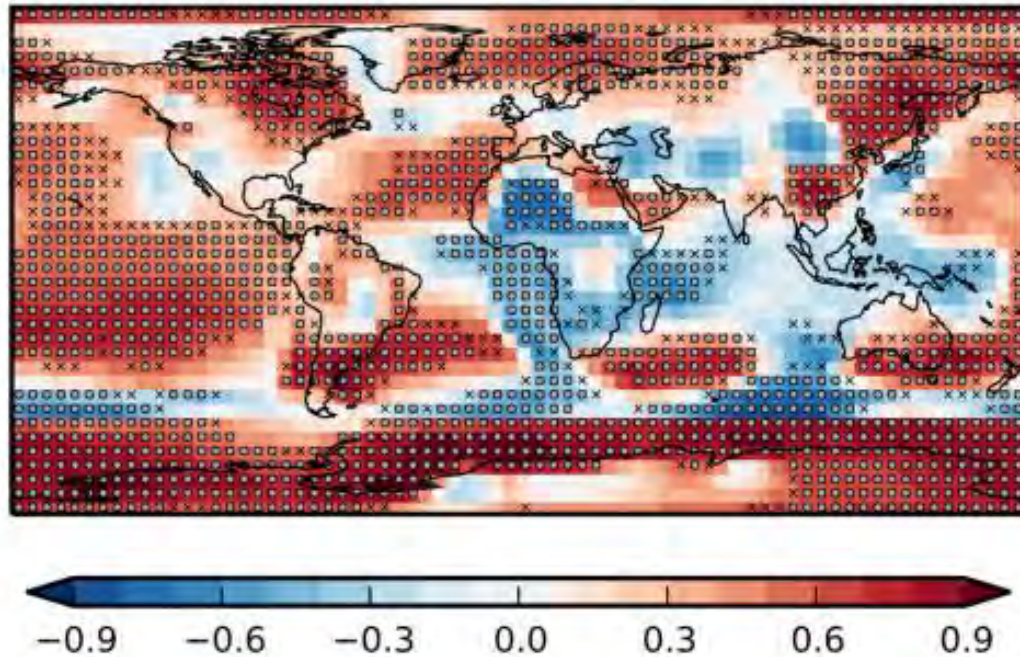
RPC should be one

RPC > 1 shows the signal to noise error

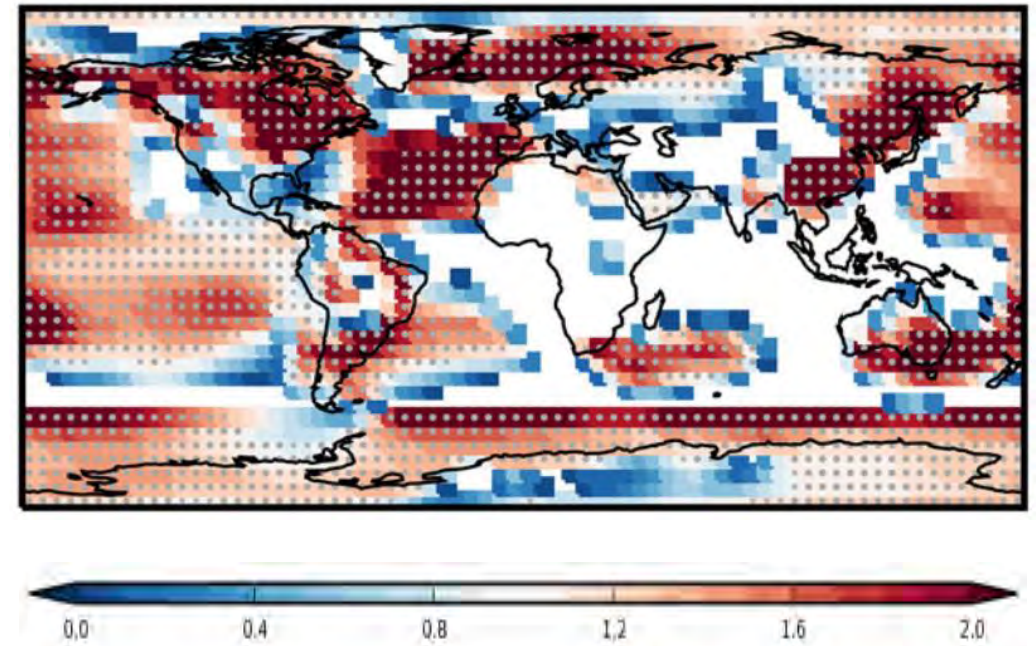
Error not seen in total variability

A key issue

MSLP skill (years 2-9)



Error in magnitude of signal (RPC)



Wherever there is skill the modelled signals are too small!

Opposite model responses!!

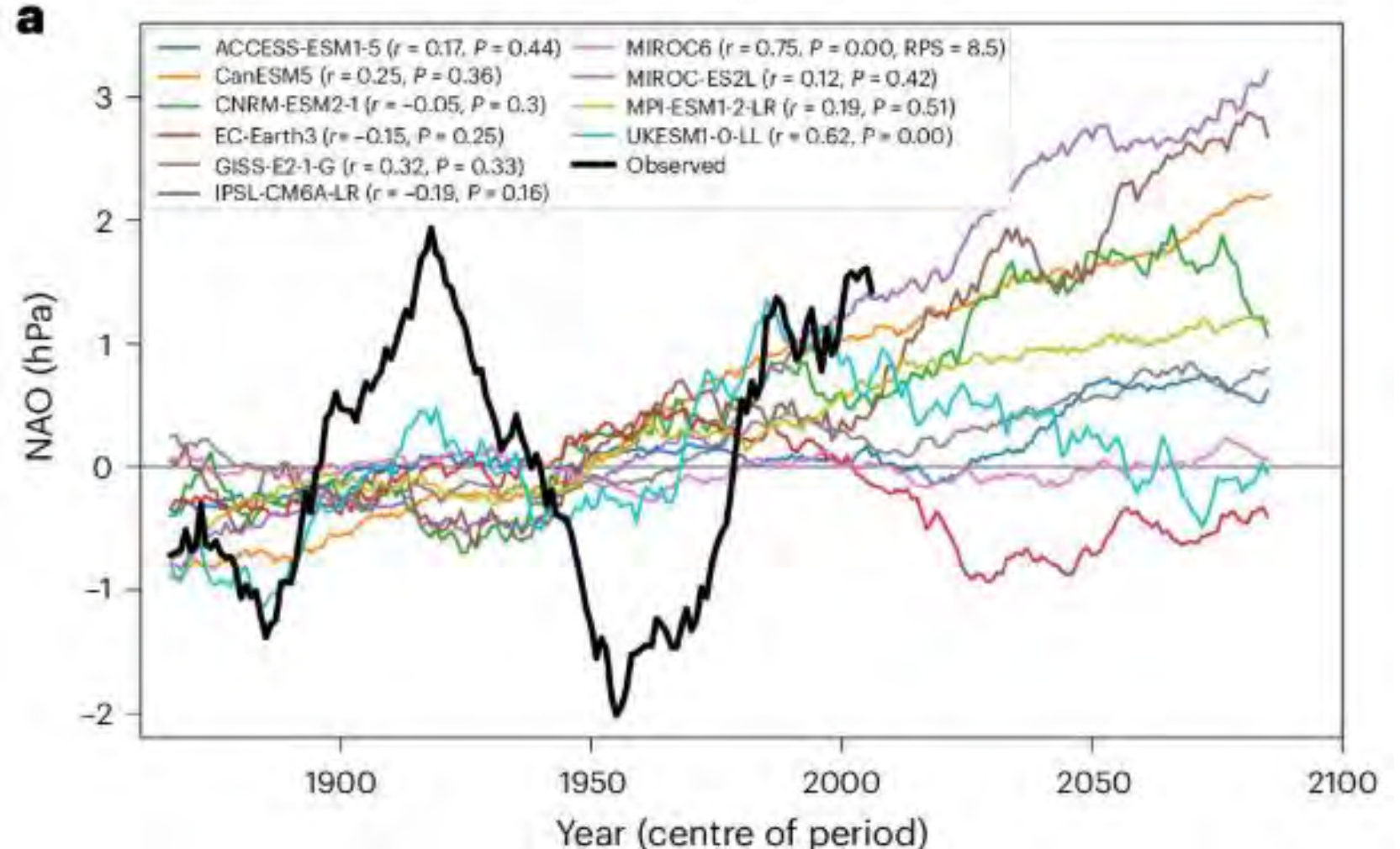
31-year NAO

Historical + ssp245

Full range of uncertainty!

MIROC6, UKESM1
significantly correlated
with obs

But very different
projections



Regression between EEI and U (31 year)

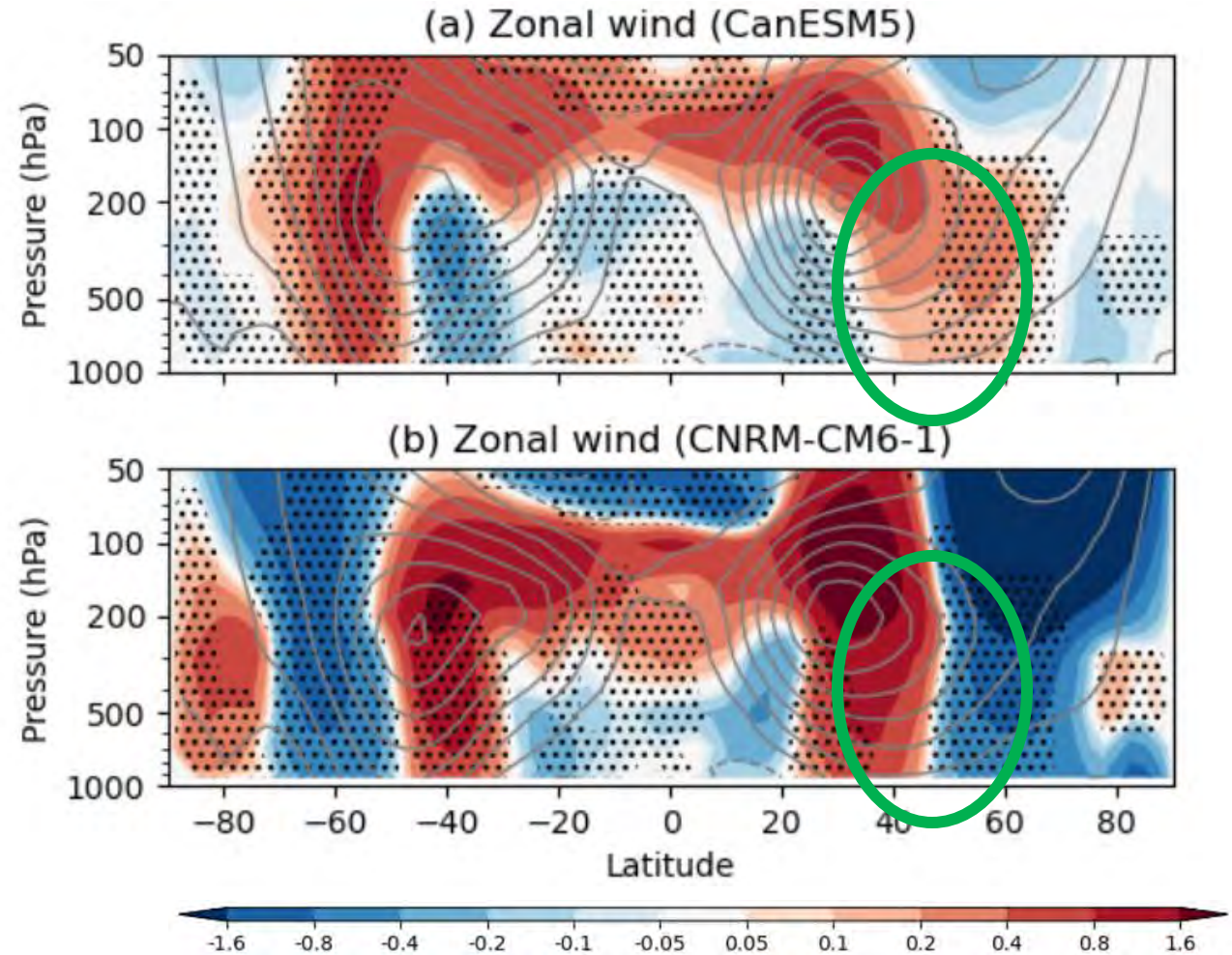
Climate responds to bring Earth's Energy Imbalance (EEI) back to equilibrium

Similar horseshoe pattern increase

Stippled where significantly opposite

CanESM5 → poleward shift

CNRM-CM6-1 → equatorward shift



Regression between EEI and T (31 year)

Positive energy imbalance → troposphere warming, thermal gradient at 200 hPa

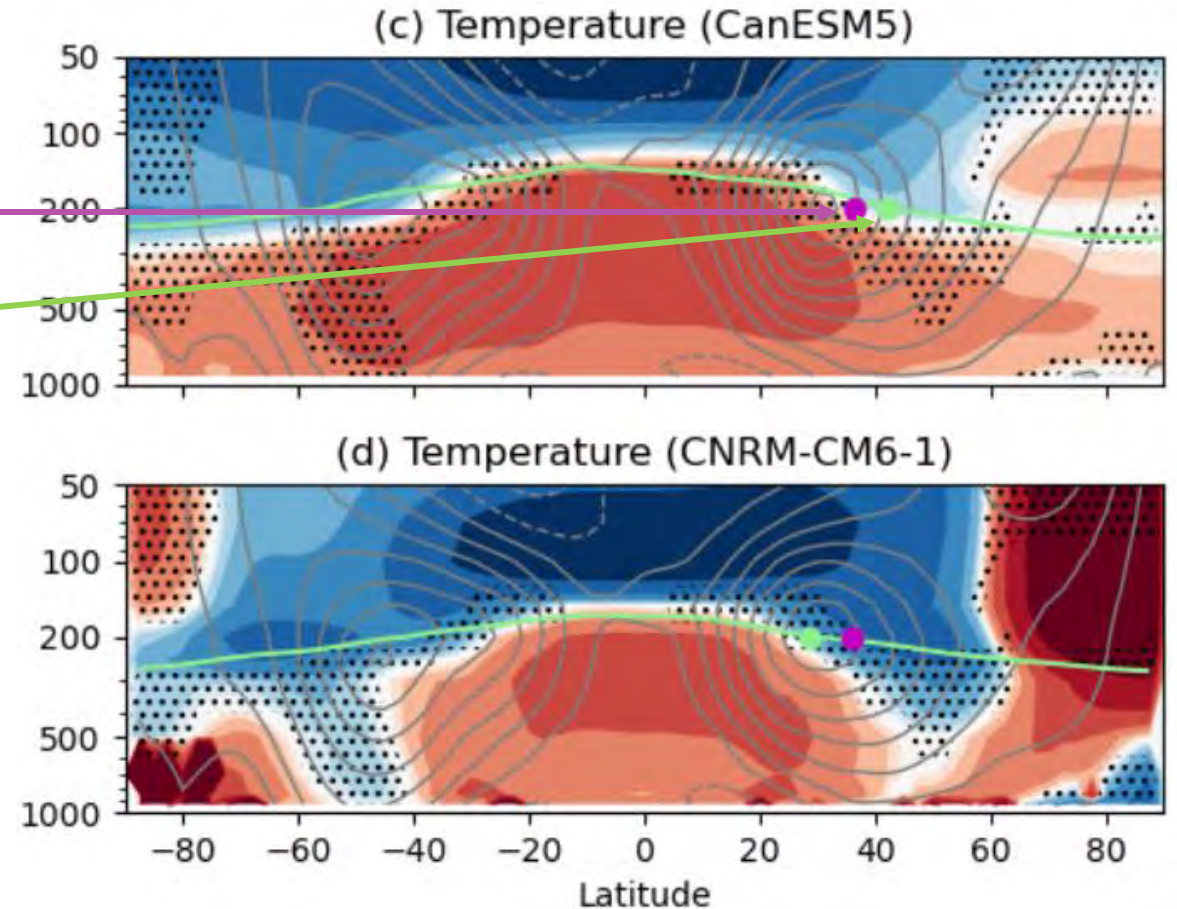
● Magenta dot = jet centroid at 200 hPa

● Green dot = hygropause latitude at 200 hPa (diagnosed by water vapour contour)

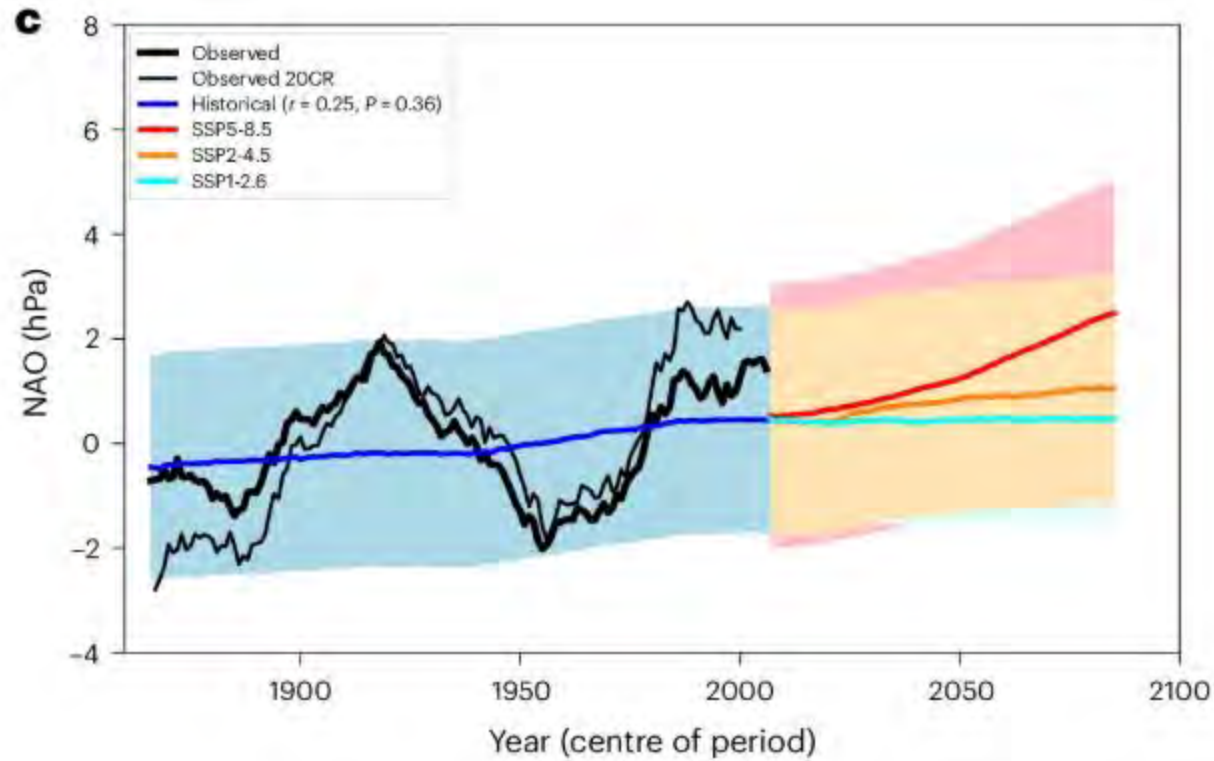
CanESM5 → hygropause latitude **poleward of jet** → poleward shift

CNRM-CM6-1 → hygropause latitude **equatorward of jet** → equatorward shift

Constraint → hygropause latitude relative to jet



Exploiting model differences

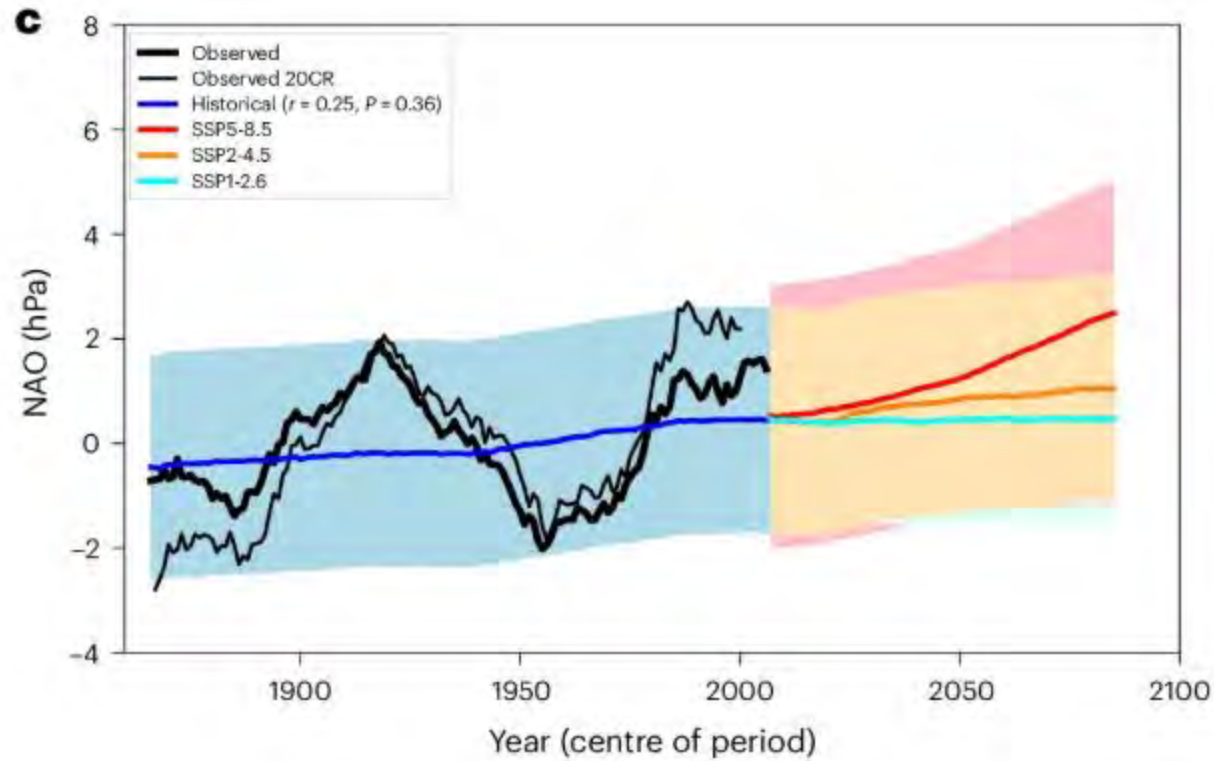


Standard multi-model mean

→ no correlation with obs

→ decadal variability **not** externally forced

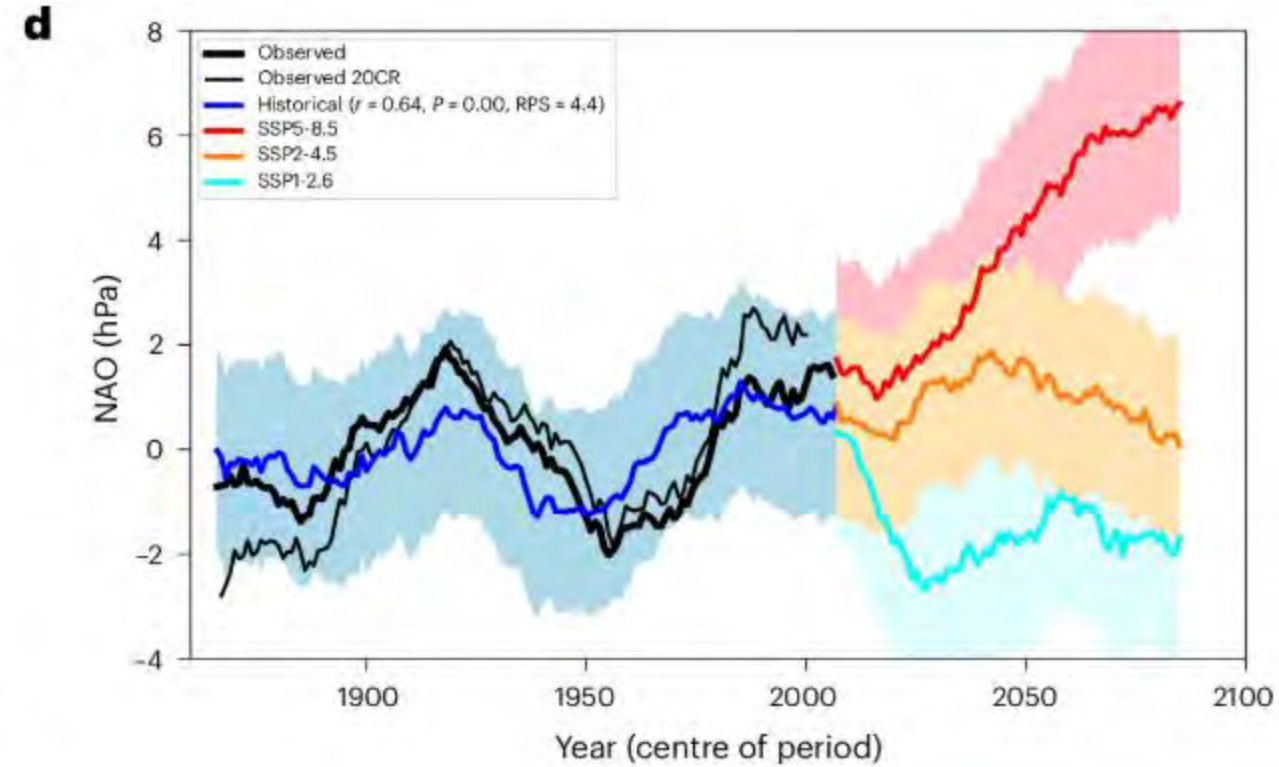
Exploiting model differences



Standard multi-model mean

→ no correlation with obs

→ decadal variability **not externally forced**



Constrained

→ high correlation with obs

→ decadal variability **is externally forced**

But subject to **signal to noise paradox** →
scale by ~4 times

Summary

Wherever decadal predictions of atmospheric circulation are **skilful** the **signals** are **too weak**

- need very large ensembles to extract predictable signals
- need to boost the forecast signal
- also true for long term NAO **projections**

Models show very different (**even opposite!**) responses to the same forcings

– **they can't all be right!**

Accounting for **model differences** and **errors** reveals externally forced NAO variability and projections to **unprecedented** levels

- **missed** if models are taken at face value
- we should not be surprised by this – it would be a **miracle** if models simulated a **perfect** signal to noise ratio!

Not accounting for **model errors** could leave society **unprepared** for impending **extremes**

Extra slides

Explaining model differences

16 hist-nat models (with at least 3 ensemble members)

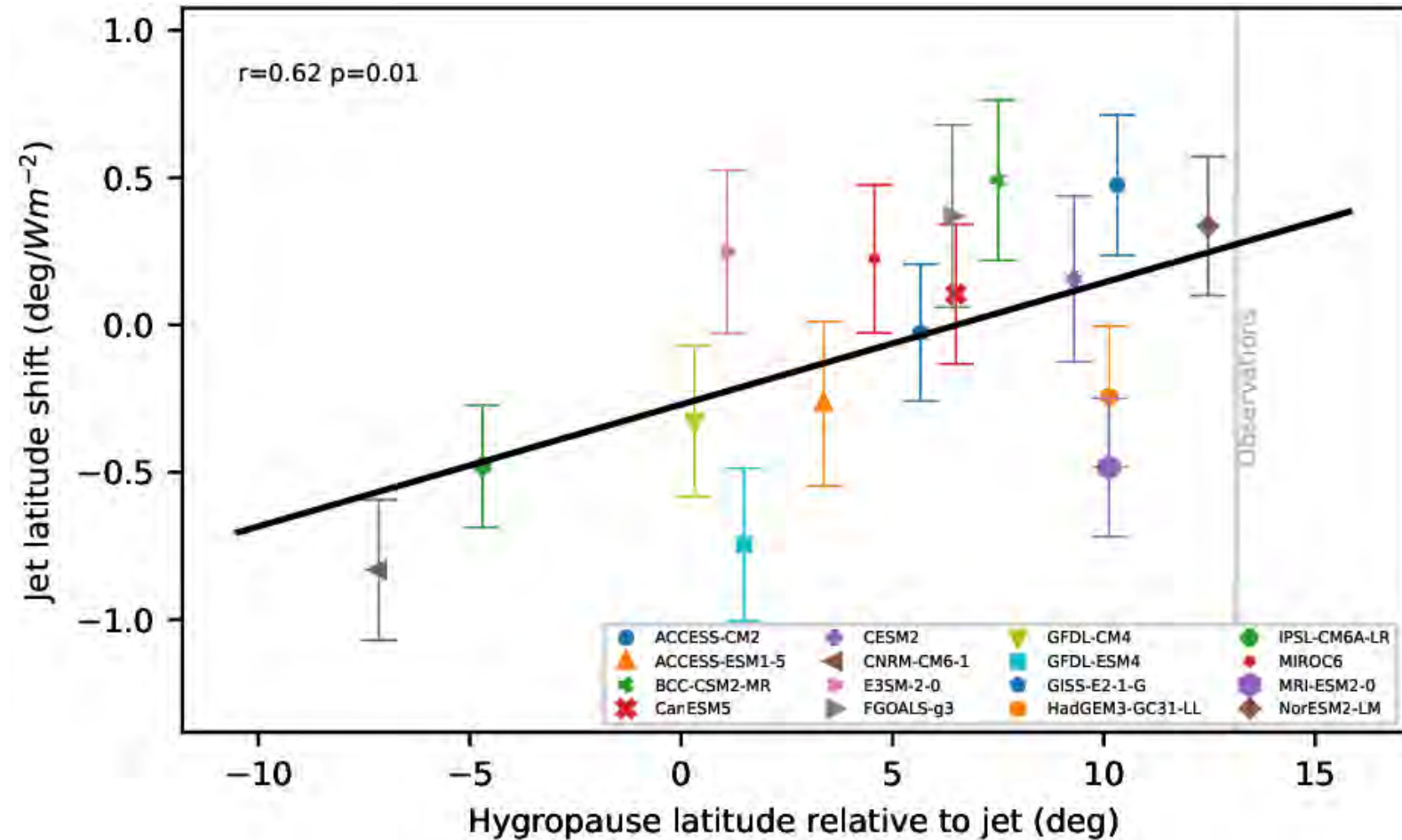
Jet shift at 200 hPa related to EEI

Significant correlation across models with hygropause latitude relative to jet ($r = 0.62$ $p = 0.01$)

Models underestimate hygropause latitude relative to jet

→ real world poleward shift

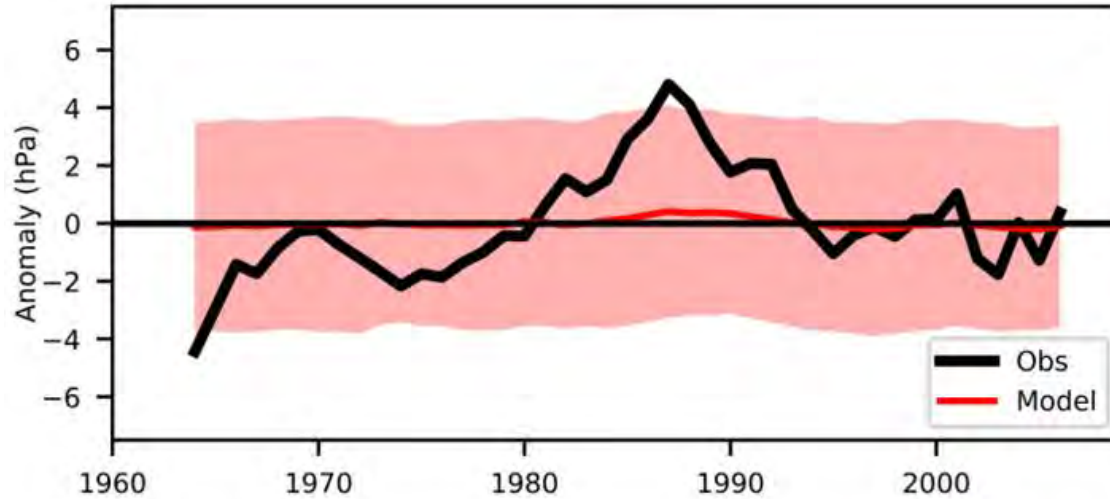
→ greater than models



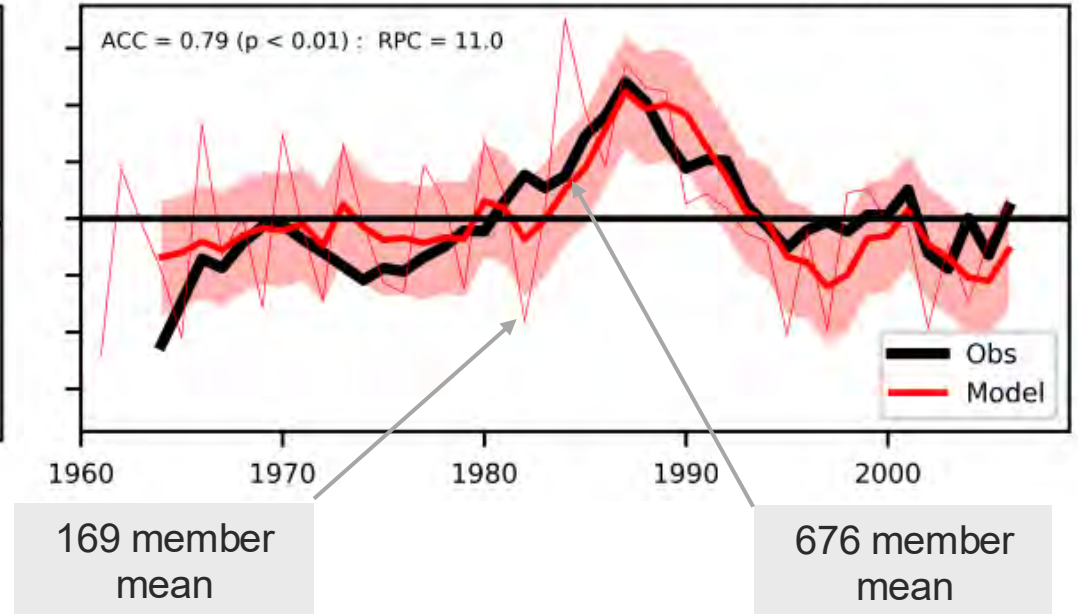
Forecast signal is MUCH too weak

NAO : Forecast years 2 to 9

Raw model output



Variance adjusted

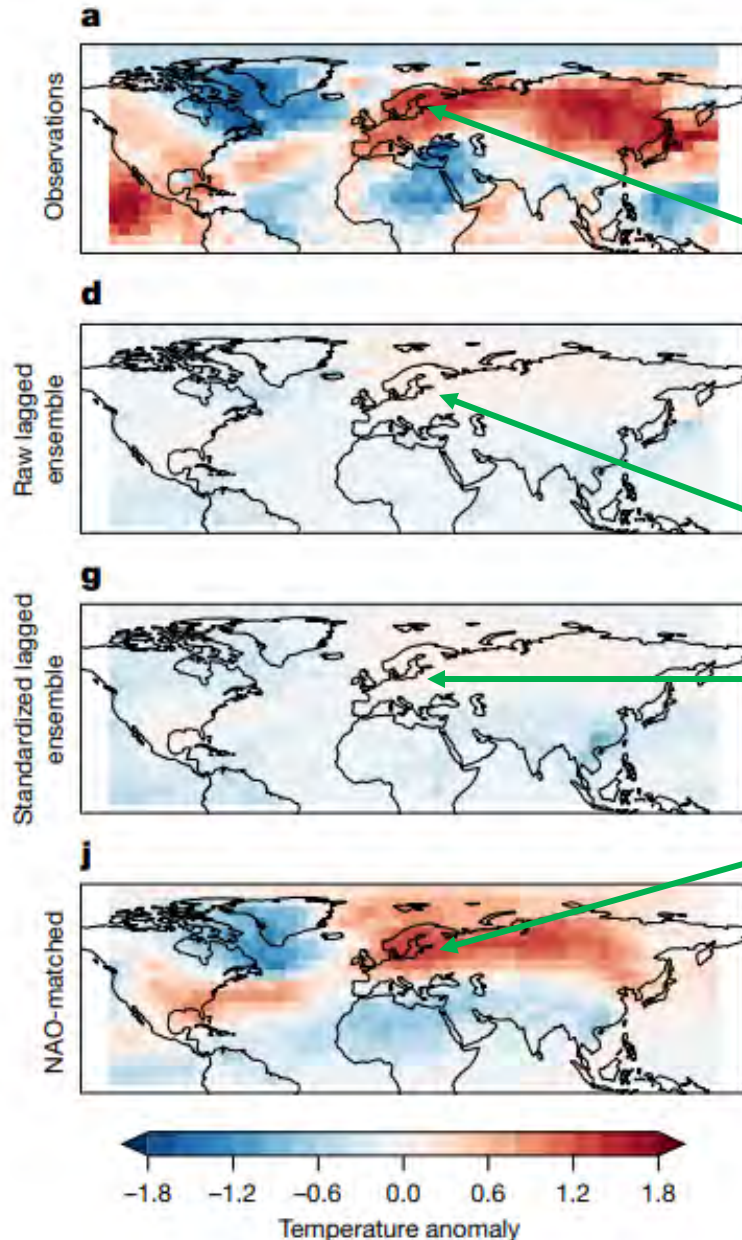
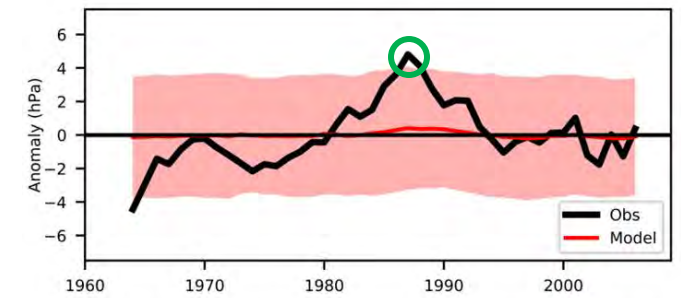


Ratio of predictable components $RPC = 11$

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

Need **100 times** the number of ensemble members to extract the signal

Not overcome by scaling



$$T = T_{\text{DYN}} + T_{\text{THERMO}} + \varepsilon$$

Real world: $T_{\text{DYN}} \gg T_{\text{THERMO}}$

Ensemble mean: $T_{\text{DYN}} \ll T_{\text{THERMO}}$ because NAO signal too small

Scaling retains the incorrect ratio $T_{\text{DYN}}/T_{\text{THERMO}}$

Can be overcome by selecting ensemble members with correct magnitude of NAO

Standard D&A approach will not work
Need to look at models in new ways

Mechanism

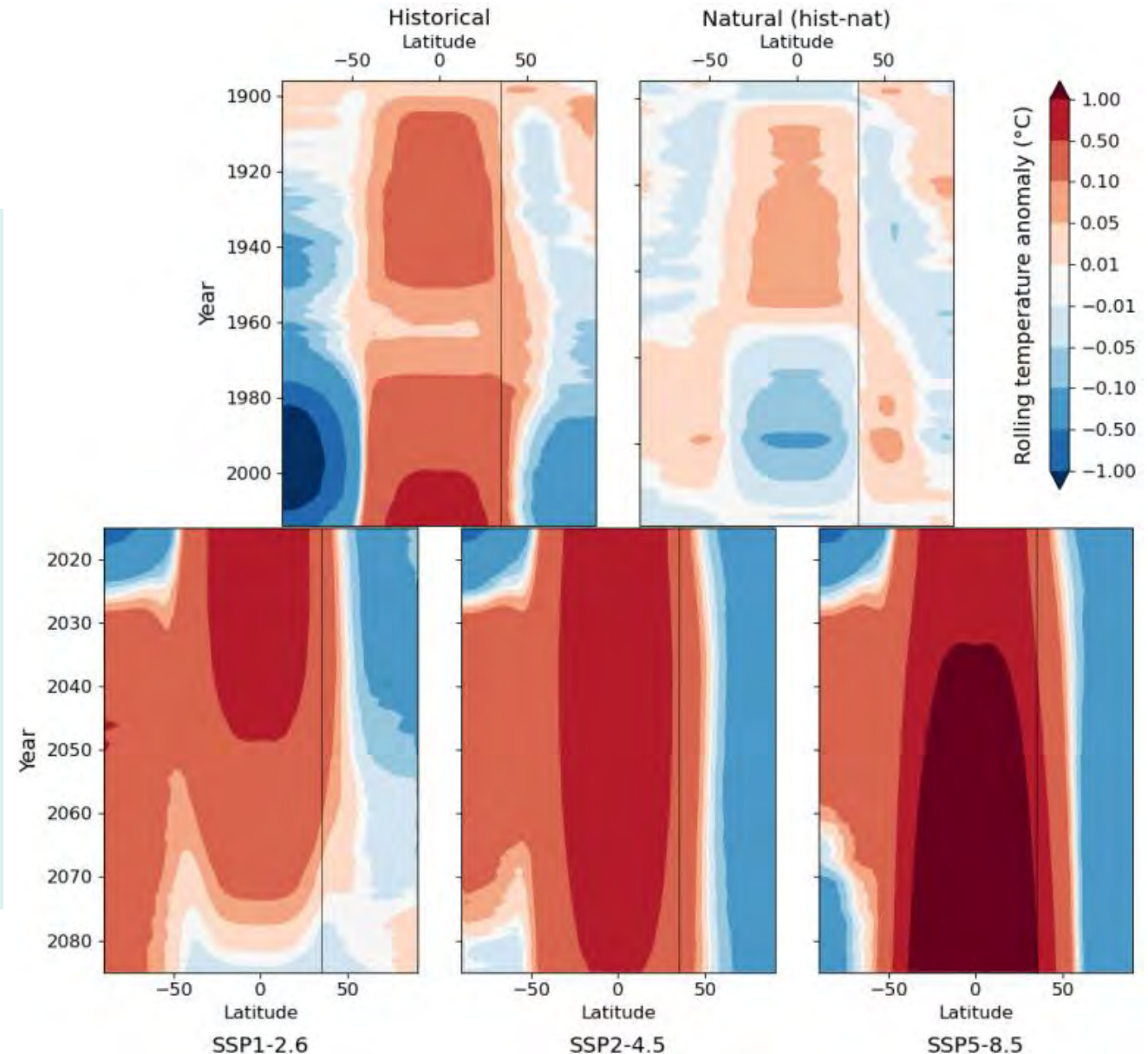
Hovmuller plots of rolling temperature at 200hPa anomalies from preceding 30-year mean (multi-model mean)

Tropical cooling following volcanic eruptions
→ minimum ~1990 (Agung+El Chichon+Pinatubo)

Greenhouse gas warming
→ minimum ~1960

$\frac{\partial \bar{T}}{\partial \phi}$ at jet latitude (35N) increases under SSP5-8.5

But reduces with mitigation



Models can have opposite responses!!

NAO response to natural forcings (solar + volcanic)

31-year rolling means

50 members CanESM5

10 members CNRM-CM6-1

→ potential role for solar and volcanic forcings?

BUT opposite responses :

CanESM5 $r = 0.67$ $p < 0.01$

CNRM-CM6-1 $r = -0.48$ $p < 0.01$

