Identifying ENSO-related Variations from the Climate Record

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(based mostly on paper by Compo and Sardeshmukh 2010)

1. **How should one identify ENSO-related variations in the climate record?**
2. **ENSO has a rather long low-frequency tail, which contributes to "ENSO-like multi-decadal variability" and trends. This is mostly climate noise that one may want to remove.**
3. **What do the trends and multi-decadal variations look like after removing ENSO?**

How should one identify ENSO-related Variations ?

Tropical SST state vector : $\mathbf{x}(t) = \mathbf{x}_e(t) + \mathbf{x}_n(t)$

ENSO part Non-ENSO part

Rest of climate state vector : $\mathbf{y}(t) = \mathbf{y}_e(t) + \mathbf{y}_n(t)$

$= \mathbf{A}\,\mathbf{x}_e(t) + \mathbf{y}_n(t)$

Note !

x_e is not necessarily orthogonal to x_n , nor is y_e to y_n

Non-orthogonality implies that one cannot estimate **A** by regressing **y(t)** on $\mathbf{x}_e\mathbf{(t)}$.

Almost all previous studies have assumed orthogonality, even though there is no physical reason to do so.

How should one identify ENSO-related Variations ?

Tropical SSTs : $\mathbf{x}(t) = \mathbf{x}_e(t) + \mathbf{x}_n(t)$

ENSO part **Non-ENSO part**

Some difficulties with traditional approaches:

1. Defining x_e as the band-pass filtered x in the 2 to 6-yr band assumes that **all** of the SST variability in this band, and none outside it, is ENSO-related.

2. Defining x_e in terms of an SST index in grid space (such as a Nino3.4 index) implies that there can never be a non-ENSO part x_n in that index *by definition*, For instance, one can never have a "global warming" signal in Nino3.4

3. Defining x_e in terms of an SST index in EOF space (such as the 1st PC) has the same problem. In addition, it assumes that x_n is orthogonal to x_e .

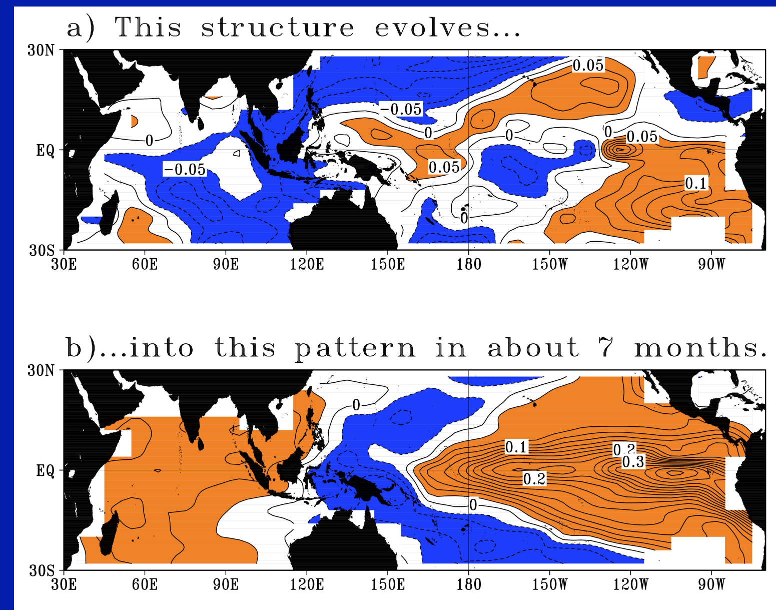
ENSO is not just a waxing and waning of the First SST EOF

A Linear Stochastic Model of tropical SST variations

$$\mathbf{x}(t+\tau) = \exp(\mathbf{L}\tau)\,\mathbf{x}(t) + \varepsilon$$

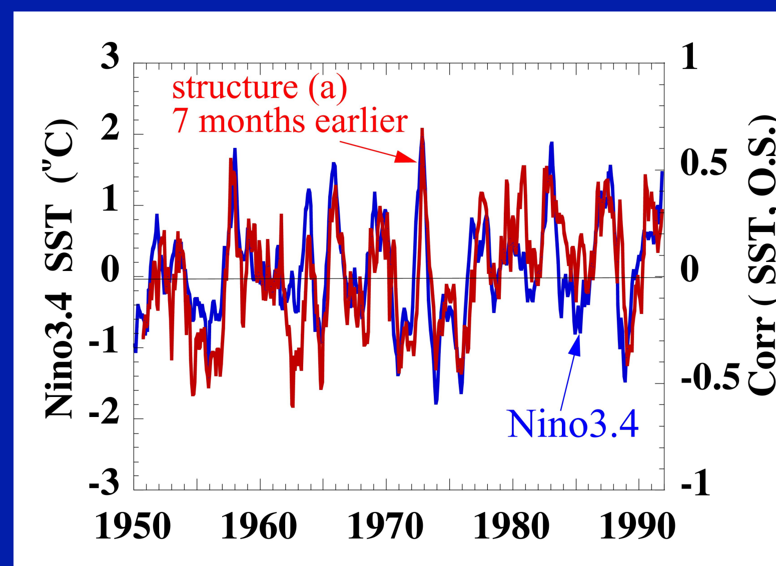
Projection of $\mathbf{x}$ on ϕ_1 tracks projection of $\mathbf{x}$ on ψ_1 7 months later, and so can be used to predict $\mathbf{x}$ 7 months later.

(see Penland and Sardeshmukh J. Climate 1995 for details)



ϕ_1

Ψ_1



How should one identify ENSO-related Variations in Tropical SSTs ?

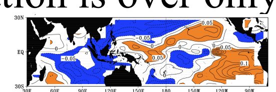
$$\mathbf{x}(t+\tau) \;=\; \exp(\mathbf{L}\tau)\;\mathbf{x}(t) \;+\; \boldsymbol{\varepsilon} \qquad (1)$$

Encouraged by the validity of (1) , Penland and Matrosova (2006) **defined the ENSO-related part $\mathbf{x}_e(t)$** of $\mathbf{x}(t)$ not in terms of any index, but **as a stochastically driven dynamical process :**

$$\boxed{\mathbf{x}_e(t+\tau) \;=\; \exp(\mathbf{L}_e\tau)\;\mathbf{x}_e(t) \;+\; \boldsymbol{\varepsilon}_e} \qquad (2)$$

evolving in an "ENSO-relevant" dynamical eigenmode subspace of the process (1), where

$$\mathbf{L}_e \;=\; \Sigma_i\,(\sigma_i+i\omega_i)\,\mathbf{u}_i\,\mathbf{v}_i^T$$

and the summation is over only those eigenvectors of $\mathbf{L}$ that contribute most to the optimal initial pattern $\boldsymbol{\phi}_1$  associated with ENSO development.

We have followed this approach here, estimating $\mathbf{L}$ from the lag covariances of monthly SST in the HadISST dataset (1949-2004) at lag 0 and lag $\tau_0 =$ 3 months as

$$\mathbf{L} \;=\; \frac{1}{\tau_o}\,\ln\left\{\mathbf{C}(\tau_o)\mathbf{C}(0)^{-1}\right\}$$

Empirical Orthogonal Functions (EOFs):

Eigenfunction of the simultaneous co-variance matrix C(0)

Patterns are static in time.

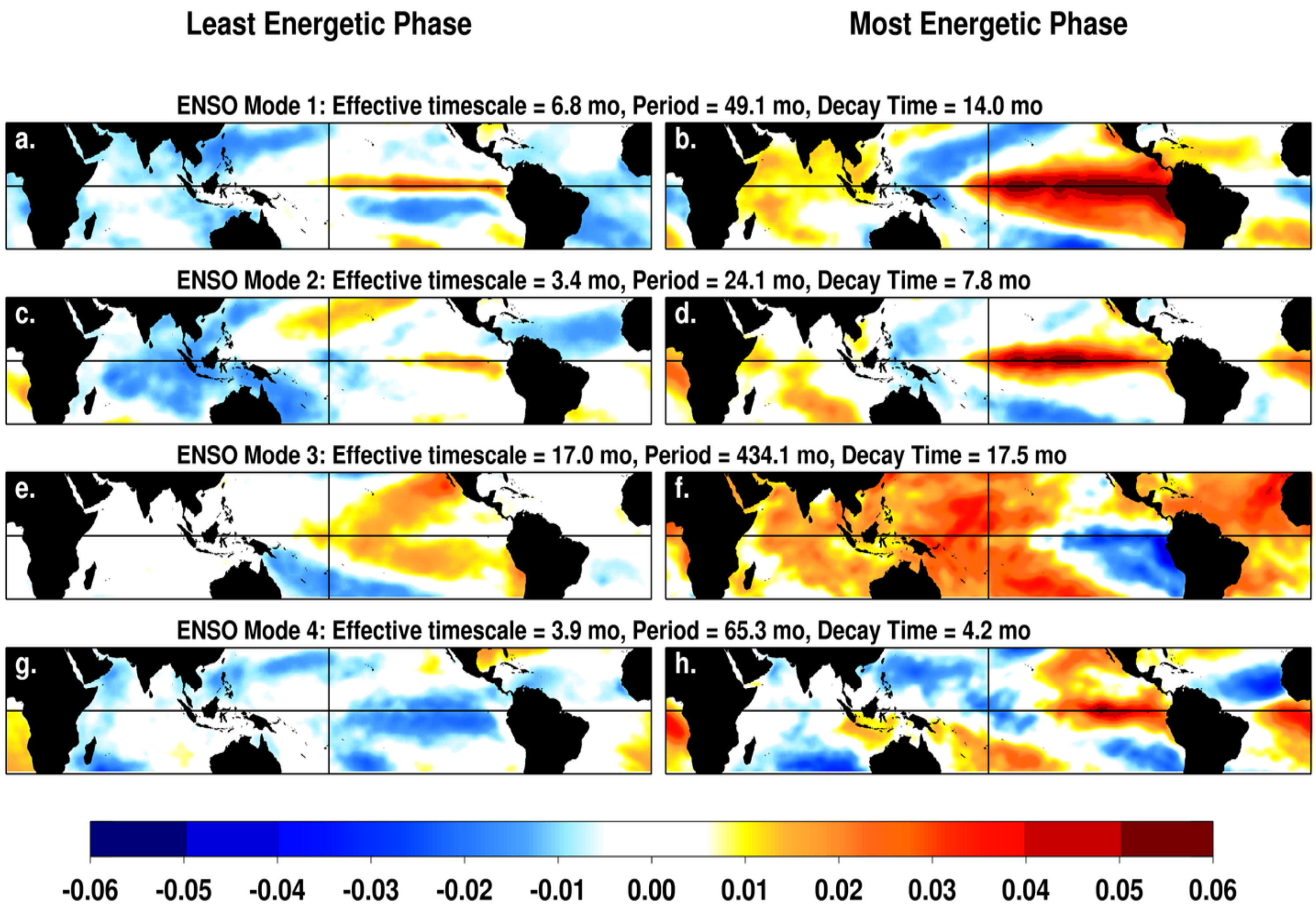
Eigenmodes:

Eigenfunctions of the 3-month lag co-variance matrix

$$\mathbf{C}(\text{tau}=3\text{ months})\mathbf{C}(0)^{-1}$$

Contain information about time evolution.

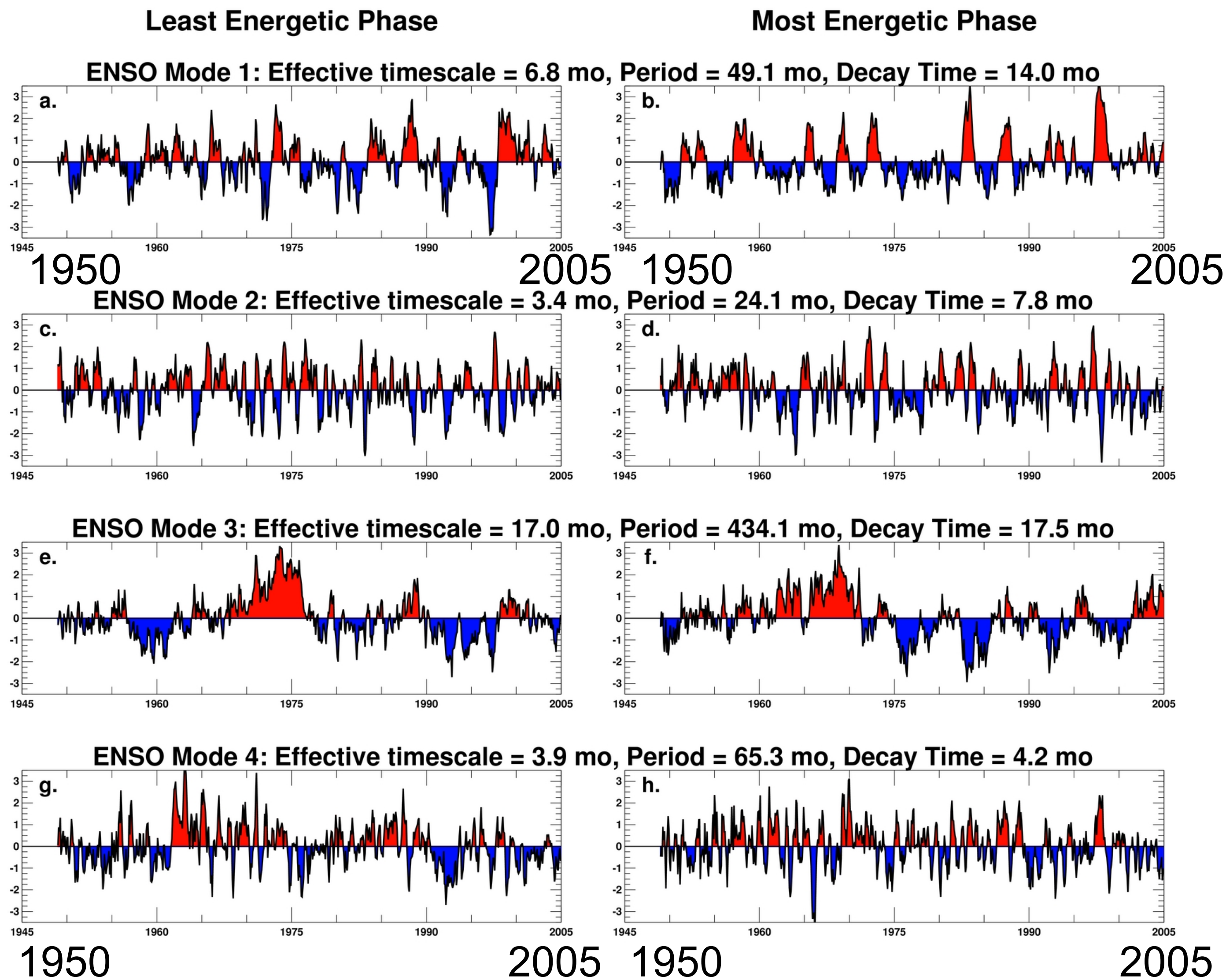
The 4 ENSO-relevant SST eigenmodes of L



Effective Time scale = $1 / (\sigma^2+\omega^2)^{1/2}$ Period = $2\pi/\omega$ Decay Time = $1/\sigma$

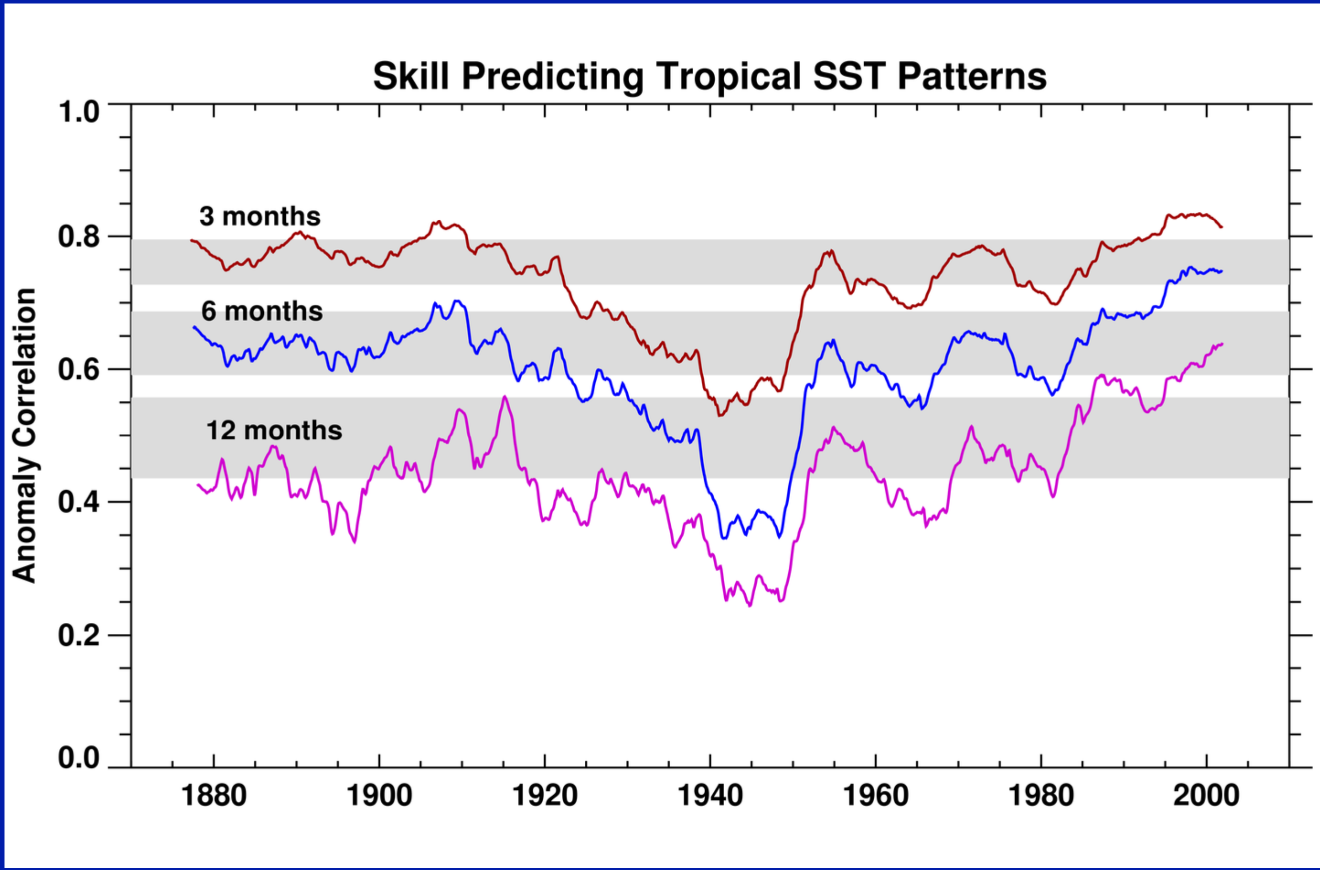
System evolves from Least Energetic to Most Energetic in ¼ period

Time Series of 4 ENSO-relevant SST eigenmodes of L



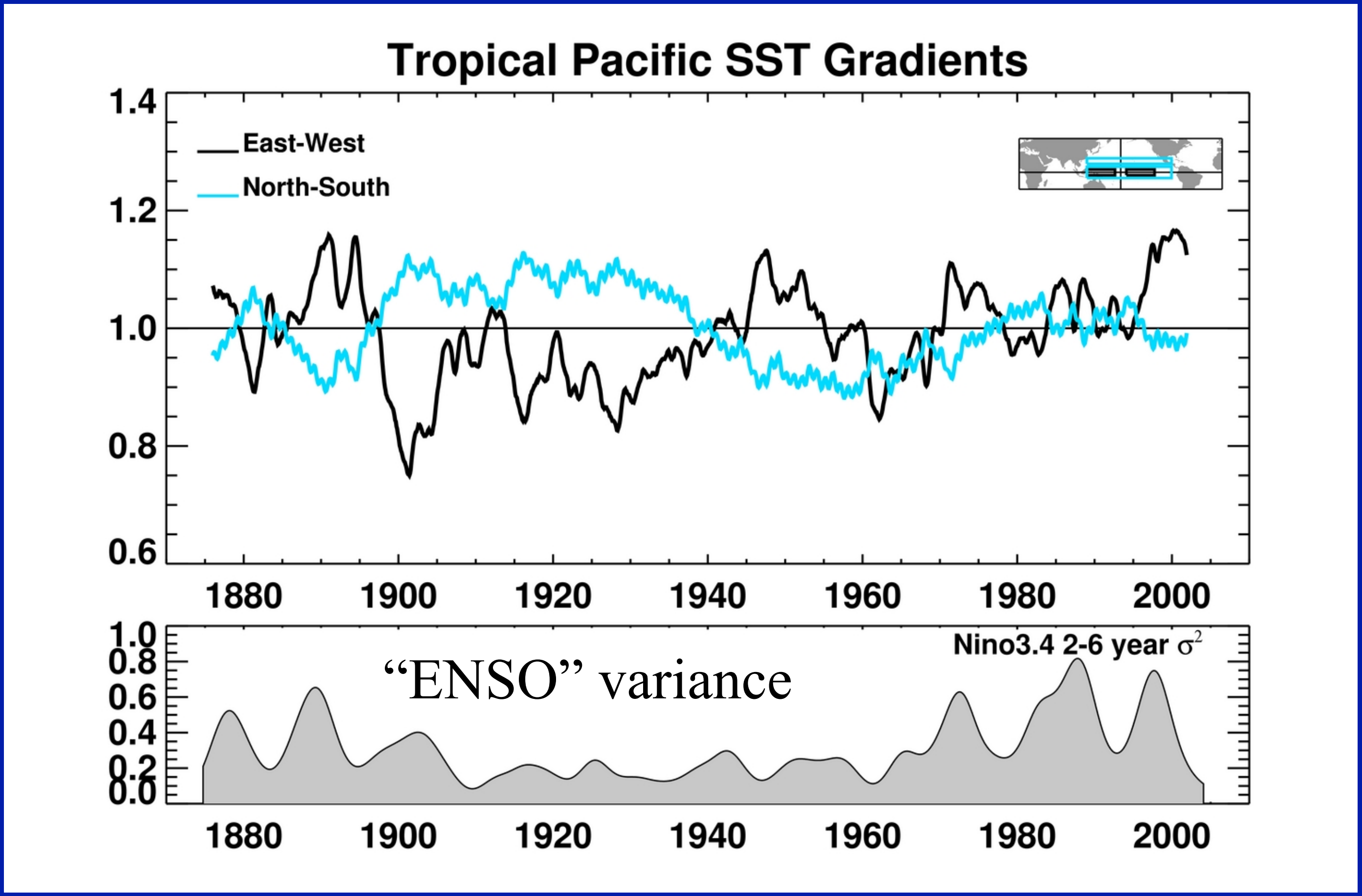
Effective Time scale = $1 / (\sigma^2+\omega^2)^{1/2}$ Period = $2\pi/\omega$ Decay Time = $1/\sigma$

Have short-term tropical SST dynamics changed substantially over the last century ?



Time series of the pattern correlation of forecast and observed tropical SST anomalies from 1871-2006. A 10 year running mean has been applied. Gray shading indicates the 95% range of expected fluctuations about the 1949-2004 mean values.

Have ENSO dynamics changed substantially over the last century ?



Time series of Pacific SST differences scaled by long term mean (1871-2006) differences.

(Black) $\Delta T_{E\text{-}W}$ between Niño3.4 and western Pacific warm scaled by longterm mean of -1.98°C.

(Blue) $\Delta T_{N\text{-}S}$ between the subtropical and tropical Pacific scaled by longterm mean of -1.74°C.

(gray shaded curve) Variance of Niño3.4 SST anomalies in the 2 to 6 year band

All time series are 10-yr running means.

To summarize our procedure for identifying ENSO-related variations :

Tropical SSTs : $\mathbf{x}(t+\tau) = \exp(\mathbf{L}\tau)\mathbf{x}(t) + \varepsilon$ over short intervals τ (~ several seasons)

$$\mathbf{x}(t) = \mathbf{x}_e(t) + \mathbf{x}_n(t)$$

$$\mathbf{x}_e(t) = \sum_{i=1,4} \alpha_i(t)\, u_\mathbf{i} = \sum_{i=1,4} [v_i^T \mathbf{x}(t)]\, u_\mathbf{i}$$

where $u_\mathbf{i}$ are the 4 ENSO-relevant eigenvectors of $\mathbf{L}$

and $v_\mathbf{i}$ are the corresponding adjoint eigenvectors

Extratropical SSTs : $\mathbf{y}(t) = \mathbf{y}_e(t) + \mathbf{y}_n(t)$

$$\mathbf{y}_e(t) = \mathbf{A}\ \mathbf{x}_e(t)$$

$$\mathbf{A} = <\mathbf{y}_b(t)\ \mathbf{x}_b^T(t)> \quad <\mathbf{x}_b(t)\ \mathbf{x}_b^T(t)>^{-1}$$

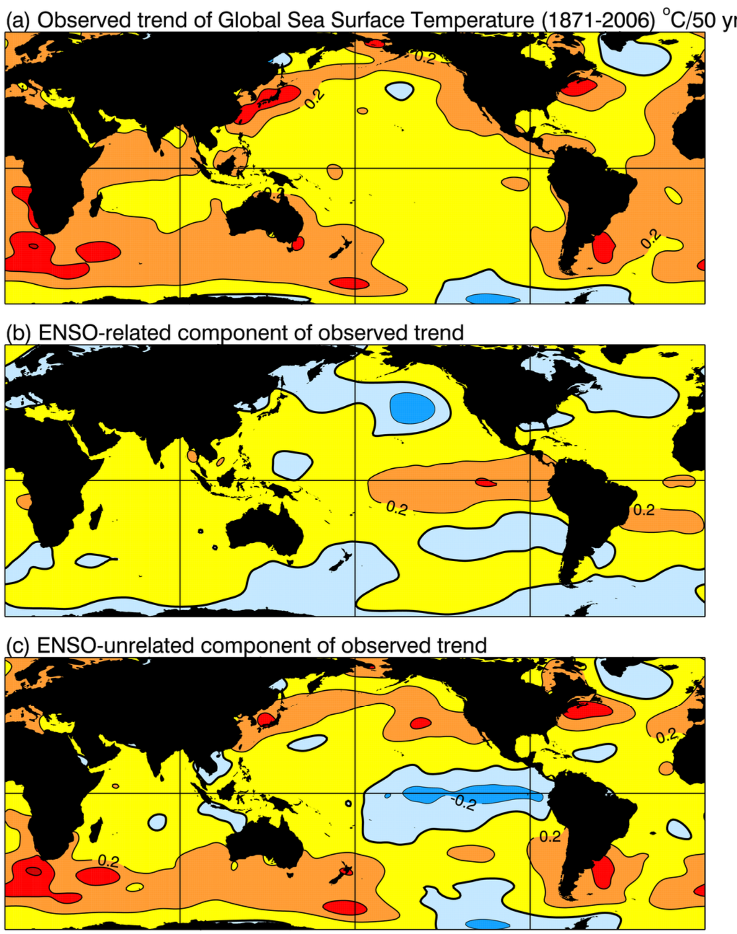
= "Atmospheric Bridge" operator

where $\mathbf{x}_b$ and $\mathbf{y}_b$ are band-pass filtered time series of $\mathbf{x}$ and $\mathbf{y}$

in the 2 to 72-month period band.

Global Maps of Linear SST Trends (contours 0.2 C/50yr)

Over 1871-2006

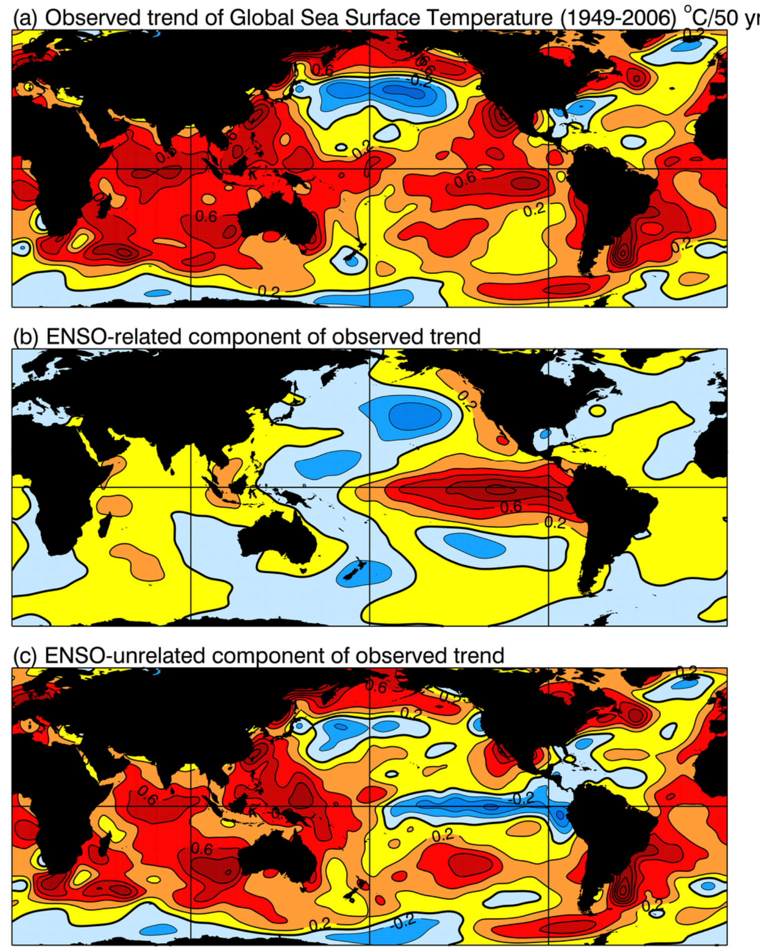


Full Trend

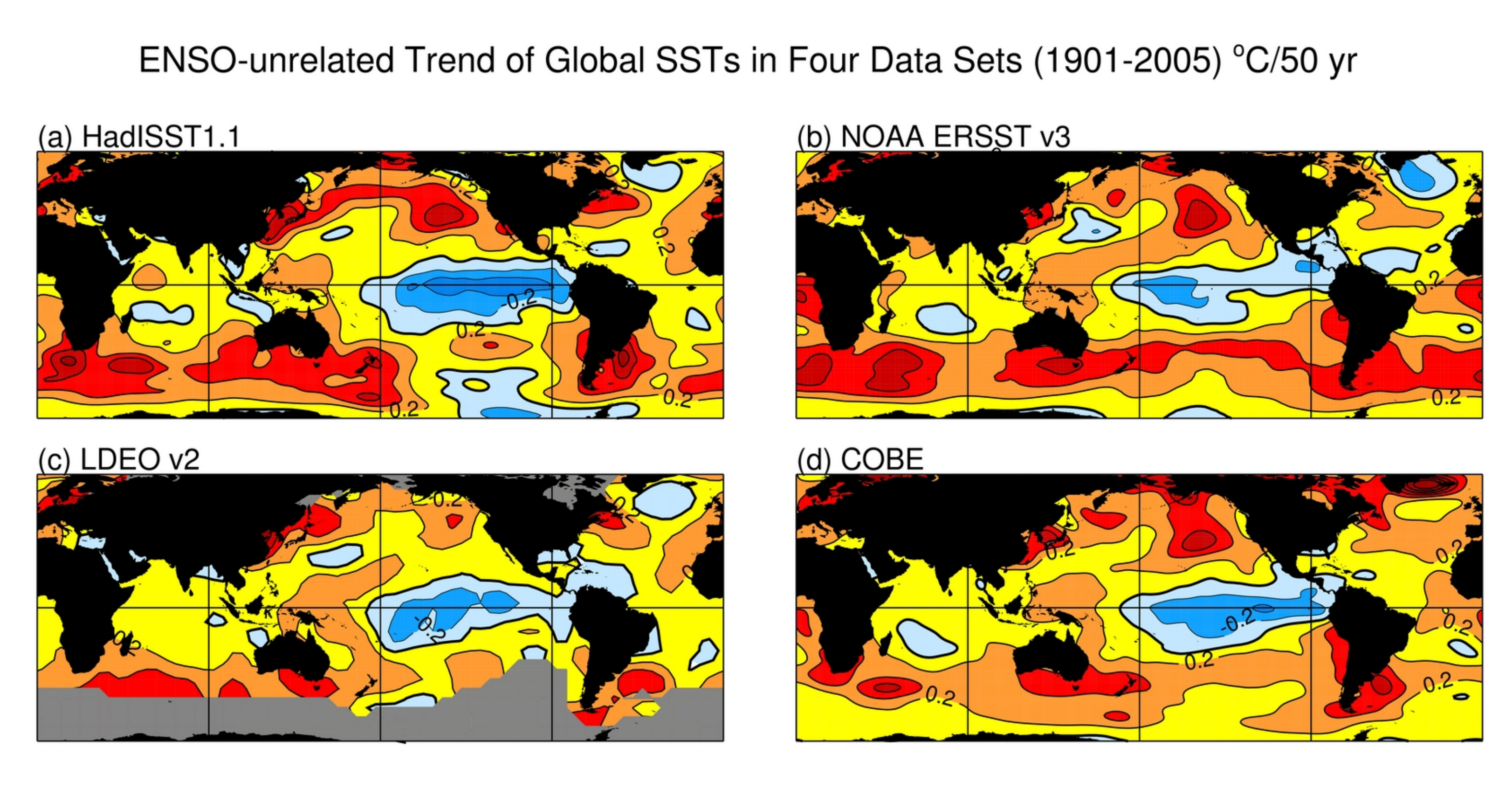
ENSO related Trend

ENSO unrelated Trend

Over 1949-2006

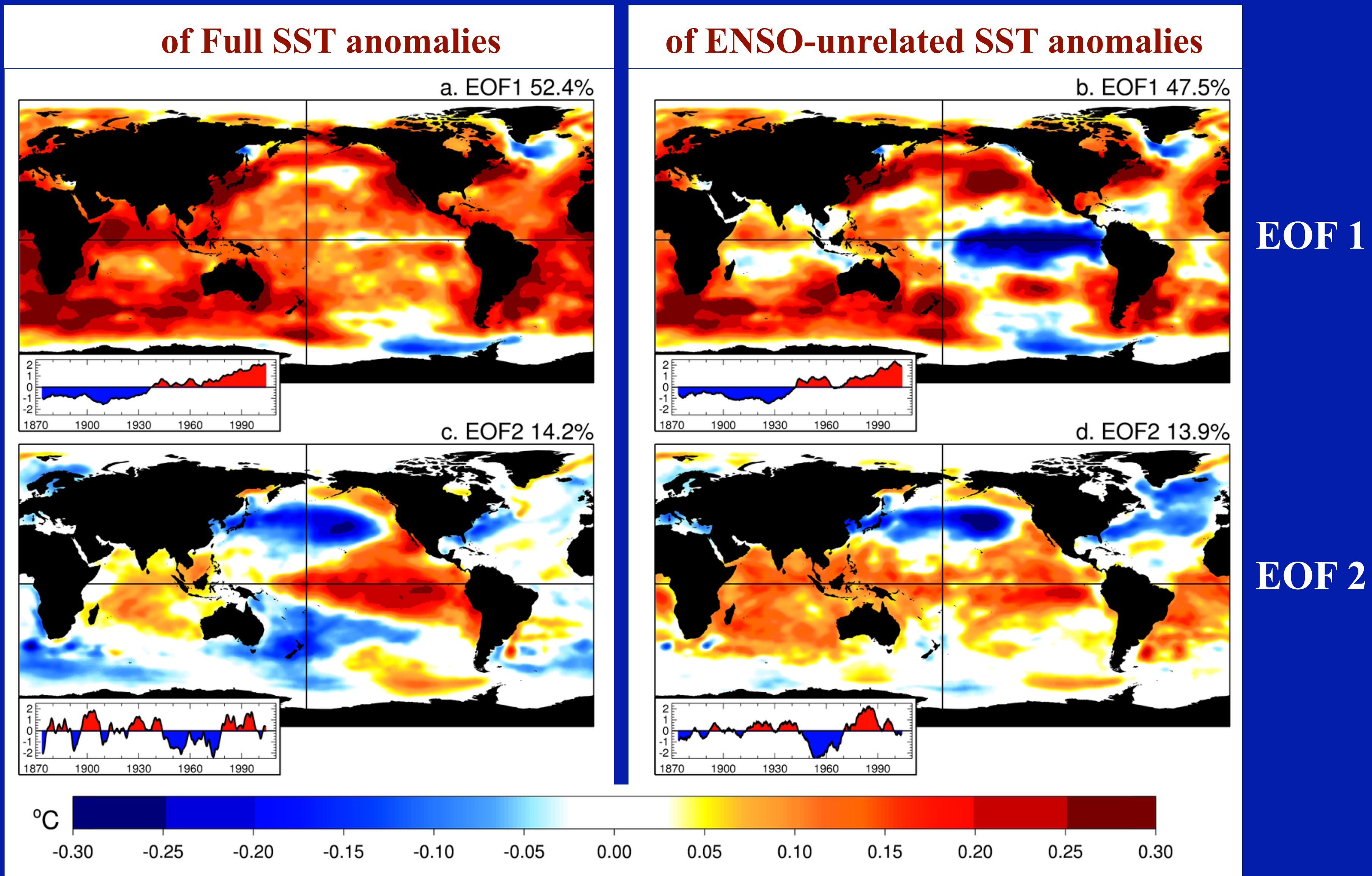


Robust result in 4 different datasets



Similar ENSO-unrelated trends found in Cane et al. 1997, Lau and Weng 1999, Guan and Nigam 2008, Solomon and Newman 2012

EOFs of 5-yr average SST anomalies



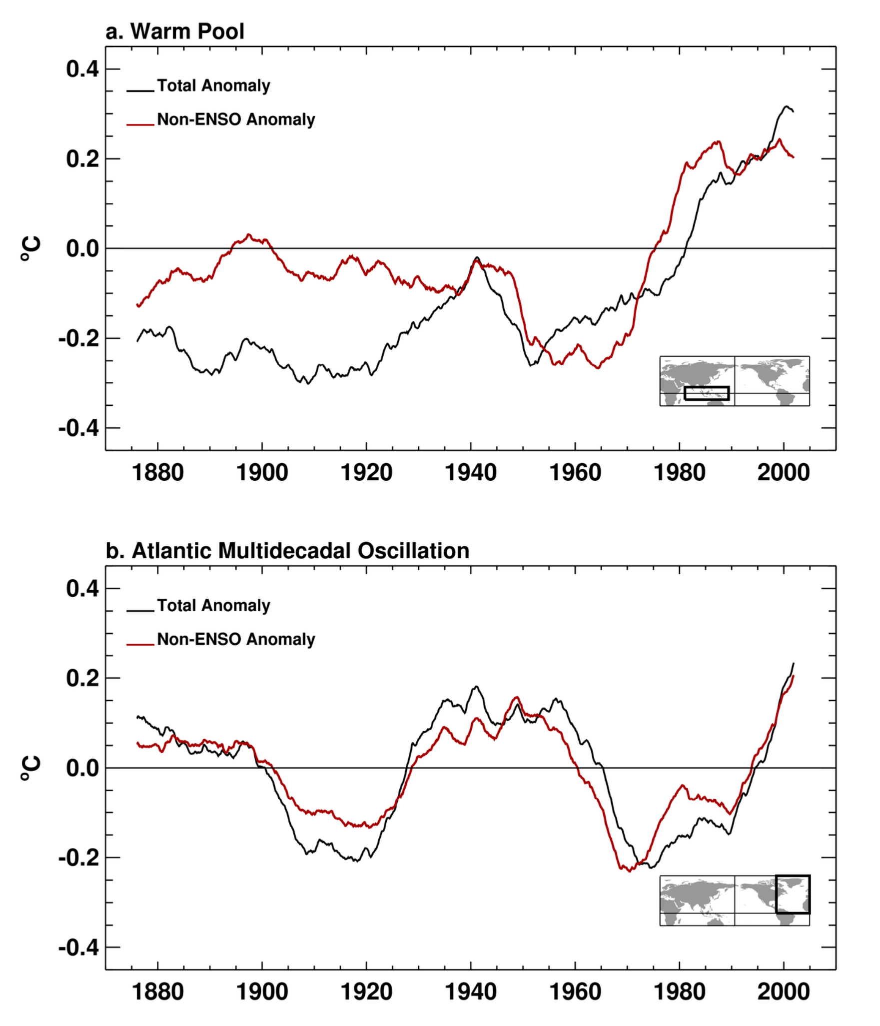
Summary

1. Identifying ENSO-related variations by regressing on any single ENSO index is problematic.
2. ENSO is not one or two numbers. It is an evolving dynamical process.
3. We identify ENSO-related SST variations with the projection on the 4 most important dynamical SST eigenmodes involved in the growth and decay of ENSO events over several seasons.
4. While the statistics associated with ENSO may have changed, the dynamics of ENSO do not appear to have changed.
5. Need to properly account for ENSO to remove it. After removing ENSO, the residual SST data reflect a combination of anthropogenic, naturally forced, and coherent internal multi-decadal variability.
6. The 1st EOF and trend of the residual SST data has a general “global warming” structure, but also a pronounced cooling in the eastern equatorial Pacific.

How does removing ENSO affect the time series of Warm Pool SSTs and the AMO index ?

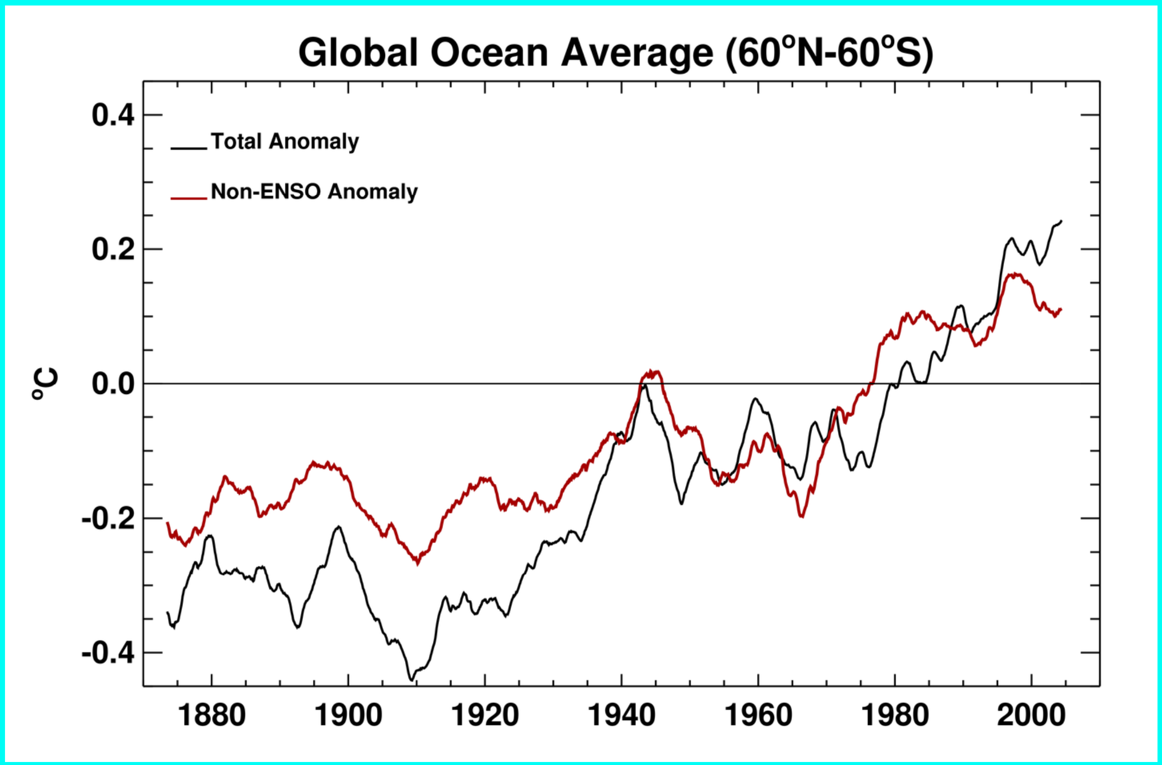
Warm Pool

AMO



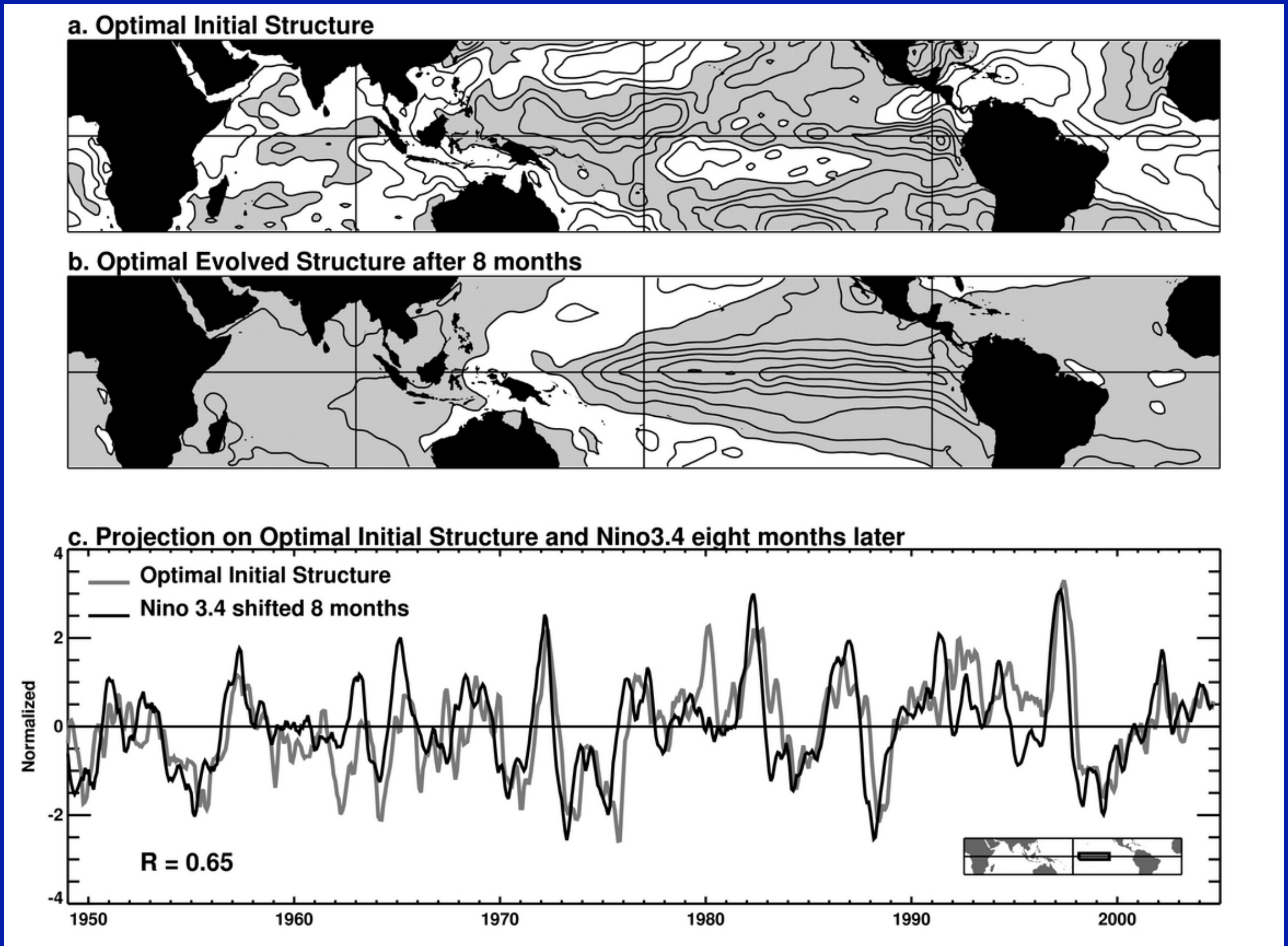
A 10-year running mean has been applied to all series.
Anomalies are relative to a 1949-2004 climatology.

How does removing ENSO affect the global-average SST ?



A 10-year running mean has been applied to both series. Anomalies are relative to a 1949-2004 climatology.

Projection of x=tropical SST field on ϕ_1 tracks projection of x on ψ_1
8 months later, and so can be used to predict x
8 months later.



Observed and Simulated Spectra of Tropical SST Variability

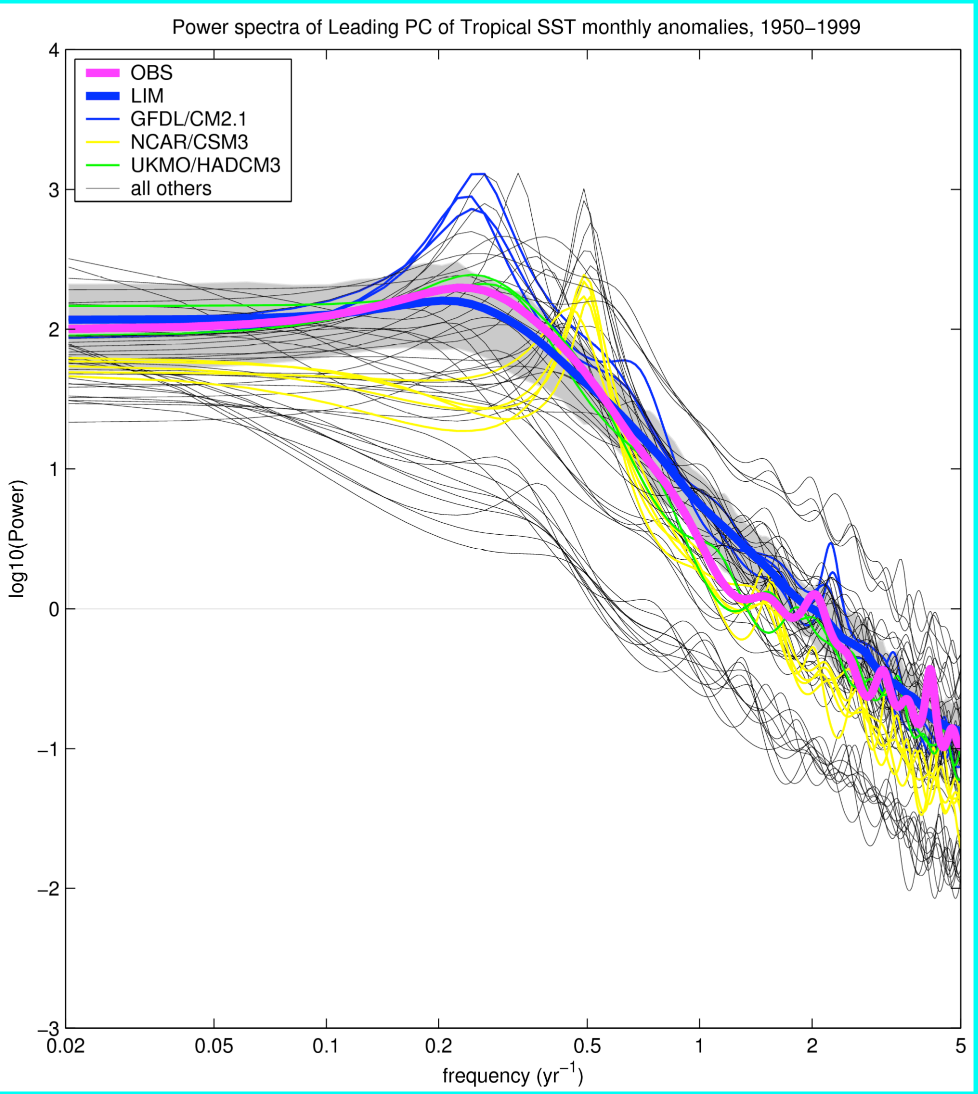
Spectra of the projection of tropical SST anomaly fields on the 1st EOF of observed monthly SST variability in 1950-1999.

Observations (Purple)

IPCC AR4 coupled GCMs
(20^{th}-century (20c3m) runs)
(thin black, yellow, blue, and green)

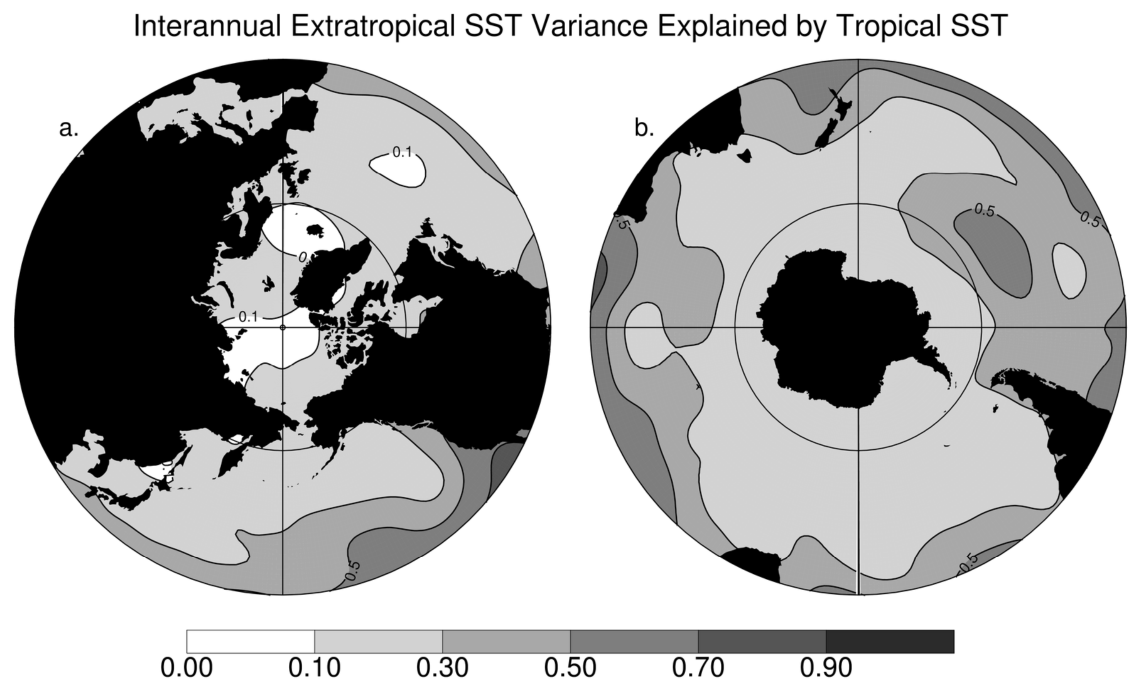
A linear inverse model (LIM) constructed from 1-week lag covariances of weekly-averaged tropical data in 1982-2005
(Thick Blue)

Gray Shading :
95% confidence interval from the LIM, based on 100 model runs with different realizations of the stochastic forcing.



From Newman, Sardeshmukh, and Penland (2008)

Fraction of extratropical SST variance explained by the “Atmospheric Bridge”



Maps of the cross-validated explained variance of seasonal SST anomalies diagnosed using the linear “atmospheric bridge” statistical model **G** and tropical SST anomalies. (a) Northern Hemisphere. (b) Southern Hemisphere. All data were bandpass filtered using wavelet filter with a response between 2 and 72 months. Contour interval is 0.2