ENSO Interdecadal Modulation in CCSM4: A Linear Inverse Modeling Approach

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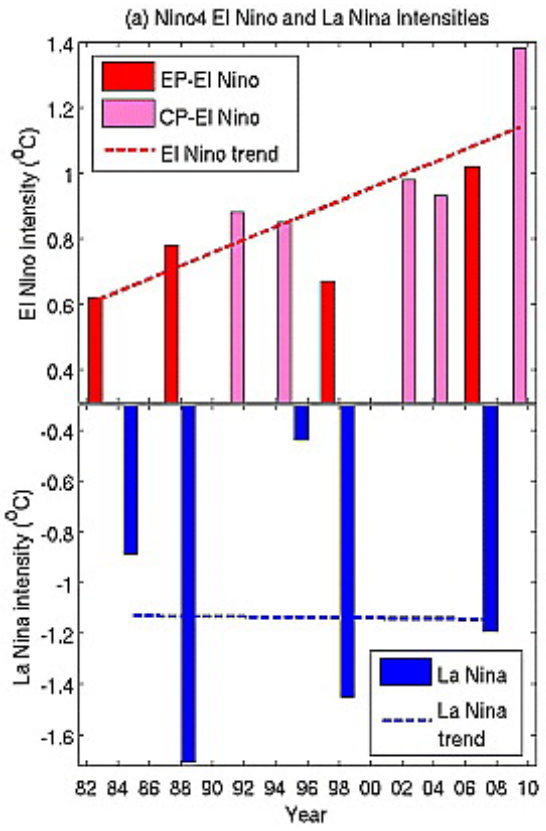
Not all ENSO events are the same

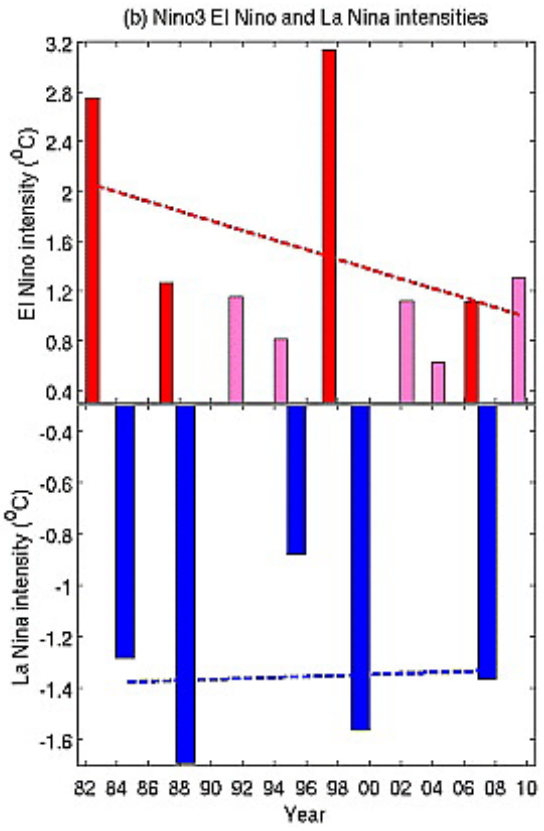
Has ENSO changed in recent decades?

ENSO character appears to have changed in recent decades

Niño4 region



Niño3 region

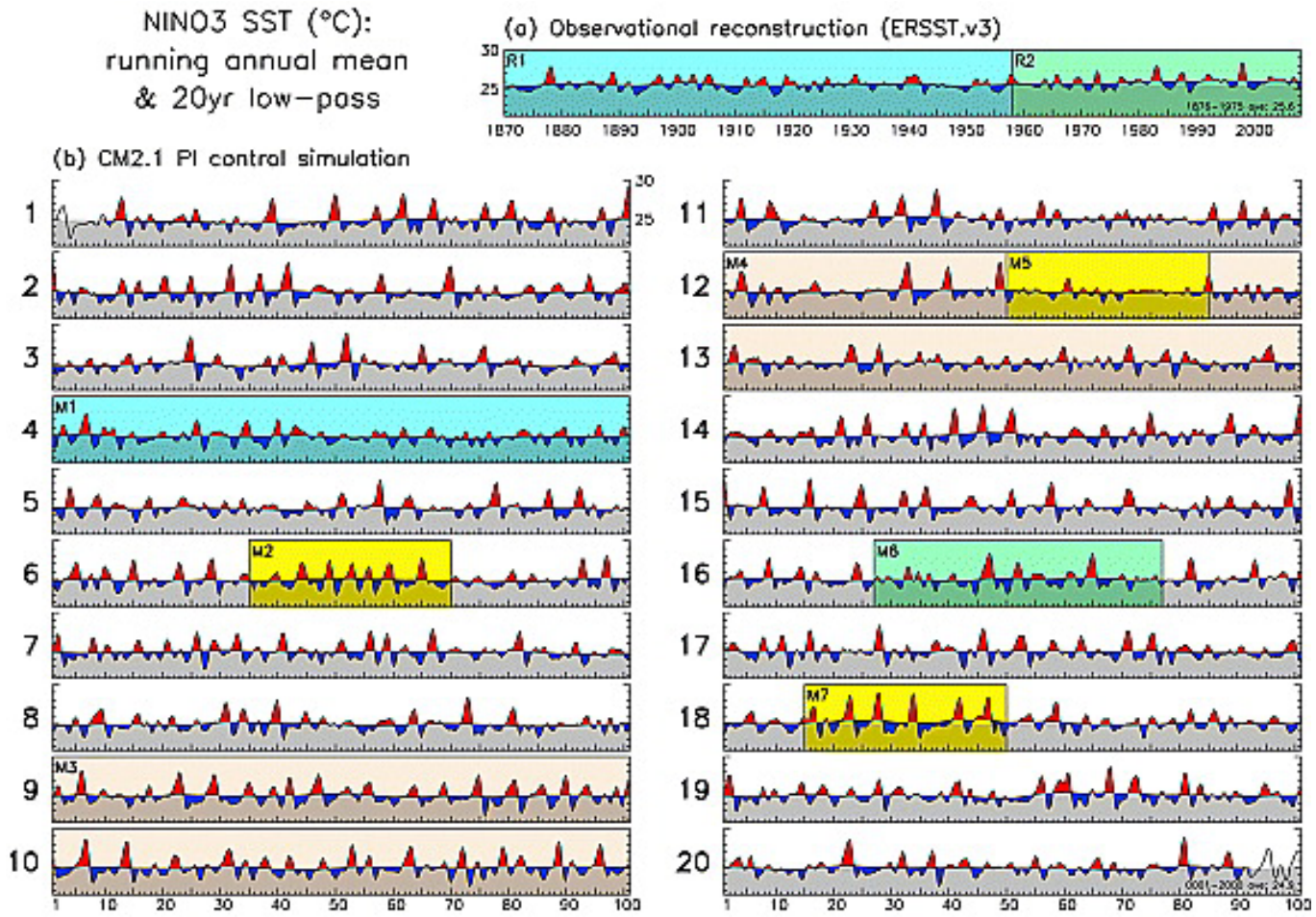


Lee and McPhaden 2010

Are historical record sufficient to constrain ENSO simulations?

Analysis of a 2000-yrs pre-industrial control with the GFDL CM2.1 coupled model

Niñ3 SSTAs (°C)



Wittenberg 2009

Niño3.4 interannual SST anomalies

HadISST (1900-2011)

CCSM4

Changes in ENSO behavior are apparent in a 1300-yr run of the NCAR-CCSM4

Deser, Phillips, Tomas, Okumura, Alexander, Capotondi, Scott, Kwon, and Obha, *J. Climate*, 2012

Basic Questions

1. Are any perceived changes in ENSO over say 50 years due to:
   - Anthropogenic forcing?
   - Changes in ENSO dynamics?
   - Changes in the statistics of the random forcing? or
   - Just sampling variations in random draws from the forcing pdf?

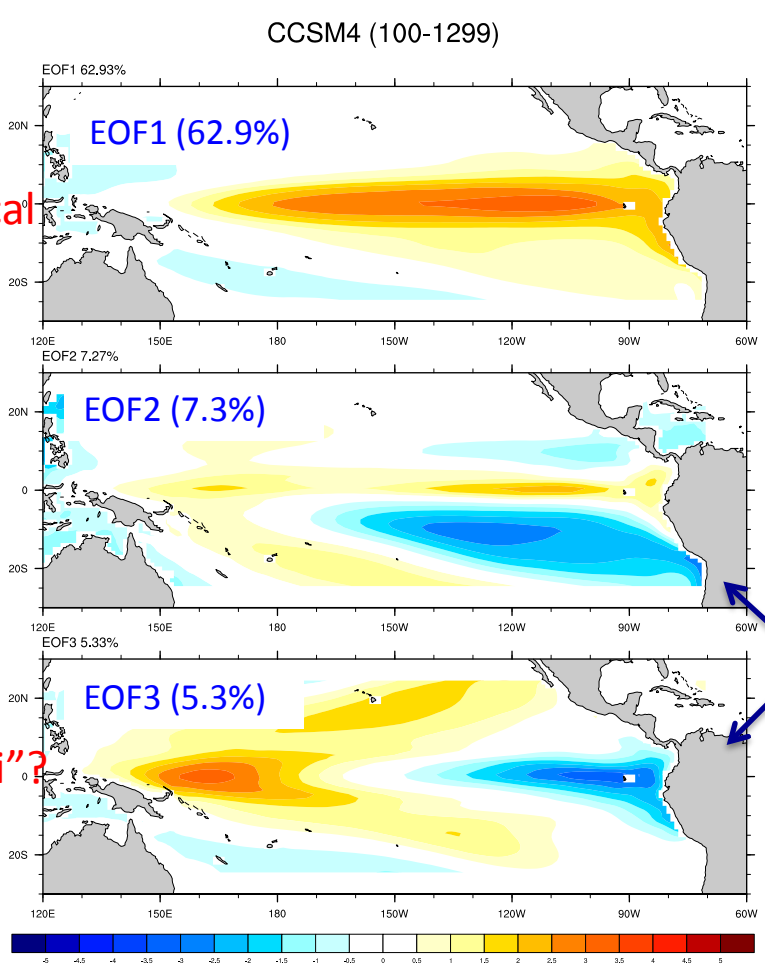
2. Are 50-yr records sufficient to sort this out?

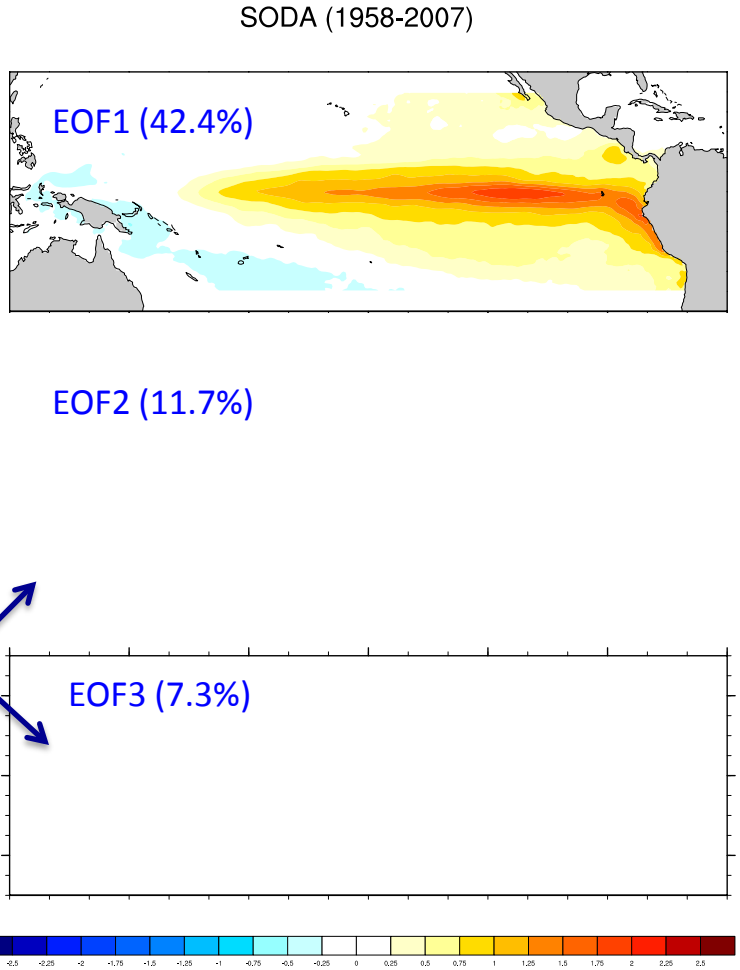
Address above questions using 1200-years (100-1299)
CCSM4 control integration

Model SST EOFs compare well with “observed”

CCSM4 (100-1299)

SODA 2.0.2/3 (1958-2007)

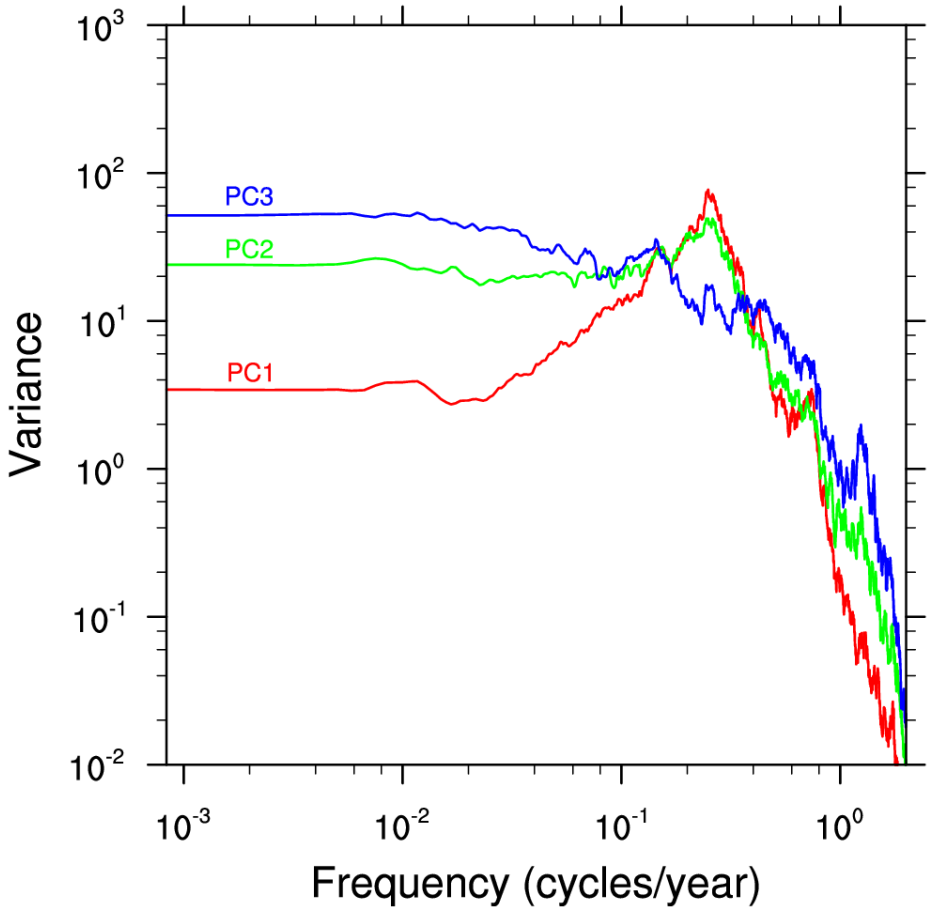




Canonical “ENSO”

“Modoki”?

Power Spectra of PC1, PC2, PC3



Addressing our basic questions in a Linear Inverse modeling (LIM) framework

(Penland and Sardeshmukh 1995; Newman et al. 2009, 2011)

Basic assumption: SSTs evolve over short time intervals *dt* as:

$$dx = Lx\,dt + S\sqrt{dt}\,r$$

x = 20-component SST anomaly state vector (PCs)

L = 20 x 20 matrix encapsulating predictable SST dynamics
S = 20 x 20 matrix of stochastic forcing amplitude covariance
r = 20-component random noise vector, each component drawn from N(0,1)

Addressing our basic questions in a Linear Inverse modeling framework (continued)

$$dx = Lxdt + S\sqrt{dt}\ r$$

For any linear and stochastically-driven system of this type we have:

$$x(t+\tau) = G(\tau)x(t) + \varepsilon$$

$$G(\tau) = e^{L\tau} = C(\tau)C(0)^{-1} \Rightarrow L = \frac{1}{\tau}\log G(\tau)$$

$$C_{ij}(\tau) = < x_i(t+\tau)x_j(t) >$$

Fluctuation-dissipation relationship:

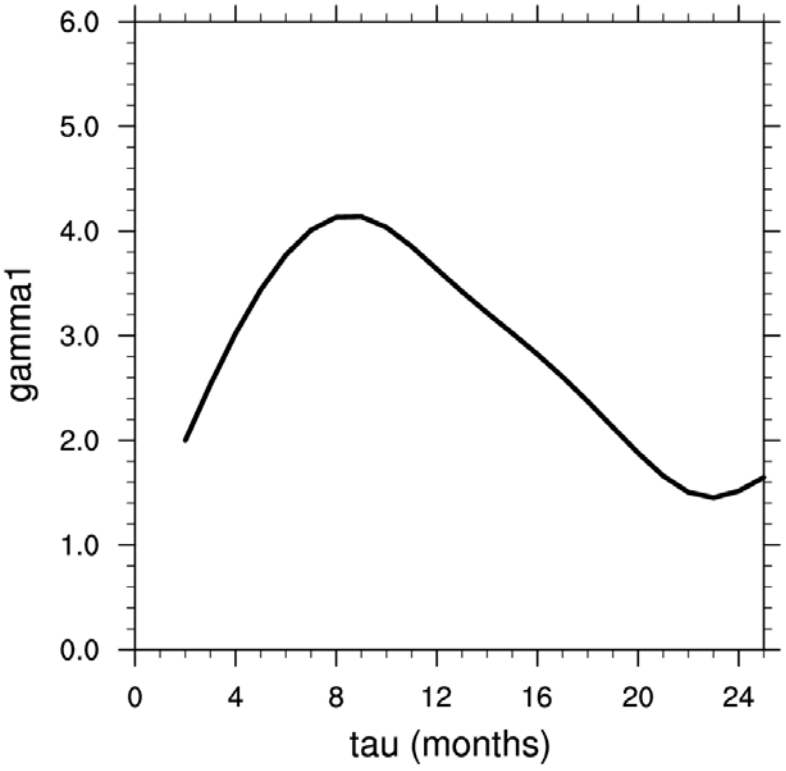
$$L\ C(0) + C(0)\ L^T = -\ S < r\ r^T > S^T = -\ Q$$

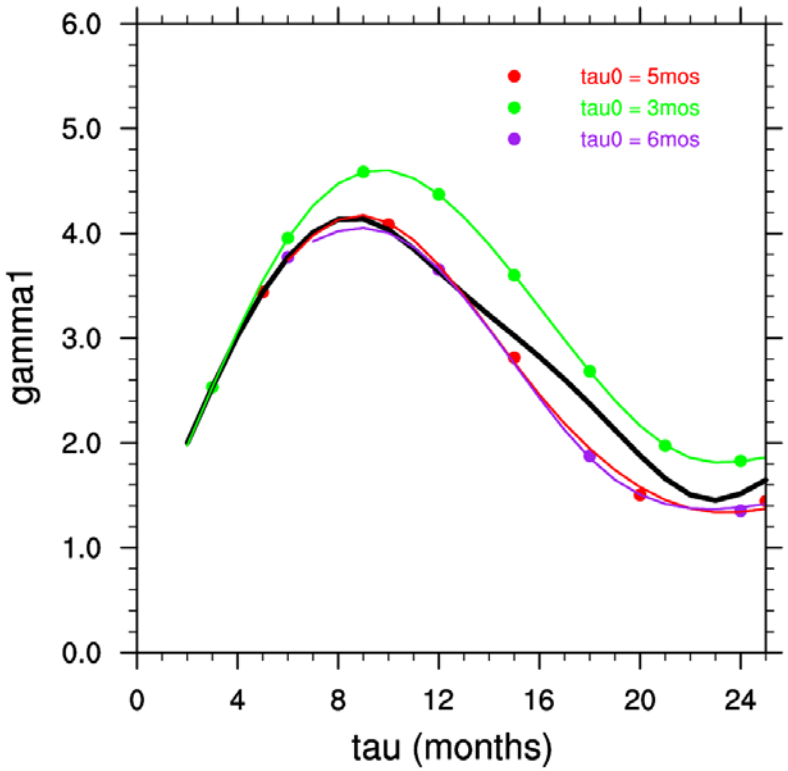
ideally, $< r\ r^T > = I$, if there is no sampling error

Maximum Amplification curve (largest singular value of G(τ)) for SST anomaly growth

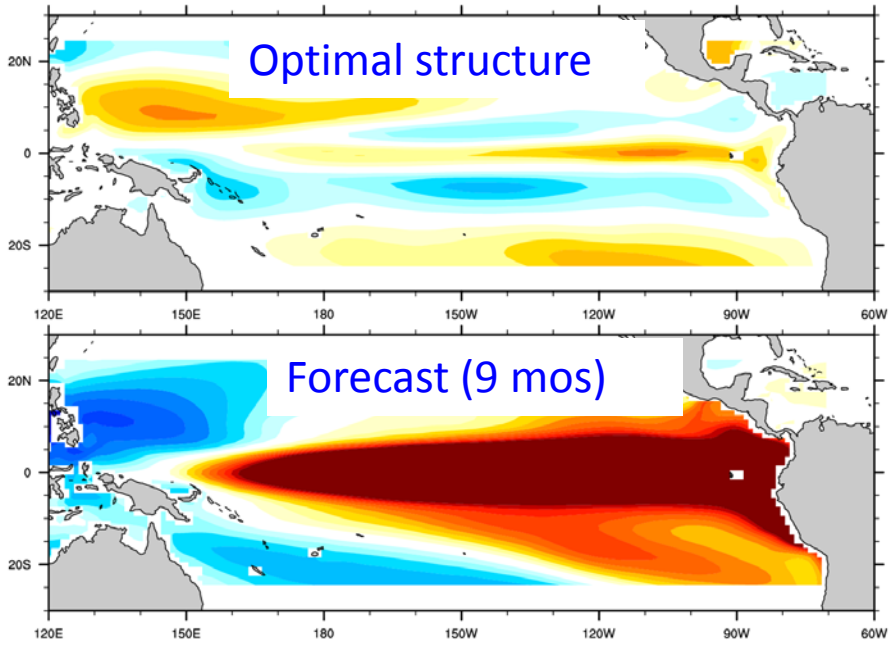
$$G(\tau) = e^{L\tau}$$

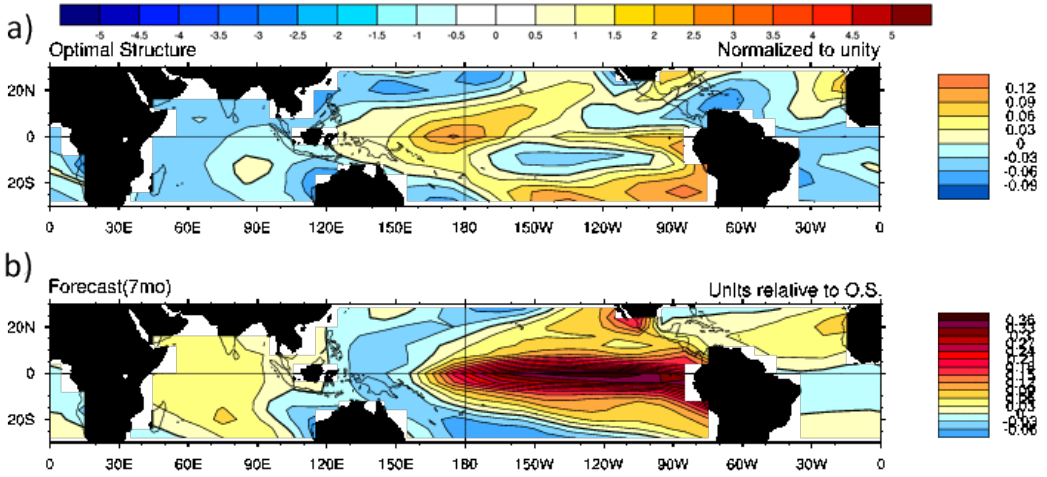
$$G(n\ \tau_0) = [G(\tau_0)]^n$$



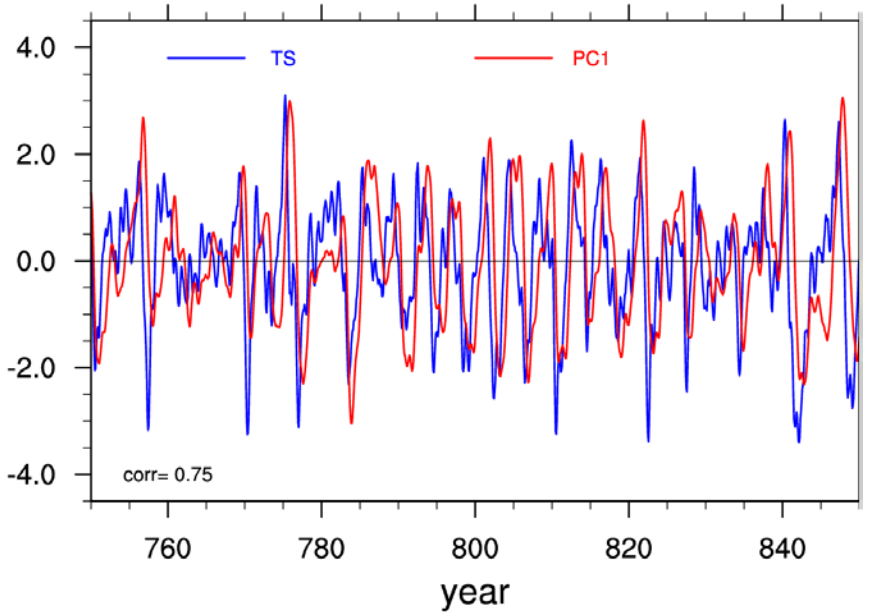


Leading right singular vector of G evolves into the left singular vector (the mature ENSO phase) 9 months later





Optimal structure time series (TS) has a correlation coefficient of 0.75 with PC1



Courtesy Cecile Penland

www.esrl.noaa.gov/psd/forecasts/sstlim

ERSST (1952-2012)

Addressing our basic questions in a Linear Inverse modeling framework (continued)

$$L\,C(0) + C(0)\,L^T = -S\,\langle rr^T \rangle\,S^T = -Q$$

Dynamics — Variability — Sampling — Stochastic forcing

Are any perceived changes in ENSO over say 50 years due to:

- Anthropogenic forcing?
- **Changes in ENSO dynamics?**
- **Changes in statistics of atmospheric forcing? or**
- **Just a sampling artifact**?

Addressing our basic questions in a Linear Inverse modeling framework (continued)

$$L\ C(0) + C(0)\ L^T = -S\ \langle rr^T \rangle\ S^T = -Q$$

Dynamics — Variability — Sampling — Stochastic forcing

We use the following measures ("metrics")
of the variability C(0), dynamics L, and stochastic forcing Q :

σ_1^2 = largest eigenvalue of C(0)=variance of PC1

γ_1^2 = largest singular value of G(τ_0=3 mos), associated with ENSO growth

q_1^2 = largest eigenvalue of Q (amplitude of the largest stochastic forcing)

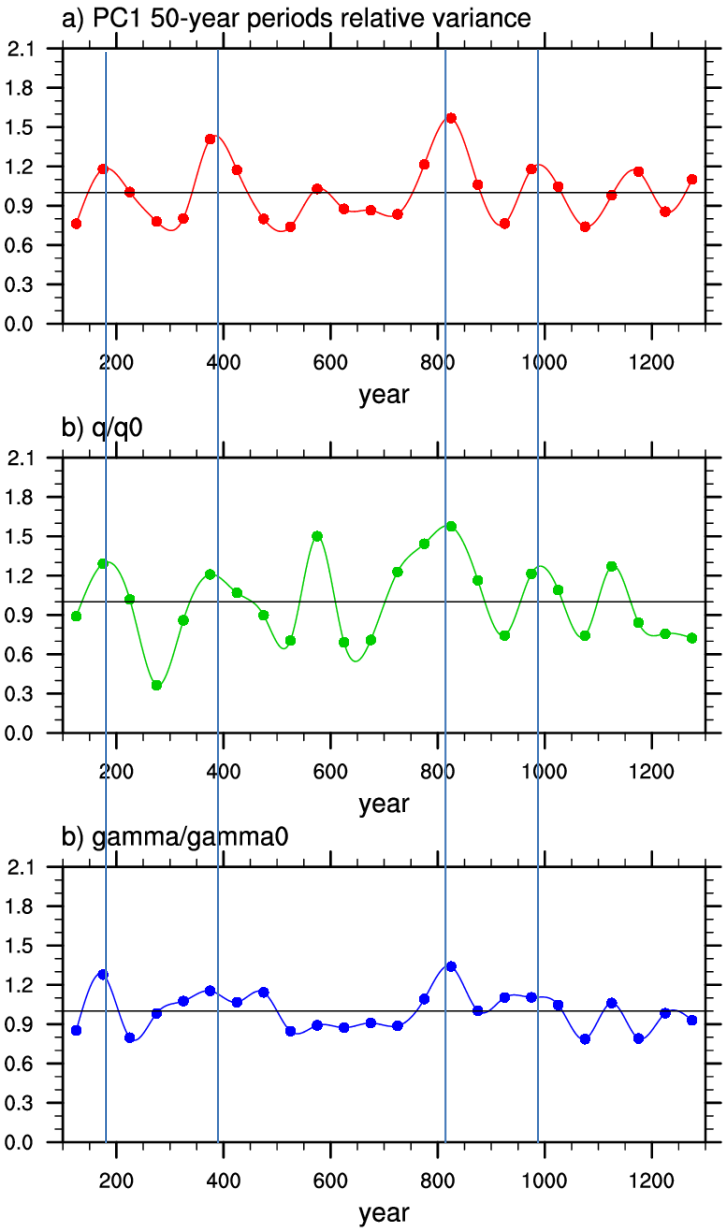
$$L\,C(0) + C(0)\,L^T = -S\langle rr^T\rangle S^T = -Q$$

σ_1 γ_1 q_1

σ_1^2 "variance"

q_1^2 "Stochastic forcing amplitude"

γ_1^2 "dynamics"



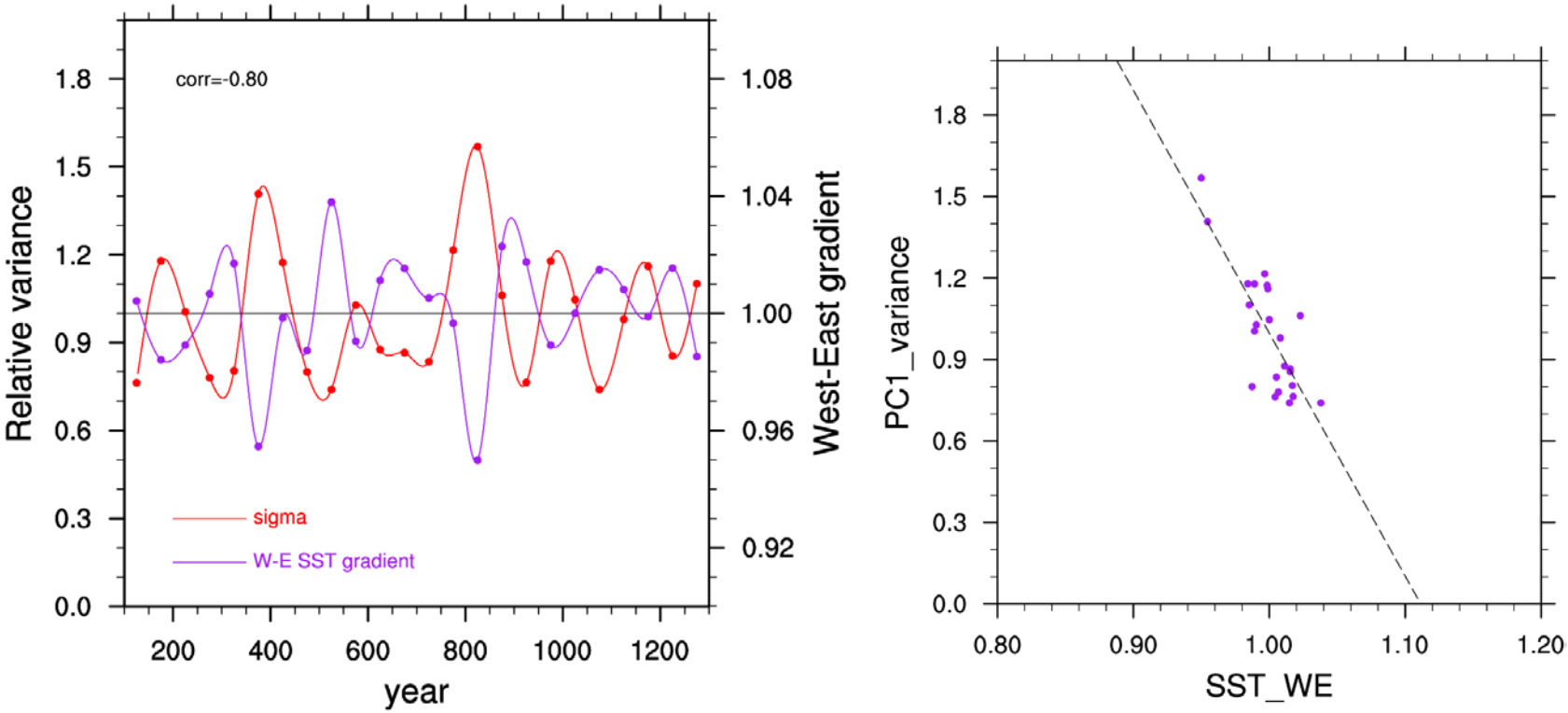
Divide the 1200-year GCM time series in 24, 50-years non-overlapping segments, and compute σ, q, and γ for each segment

Interdecadal variations are evident in all three quantities

Variations of zonal SST gradient on 50-yr time scales are negatively correlated with variations of ENSO variance

West minus East SST gradient
(5°S-5°N, 120°E-170°E) minus (5°S-5°N, 140°W-90°W)

Correlation coefficient= -0.80

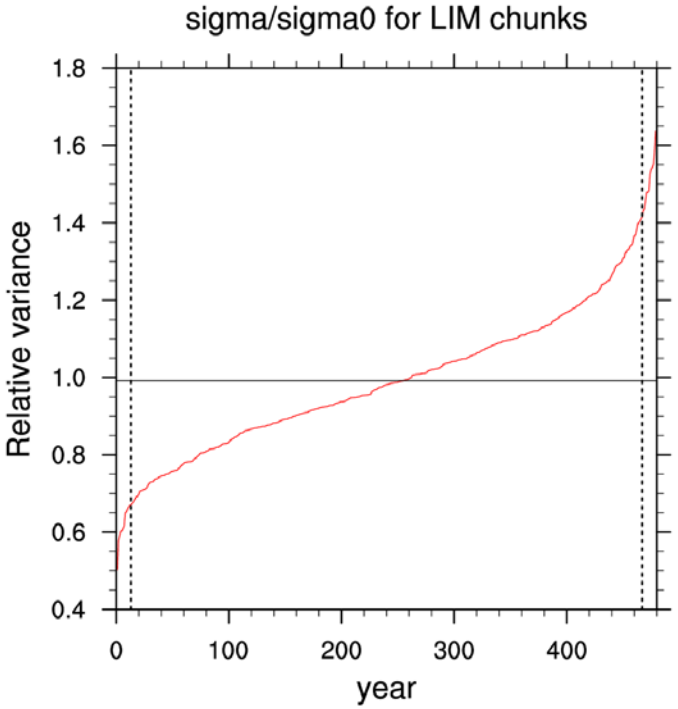


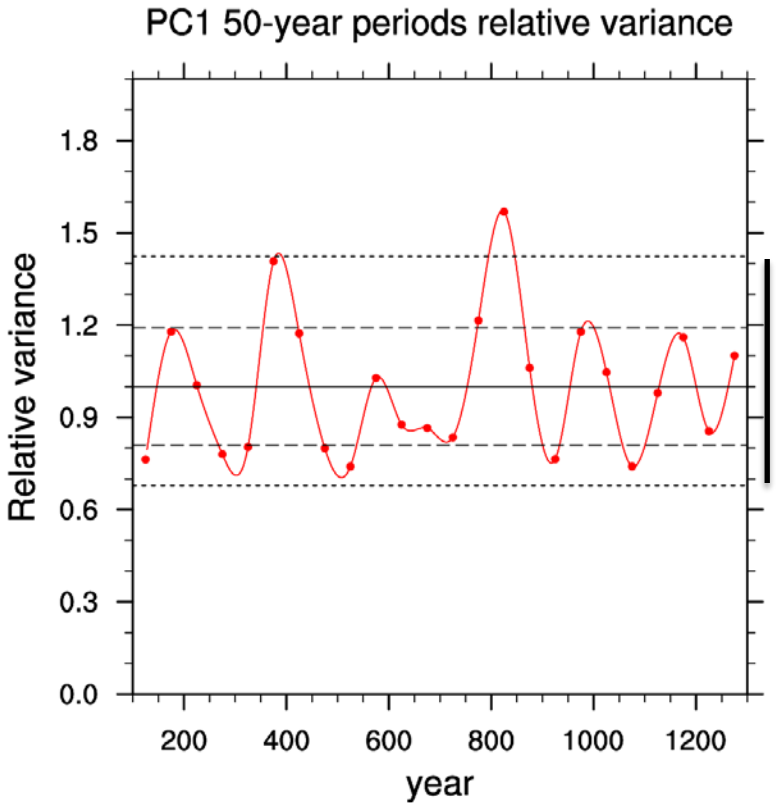
Are the changes in variance, dynamics, and stochastic forcing amplitude statistically significant?

Null hypothesis: changes are driven entirely by noise

$$dx = Lxdt + S\sqrt{dt}\ r$$

The Empirical Dynamical Model (EDM) was run for 24000 years (480 50-yrs segments)
σ, γ, and *q* were computed for each segment

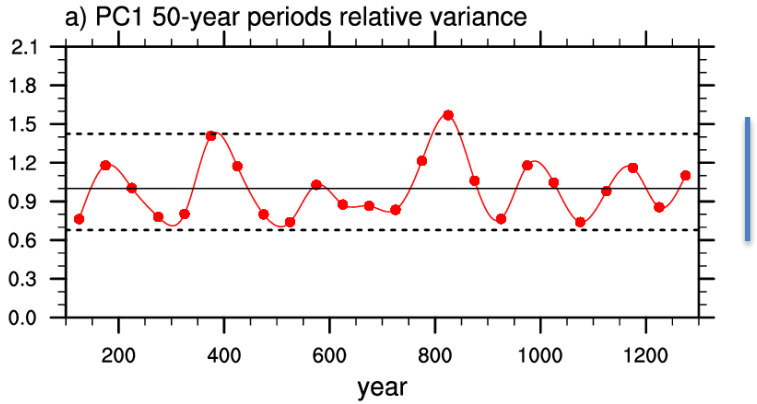




95%

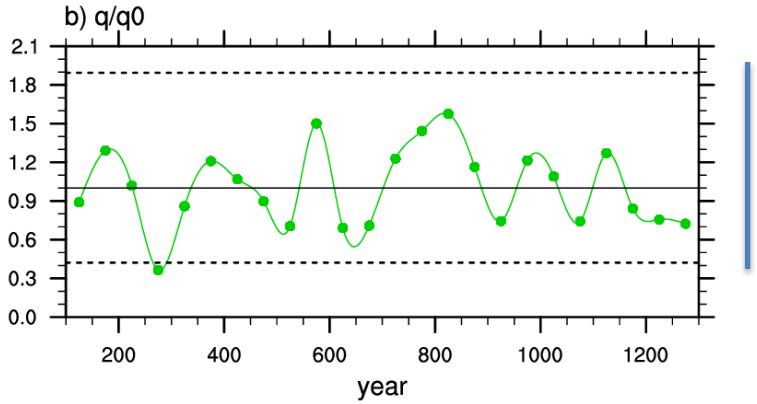
Variations in σ, *q*, and γ are not statistically significant

σ_1^2 "variance"



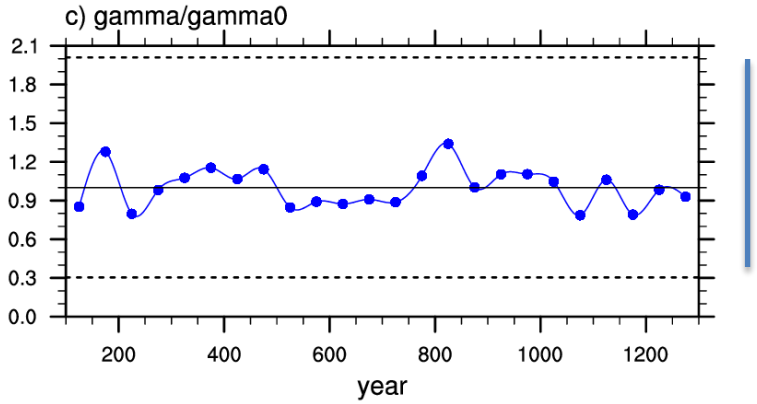
95%

q_1^2 "Stochastic forcing amplitude"



95%

γ_1^2 "dynamics"



95%

Conclusions

Are any perceived changes (σ) in ENSO over say 50 years due to:

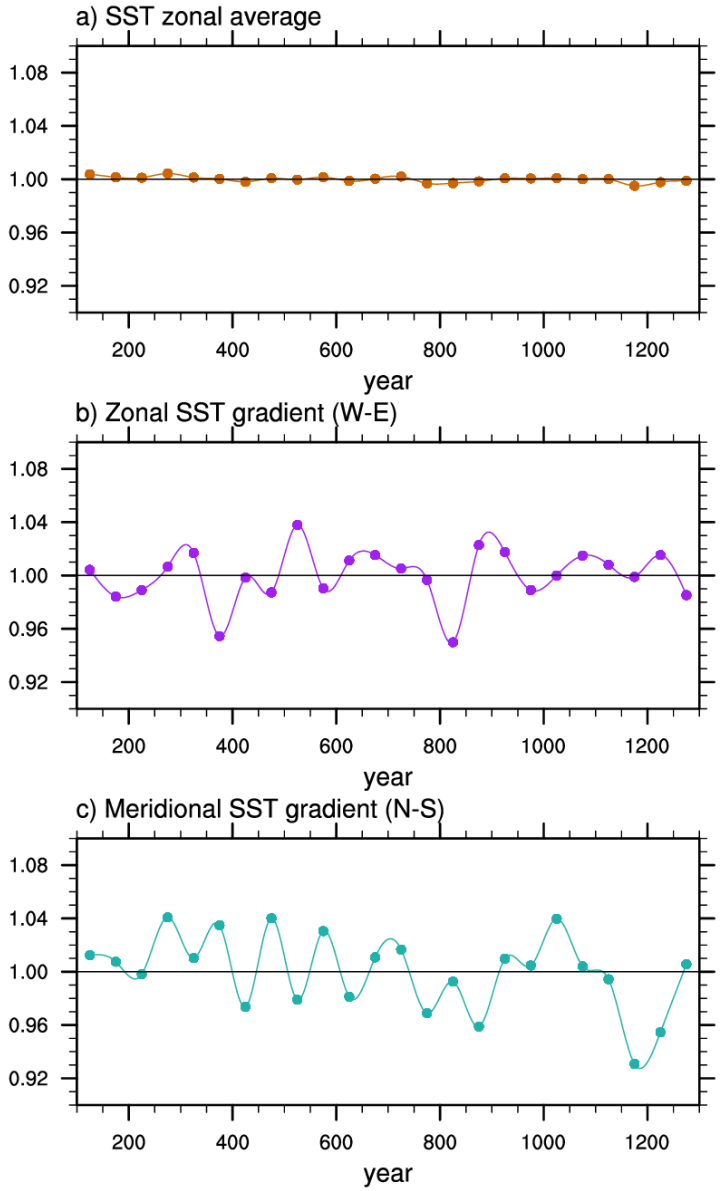
- Anthropogenic forcing? (not an issue in this 1200-yr pre-industrial run)
- Changes in ENSO dynamics (γ)?
- Changes in statistics of atmospheric forcing (*q*)? or
- Just a sampling artifact (*r*)?

Changes from epoch to epoch in this 1200-yr simulation are due to sampling variability.

Are 50-yr records sufficient to sort this out?

NO, given that variations in 50-yr ENSO statistics arise just from sampling in this 1200-yr run

Are there mean state changes associated with changes in system dynamics L?



Zonal SST average

2.5°S-2.5°N, 120°E-100°W

Note that these are essentially zero

West minus East SST gradient

(5°S-5°N, 120°E-170°E) minus (5°S-5°N, 140°W-90°W)

Note that these changes are of order 5%

North minus South SST gradient

(15°-25°N, 125°E-90°W) minus (5°S-5°N, 125°E-90°W)

Note that these changes are of order 5%

PDF of positive and negative ENSO events does not support rectification of ENSO variability (from El Nino events being possibly stronger than La Nina events) on to 50-yr mean state changes *in this model*