How important are ENSO and the MJO to tropical subseasonal predictability?

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Use Linear Inverse Model (LIM) to *make predictions* and *diagnose predictability*

Empirically model the *evolution* of climate anomalies with the linear stochastically forced dynamical system

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

$\mathbf{x}(t)$: series of maps, $\mathbf{L}$: stable operator, $\mathbf{F}_s$: white noise (also maps) that could be linearly dependent on $\mathbf{x}$

- **Linear model, not linearization of equations**: characterize predictable dynamics in nonlinear system
- **Multivariate, not univariate, nonnormal linear dynamics:** anomalies can growth and evolve
- (Ensemble mean) forecasts for lead τ : $\mathbf{x}(t+\tau) = exp(\mathbf{L}\tau)\mathbf{x}(t)$; ensemble spread due to $\mathbf{F}_s$
- "Forecast the forecast skill": based on forecast signal-to-noise

Low-order model (prefiltered in EOF space: <100% variance retained)
Determine LIM from 0 and 1-lag covariance of **x** [$\mathbf{C}(1)\mathbf{C}(0)^{-1}$, as in AR1 model]
Hindcasts: determined from ten-fold cross-validation, verification data *not* EOF filtered
Simplifications: assume noise is independent of ***x****, fixed* ***L*** *over analysis dataset*

We will use LIM here to:

1) Benchmark forecast skill of numerical dynamical models
2) Diagnose important dynamical processes, especially coupling
3) Estimate predictability (that is, predictable variations of skill)

In LIM: maximum forecast signal leads to maximum forecast skill

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

$\mathbf{L}$ = constant, $\mathbf{F}_s$ = additive (state-independent) noise.

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

"signal"

"noise"

Expected forecast error covariance

(assuming no initial error) :

$$\mathbf{E}(\tau) = \langle \varepsilon\varepsilon^{\mathrm{T}} \rangle = \mathbf{C}(0) - \mathbf{G}\,\mathbf{C}(0)\,\mathbf{G}^{\mathrm{T}}$$

Expected forecast anomaly correlation

$$\rho_{\infty} = \frac{s}{\sqrt{1+s^2}}, \text{ where } s^2 = \frac{[\mathbf{G}\,\mathbf{C}(0)\,\mathbf{G}^{\mathrm{T}}]_{ii}}{[\mathbf{E}(\tau)]_{ii}}$$

Larger signal related to "optimal" perturbation
[leading singular vector of G(τ)]

Tropical "C-LIM"

"C-LIM": 5-day running mean tropical anomalies (1982-2011)

Ocean: ***SST/20°C isotherm depth***

Atmosphere: ***OLR/200&850 mb wind***

Low-order model (prefiltered in reduced EOF space)

Determine LIM from 0 and 5-day lag covariance of **x** (as in AR1 model)

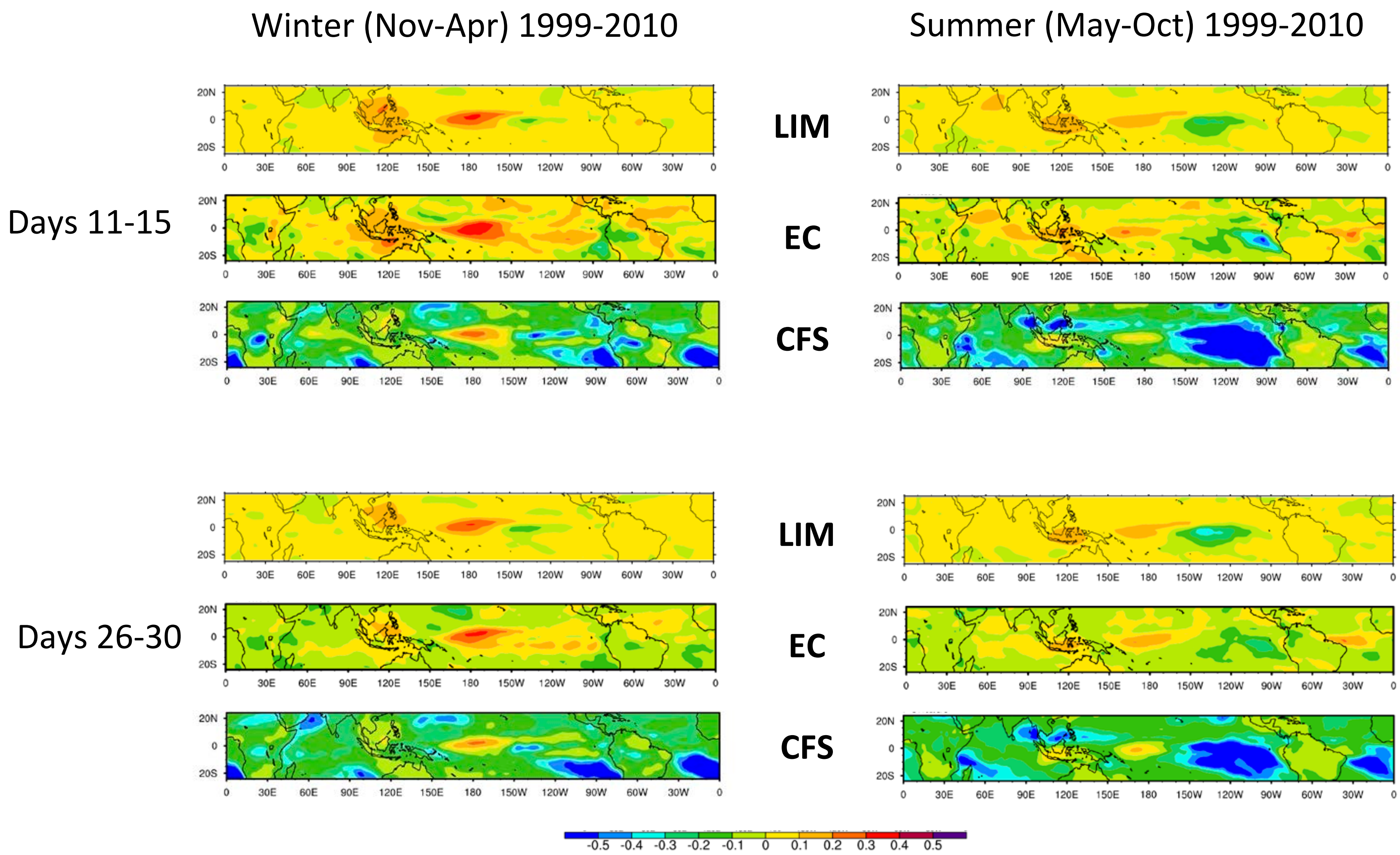
Hindcasts: determined from cross-validation (10% data withheld)

Run at CPC as part of guidance used in Weeks 3/4 product

"C-LIM2.0"

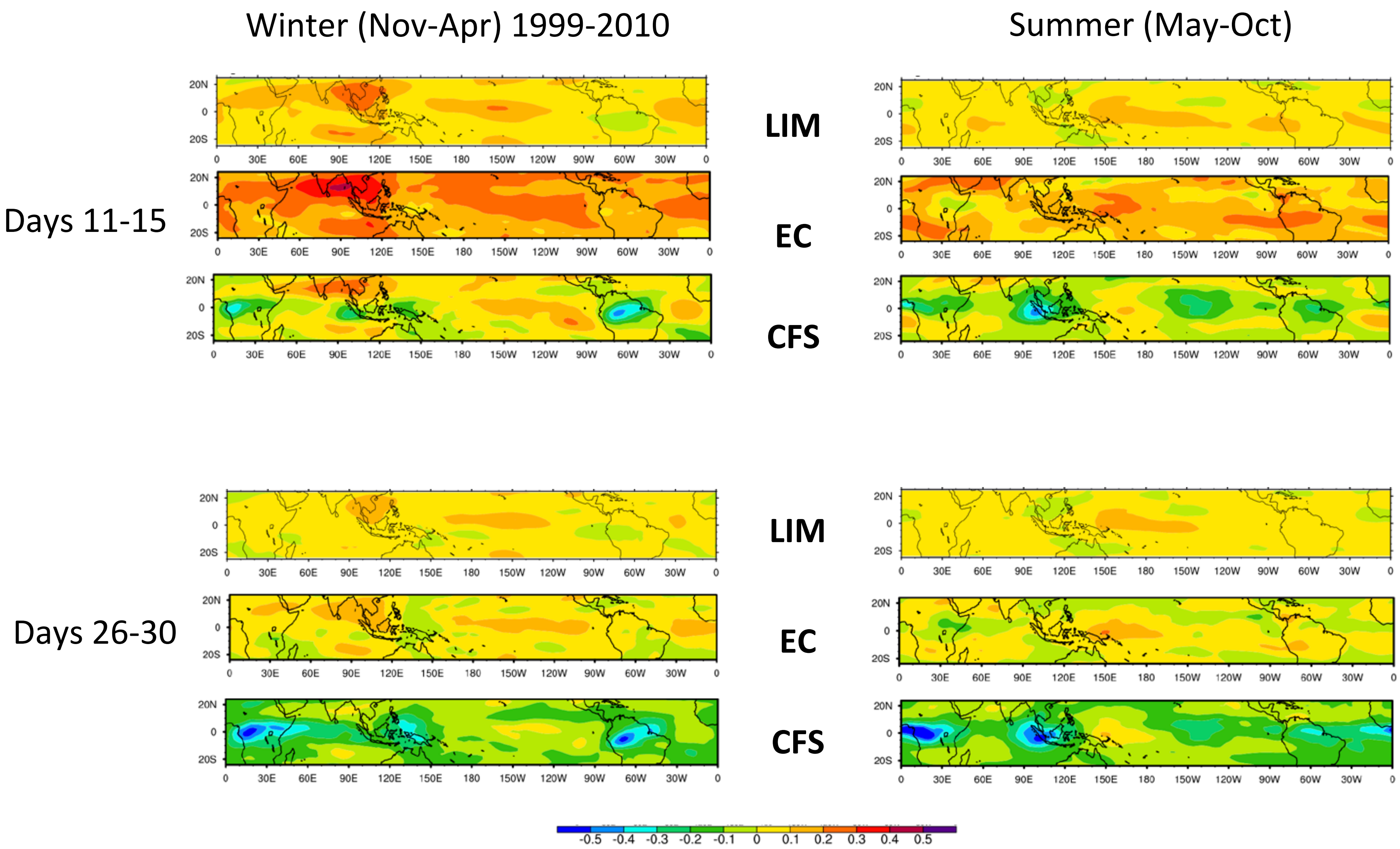
- **Use original C-LIM to *dynamically filter* coupled (interannual) space from anomalies**
- **Construct separate winter (NDJFMA) and summer (MJJASO) LIMs from residual anomalies**
- **Hindcasts/Forecasts are the sum of these two systems**

LIM, CFS2, EC-2016 models have comparable OLR skill



RMS Skill score = 1 –standardized error

LIM, CFS2, EC-2016 models have (mostly) comparable U200 skill



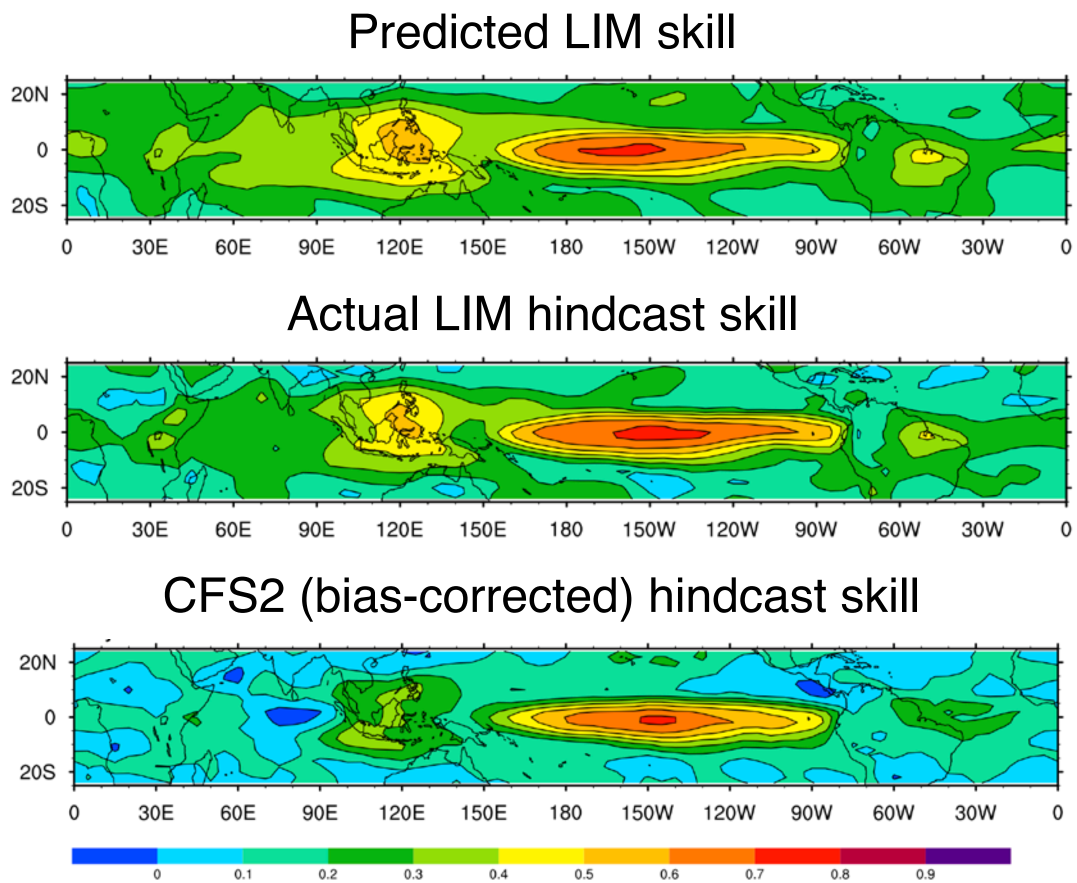
RMS Skill score = 1 –standardized error

LIM predicts patterns of skill: some places are more predictable than others

OLR Days 16-20 hindcast skill

Average skill has spatial structure because so does average signal-to-noise variance

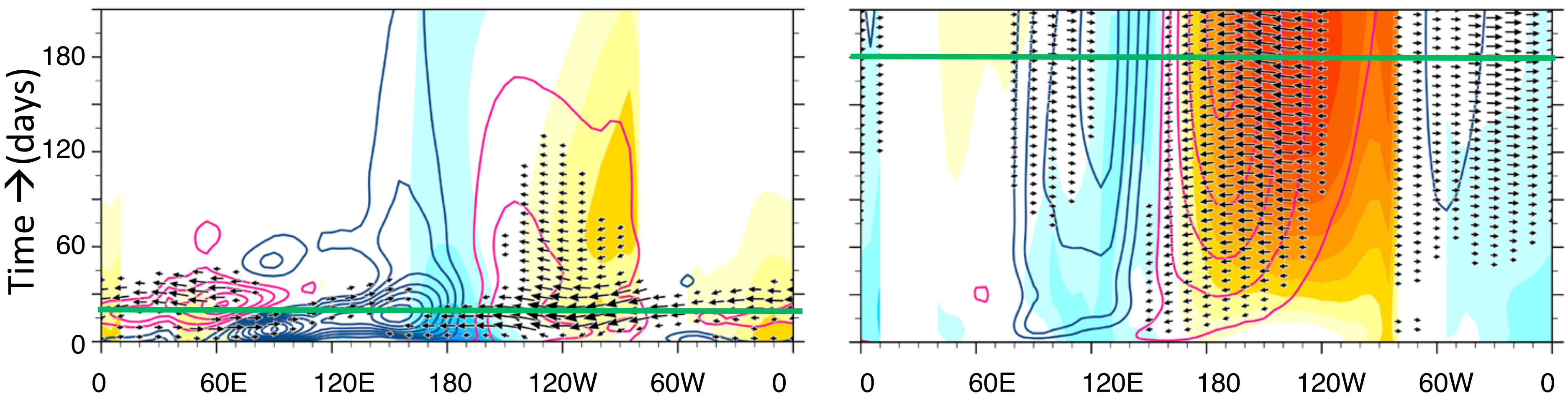
Skill is local anomaly correlation, all year



Maximum forecast signal comes from optimal amplification

OLR "optimal" amplification over 20 days

SST "optimal" amplification over 180 days



Hovmoller: equatorial (8S-8N) average

Contours: OLR
Shading: SST
Vectors: 850 hPa winds
Z20, 200 hPa winds not shown

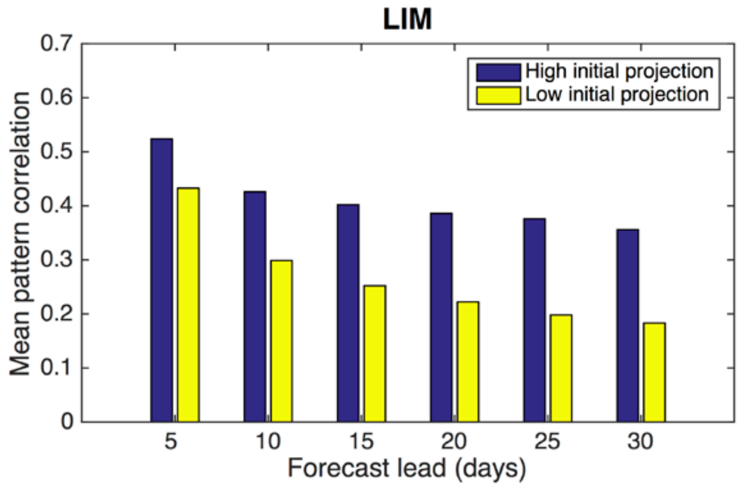
Skill is higher when initial conditions strongly project on optimal growth structure

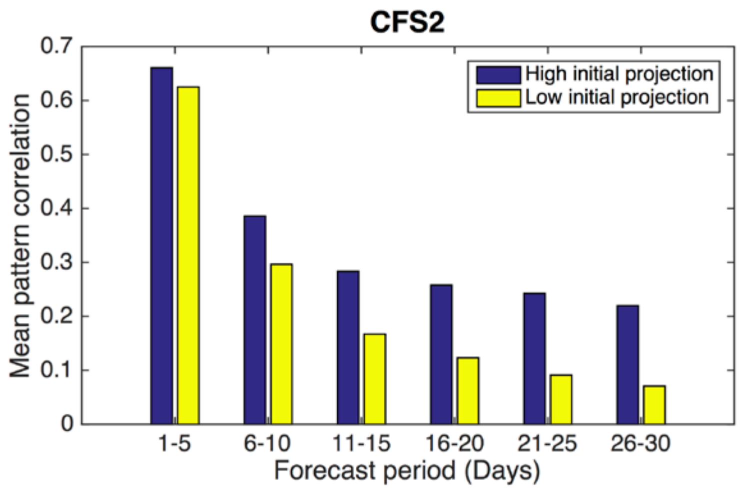
Tropical OLR skill split into cases with either **high** or **low** initial projection on optimal growth pattern.

On average, LIM predicted skill is realized by hindcasts (when predicted skill > 0.4)

Skill measure: pattern correlation of Tropical IndoPacific OLR anomaly forecast with verification

LIM identifies more skillful forecast cases *a priori*





Go further: how does air-sea coupling impact forecasts?

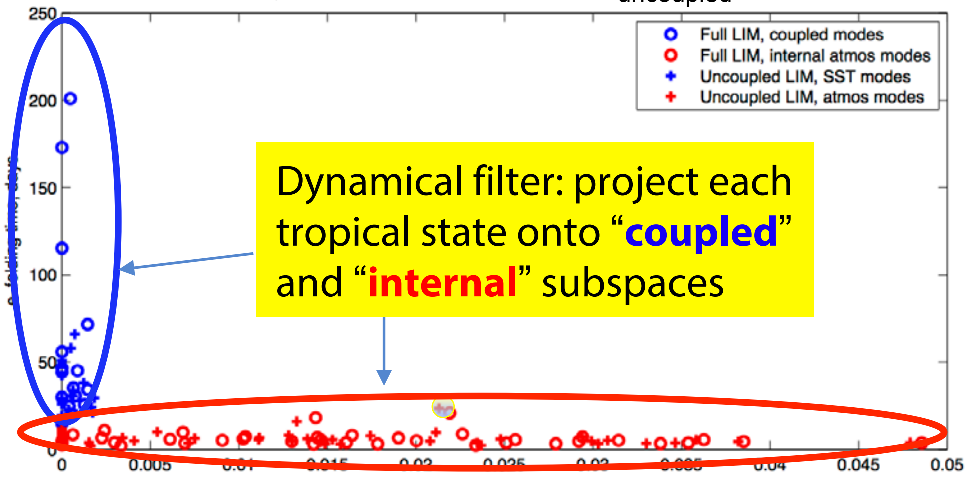
Two distinct eigenmode spaces in **L**

"coupled" (blue)
Longer eft, low frequency modes strongly modified by coupling within L

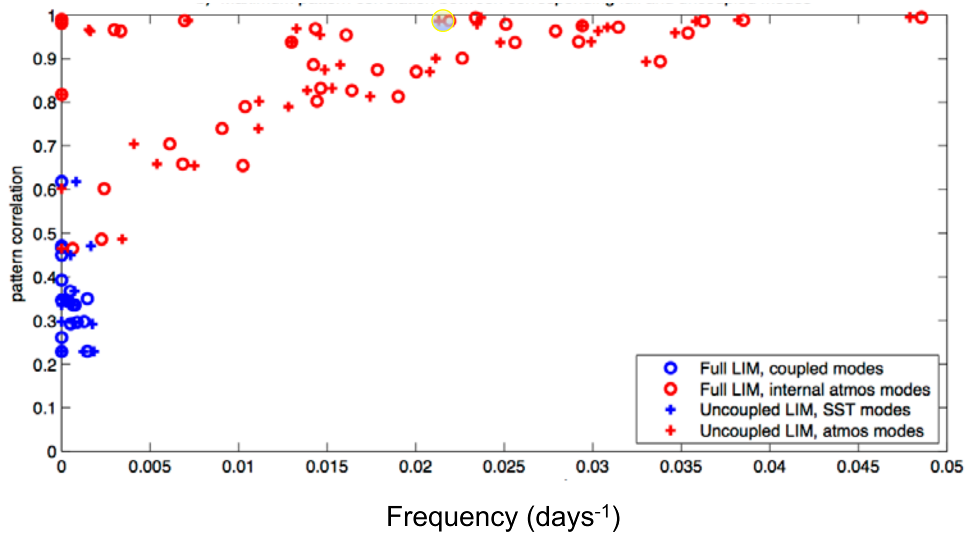
"internal atmospheric" (red)
Short eft, high frequency modes largely only slightly modified by coupling within L

MJO eigenmode is shaded

Eigenvalues of **L** and $\mathbf{L}_{uncoupled}$



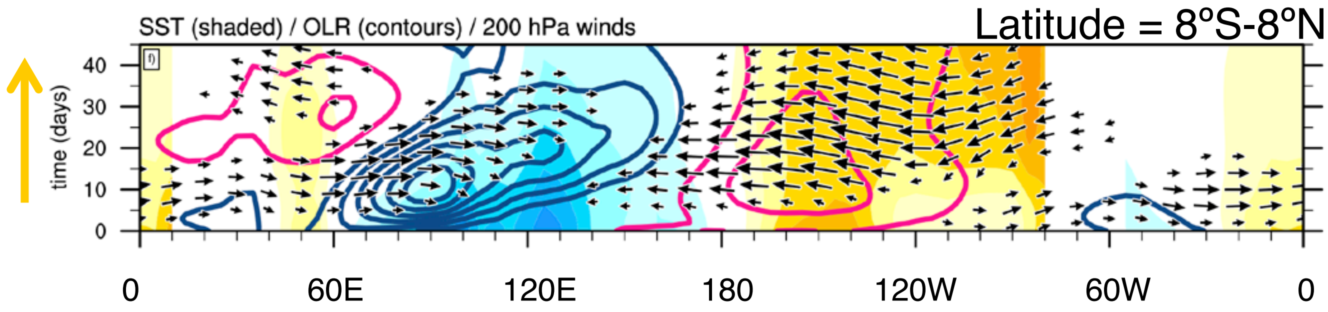
Maximum pattern correlation between corresponding full and uncoupled modes



Newman, Sardeshmukh, Penland 2009

Optimal structure for 20-day OLR anomaly growth, decomposed into coupled and internal spaces

total

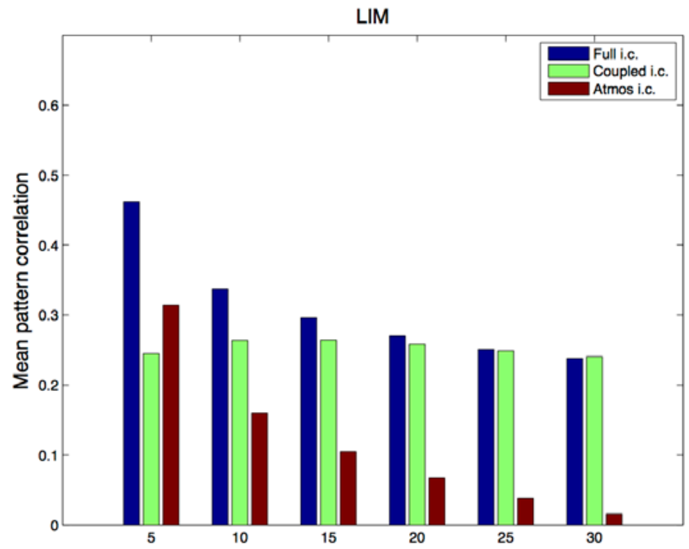


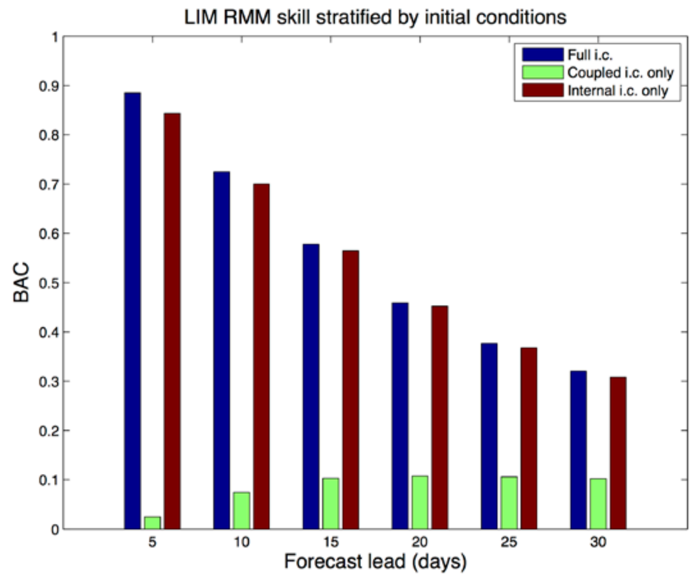
Shading: SST
Contours: OLR
Vectors: 200 mb winds

Most LIM skill due to coupled space initial conditions for leads greater than about 3 weeks

Pattern correlation of tropical IndoPacific OLR LIM hindcasts, 1982-2009, where forecast initial conditions are either:

Full
Coupled space only
Internal space only

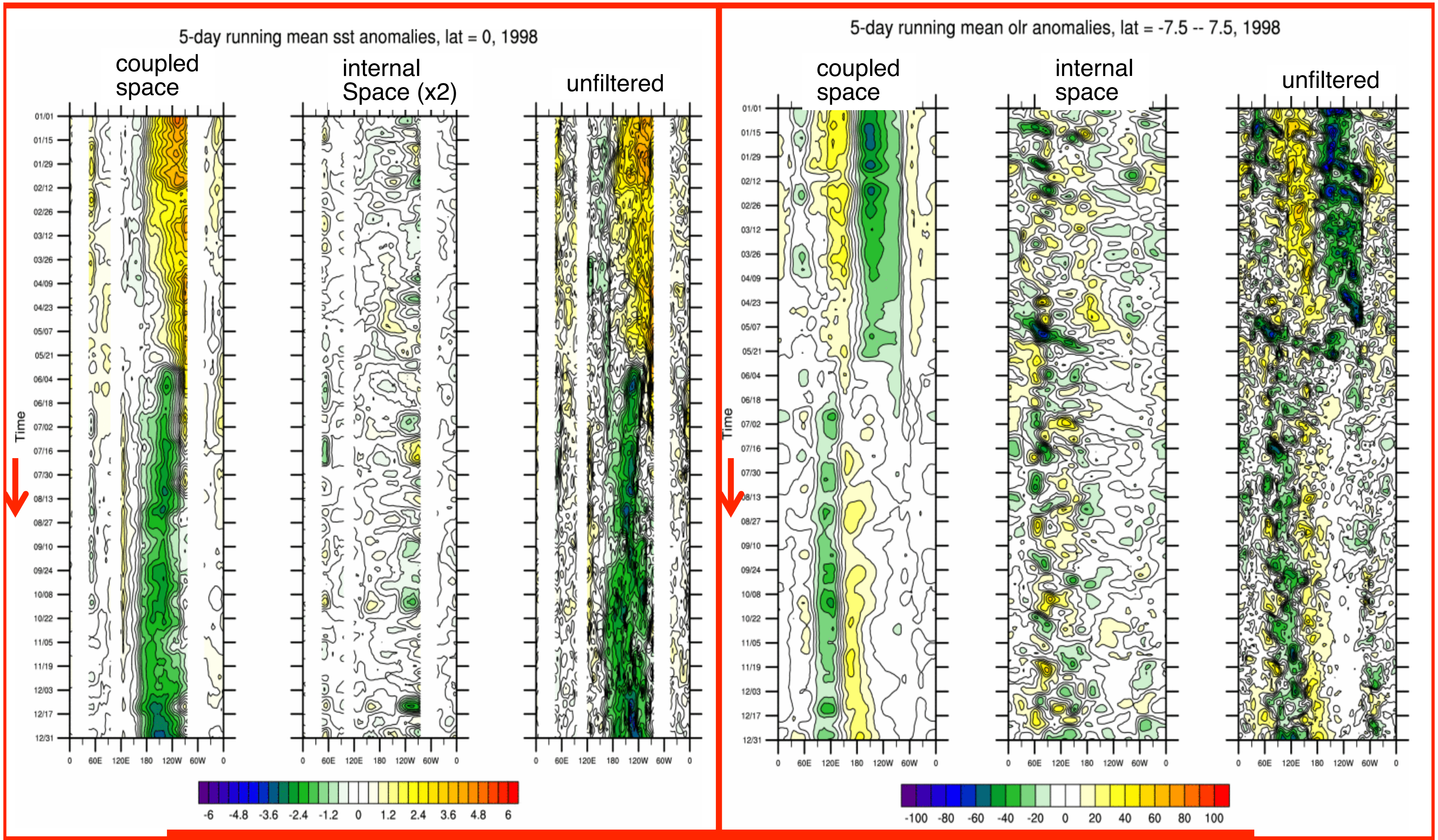




Summary

- LIM is useful for climate diagnosis and forecast uncertainty quantification **because** its forecast skill is comparable with coupled GCMs
  - Provides key -- and still relevant -- benchmark for GCM skill
  - Diagnostics of dynamics and predictability: where do models go wrong
- In the Tropics, there are two *nonorthogonal* linear dynamical systems:
  - Slow (~interannual) coupled space: more predictable, ENSO in this space
  - Fast (~intraseasonal) internal atmosphere space: less predictable, but MJO in this space
  - Most S2S skill comes from slow space, even at relatively short (<1 month) leads
    - Maximum anomaly growth is due to destructive→constructive interference between these space
- Subseasonal-interannual tropical forecast skill may be *predicted* based on LIM signal-to-noise
  - **S2S skill is low on average but forecasts of opportunity can (and must) be identified *a priori***
  - Similar results for extratropical SLP anomalies; see John Albers Poster P-A1-03 today

Using the LIM to "filter" the data



no temporal filter is applied → interannual variability defined dynamically