Empirical climate models of coupled tropical atmosphere-ocean dynamics

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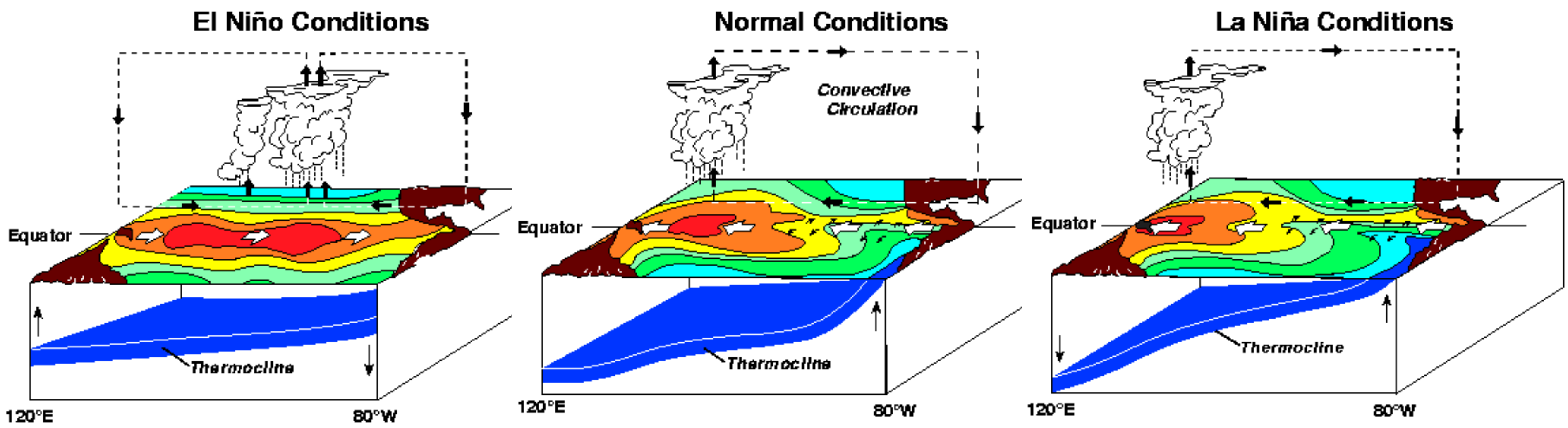
Outline of talk

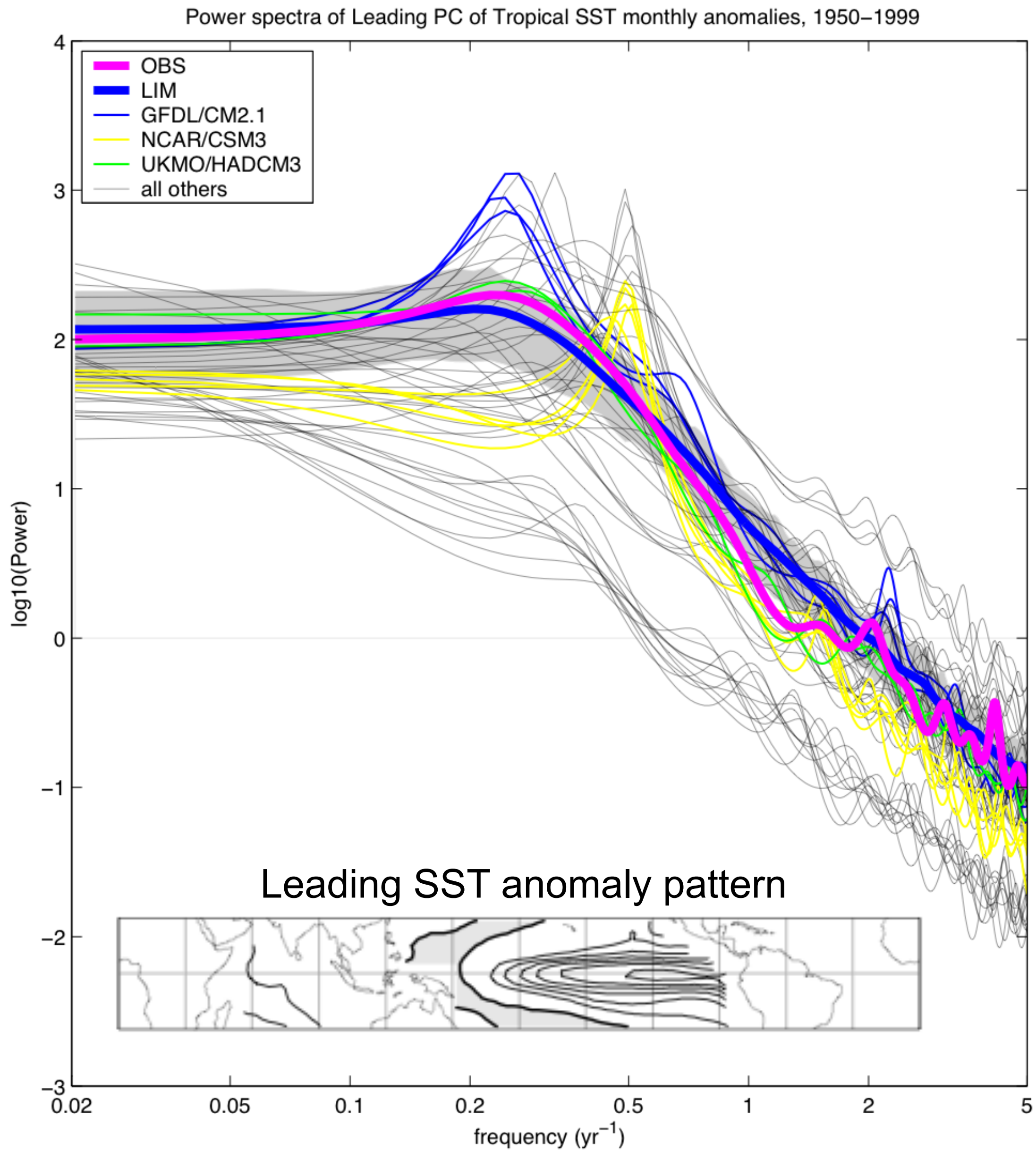
- ENSO and MJO: Two tropical phenomena that coupled GCMs need to get right
  - But do they?
- Diagnosis of dynamics via empirical model
  - Penland and Sardeshmukh (1995) Linear Inverse Model ("LIM")
- Tropical dynamics on weekly timescales
  - Atmosphere-SST model
- Tropical dynamics on seasonal timescales
  - Surface winds-Ocean model
- Key conclusion: linear stochastically-forced empirical model simulates large-scale tropical dynamics as well as fully nonlinear coupled GCMs

El Nino-Southern Oscillation (ENSO)

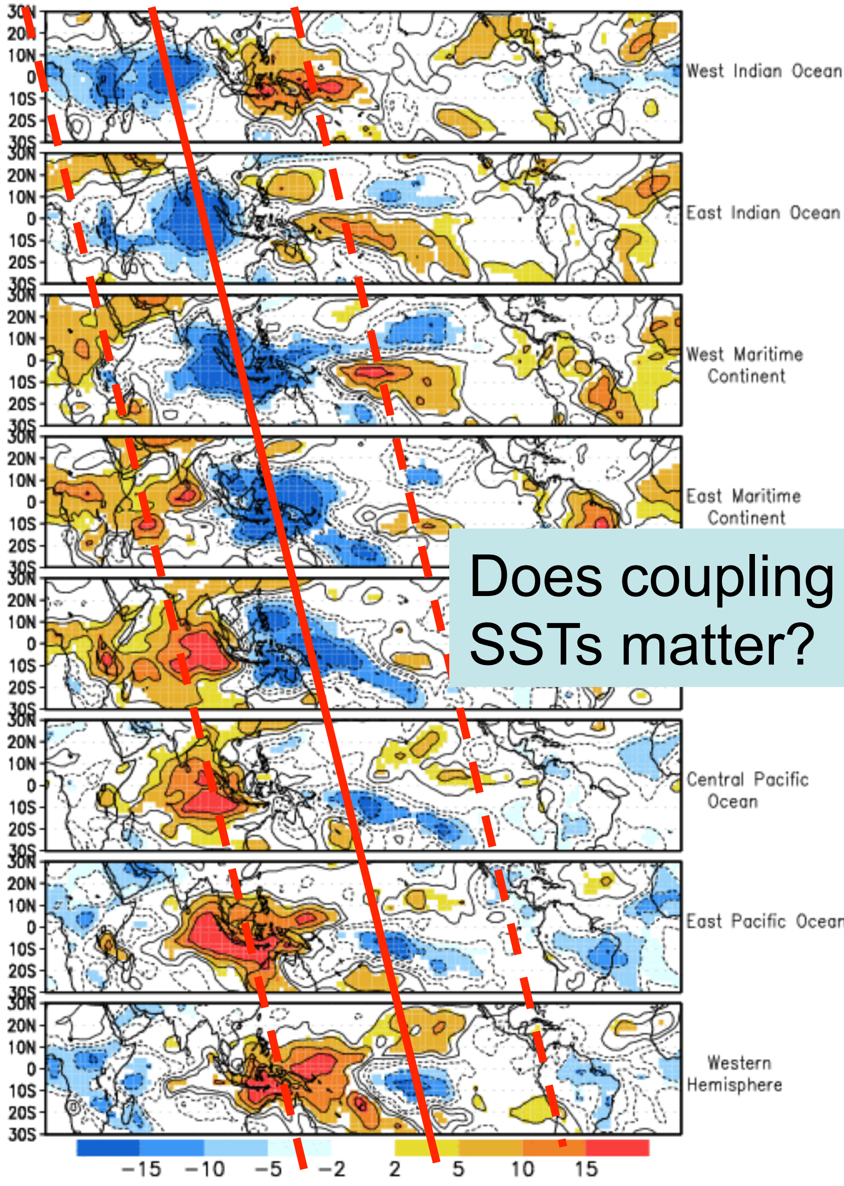
- Dominant mode of interannual atmosphere-ocean variability in Tropical Pacific, with 2-7 yrs spectral peak
- Oscillatory theories (driving thermocline to change sign)
  - Delayed oscillator (Kelvin/Rossby waves + western reflection)
  - Recharge/discharge oscillator (mass/warm water transport)
  - Advective/reflective oscillator (warm pool edge is advected)
  - Western pacific oscillator (Western pacific coupling)
- Episodic theories (precursor initiates development)



ENSO in IPCC AR4 "20th-century" CGCMs compared to observations, 1950-1999

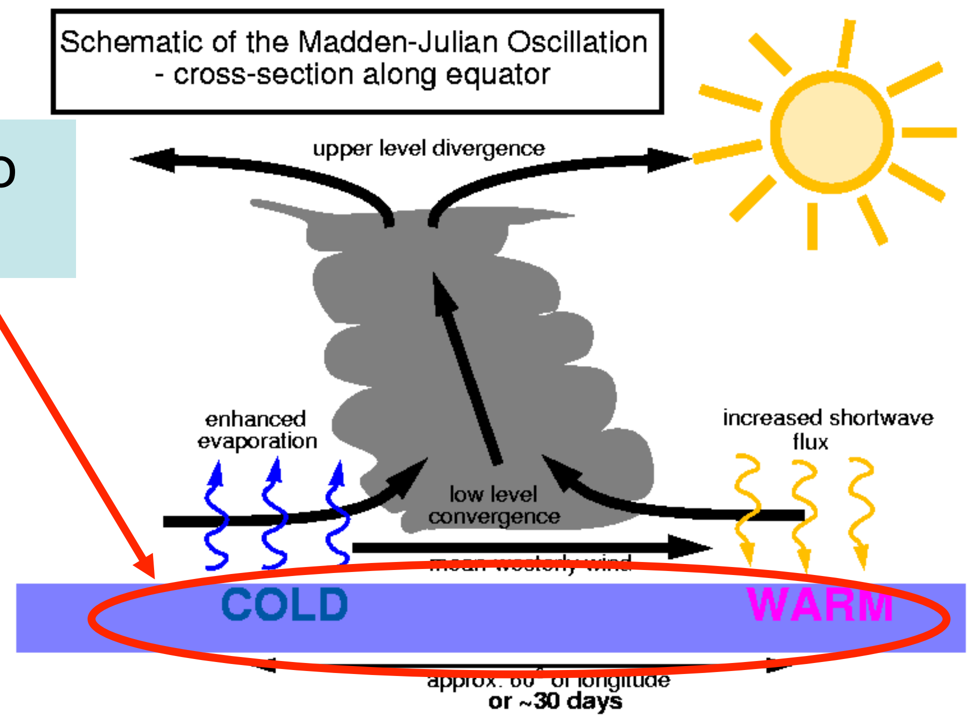


Madden-Julian Oscillation (MJO)



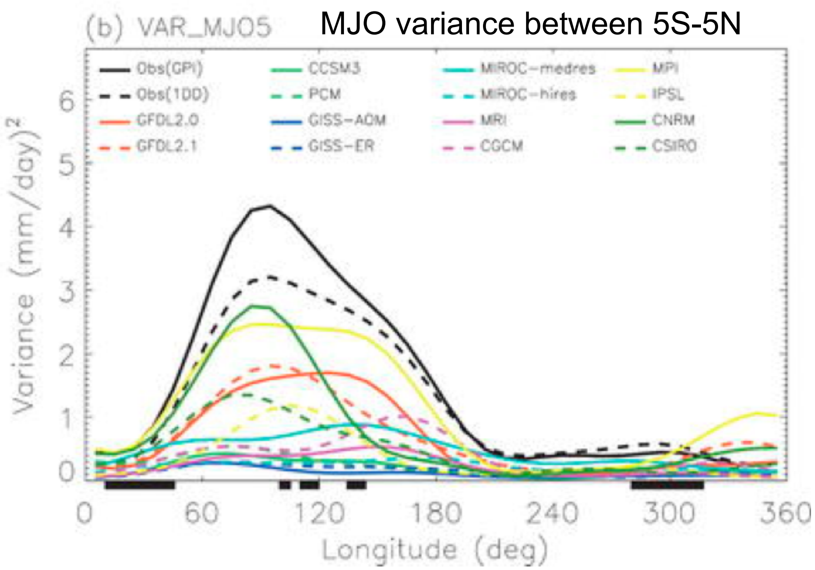
A broad area of active precipitation (blue) and suppressed precipitation (red) propagating eastwards around the equator at intervals ranging between about 30 to 60 days.

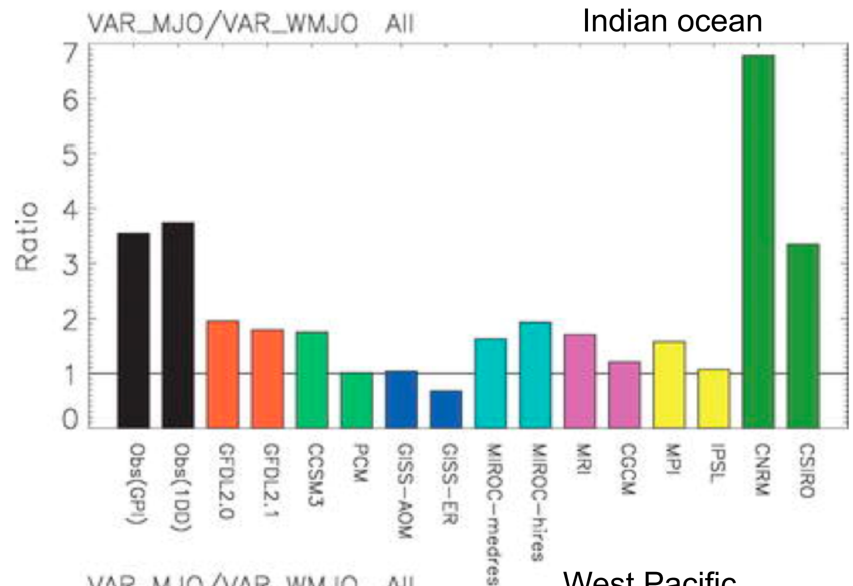
Does coupling to SSTs matter?

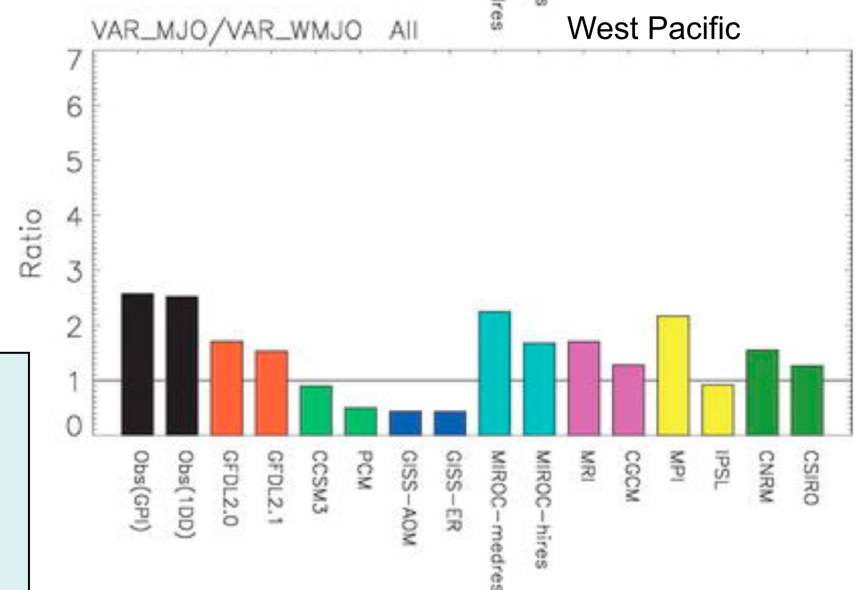


Courtesy Pete Inness

MJO in IPCC AR4 CGCMs







MJO in GCMs has errors in
- variance (too weak)
- eastward variance (too little)
- phase speed (too fast)
- vertical structure (not top heavy)

From Lin et al. (2006)

What are the GCMs missing?

- Is the problem in the AGCM and/or OGCM?
- Is the problem related to air-sea coupling?

How can we diagnosis this?

- theoretical models
- “intermediate complexity” models
- empirical models

Some requirements for an empirical model

- Capture the *evolution* of anomalies
  - Growth/decay, propagation
  - need anomaly tendency: *dynamical* model
  - Can relate to physics/processes and estimate predictability?
- Limited data + Occam's razor = not too complex
  - How many model parameters are enough?
  - Problem: is model fitting signal or noise?
  - Test on independent data (or at least cross-validate)
- Testable
  - Is the underlying model justifiable?
  - Where does it fail?

➔ Previous success of linear diagnosis/theory suggests potential usefulness of linear empirical model

Two types of linear approximations

- "Linearization" : *amplitude* of nonlinear term is small compared to *amplitude* of linear term
  - ➔ Then *ignore* nonlinear term
- "Coarse-grained" : *time scale* of nonlinear term is small compared to *time scale* of linear term
  - ➔ Then *parameterize* nonlinear term as (second) linear term + unpredictable white noise: **N(x) ~ Tx + ξ**

For example, surface heat fluxes due to rapidly varying weather driving the ocean might be approximated as

$$\frac{dT_o}{dt} = -\lambda T_o + \text{white noise}$$

(SST-only) Linear Inverse Models (LIMs)

Penland and Sardeshmukh (1995) suggested that tropical SST variability can be viewed as

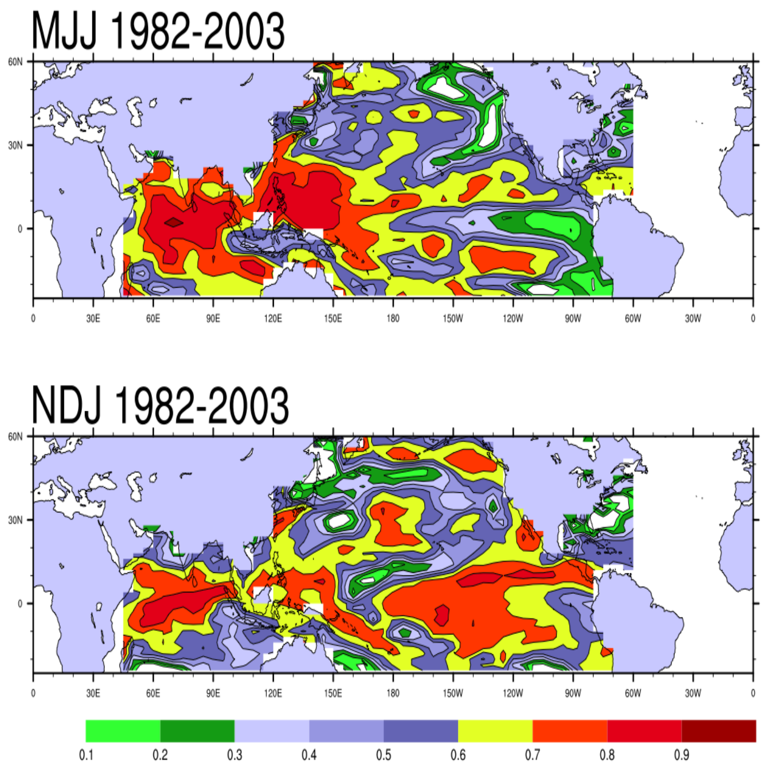
$$\frac{d\mathbf{T}_O}{dt} = \mathbf{L}\mathbf{T}_O + \mathbf{F}_s$$

$\mathbf{T}_O$ = SST (state vector) maps
L = stable linear dynamical operator
$\mathbf{F}_s$ = white noise

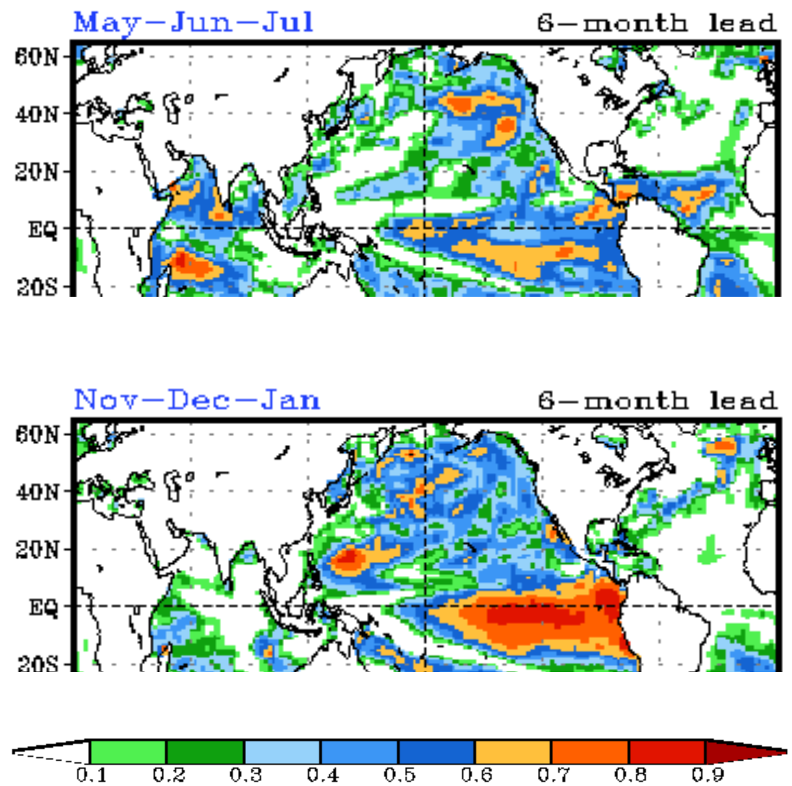
- "**Effectively linear**" -- stochastic approximation when decorrelation time scale of nonlinear processes << decorrelation time scale of linear processes
- Multivariate extension of univariate red noise (e.g., Frankignoul and Hasselmann)
- Determine **L** in an *inverse* sense through data analysis

Skill of SST forecasts from **SST-only LIM** is comparable to (bias-corrected) NCEP's **CFS** (NOAA's ENSO forecast GCM)

8-month LIM seasonal forecasts
(verified against HadISST SSTs)



6-month CFS seasonal forecasts
(verified against GODAS SSTs)



Coupled LIM ("C-LIM")

- State vector is atmosphere + SST
- Weekly time scales
- How important is air-sea coupling for ENSO and the MJO?

Linear inverse model (LIM)

x(t) = 47-component vector whose components are the time-varying coefficients (PCs) of the leading EOFs of:

20 T_o *SST*
7 Ψ *streamfunction*
17 H *heating*
3 χ *velocity potential*

L is thus a 47x47 matrix

Tropical (25^OS-25^ON) EOFs constructed from 7-day running mean anomalies, 1982-2005 (annual cycle removed)

Atmos: chi-corrected NCEP Reanalysis
SST: NCEP OI V2

Trained on 6-day lag

A multilinear system driven by white noise:

$$d\mathbf{x}/dt = \mathbf{L}\mathbf{x} + F_s$$

has τ_o-lag and zero-lag covariance related as

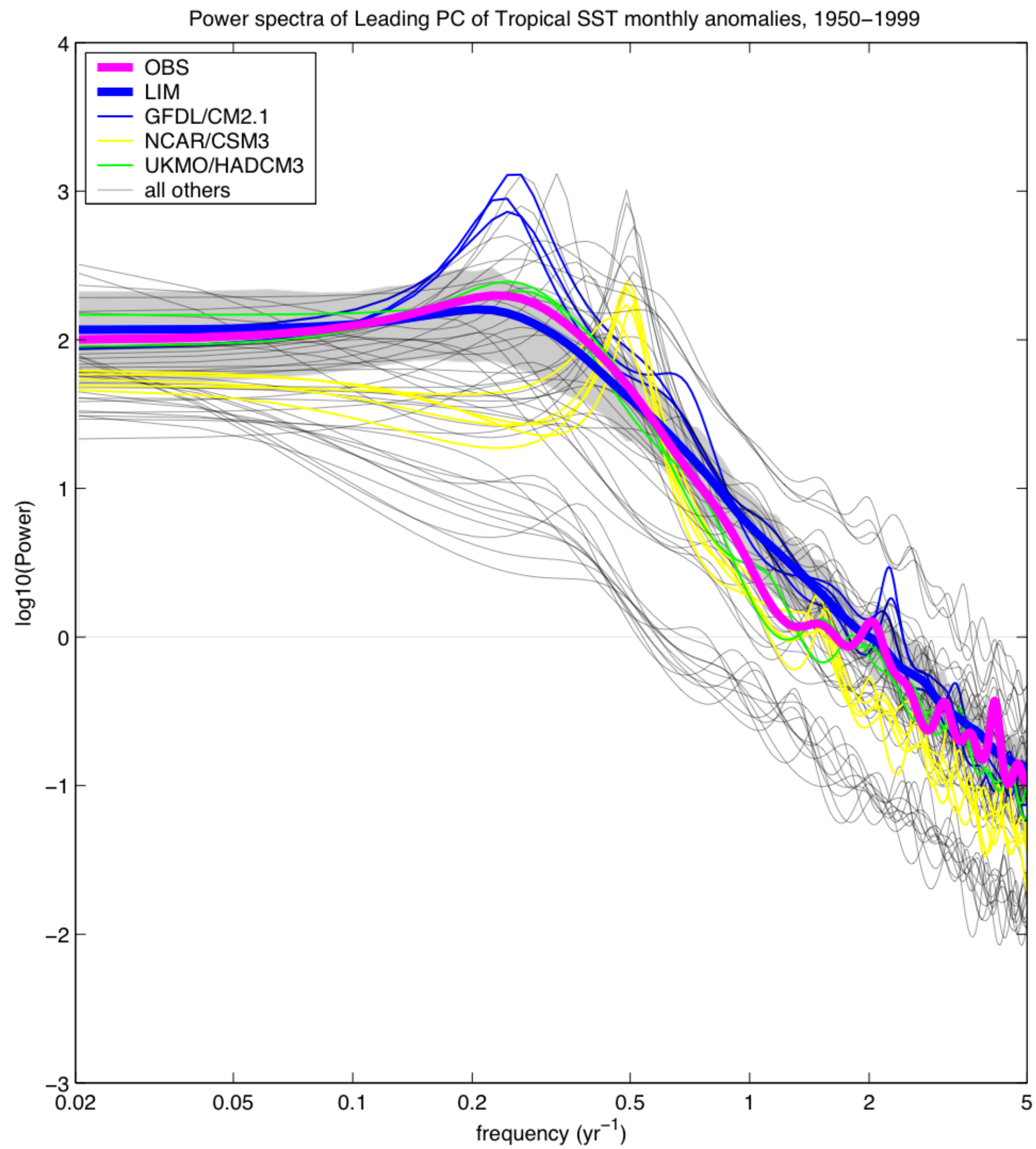
$$\mathbf{C}(\tau_o) = exp(\mathbf{L}\,\tau_o)\mathbf{C}(0) = \mathbf{G}(\tau_o)\mathbf{C}(0)$$

So we can determine **L** from data.
Test for linearity: $\mathbf{L} \neq f(\tau_o)$, $\mathbf{C}(\tau) = exp(\mathbf{L}\,\tau)\mathbf{C}(0)$

- Forecasts: $\mathbf{x}(t+\tau) = exp(\mathbf{L}\,\tau)\,\mathbf{x}(t) = \mathbf{G}(\tau)\,\mathbf{x}(t)$
- Eigenmodes (**u**) of **L** : $\mathbf{L}\mathbf{u} = \mathbf{u}\lambda$
- "Optimal" growth due to interference of *nonnormal* eigenmodes (λ can be complex)

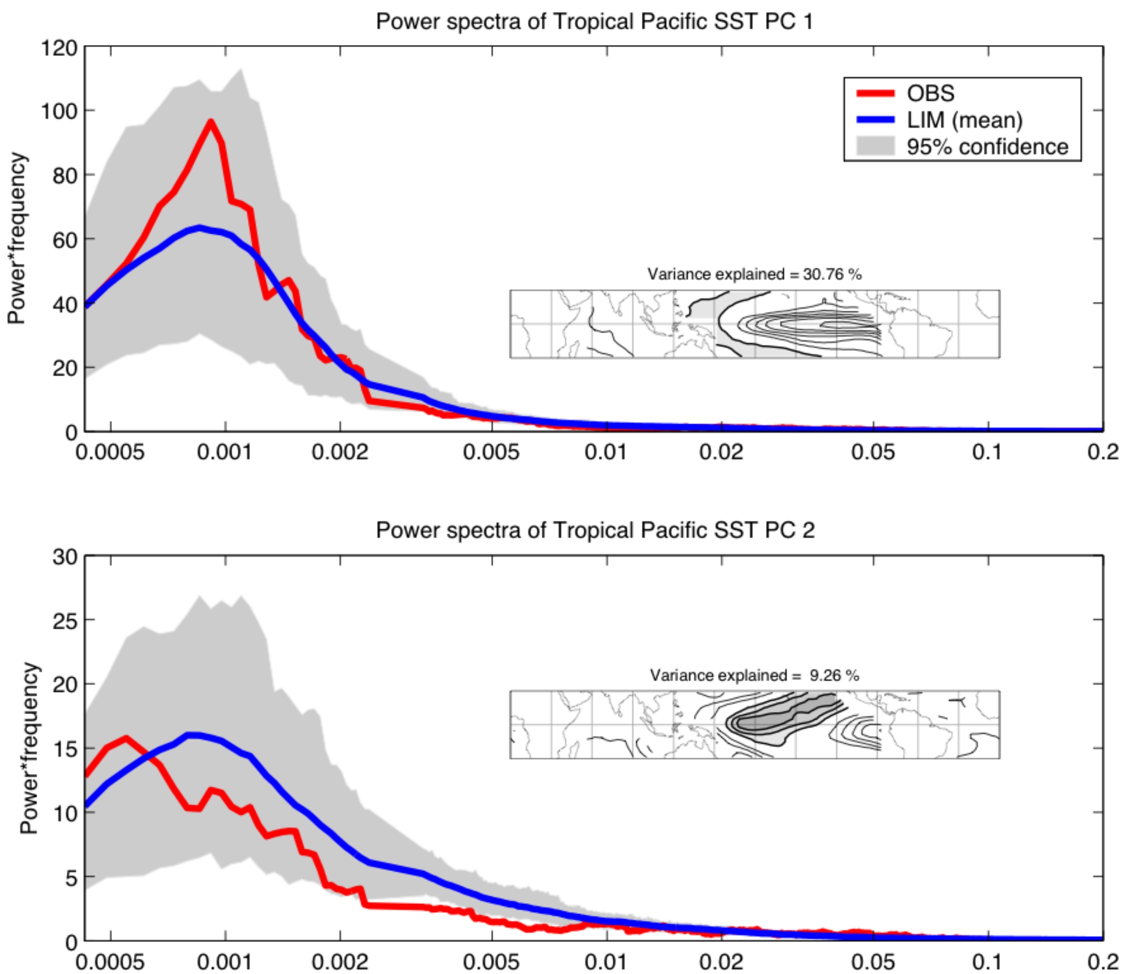
ENSO in C-LIM and IPCC AR4 “20th-century” CGCMs compared to observations, 1950-1999

C-LIM simulation of observed variability is just as good as in coupled GCMs, so we can use it to reliably quantify coupling effects.



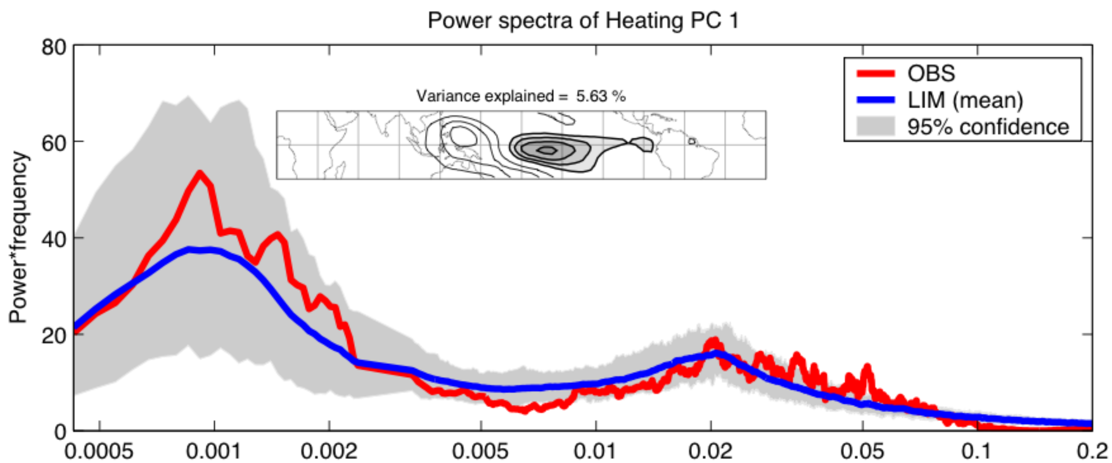
Test of linearity

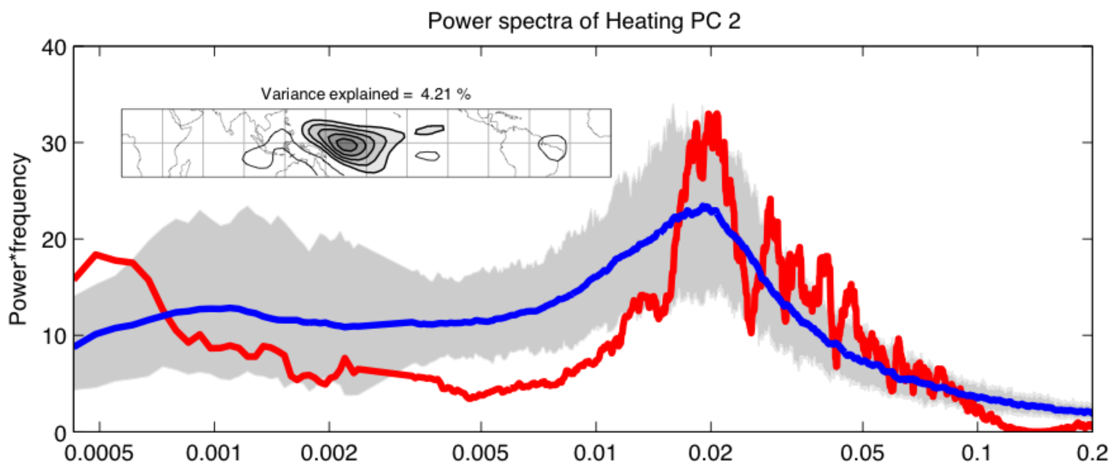
C-LIM predictions of SST spectra



Test of linearity

C-LIM predictions of heating spectra





What are the effects of the SST-atmosphere coupling?

Turn "off" coupling

LIM can be written in its component parts as:

$$\frac{d\mathbf{x}}{dt} = \frac{d}{dt}\begin{bmatrix}\mathbf{T}_O \\ \mathbf{x}_A\end{bmatrix} = \begin{bmatrix}\mathbf{L}_{OO} & \mathbf{L}_{AO} \\ \mathbf{L}_{OA} & \mathbf{L}_{AA}\end{bmatrix}\begin{bmatrix}\mathbf{T}_O \\ \mathbf{x}_A\end{bmatrix} + \begin{bmatrix}\text{SST noise} \\ \text{atmospheric noise}\end{bmatrix}$$

To "uncouple" ocean from atmosphere, define

$$\mathbf{L}_{uncoupled} = \begin{bmatrix}\mathbf{L}_{OO} & \mathbf{0} \\ \mathbf{0} & \mathbf{L}_{AA}\end{bmatrix}$$

This is *not* the same as constructing separate A-LIMs and O-LIMs.

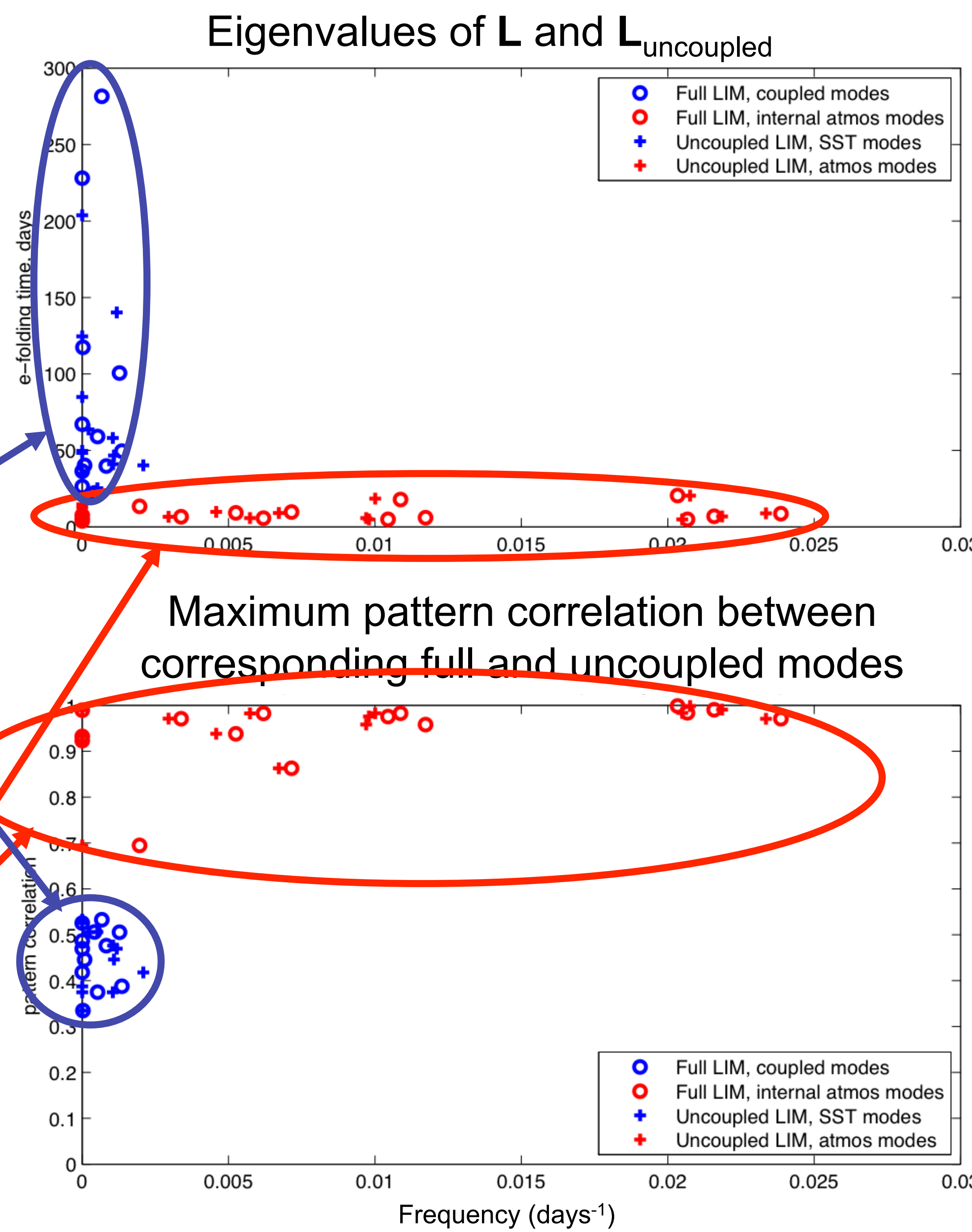
Removing coupling: greatly decreases interannual power
almost no effect on intraseasonal power

Comparing L and $L_{uncoupled}$

Two distinct classes of eigenmodes of L

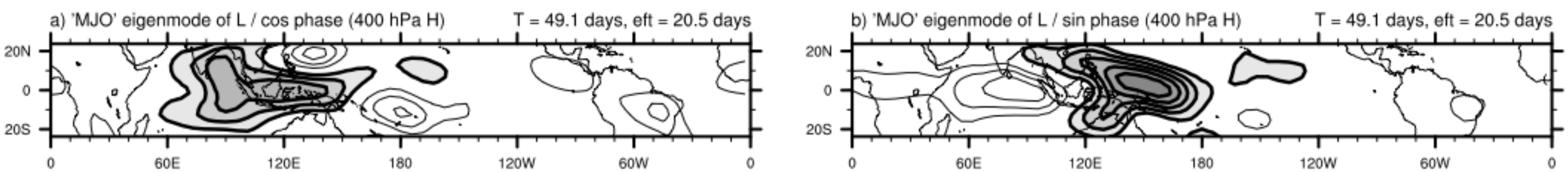
<u>"coupled"</u>
Longer eft, low frequency modes strongly modified by coupling

<u>"internal atmospheric"</u>
Short eft, high frequency modes very slightly modified by coupling

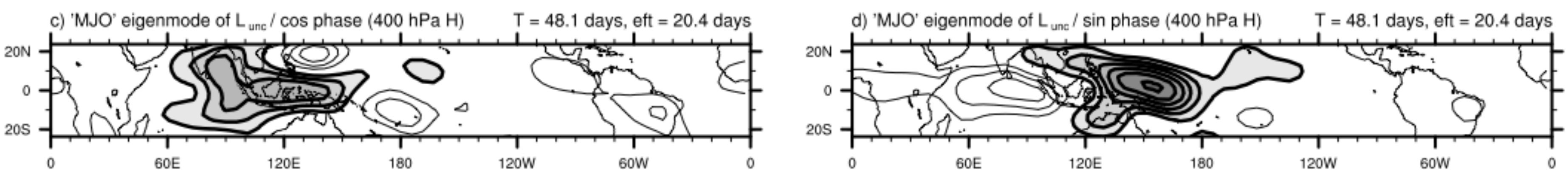


Coupling has minor effect on leading internal (MJO-like) eigenmode

“MJO” eigenmode, full operator



“MJO” eigenmode, uncoupled operator



Project tropical state vector **x** into "coupled" and "internal" subspaces of full operator **L**

Define

$$\mathbf{x} = \mathbf{x}^{\text{coup}} + \mathbf{x}^{\text{int}}$$

where

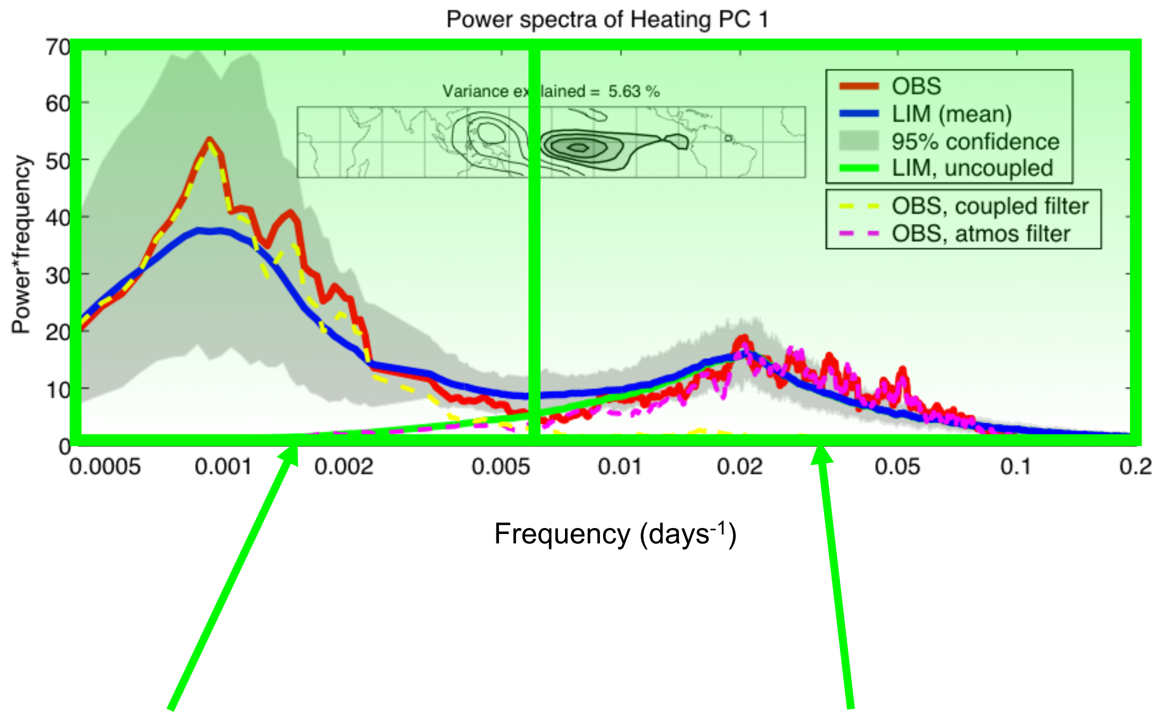
$$\mathbf{x}^{\text{coup}} = \sum_j \mathbf{u}_j^{\text{coup}} \alpha_j^{\text{coup}}(t) \qquad \mathbf{x}^{\text{int}} = \sum_j \mathbf{u}_j^{\text{int}} \alpha_j^{\text{int}}(t)$$

Note: $\mathbf{x}^{\text{coup}}$ and $\mathbf{x}^{\text{int}}$ need not be orthogonal

Projection on coupled and internal modes

Heating PC 1: Coupled and internal spaces do not overlap ➔

"ENSO" and "MJO" variance can be separated



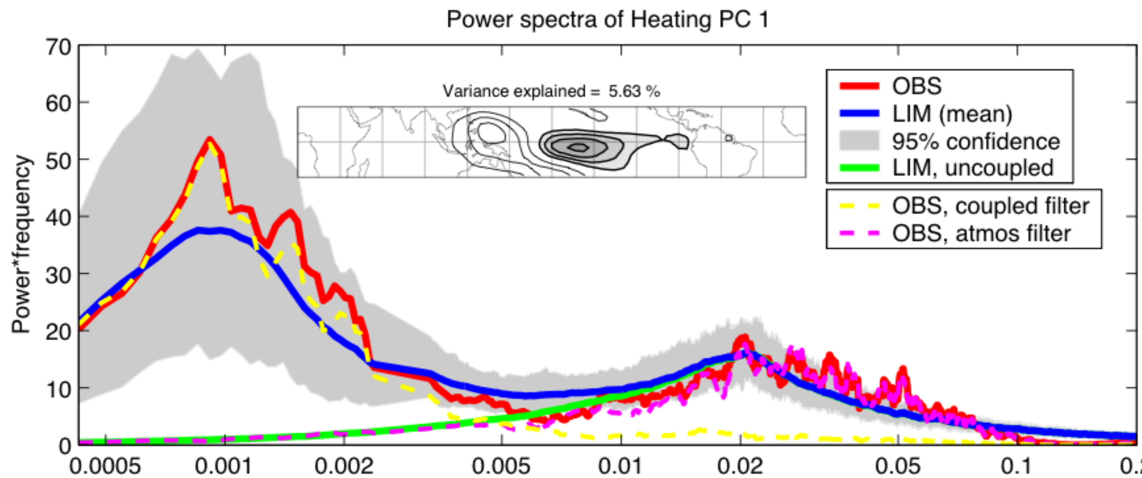
Variability in coupled space

Variability in internal space

Projection on coupled and internal modes

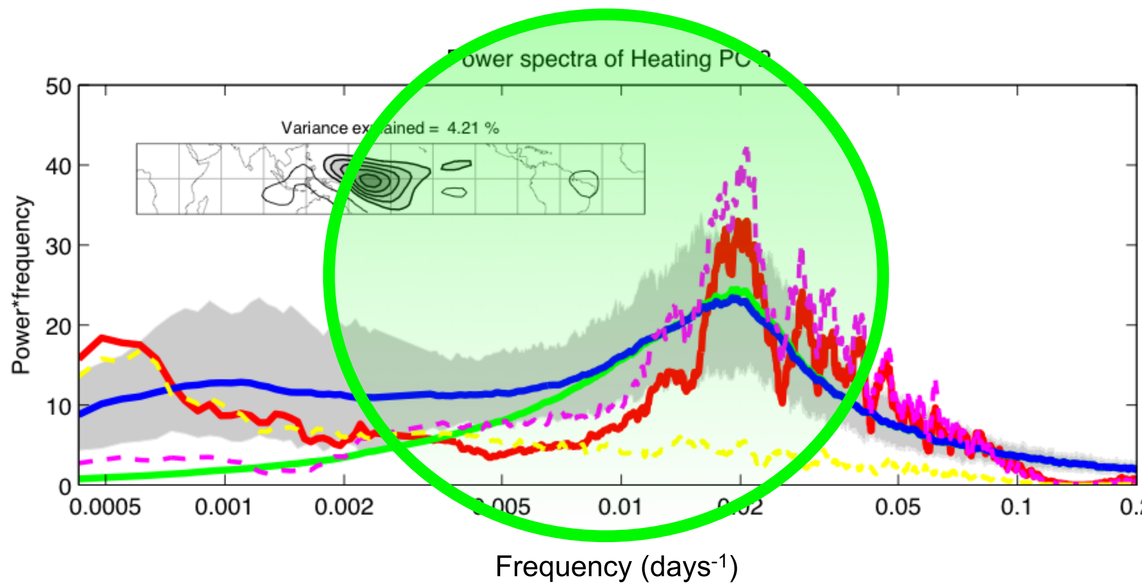
Heating PC 1: Coupled and internal spaces do not overlap ➔

“ENSO” and “MJO” variance can be separated



Heating PC 2: Coupled and internal spaces overlap ➔

“ENSO” and “MJO” variance cannot be separated



Conclusions (part I)

- C-LIMs useful for diagnosis of tropical air-sea coupling
  - Forecast skill competitive with coupled GCMs (C-LIM forecasts: http://www.cdc.noaa.gov/forecasts/clim/)
  - Reproduces observed spatio-temporal statistics, even on much longer time periods
- In Tropics, two nonorthogonal linear dynamical systems:
  - Slow (~interannual) coupled space
  - Fast (~intraseasonal) internal atmosphere space
- MJO: an internal atmospheric phenomenon only weakly coupled to SST
- Why, then, does coupling in GCMs affect MJO?
  - Impacts MJO anomalies through changes in *mean* climate
  - May improve ENSO-related evolution confused with MJO

One drawback: these LIMs generally use SST (T_o) as a proxy for the entire ocean.

This is ok if the remaining ocean state vector Z is

$$\mathbf{Z} = \mathbf{B}\mathbf{T}_o + \text{white noise}$$

since then the **Z**-dependence of $\mathbf{T}_o$ is implicit.

Even then: how do we interpret an SST-only LIM?

Extended LIM

- State vector is SST + thermocline + wind stress
- Seasonal time scales
- How do longer subsurface time scales matter in SST LIM?

Extending LIM to the thermocline

A multilinear system driven by white noise:

$$d\mathbf{x}/dt = \mathbf{Lx} + F_s$$

has τ_o-lag and zero-lag covariance related as

$$\mathbf{C}(\tau_o) = exp(\mathbf{L}\,\tau_o)\mathbf{C}(0) = \mathbf{G}(\tau_o)\mathbf{C}(0)$$

So we can determine **L** from data.
Test for linearity: $\mathbf{L} \neq f(\tau_o)$, $\mathbf{C}(\tau) = exp(\mathbf{L}\,\tau)\mathbf{C}(0)$

- Forecasts: $\mathbf{x}(t+\tau) = exp(\mathbf{L}\,\tau)\,\mathbf{x}(t) = \mathbf{G}(\tau)\,\mathbf{x}(t)$
- Eigenmodes (**u**) of **L** : $\mathbf{Lu} = \mathbf{u}\lambda$
- "Optimal" growth : Eigenvectors of $\mathbf{GDG}^T$

x(t) = 23-component vector whose components are the time-varying coefficients (PCs) of the leading EOFs of:

13 T_O	*SST*
7 Z_{20}	*20°C depth*
3 τ_x	*zonal wind stress*

L is thus a 23x23 matrix

("SST-only": 23 T_O)

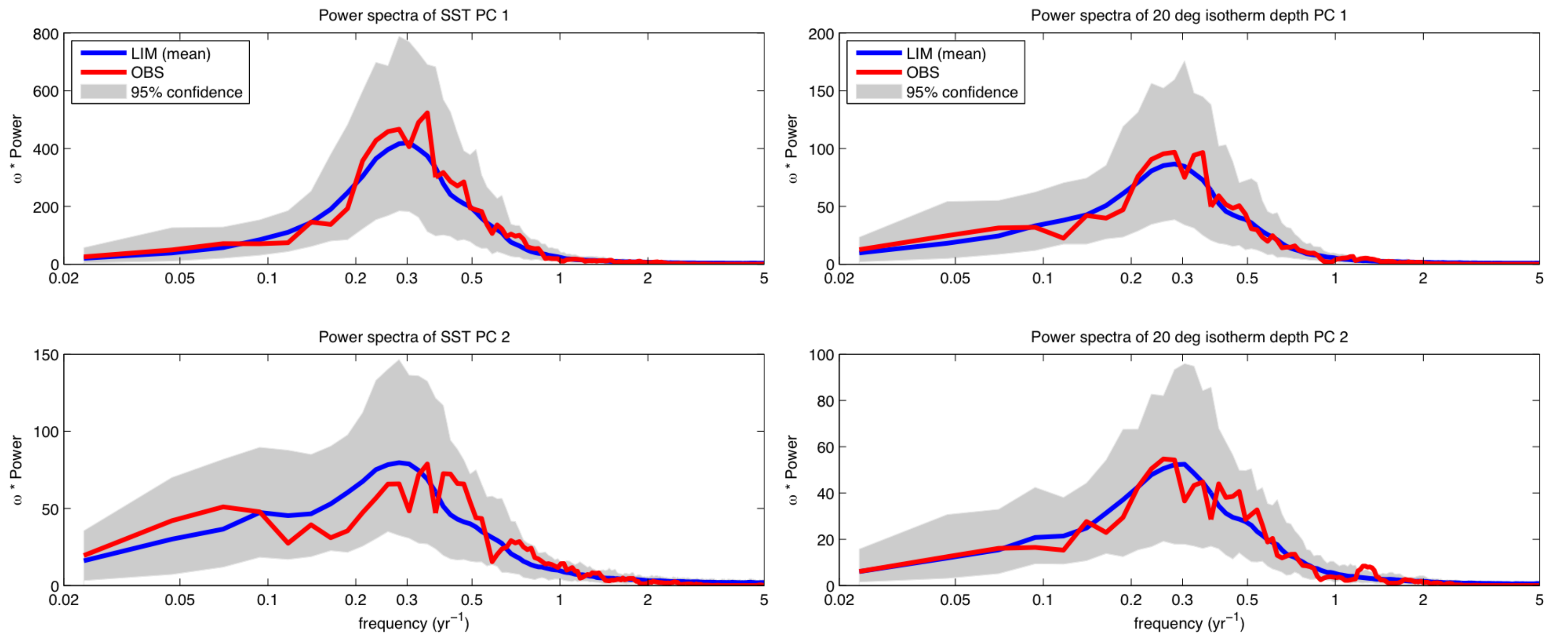
Tropical (25°S-25°N) EOFs constructed from 3-month running mean anomalies, 1959-2000 (annual cycle removed)

SST: HadISST
Depth: SODA
Wind stress: NCEP/NCAR Reanalysis

Trained on 3-month lag

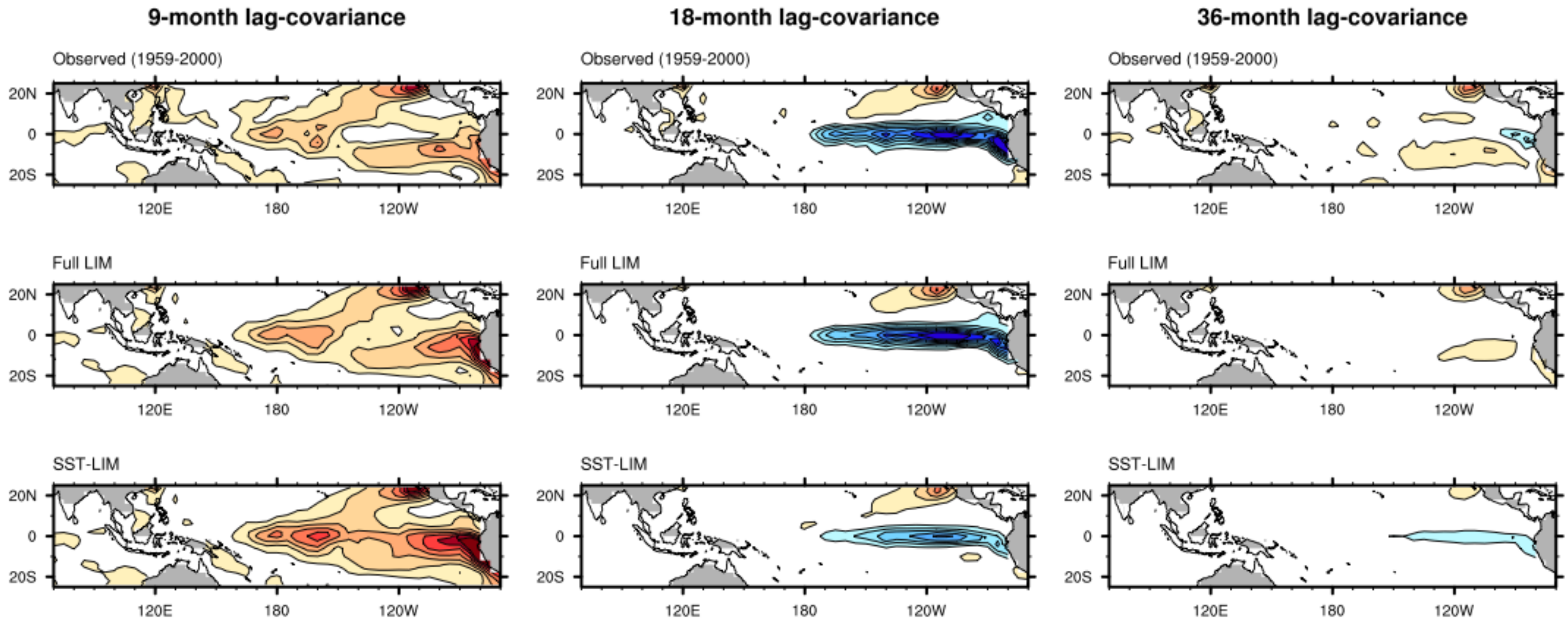
Test of linearity

LIM prediction of SST, Z_{20} spectra for 1959-2000



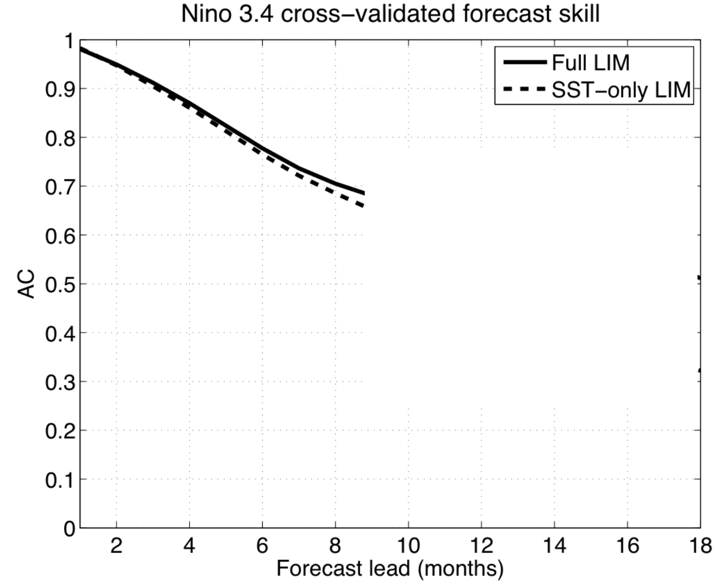
Adding thermocline depth to an SST-only LIM improves statistics of the **simulation of SST anomaly evolution** (lag-covariability).

Red = positive (persistence) Blue = negative

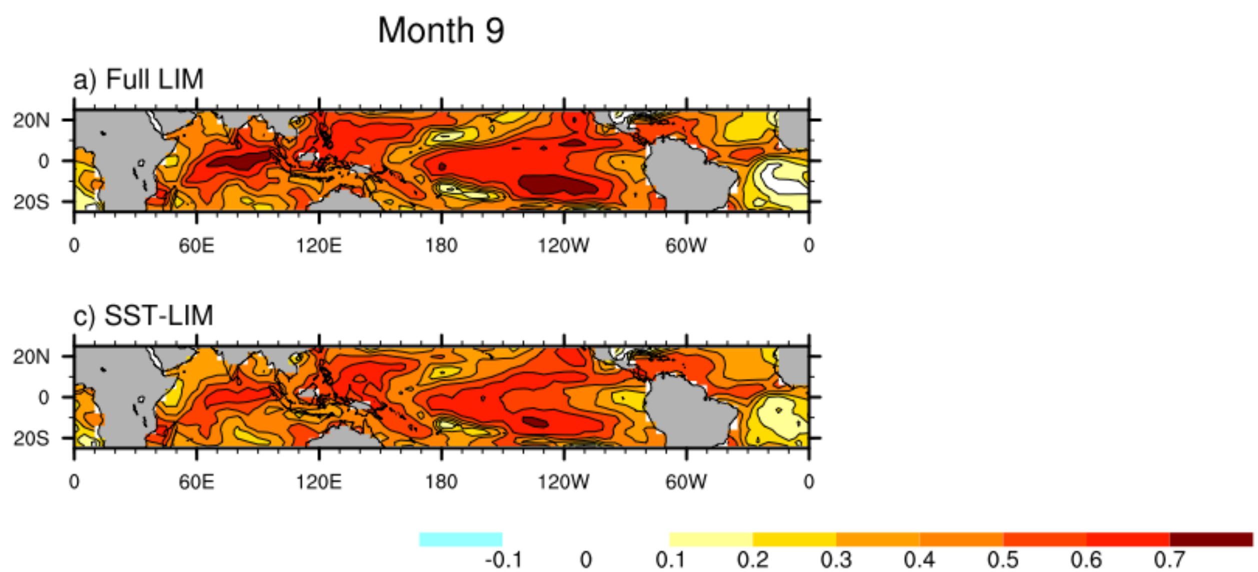


From Newman, Alexander, and Scott (2009)

Adding thermocline depth to an SST-only LIM has a **small effect** on **medium-range (<9 months) forecast skill** both in the Nino3.4 region (right) and throughout the tropical Pacific (below).

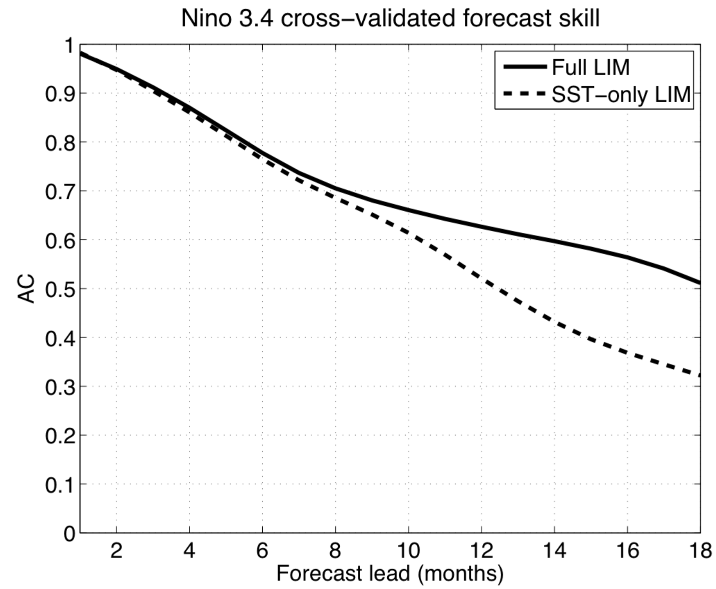


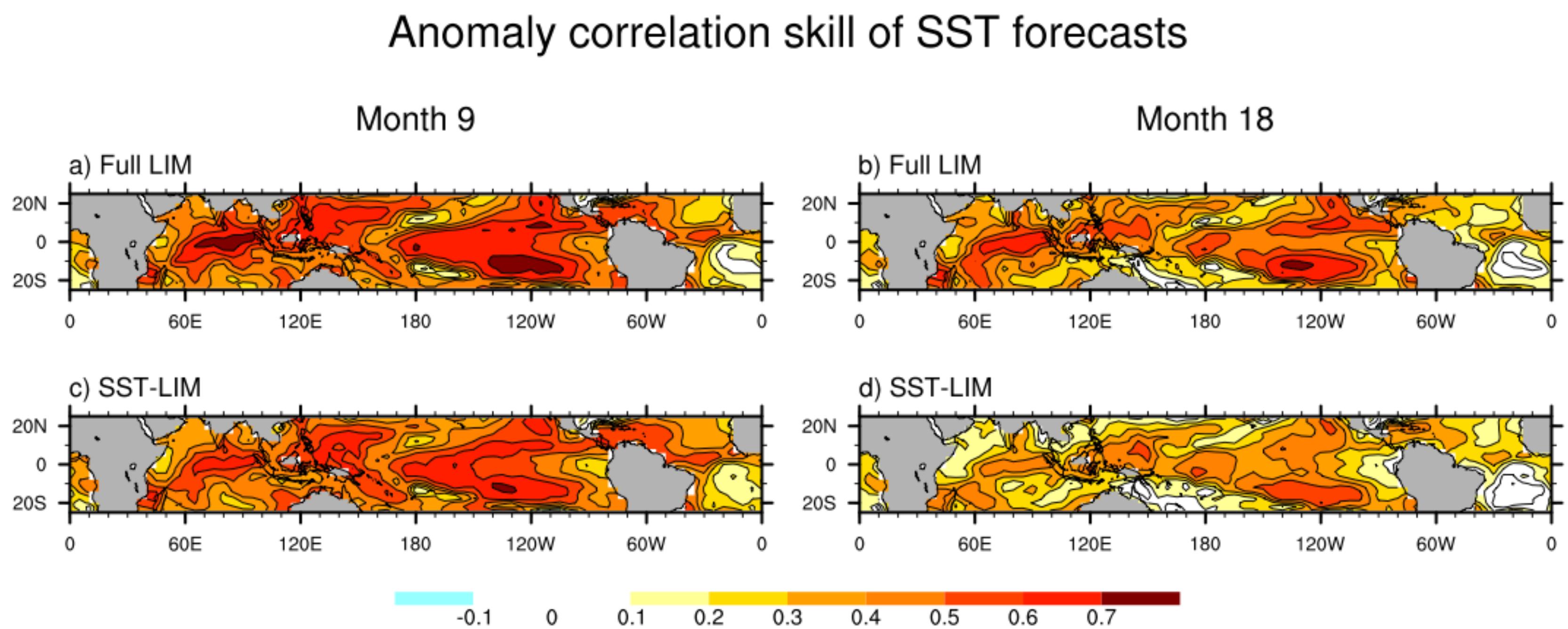
Anomaly correlation skill of SST forecasts



From Newman, Alexander, and Scott (2009)

However, adding thermocline depth to an SST-only LIM **improves long-range forecast skill** both in the Nino3.4 region (right) and throughout the tropical IndoPacific (below).

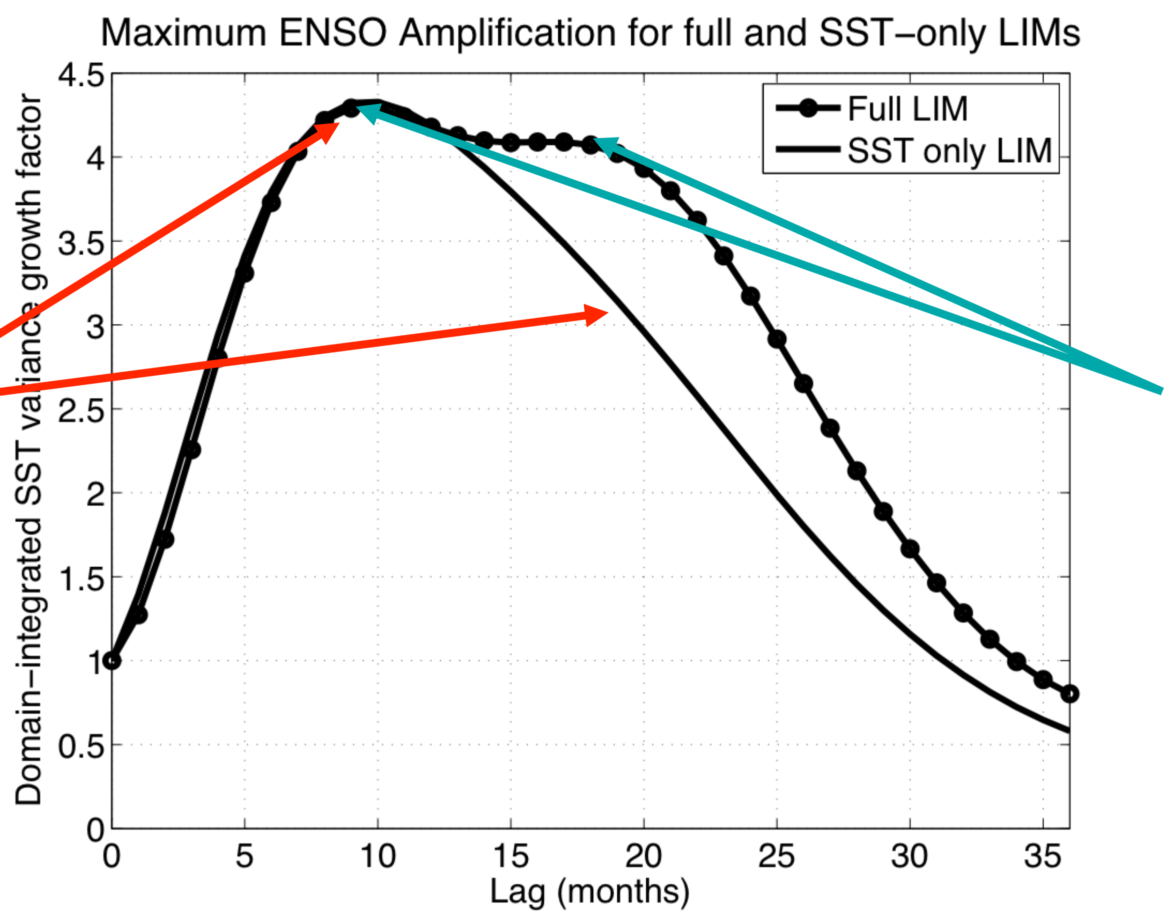




From Newman, Alexander, and Scott (2009)

Adding thermocline depth to SST-only LIM **changes the nature of “optimal” anomaly growth for time intervals > 9 months**

These represent the same optimal structure.



These represent different optimal structures.

Loop: evolution from 9-month and 18-month optimal structures

Diagnosing ocean processes in the LIM

LIM can be written in its component parts as:

$$\frac{d\mathbf{x}}{dt} = \frac{d}{dt}\begin{bmatrix} \mathbf{T}_O \\ \mathbf{Z}_{20} \\ \tau_x \end{bmatrix} = \begin{bmatrix} \mathbf{L}_{TT} & \mathbf{L}_{ZT} & \mathbf{L}_{\tau T} \\ \mathbf{L}_{TZ} & \mathbf{L}_{ZZ} & \mathbf{L}_{\tau Z} \\ \mathbf{L}_{T\tau} & \mathbf{L}_{Z\tau} & \mathbf{L}_{\tau\tau} \end{bmatrix}\begin{bmatrix} \mathbf{T}_O \\ \mathbf{Z}_{20} \\ \tau_x \end{bmatrix} + \begin{bmatrix} \text{sst noise} \\ \text{thermocline noise} \\ \text{wind stress noise} \end{bmatrix}$$

We can then diagnose how different terms impact dynamics:

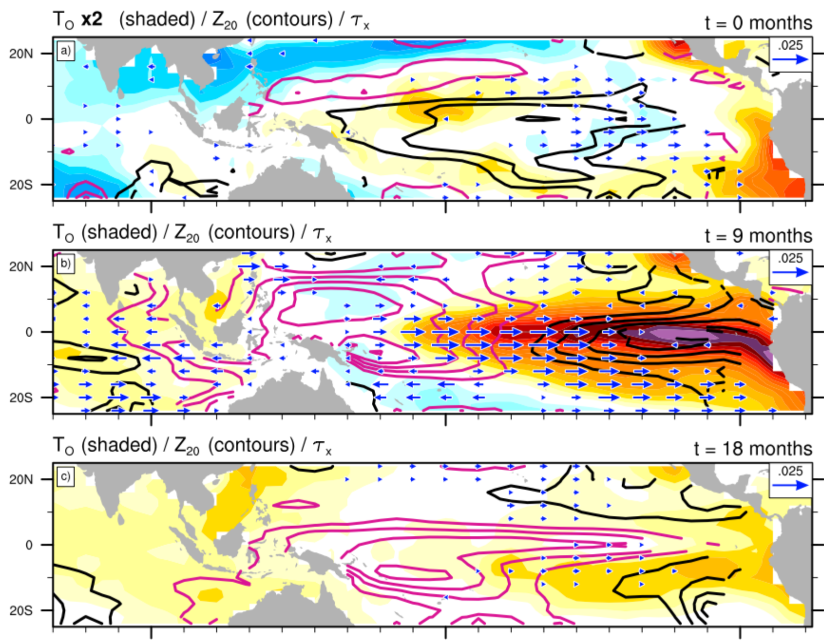
$$\frac{d\mathbf{T}_O}{dt} = \mathbf{L}_{TT}\mathbf{T}_O + \mathbf{L}_{ZT}\mathbf{Z}_{20} + \mathbf{L}_{\tau T}\tau_x + \text{sst noise}$$

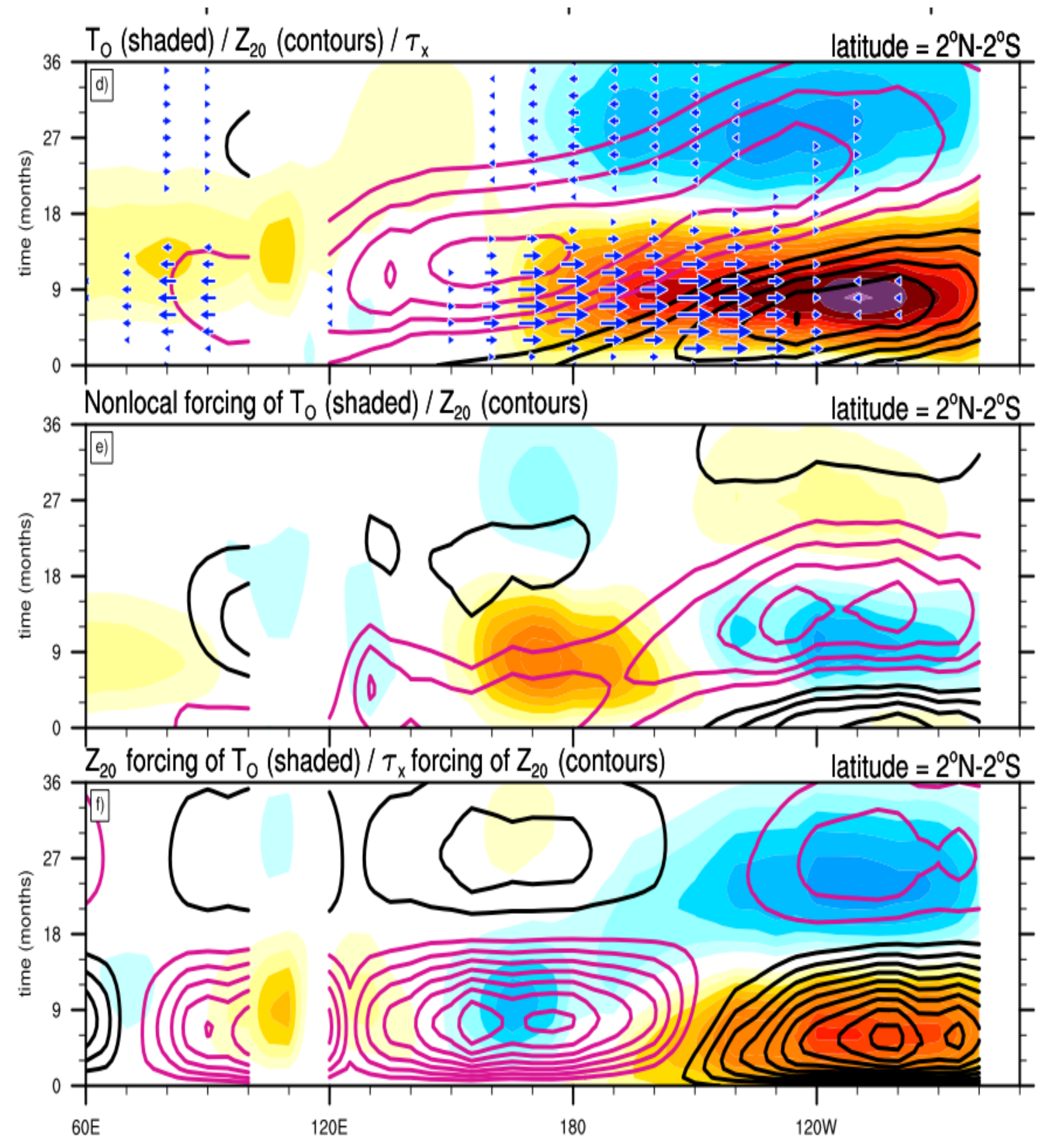
This has both local (damping) and non-local (advection, eddy mixing) parts

This includes local thermocline and upwelling feedbacks, and non-local advective feedback

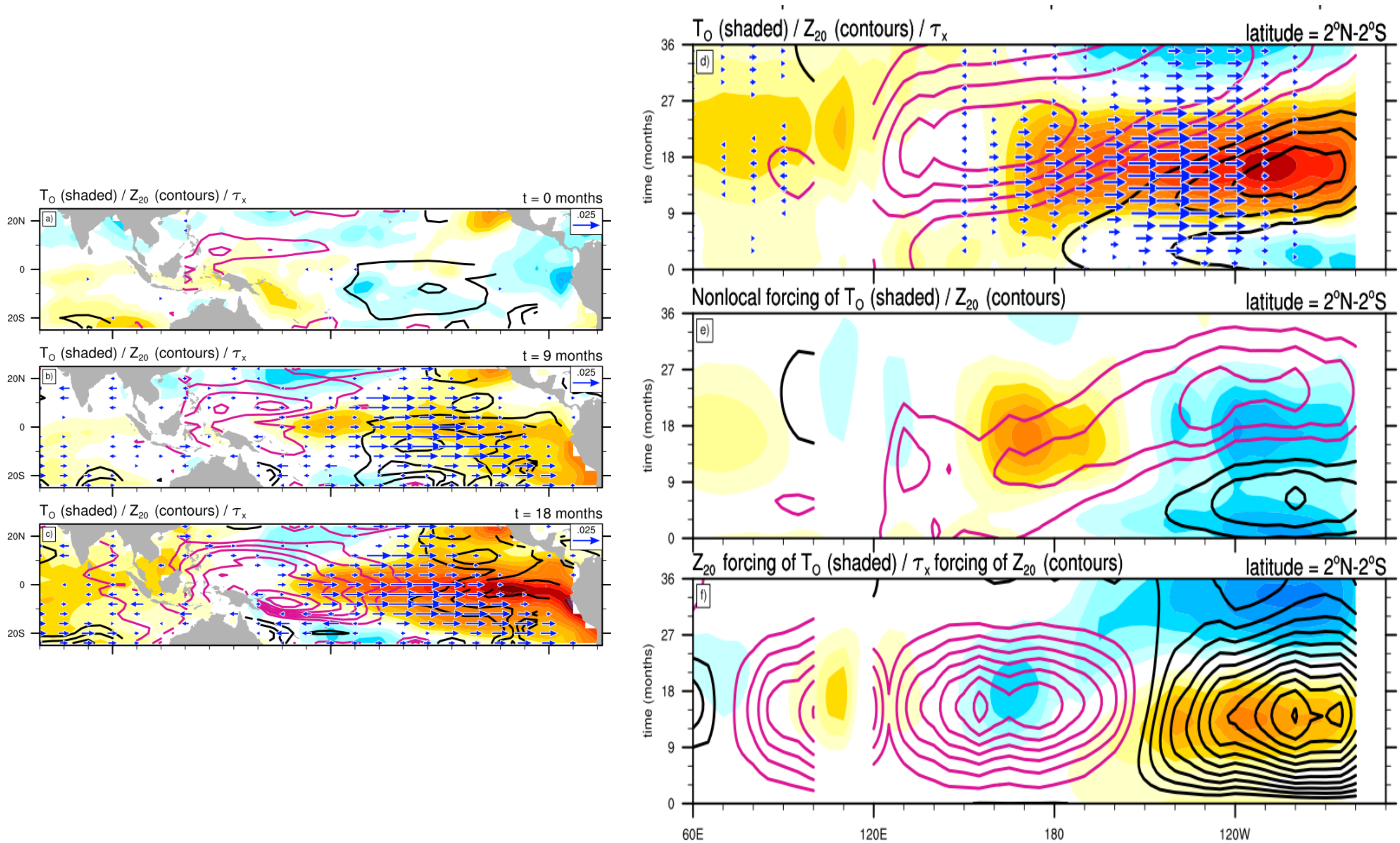
Stand-in for turbulent and radiative heat fluxes?

Evolution from 9-month optimal structure





Evolution from 18-month optimal structure



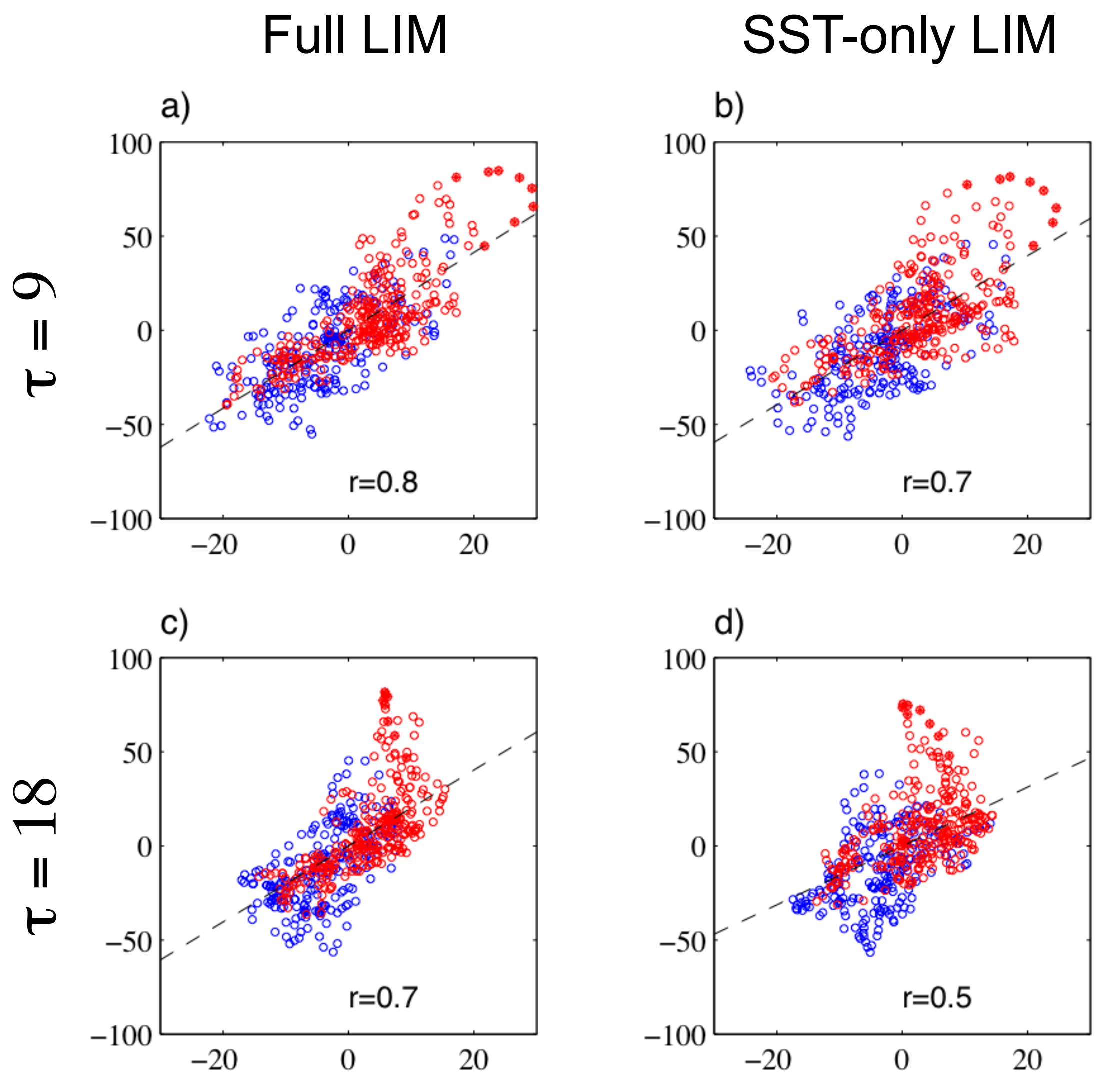
Adding thermocline depth to SST-only LIM **improves relevance of "optimal" anomaly structures**

Panels show

projection of data on optimal initial condition

vs.

projection of data on final "evolved" anomaly



Key eigenmodes contributing to optimal growth (loop)

Conclusions (part II)

- Adding thermocline depth to SST-only LIM improves linear model on longer time scales
  - Enhanced forecast skill (predictability limit?)
  - Statistics of anomaly evolution better simulated
  - “New” optimal anomaly growth over > 9 months
- LIM can be used to diagnose ENSO dynamics
  - Optimal growth due to a few stable eigenmodes
  - Details of wind response to SST crucial
- Full “climate” LIMs possible?
  - from observations (maybe)
  - from GCMs (for diagnosis)