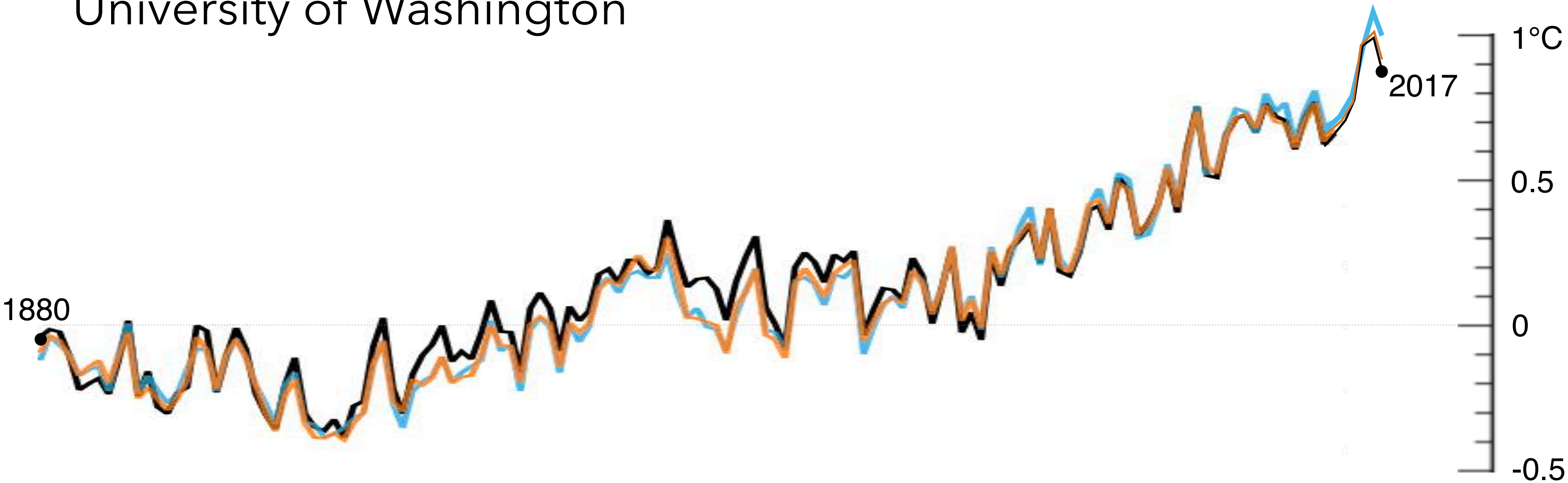
Separating climate variability and climate change:

How many ensemble members are needed?

Robert C. Jnglin Wills

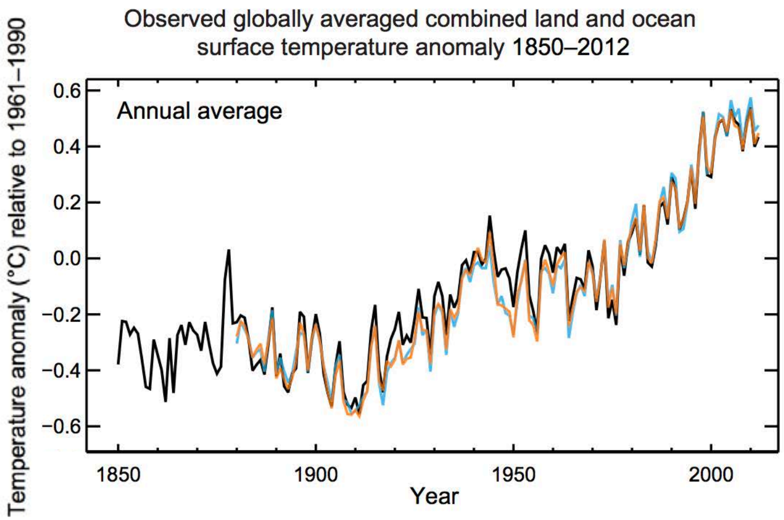
University of Washington



Tapio Schneider, David Battisti, Kyle Armour

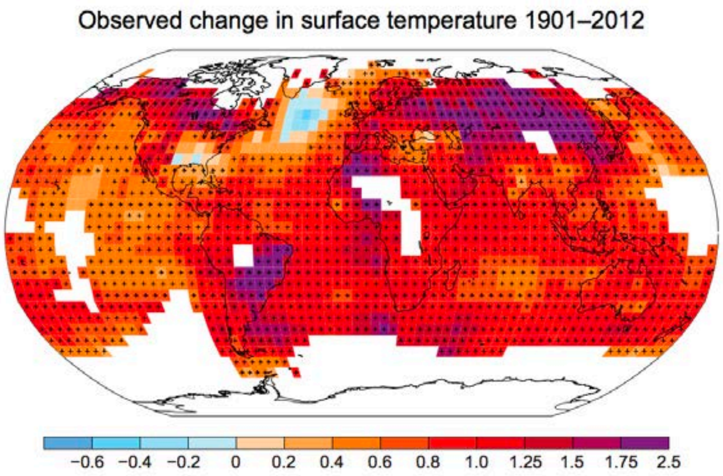
The Large Ensembles Workshop – July 25, 2019

Canonical methods for identifying the climate response to external (e.g., anthropogenic) forcing



Spatial (e.g. global) average:

- Loses spatial information
- Which regions are responsible for the changes in the rate of global warming?

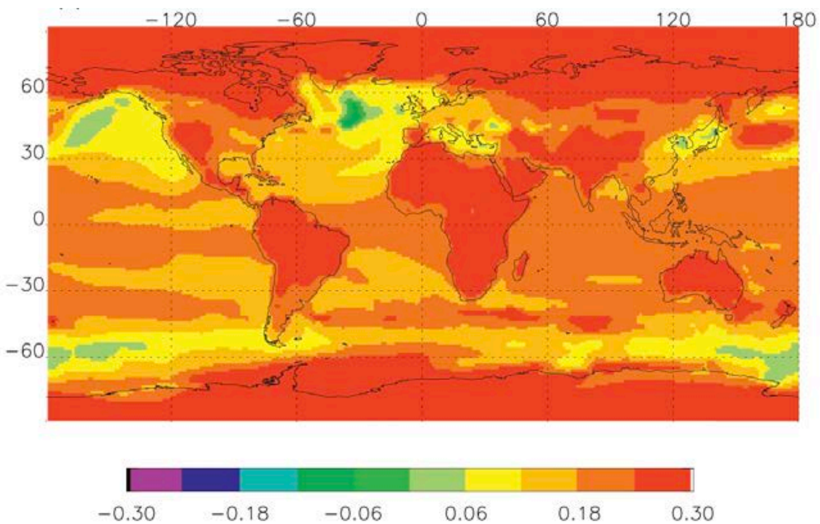


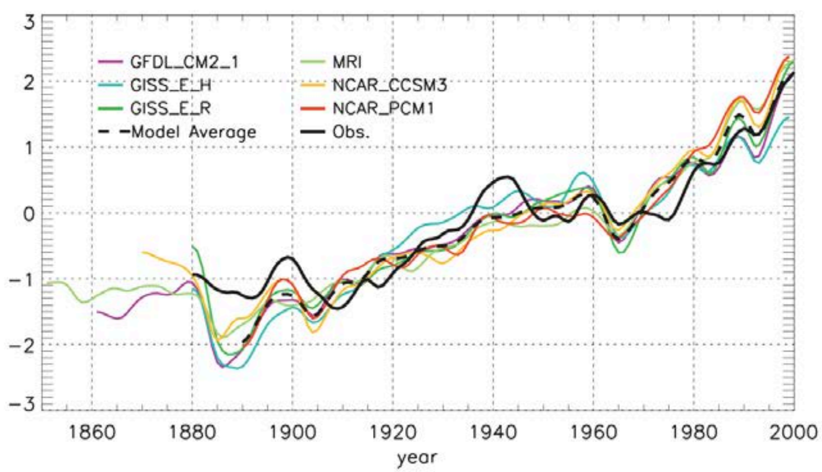
Local linear trend:

- Loses temporal information
- What are the relative timings of warming in different regions?

IPCC AR5 – Figure SPM.1

Signal-to-noise maximizing EOF analysis





- Find temperature pattern (linear combination of EOFs) with the highest ratio of climate **signal** (ensemble members agree on timing of change) to **noise** (ensemble members don't agree)

- Ting et al. 2009 applied this method to CMIP3 models with multiple ensemble members each, but it is also useful for a single-model large ensemble

Ting et al. 2009

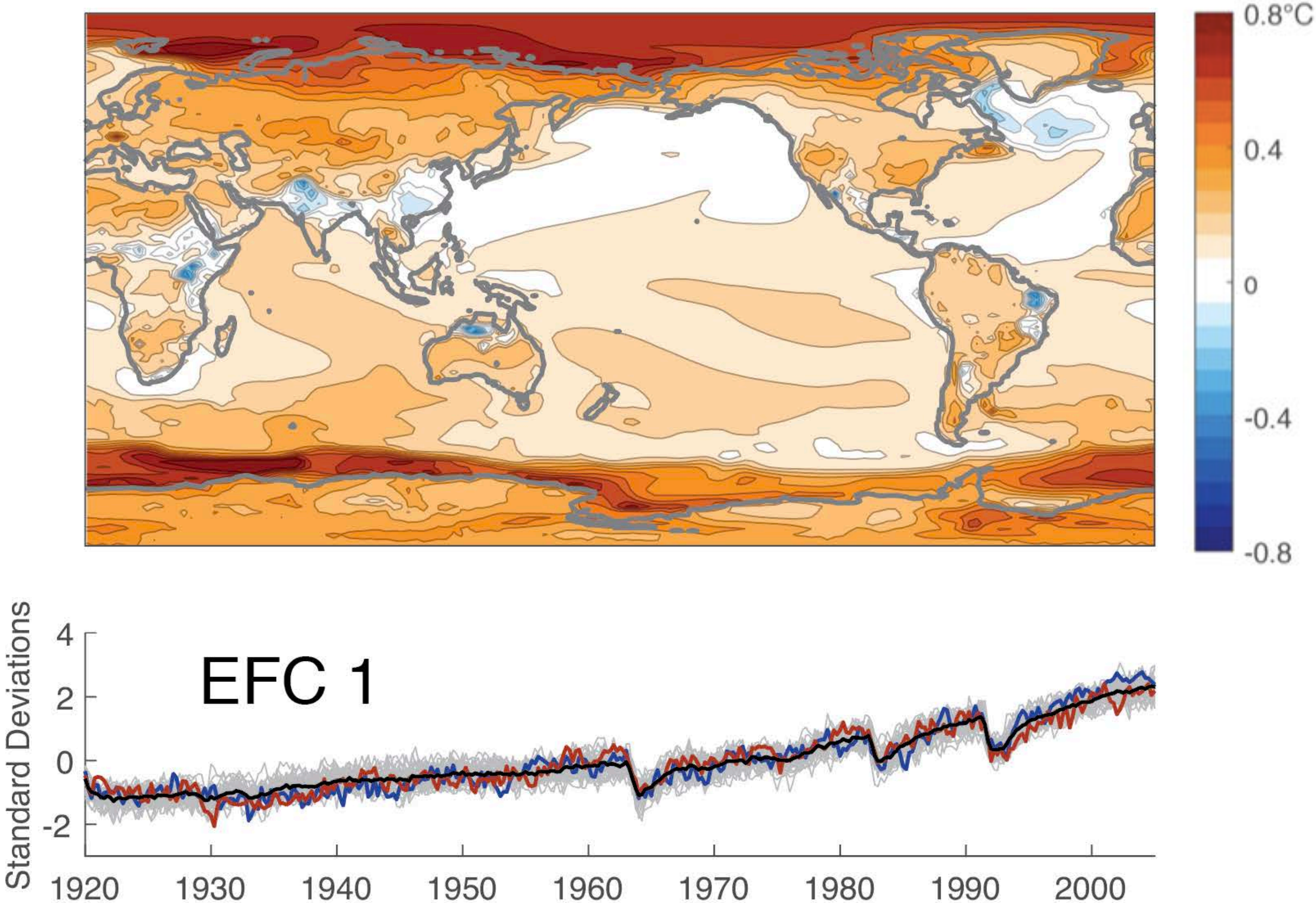
Signal-to-noise maximizing EOF analysis of CESM Large Ensemble

1. CESM1 40-member historical ensemble
   (3-month average temperature anomalies, 1920-2005)

2. Find temperature patterns for which ensemble members have the maximum agreement on the temporal evolution (***externally forced patterns***)

3. Requires ensemble of simulations (a drawback I will return to)

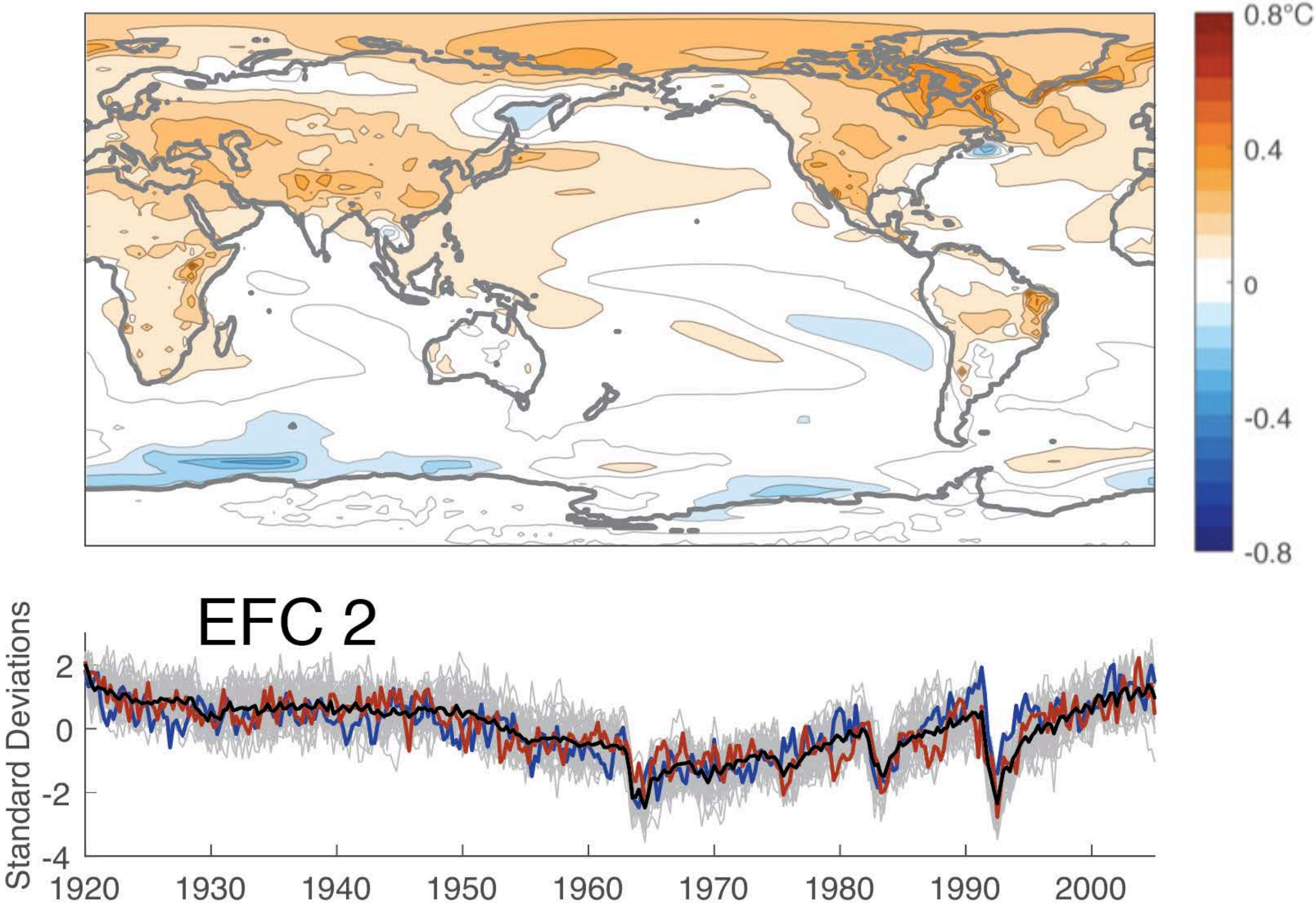
1st externally forced pattern



150 EOFs included

Wills et al., in prep. – Analysis of CESM Large Ensemble

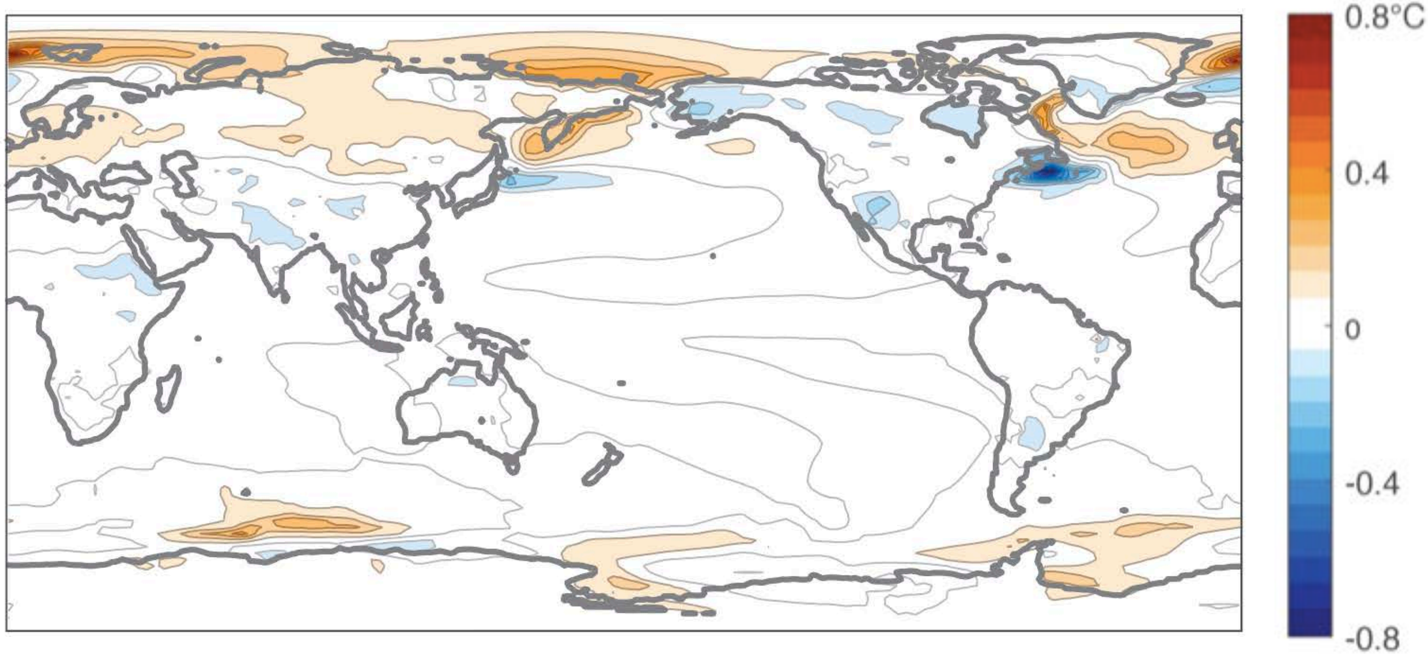
2nd externally forced pattern

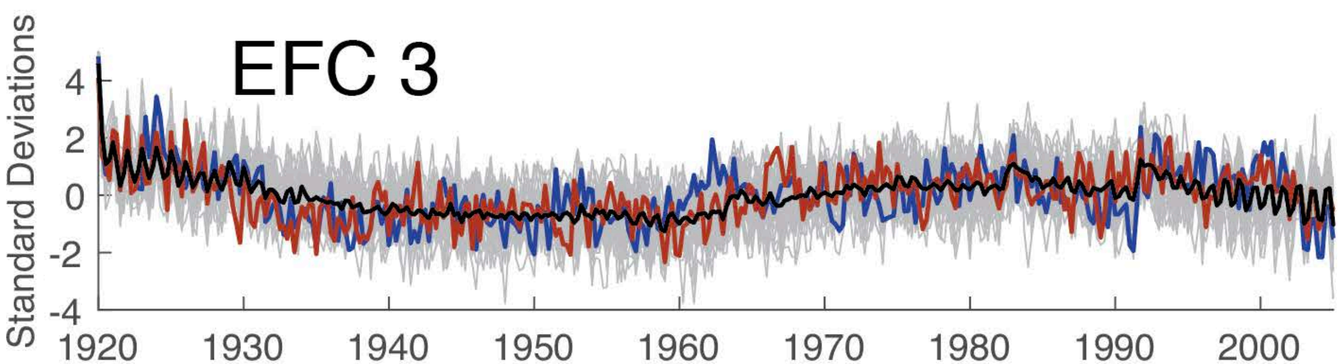


150 EOFs included

Wills et al., in prep. – Analysis of CESM Large Ensemble

3rd externally forced pattern

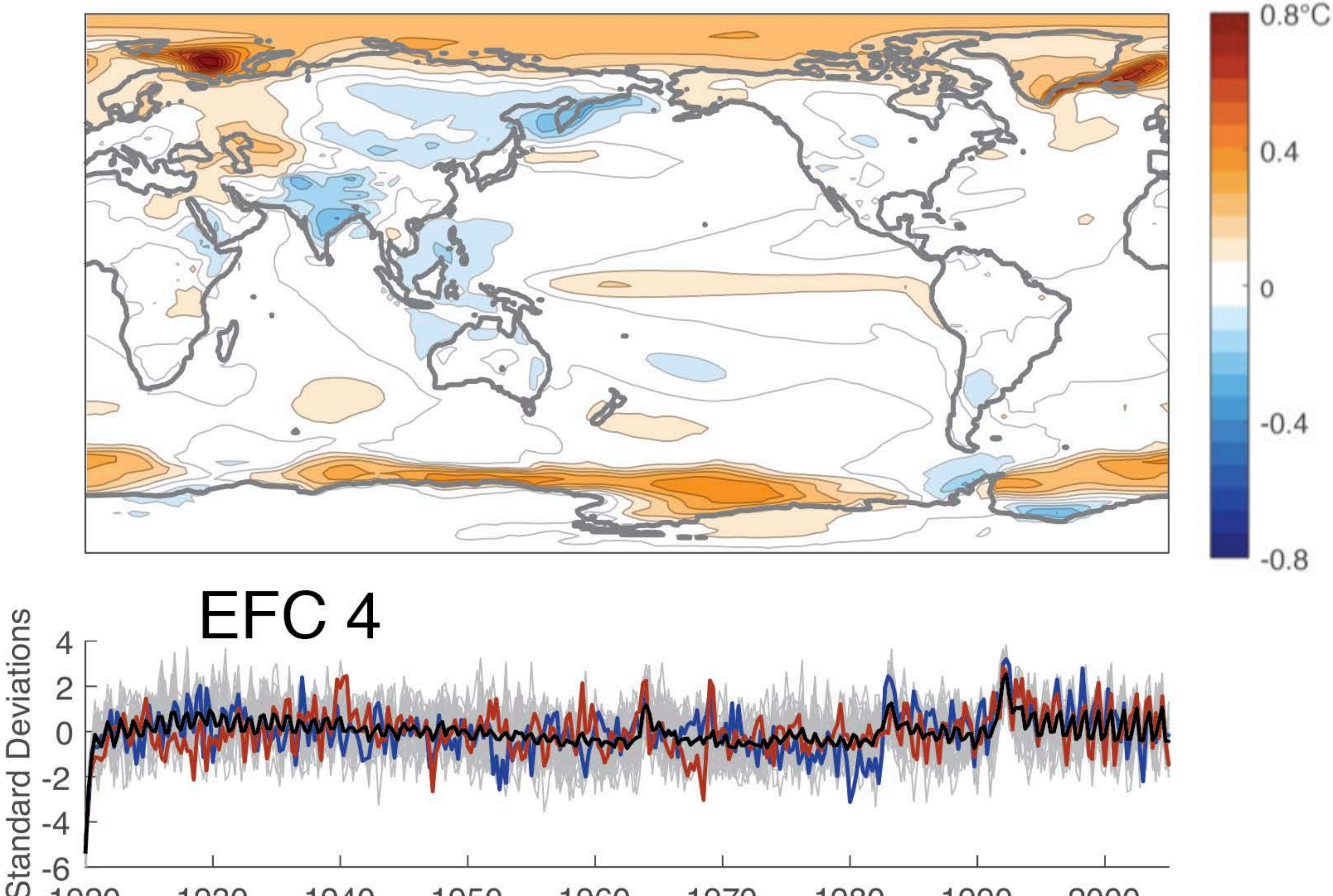




150 EOFs included

Wills et al., in prep. – Analysis of CESM Large Ensemble

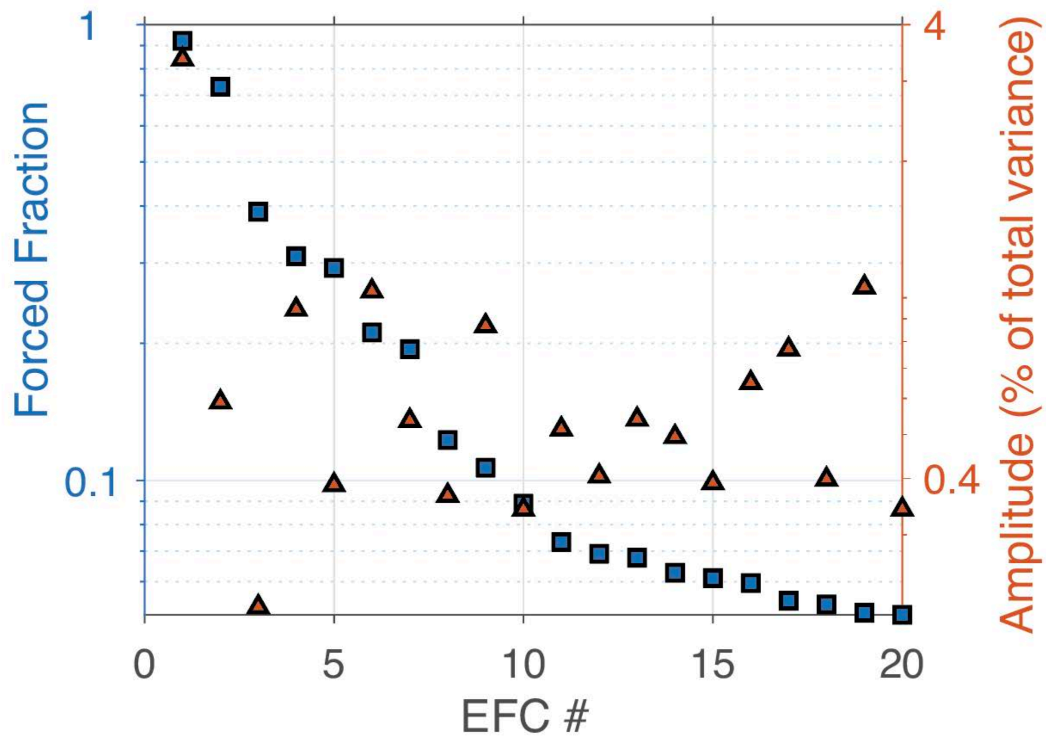
4^{th} externally forced pattern



150 EOFs included

Wills et al., in prep. – Analysis of CESM Large Ensemble

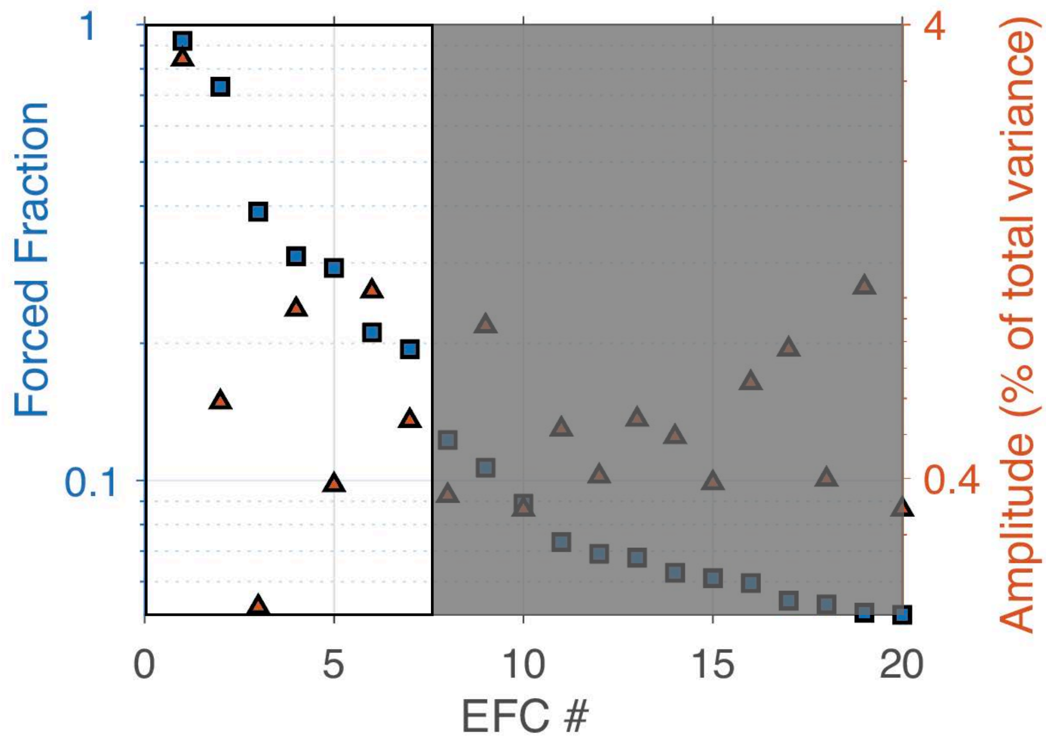
How many patterns constitute forced response?



- Note eigenvalue reductions after EFCs 2, 5, 7, and 10

Wills et al., in prep. – Analysis of CESM Large Ensemble

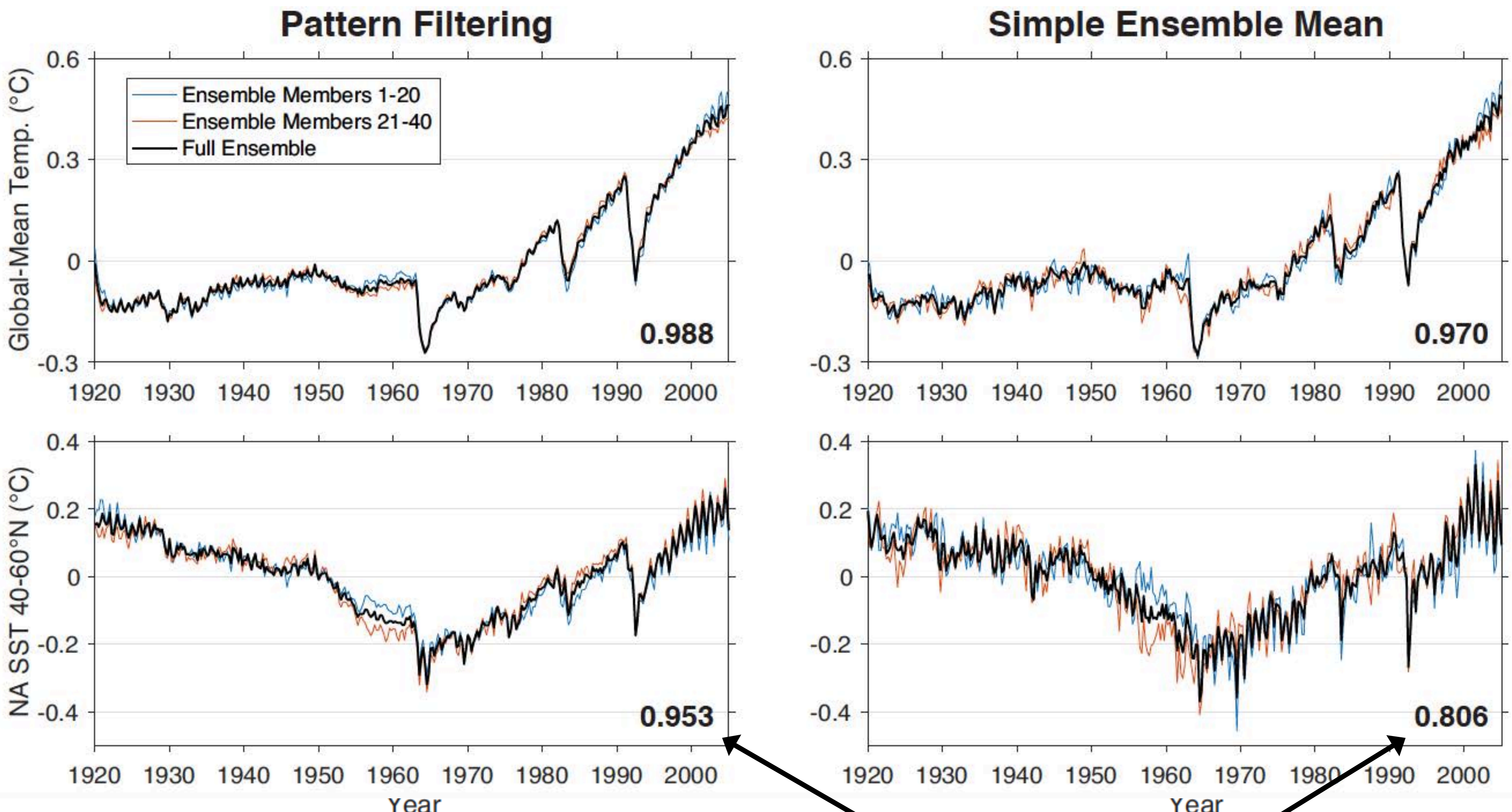
How many patterns constitute forced response?



- Note eigenvalue reductions after EFCs 2, 5, 7, and 10
- **Pattern Filtering:** Keep only variance associated with leading forced patterns (7 in this case)

Wills et al., in prep. – Analysis of CESM Large Ensemble

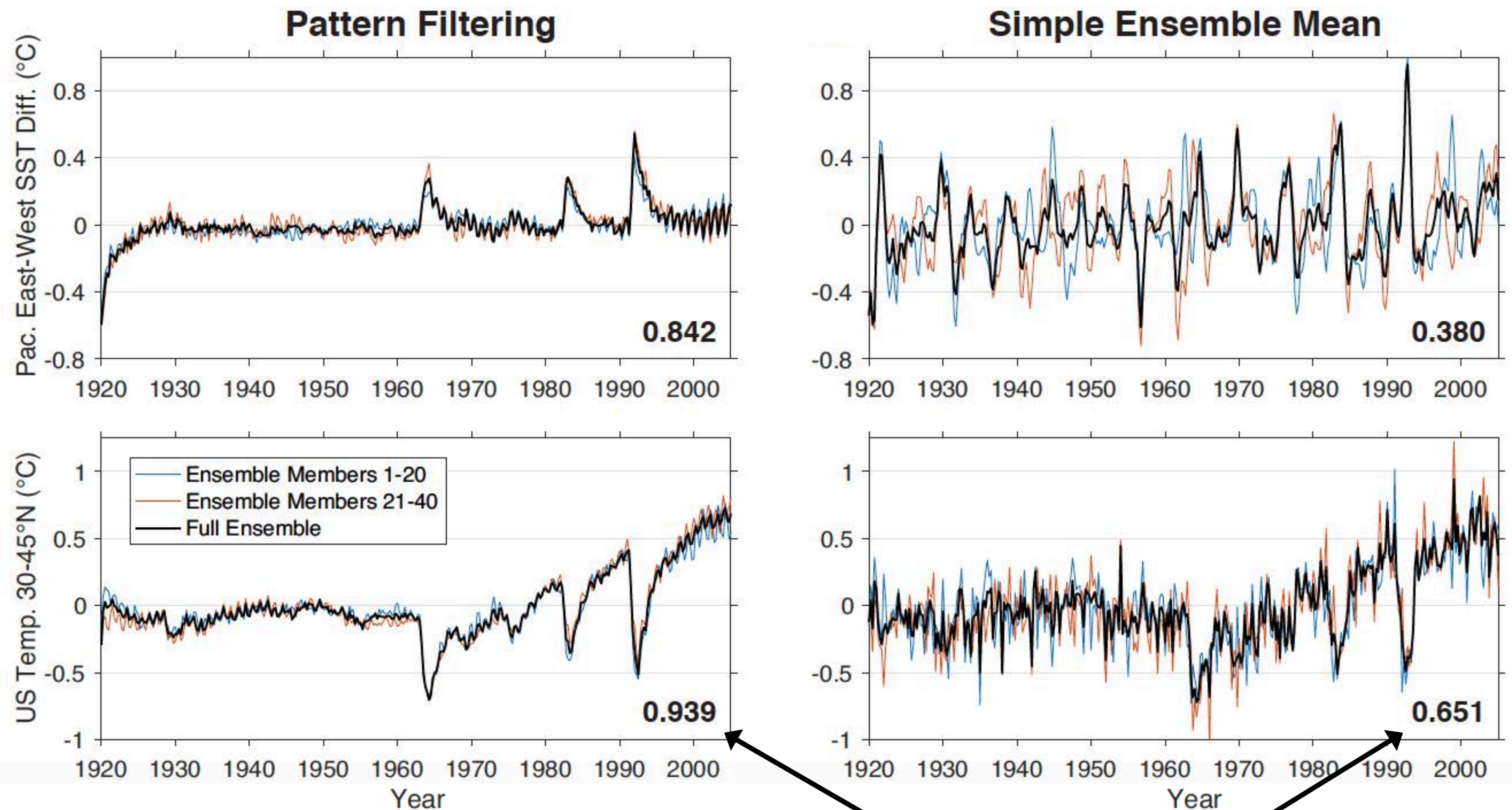
Comparison of 20-member half ensembles



Correlation between half ensembles

Wills et al., in prep. – Analysis of CESM Large Ensemble

Comparison of 20-member half ensembles

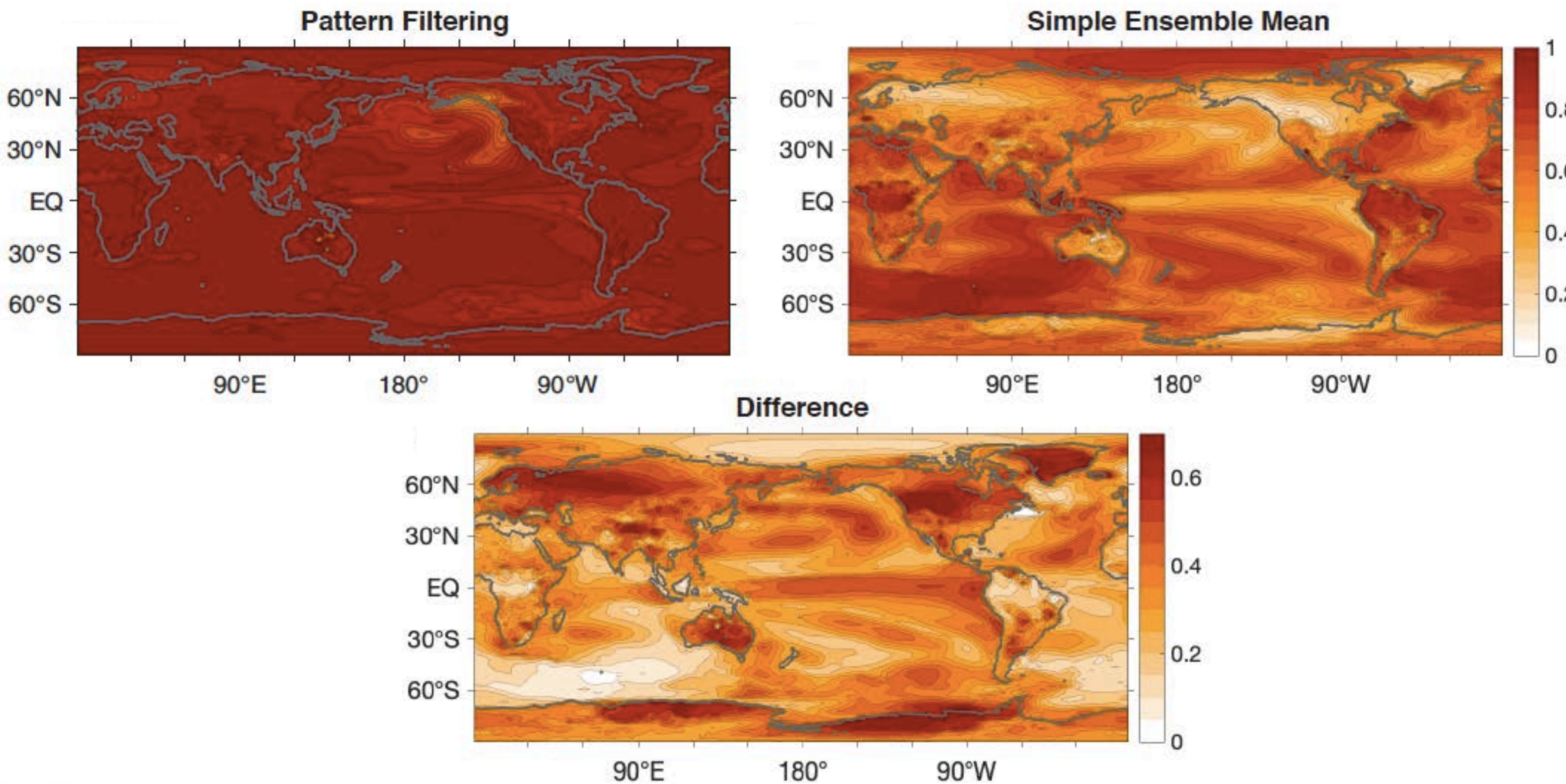


Correlation between half ensembles

Wills et al., in prep. – Analysis of CESM Large Ensemble

Comparison of 20-member half ensembles

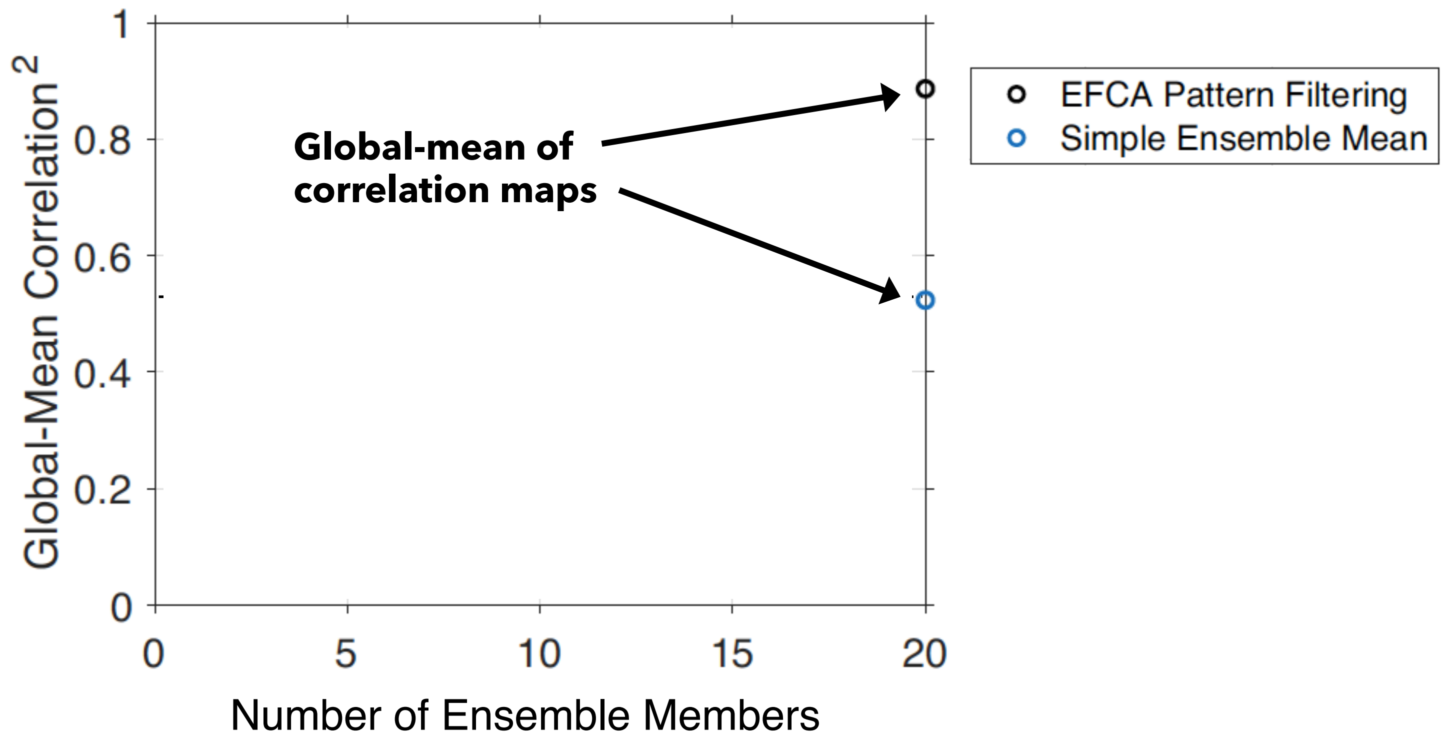
Grid-point correlation between halves of large ensemble



Wills et al., in prep. – Analysis of CESM Large Ensemble

How many ensemble members are needed?

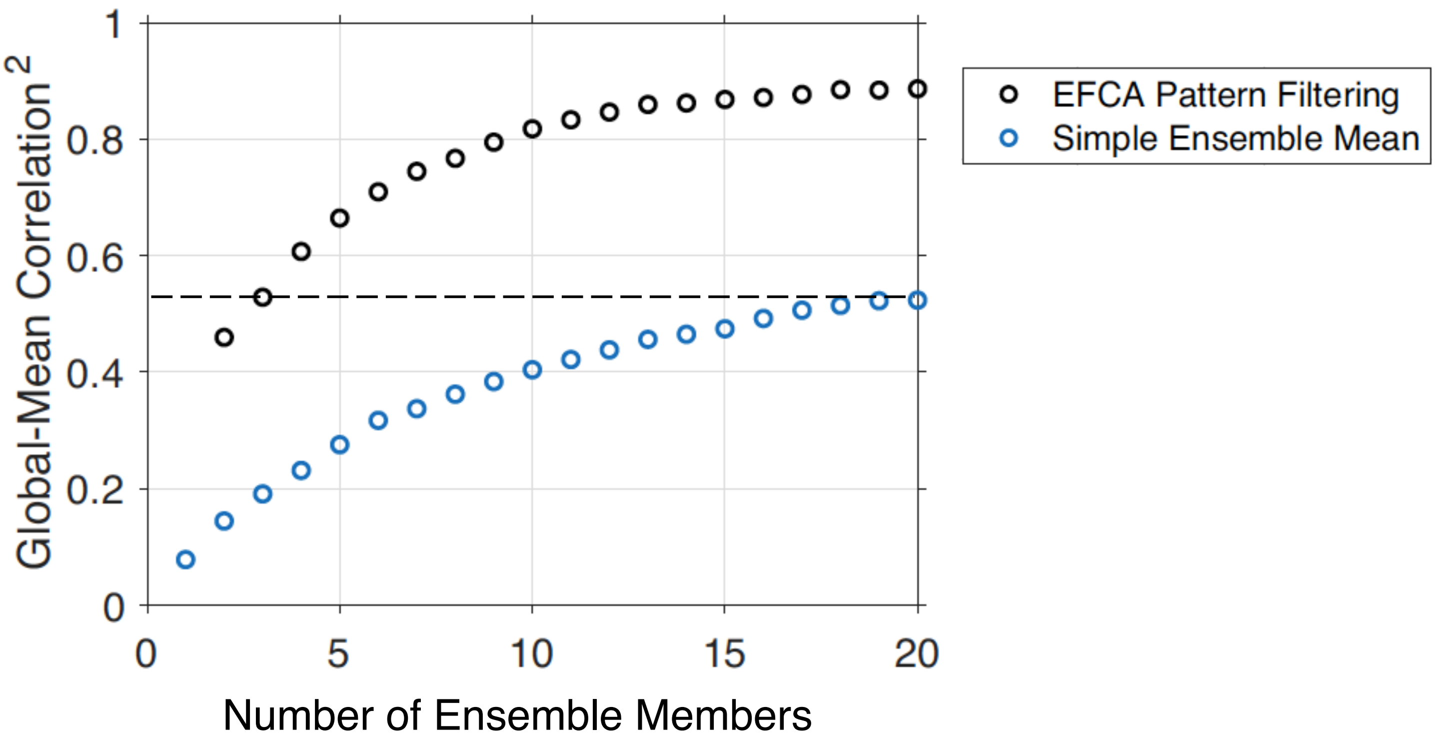
Global-mean of grid-point correlation^2 with opposite 20-member half ensemble (pattern filtered)



Wills et al., in prep. – Analysis of CESM Large Ensemble

How many ensemble members are needed?

Global-mean of grid-point correlation^2 with opposite 20-member half ensemble (pattern filtered)



- **Pattern filtering can extract the forced response with ~7 times fewer ensemble members than simple mean!**

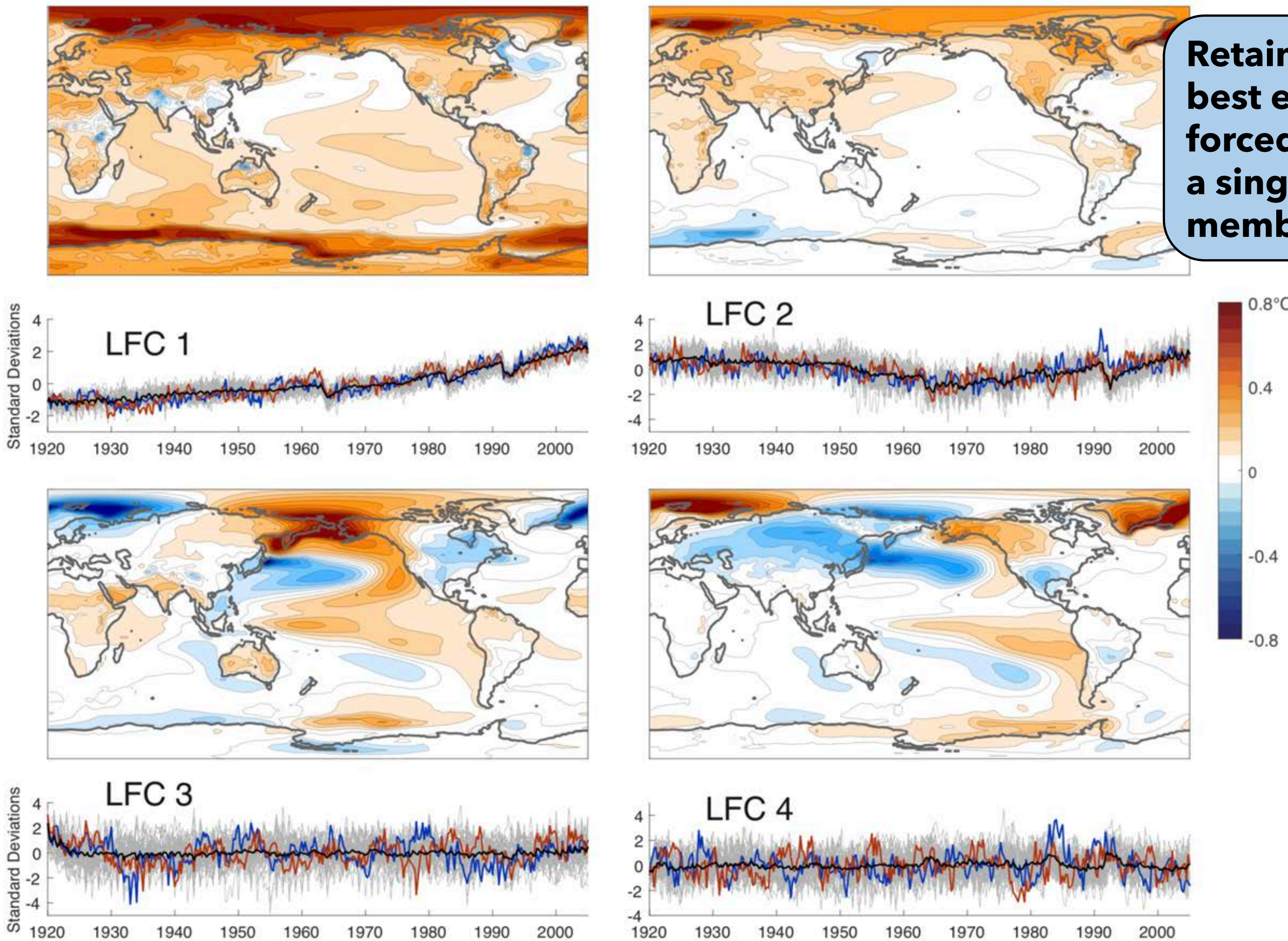
Wills et al., in prep. – Analysis of CESM Large Ensemble

What can we do with a single ensemble member?

1. Forced climate responses differs in time scale from most internal variability

2. Instead find temperature patterns with the maximum ratio of low-frequency (decadal) to high-frequency variance
   - **Low-frequency component analysis** (LFCA, *Wills et al. 2018*)
   - Initially suggested by *Schneider & Held (2001)* as a means to isolate forced response in observations
   - Used recently to identify patterns and mechanisms of decadal variability in the Pacific (*Wills et al. 2018, 2019, GRL*) and Atlantic (*Wills et al. 2019, J. Climate*)

Low-frequency components of CESM-LE

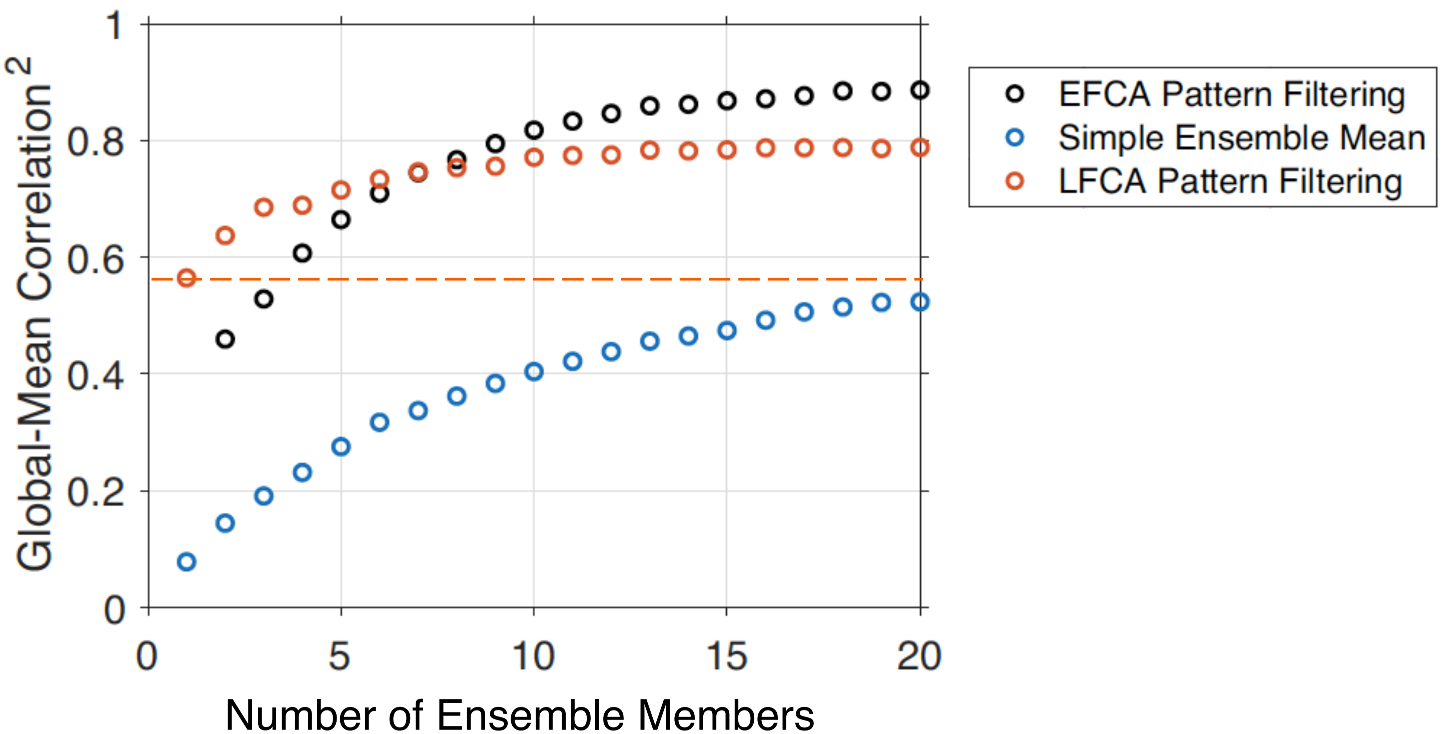


Retain 2 LFCs as best estimate of forced response in a single ensemble member

Wills et al., in prep. – Analysis of CESM Large Ensemble

How many ensemble members are needed?

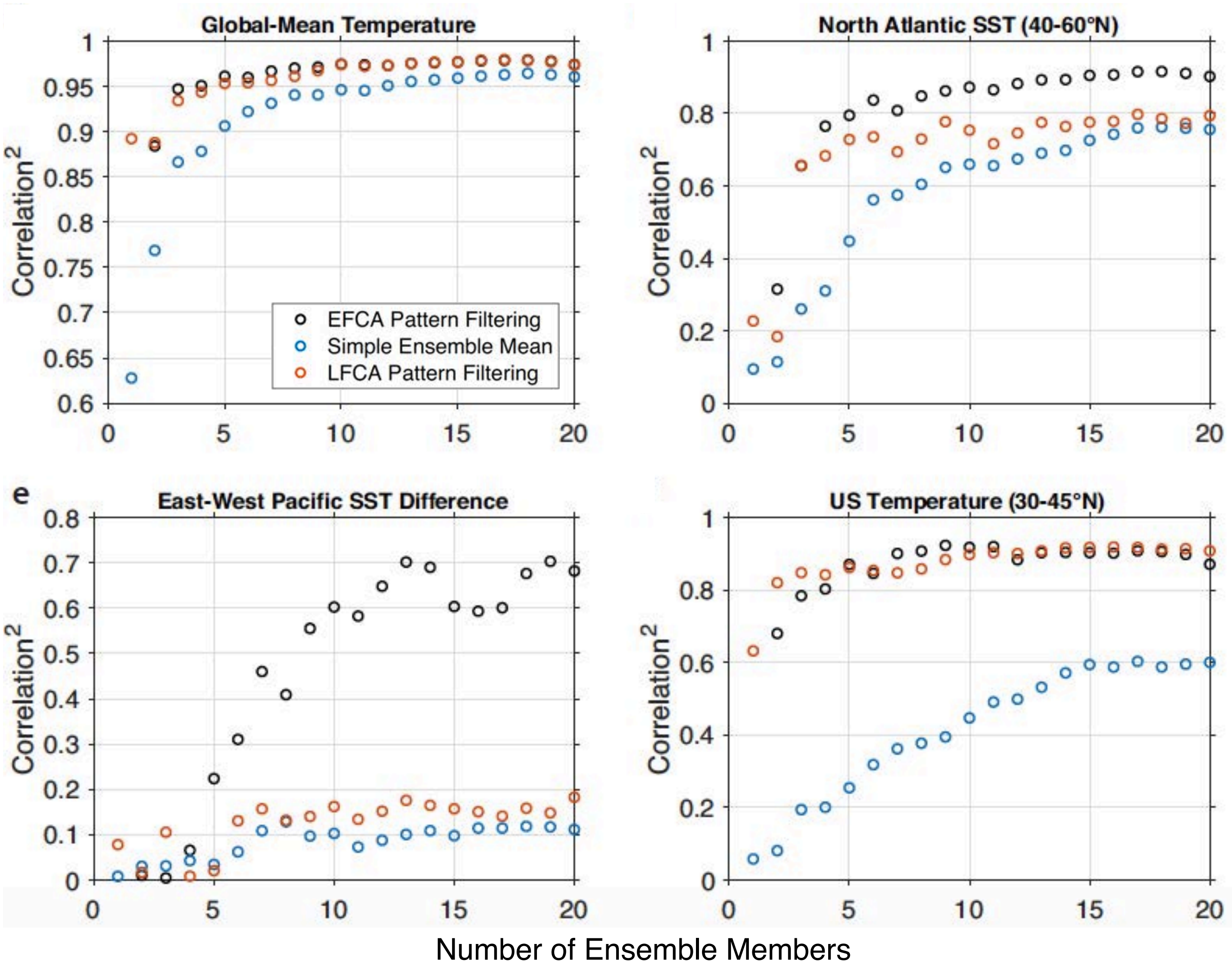
Global-mean of grid-point correlation^2 with opposite 20-member half ensemble (pattern filtered)



- **LFCA of a single ensemble member identifies forced response better than 20-member ensemble mean!**

Wills et al., in prep. – Analysis of CESM Large Ensemble

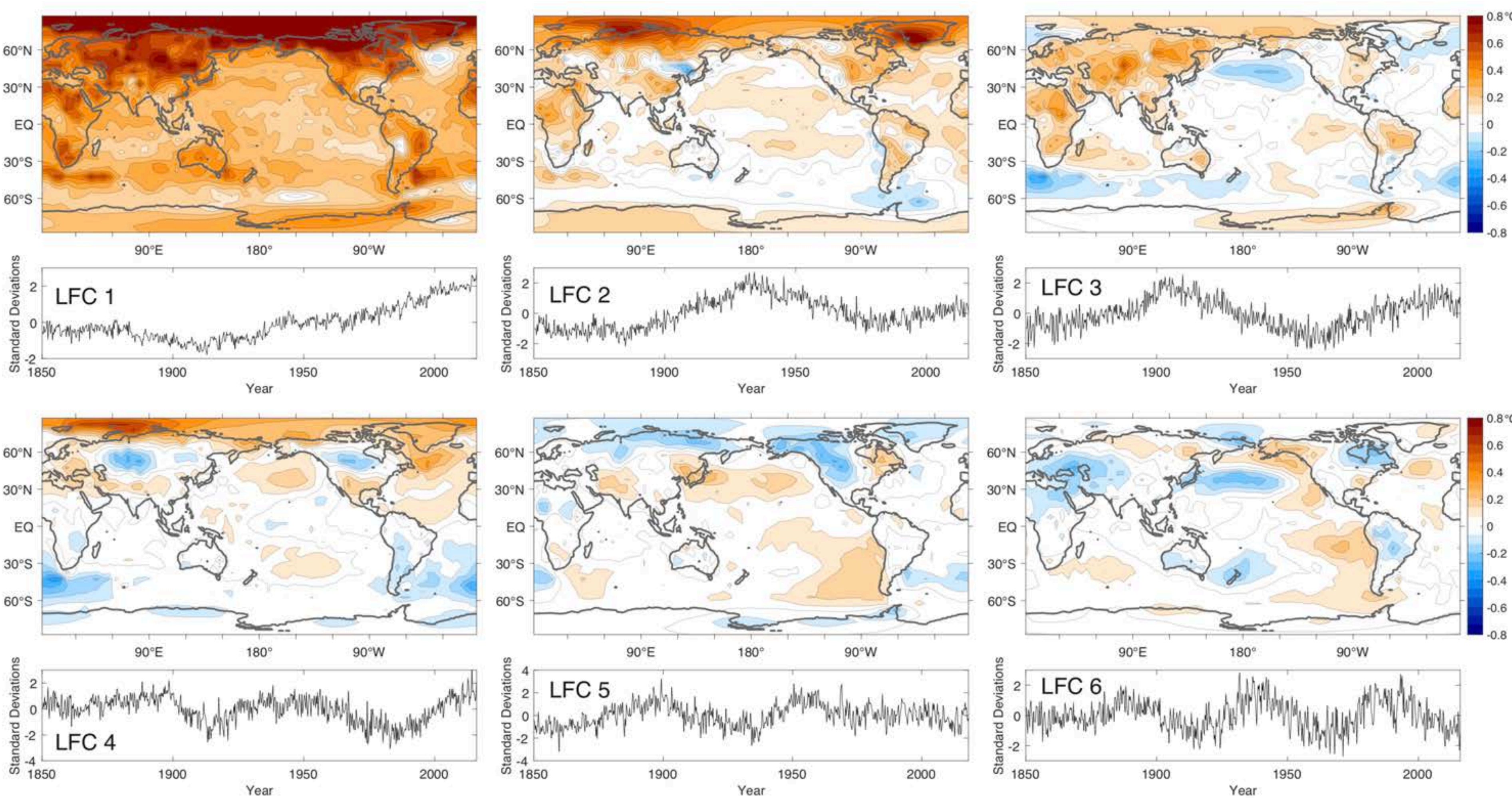
Comparison between pattern filtering and simple ensemble mean for large-scale averages



Wills et al., in prep. – Analysis of CESM Large Ensemble

LFCA of HadCRUT4 Observations

Choosing which patterns are forced becomes much more problematic in observations

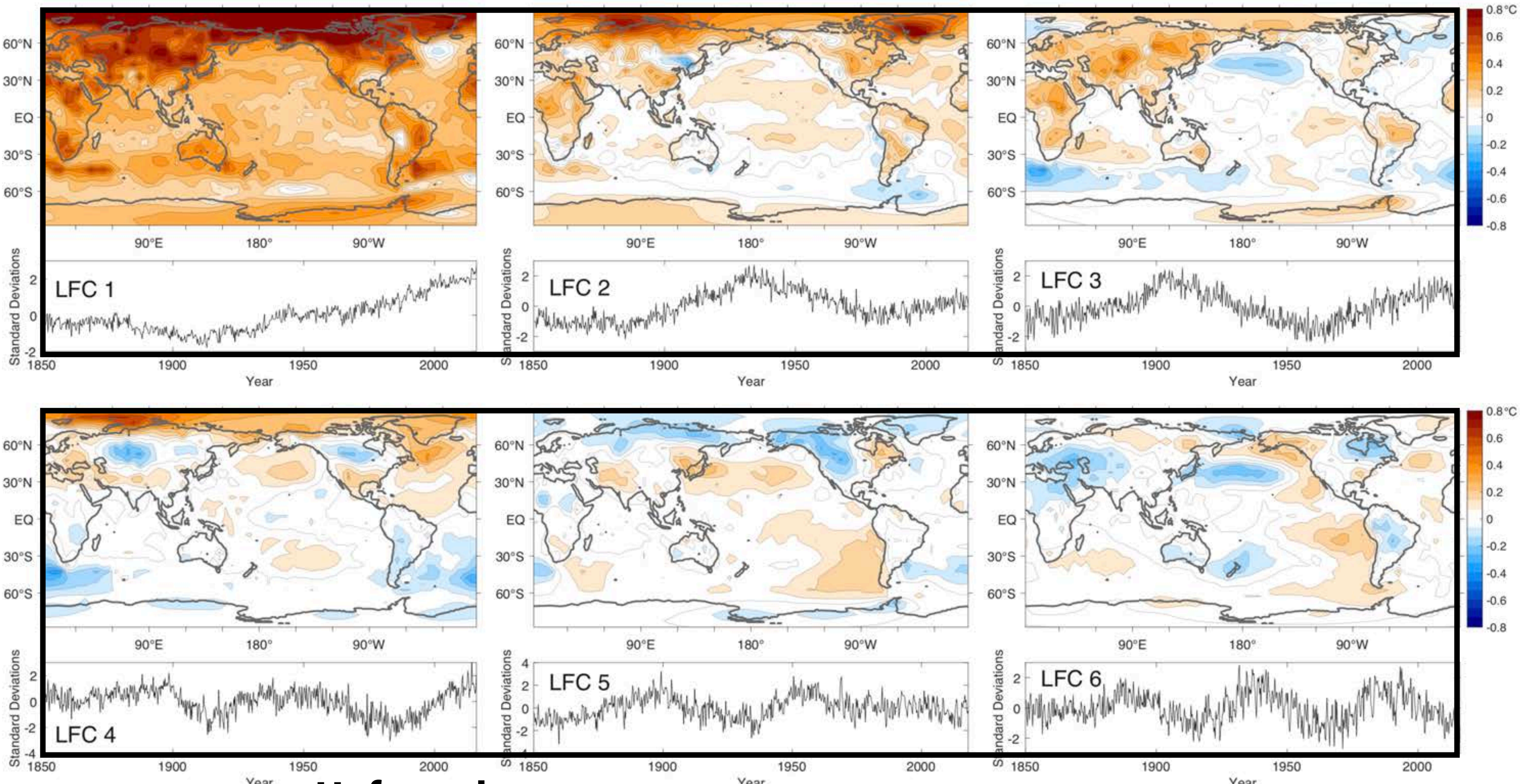


Wills et al., in prep. – Analysis of HadCRUT4

LFCA of HadCRUT4 Observations

Choosing which patterns are forced becomes much more problematic in observations

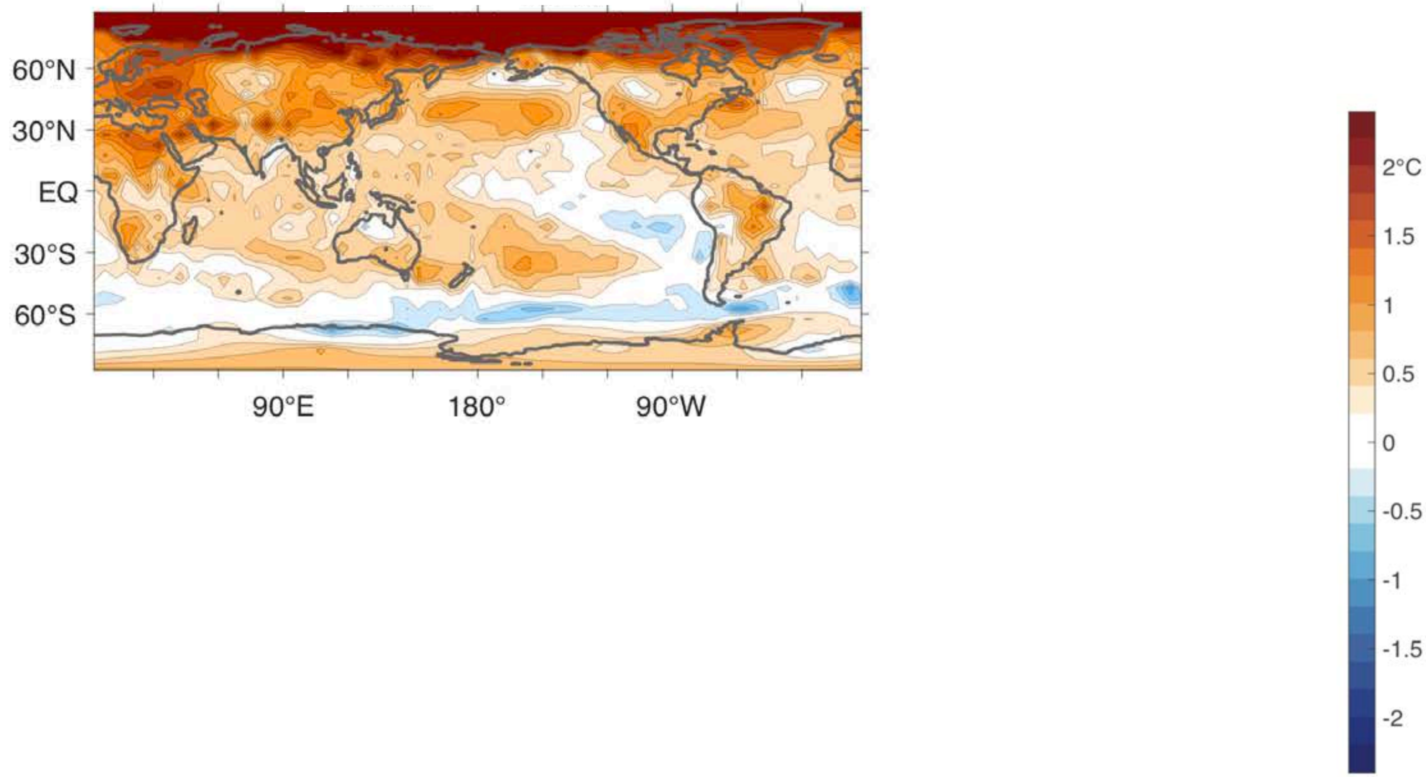
Forced



Unforced

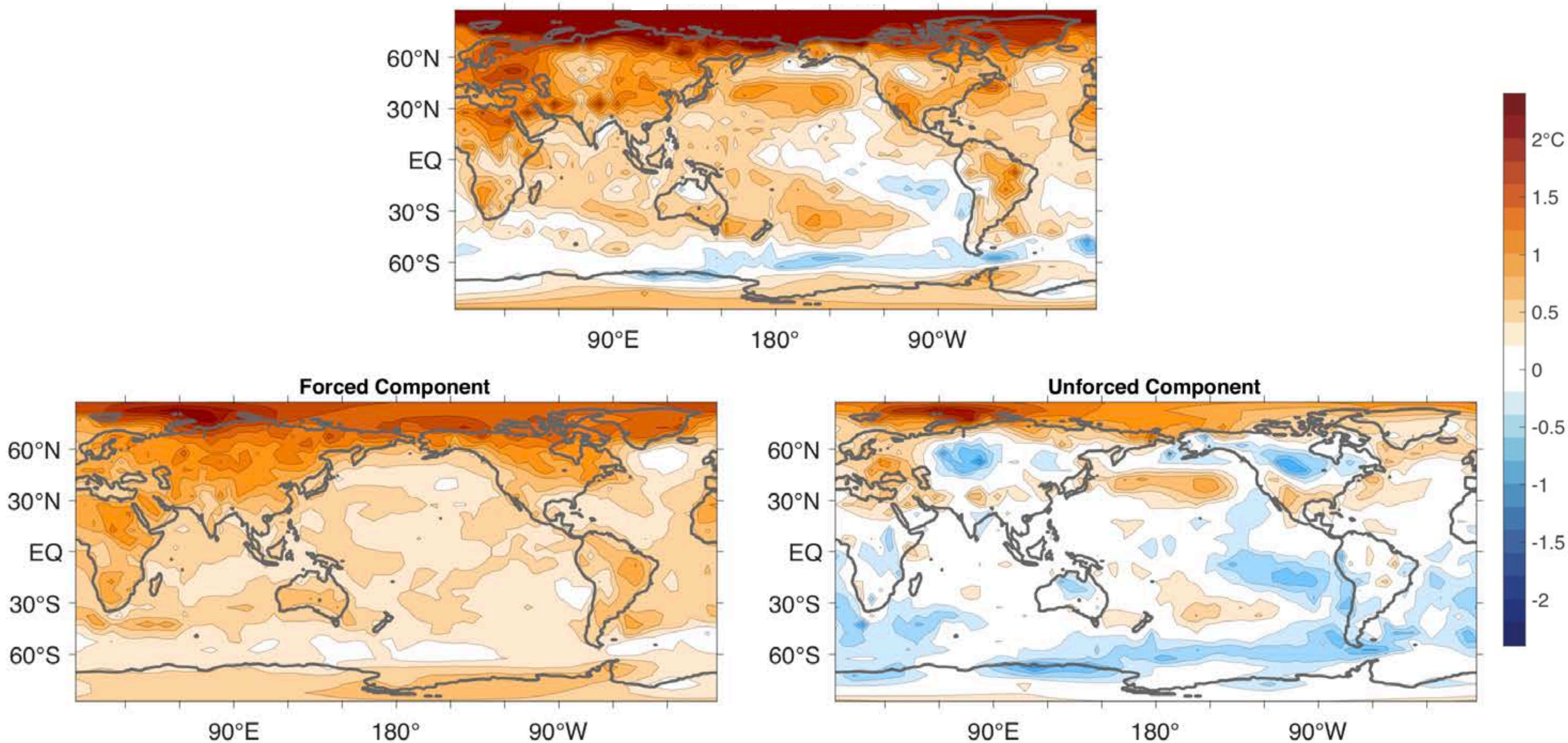
Wills et al., in prep. – Analysis of HadCRUT4

HadCRUT4 (Cowtan & Way) Temperature Change (2009-2018) – (1979-1988)



Wills et al., in prep. – Analysis of HadCRUT4

HadCRUT4 (Cowtan & Way) Temperature Change (2009-2018) – (1979-1988)



Wills et al., in prep. – Analysis of HadCRUT4

Conclusions:

1. Internal variability (especially ENSO) is aliased into ensemble-based estimates of the forced climate response
2. By identifying patterns that are robust across the ensemble (and those that aren't), we can identify the forced response with 5-10x fewer ensemble members (especially for local temperature)
3. **Low-frequency component analysis** provides a promising tool for identifying the forced response in a single realization, but requires subjective decision on the number of patterns to include

Potential applications:

1. Identifying and studying climate signals with a small signal-to-noise ratio (e.g., tropical Pacific SST gradient changes)
2. Identifying forced temperature changes within a model ensemble to subtract from other ensembles in the same model (e.g., single-forcing, decadal prediction)
3. Removing the forced response from modes of internal variability in observations