

2B. ENSO in the modern climate: the physics

(a summary of what comes next)

- **ENSO is the result of coupled atmosphere-ocean physics that is intrinsic to the tropical Pacific.**
 - Ocean models must be forced by Southern Oscillation to produce 'El Ninos';
 - Atmosphere models must be forced by 'El Nino' SST to produce the Southern Oscillation.
- **ENSO is a true mode of the coupled system**
 - ENSO is the leading eigenmode (Floquet mode) of the linearized equations for the tropical atmosphere and ocean.
- **The ENSO mode is strongly dependant on the climatological mean state.**
 - It strongly determines the amplitude, spatial and temporal character of ENSO
 - The mean state annual cycle causes the ENSO mode to peak at the end of the calendar year.
- **Stochastic forcing of the ENSO mode yields output that is consistent with the “robust observations” of ENSO (including the skewness in the eastern Pacific*)**
- Much of the energy for forcing ENSO comes from uncoupled atmospheric weather (wobbling of the jet in the NH winter)
- ENSO affects are teleconnected from the tropical Pacific by well-understood atmosphere and ocean dynamics:
 - Atmospheric impact is nearly global in extent.

The ENSO Mode

The modes of the coupled atmosphere-ocean system are found by linearizing the atmosphere and ocean equations about the observed mean state:

$$\frac{d\vec{X}}{dt} = B(t) \cdot \vec{X} \quad \text{-->} \quad (1)$$

where $\vec{X}$ is the vector of state variables (SST, 3-D flow fields, thermocline depth, etc) and B is the cyclostationary (due to the mean fields) dynamical matrix.

Solving (1), we have

$$\vec{X}(t_2) = \exp\left(\int_{t_1}^{t_2} B ds\right) \vec{X}(t_1) \equiv R(t_2, t_1) \vec{X}(t_1) \quad (2)$$

where the propagator matrix $\mathbf{R}$ is defined using data. Hence,

$$\begin{aligned} R_1 &\equiv R(\text{Feb}, \text{Jan}) = \exp\left(\int_{\text{Jan}}^{\text{Feb}} B(\text{Jan}) ds\right) \\ R_2 &\equiv R(\text{Mar}, \text{Feb}) = \exp\left(\int_{\text{Feb}}^{\text{Mar}} B(\text{Feb}) ds\right); \text{ etc} \end{aligned} \quad (3)$$

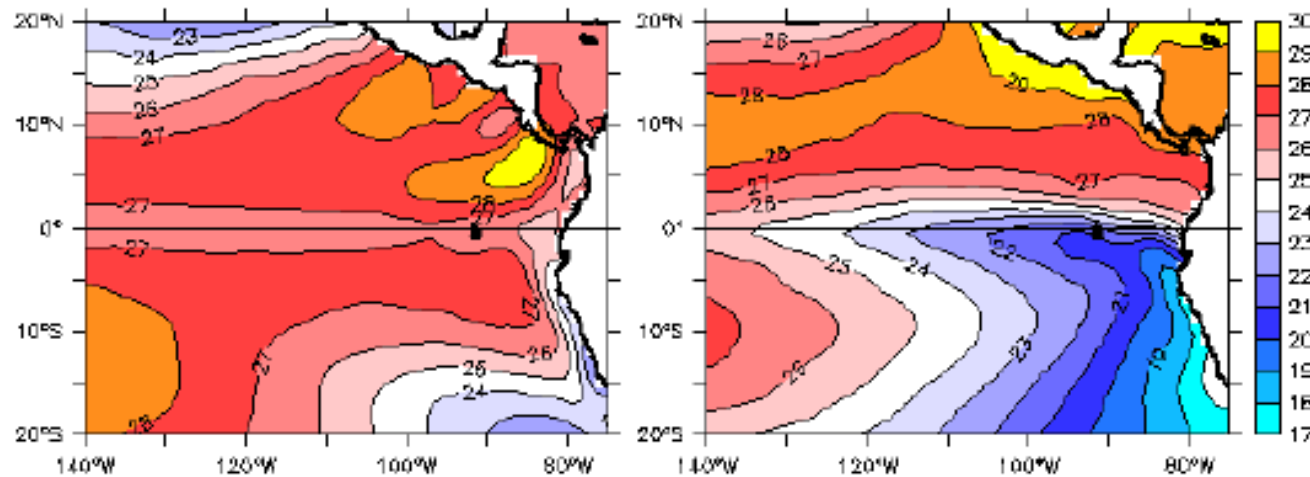
Thus, the yearly propagator is $R_{\text{year}} = R_{12} R_{11} \dots R_2 R_1$. (4)

The Annual Cycle in the tropical Pacific

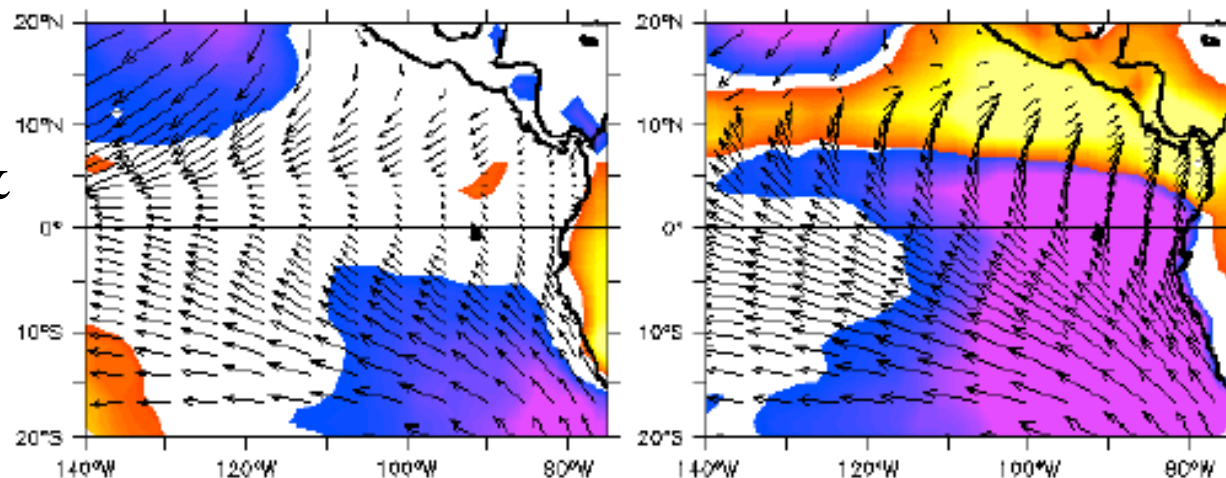
March

September

SST



Winds &
Clouds



Climatologies from Reynolds SST (1981–96), FSU Winds (1961–90), ISCCP Clouds (1983–91)

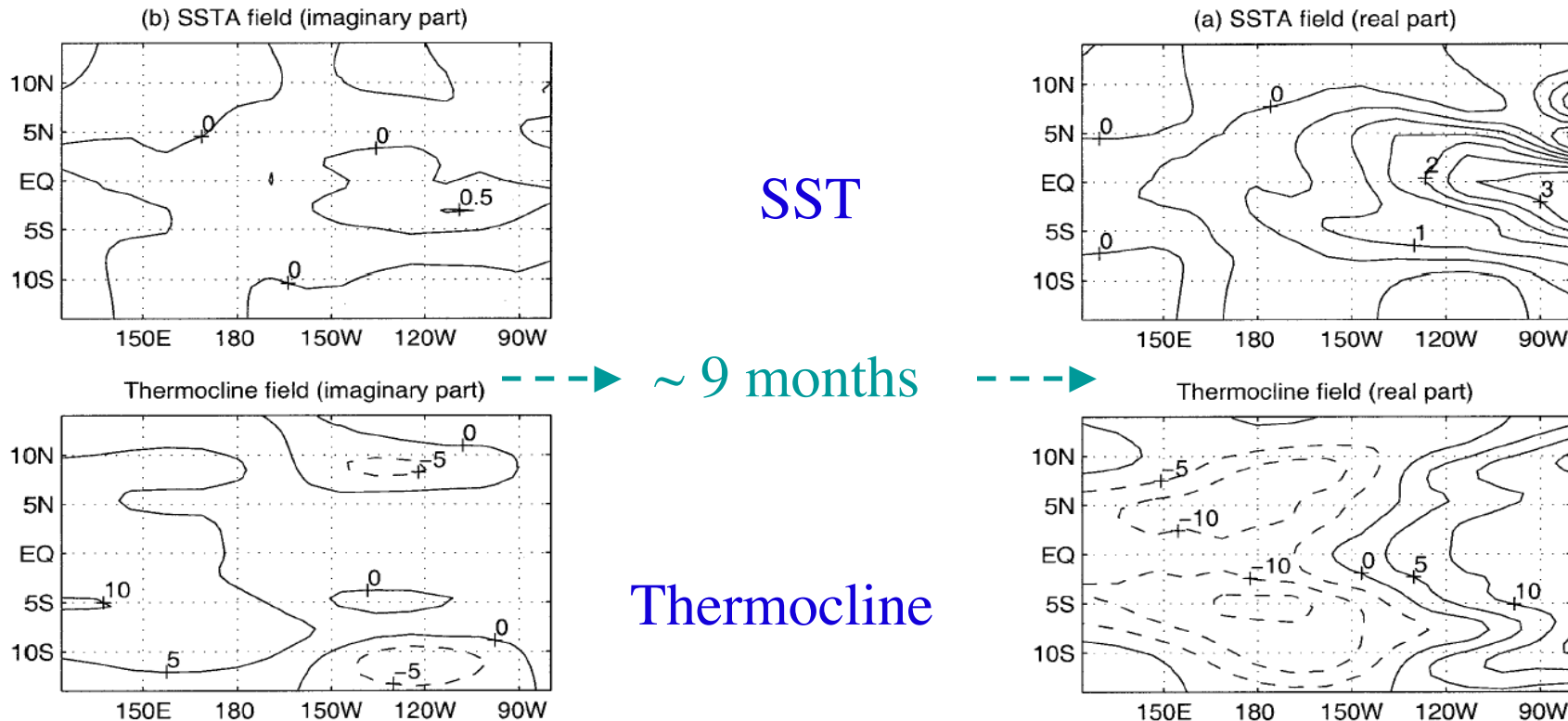
Orange shading shows high clouds >25%, Blue shading shows stratus clouds >30%

The ENSO Mode (cont)

- The eigen (Floquet) analysis of $\mathbf{R}_{year}$ are the true thermo-dynamic modes of the coupled atmosphere system.
 - The eigenvalues of $\mathbf{R}_{year}$ yield the frequency and growth rate of the modes, with structures given by the eigenvectors.
 - In general, the modal structures depend on the month.
- The leading (least damped) mode is the ENSO mode. The ENSO mode:
 - Structure depends strongly on the annual mean inhomogeneity in the climatology, and weakly on the seasonal cycle;
 - Tends to peak at the end of the calendar year due to the cyclostationary mean field;
 - Has a rich frequency structure, but a strong spectral peak at 3-4 years;
 - Has an 'e-folding' decay time of two years.
- The ENSO mode features:
 - Ocean thermodynamic processes rich and varying during the ENSO cycle;
 - Dynamical adjustment of the ocean (dispersion on an equatorial beta-plane) is crucial to the evolving ENSO event, including event onset, peak, decay and the ensuing cold event.
- ENSO is a true mode of the coupled atmosphere/ocean system in the Pacific basin.

ENSO is a true mode of the coupled atmosphere/ocean system in the Pacific

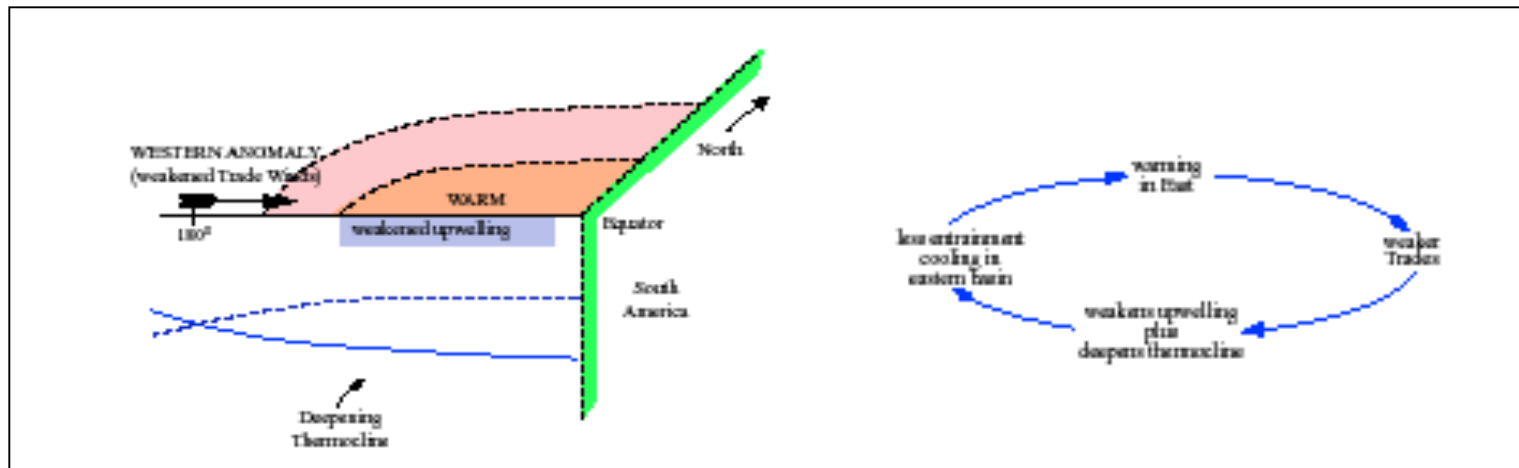
The first eigenmode of R_{year} is the ENSO mode.



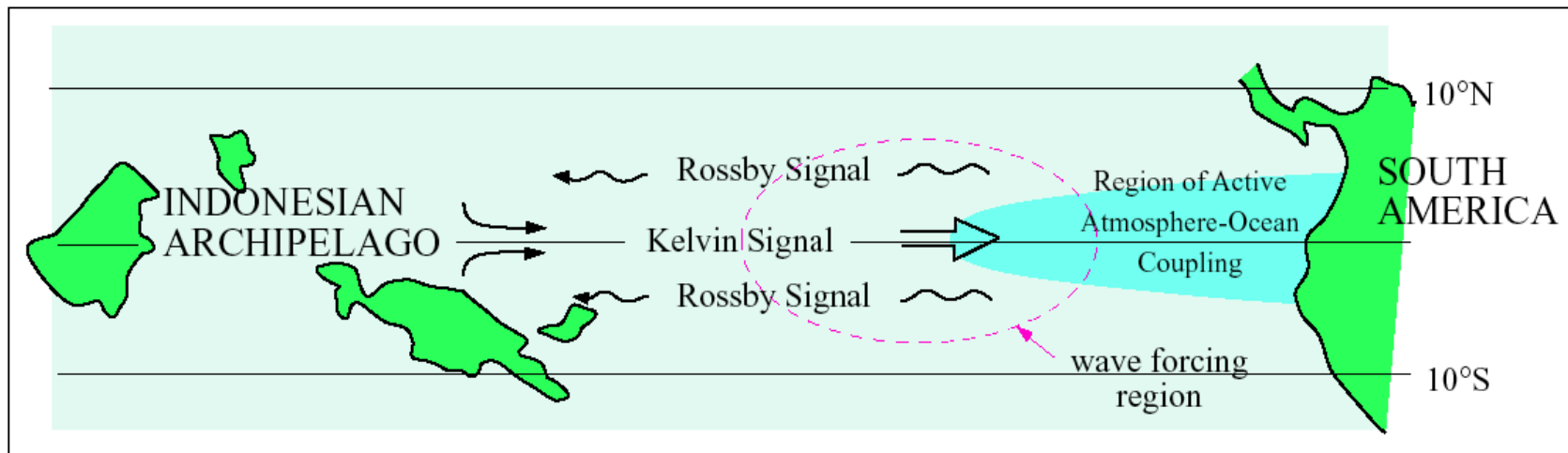
The “ENSO mode” features the so-called Delayed Oscillator Physics (Bjerknes Feedback and basin-scale ocean dynamical adjustment)

Basic elements of ENSO in observations and models

Bjerknes
&
Feedback



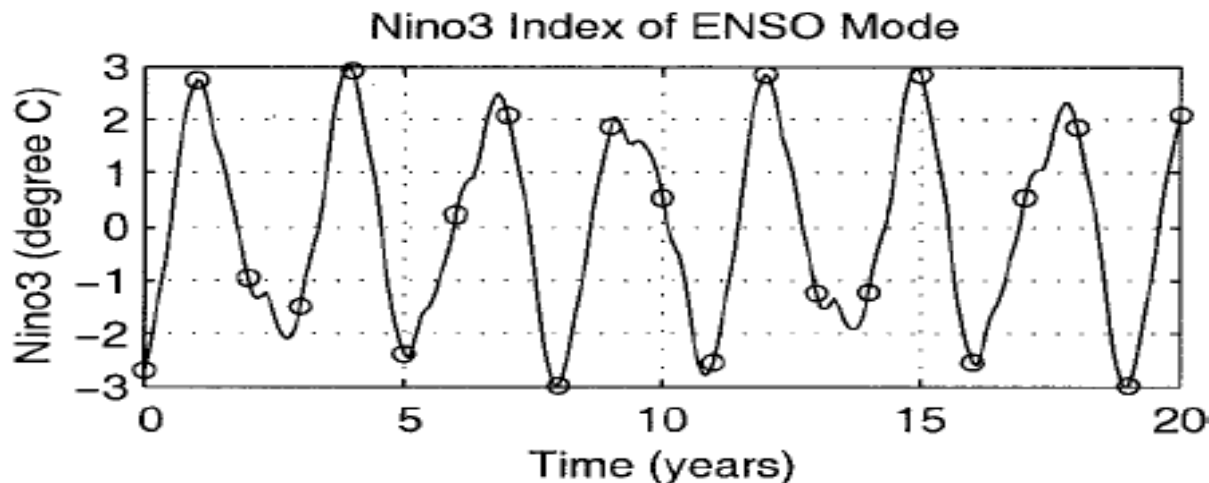
Ocean Adjustment



This physics is often called the “delayed oscillator” model of ENSO; aka the SST mode (Neelin 1991) or the Recharge Oscillator (Jin 1997) -- toy models of the tropical atmosphere-ocean system.

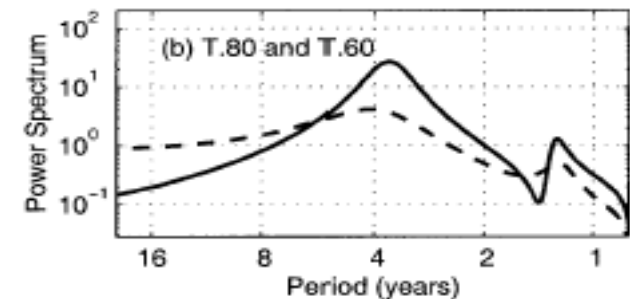
The ENSO mode (cont)

ENSO exists because of the structure in the annual *average* state of the atmosphere and ocean in the tropical Pacific.



ENSO tends to peak at the end of the calendar year (mainly) because of the annual cycle in the basic state.

Spectrum of the pure ENSO mode



The ENSO mode and Observations

- The ENSO mode shares many features of the observed (composite) ENSO cycle:
 - Bjerknes' "local" atmosphere/ocean feedbacks in equatorial zone.
 - A buildup of warm water in the equatorial wave guide that precedes the warming in the eastern Pacific Ocean (ie, the warm phase of ENSO)
 - The spatio-temporal evolution of ocean heat content (via adiabatic dynamics) throughout the onset, growth and decay of a warm event.

e.g., Kessler 1990; Bigg and Blundell 1992; Mantua and Battisti 1994; Wakata and Sarachik 1991; Rosati et al. 1995; Schneider et al. 1995.

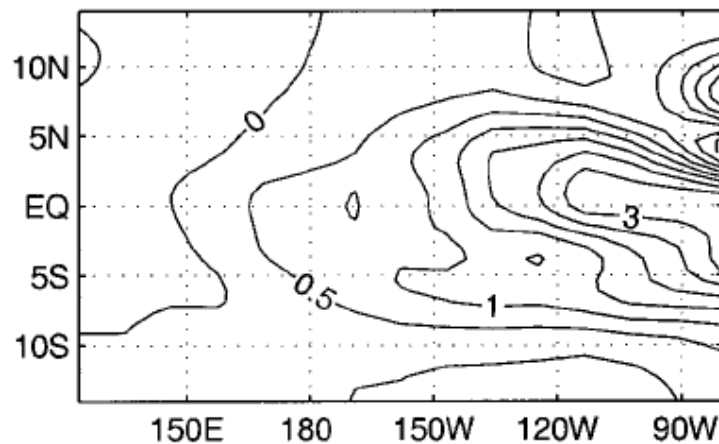
- The ENSO mode is also consistent with the following observations:
 - ENSO peaks at the end of the calendar year because of the annual cycle in the background state of the coupled system.
 - El Nino events (warm phase of ENSO) last about one year.
 - The Indian Ocean does not support ENSO variability (homogeneous basic state).

ENSO as a linear, stochastic system

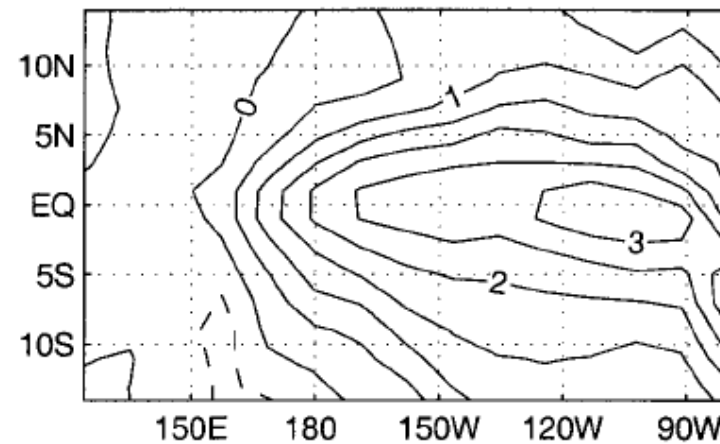
Forcing the ENSO mode by white noise -- reproduces qualitatively all of the 'robust observations'

1st EOF of SST

Model

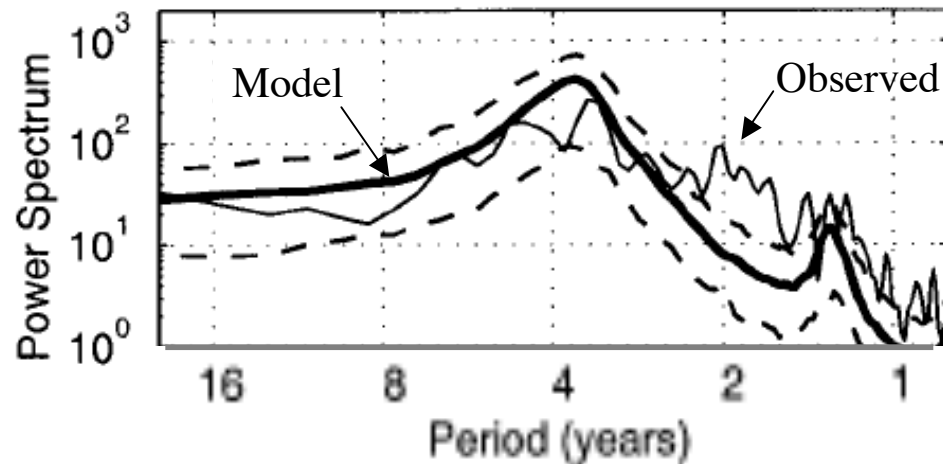


Observations



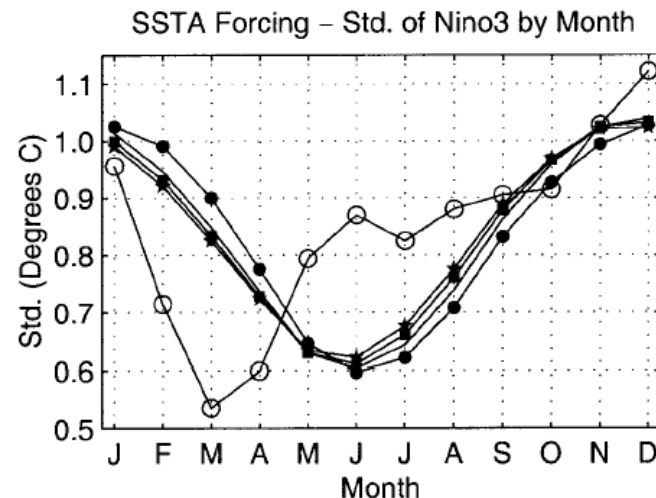
ENSO as a linear, stochastic system (cont)

The Power Spectrum of Nino3.4



Power is in a broad spectral band, centered on four years

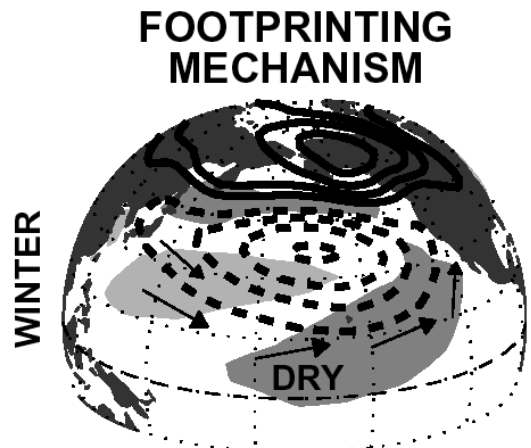
The linear model forced by white noise tends to have ENSO peak at the end of the calendar year, and features the observed “Spring Barrier (not shown)”. Additional seasonality due to the seasonality in forcing (Vimont et al 2003)



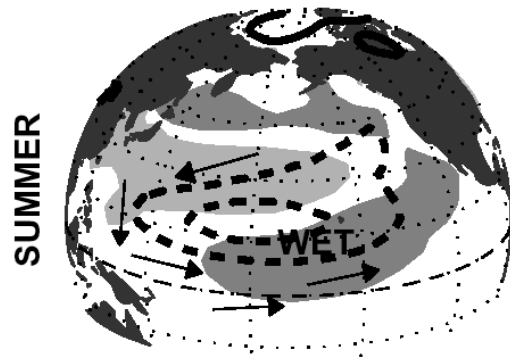
The observed skewness in Nino3 is reproduced by performing perturbation experiments with the full nonlinear atmosphere-ocean model.

What is the source of energy for ENSO in Nature? Why is ENSO irregular?

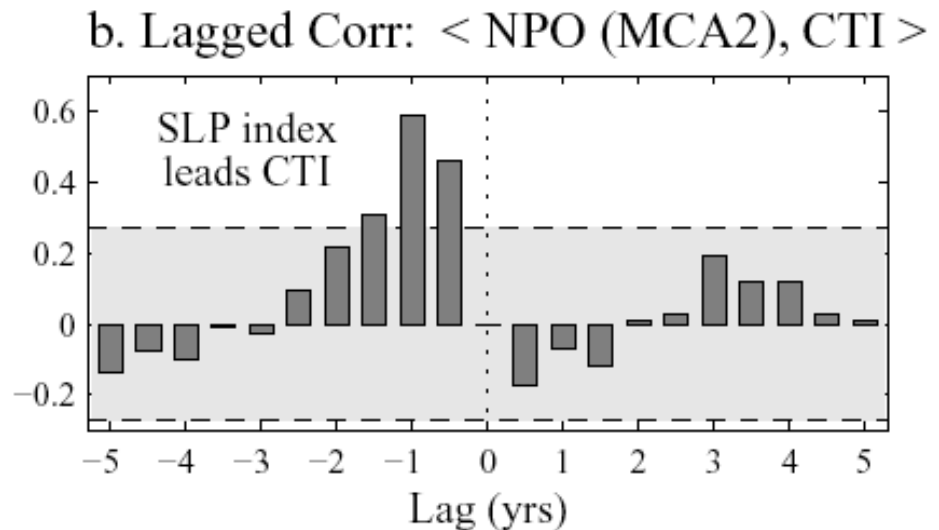
The Seasonal Footprinting Mechanism



A. ATM imparts SST footprint onto the ocean during the winter months



B. SST footprint persists into the following summer, when it forces ATM



- ENSO is variable, in part, because the mode feels the annual cycle.
- The Seasonal Footprinting Mechanism accounts for about 35-50% of ENSO variance.
- Other factors responsible for irregularity?
 - Synoptic storms (westerly wind bursts)?

2C. Implications of the physics

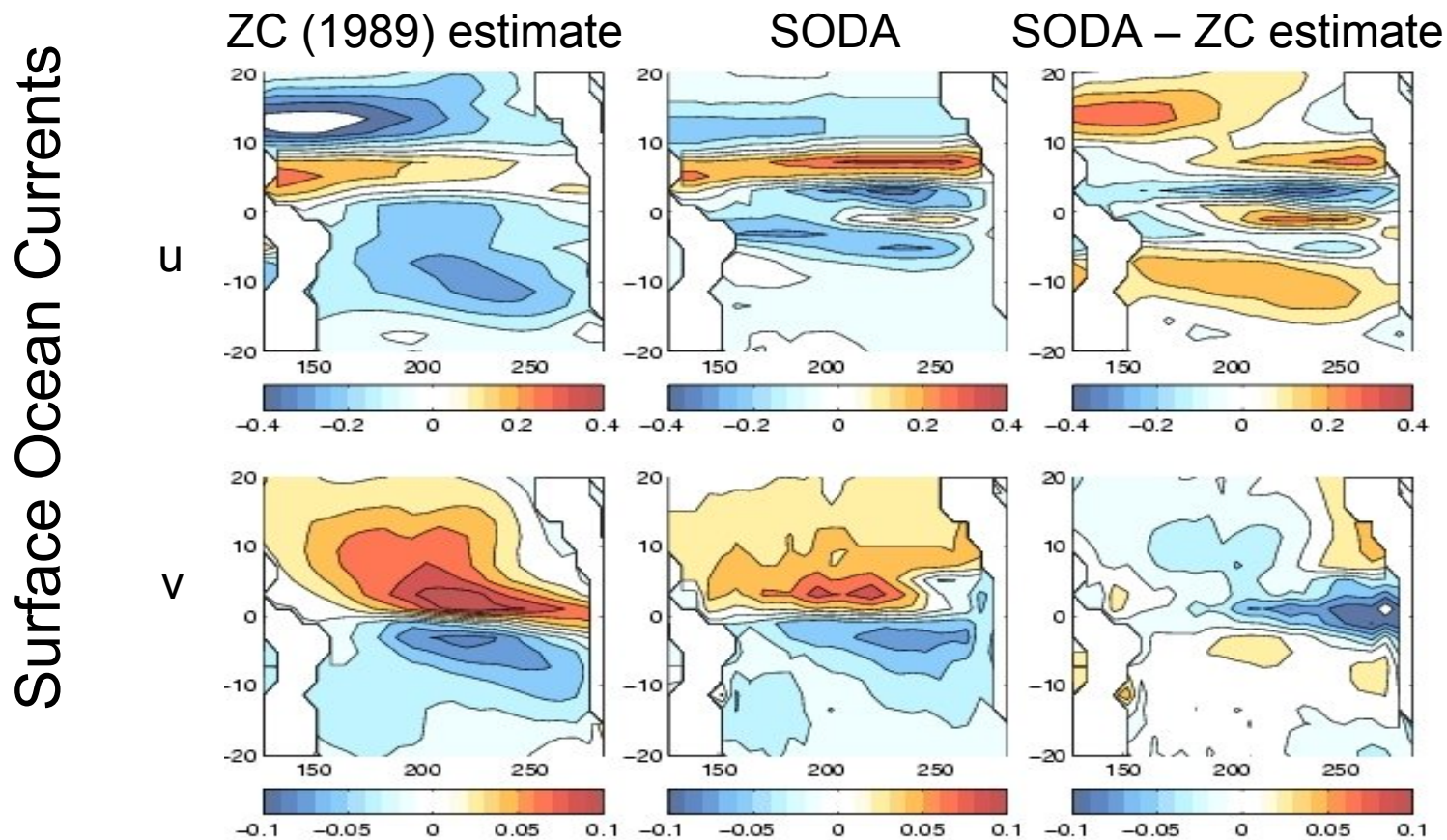
- The amplitude and spatio-temporal properties of the ENSO mode are highly sensitive to:
 - the structure in the climatological mean state;
 - the spatial and temporal structure of the noise forcing (how well it projects onto the adjoint of the mode).
- Hence, for a global climate model to simulate realistic ENSOs is that the model has to have:
 - a realistic mean state;
 - an adequate representation of all important processes acting in the ENSO mode;
 - an adequate representation of the important noise forcing.
- This theory suggests that ENSO should be predictable up to two years in advance

2D. A final look at the ENSO mode

- The Zebiak/Cane (1987) model features a plausible looking ENSO mode
- The ZC model does not include the stochastic forcing that was subsequently shown (Vimont et al 2000) to provide the energy for stimulating the ENSO mode
 - Hence, to see the ENSO mode in the model, it was tuned (e.g., by doubling the drag coefficient, etc) to make the ENSO mode globally unstable.
- More realistic parameters in the linearized ZC model (LOAM) results in the ENSO mode, but it is stable (Thompson and Battisti 2000)
- The ZC model is an anomaly model about a prescribed mean state
 - Climatological mean states (especially ocean) were poorly known in the 1980s and 1990s

2D. A final look at the ENSO mode

- Better estimates of the climatological mean fields now exist, especially for SST and thermocline depth, surface winds and ocean currents.



2D. A final look at the ENSO mode

These new (observed) mean states are placed into LOAM (the linearized ZC model) using realistic parameters

		mode period (years)	mode decay (year ⁻¹)
LIM fit to obs	observations	4.1-3.5 [#]	0.63-0.22 [#]
ZC(1989)	LOAM(B88)	2.8	1.82
ZC(new param)	LOAM(T80)	3.8	0.8
Realistic	LOAM(a)	3.7	0.53
Mean	LOAM(b)	4.2	0.48
States	LOAM(c)	4.9	0.34

- The leading Floquet mode of LOAM with more realistic mean states is still the ENSO mode, and it is stable.

[#] The observed ENSO mode is found from a linear inverse model of the historical data

The new mean states inserted into LOAM support a more realistic ENSO

	Model	ENSO Mode		Variance (%)	
		growth (year^{-1})	period (years)	EOF 1	EOF 2
Observed	Kaplan	0.63 (a)	4.1 (a)	50	9.2
		0.53 (b)	3.5 (b)		
	NCEP/OI	0.22 (c)	3.8 (c)	45	12
Obs Mean States	B88M	1.82	2.8	92	4.2
	LOAM(T80)	0.80	3.8	83	3.5
	LOAM(a)	0.53	3.7	48	6.7
	LOAM(b)	0.48	4.2	42	4.7
	LOAM(c)	0.34	4.9	34	3.8

Which mean state change mattered most?

Better constraints
on *all* of mean state
variables, but
especially the 3D
ocean currents

Experiment Name	Description	growth (yr^{-1})	period (yr)
LOAM(T80)	Original Mean Fields	0.80	3.8
LOAM(a)	Observed Mean Fields	0.53	3.7
Exp a	T80 + SODA SST	0.89	3.5
Exp b	T80 + SODA Winds	0.86	3.8
Exp c1	T80 + SODA Horizontal Currents	0.49	4.5
Exp d	T80 + SODA Upwelling, Γ and δ	0.32	3.3
Exp e	T80 + SODA SST and Winds	1.09	3.3
Exp c2	T80 + SODA Zonal Currents	0.77	4.2
Exp c3	T80 + SODA Meridional Currents	0.57	4.0