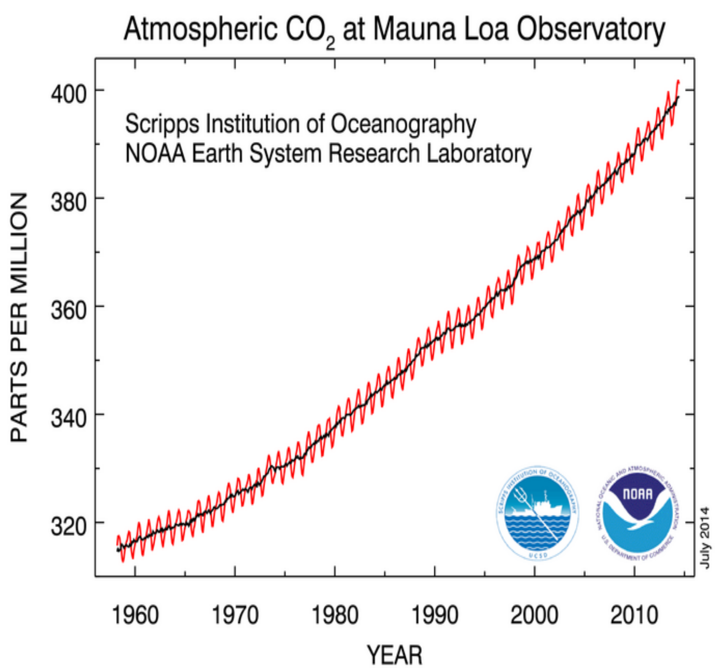
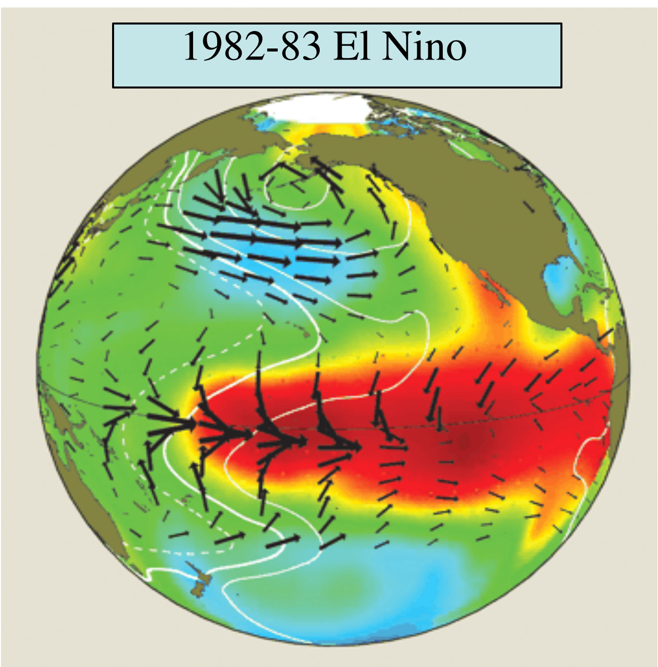
Does Higher CO2 Concentration Cause Stronger El Nino Events?

Is there a Case for a More Affirmative Answer than What is Stated in IPCC AR5?

De-Zheng Sun, Jiabing Shuai, Xiao-Wei Quan, and Martin Hoerling

CIRES, University of Colorado &
Earth System Research Laboratory, NOAA





Outline

1. The Consensus View from IPCC AR5
2. Our View
3. The Scientific Basis for Our View
   - **(1) Insights From an Analytical Model: Why and How Intensity of Heating May Matter?**
   - (2) Results From a Hybrid Model: Z-C Model May Indeed Have a Caveat—It is in the Subsurface.
   - (3) Implications From Forced Ocean GCM Experiments: ENSO Activity May Elevate, But the Elevation Is Likely Self-Destructive, Leading to Decadal Modulation/Variability.
   - **(4) Results From an Analysis of CMIP Models: A Case for Being Selective?**
   - **(5) Results from the Newest NCAR Climate Model-CESM: The Latest May be Indeed the Best!**
5. Summary
6. Some Planned Research

The View of IPCC

“Because the change in tropical mean conditions in a warming climate is model dependent (especially the zonal gradient), changes in ENSO intensity for the 21st century are uncertain----. There is high confidence, however, that ENSO will remain the dominant mode of natural climate variability”—IPCC AR5

PSD
Attribution team on El Nino Change

Our View

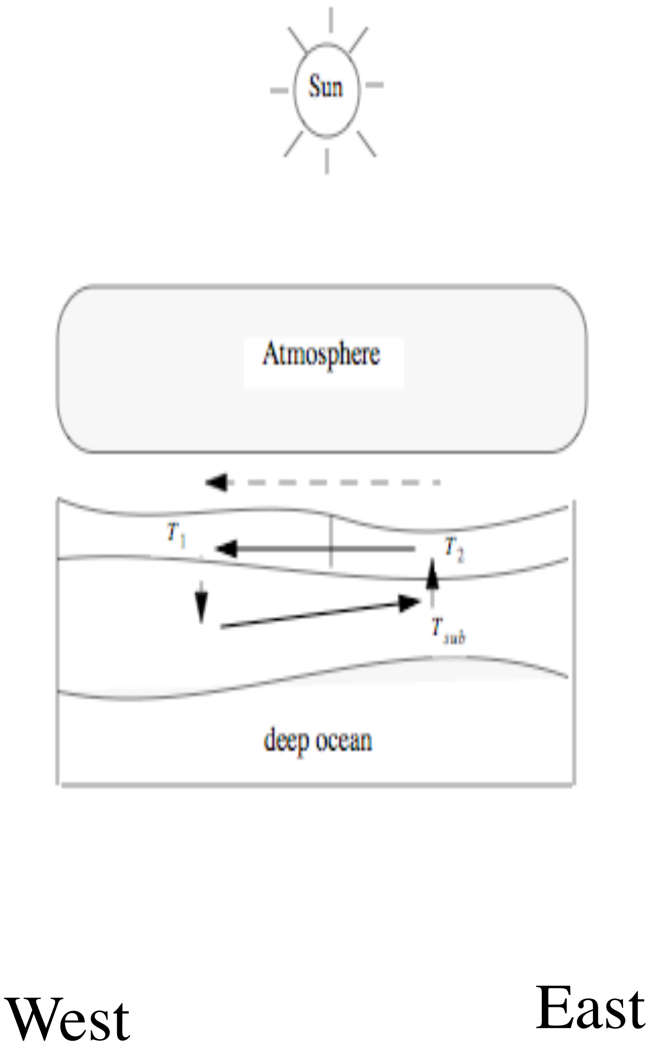
1. **The very existence of a climate regime supporting a recurrent occurrence of El Nino events is due to a sufficiently strong radiative hearting over the equatorial Pacific.**

2. **An even stronger radiative heating from a greater CO_2 concentration may cause stronger El Nino events. (The anthropogenic forcing may already have played a role in the making of the 1982-83 and the 1997-98 El Nino Events!)**

3. **An elevation of ENSO activity due to a greater GHG forcing is unlikely monotonic or constant with time, but take the form of zigzag: decades of intensified activity followed by decades of relative quiescence.**

4. **It is the response of El Nino events that determines the response in the m state in the tropical Pacific, not the other way around!**

Why and How Intensity of Heating May Matter: Insights from An Analytical Model



$$\frac{dT_1}{dt} = c(T_e - T_1) + sq(T_2 - T_1)$$

$$\frac{dT_2}{dt} = c(T_e - T_2) + q(T_{sub} - T_2)$$

$$q = \frac{\alpha}{a}(T_1 - T_2)$$

$$T_{sub} = \Phi\left(-H_1 + h_2^{'}\right)$$

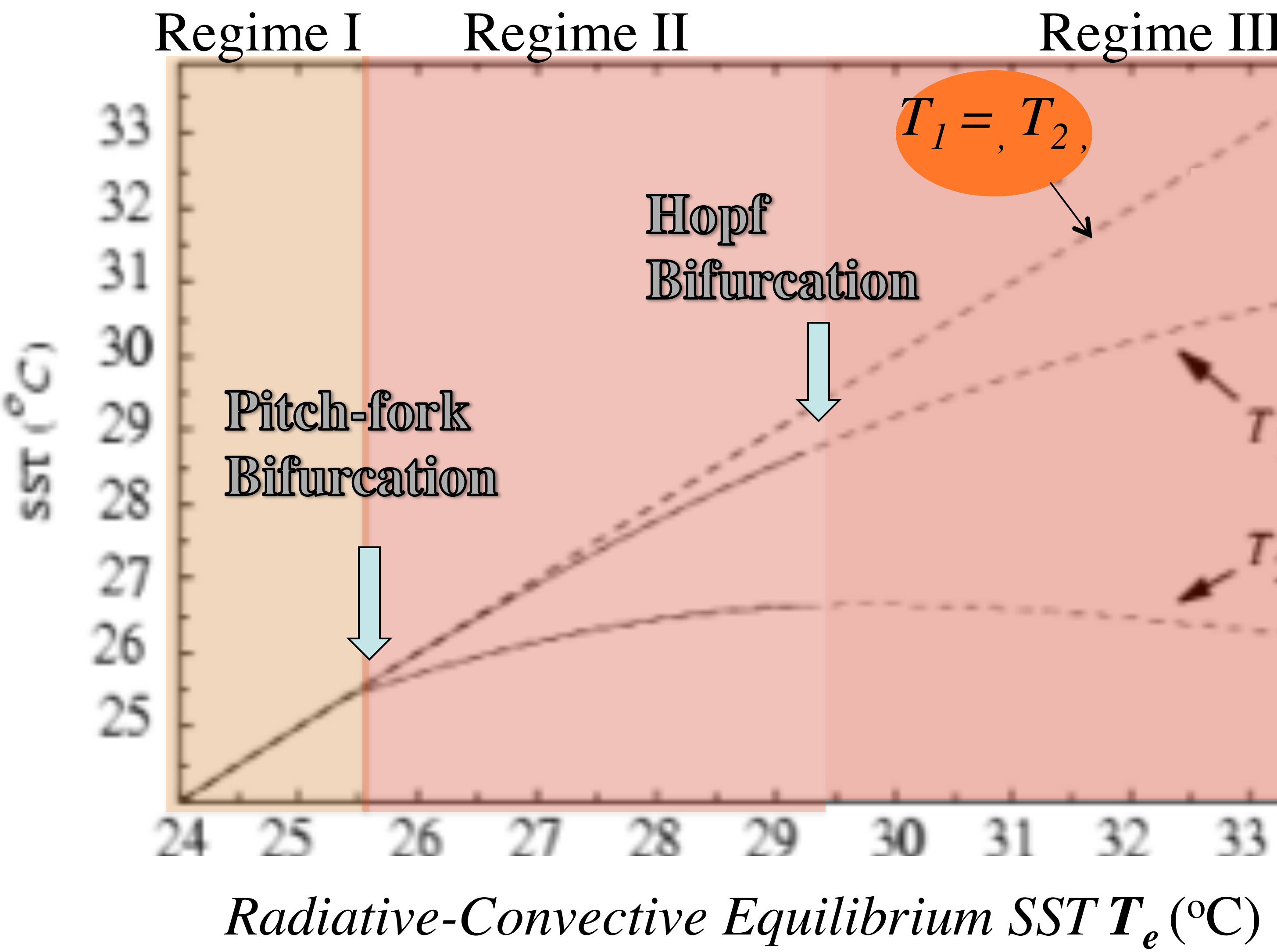
$$\Phi(z) = T_e - \frac{T_e - T_b}{2}\left(1 - \tanh\left(\frac{z + z_0}{H^*}\right)\right)$$

$$h_2^{'} - h_1^{'} = -\frac{H_1}{H_2} H \frac{\alpha}{b^2}(T_1 - T_2)$$

$$\frac{1}{r}\frac{dh_1^{'}}{dt} = -h_1^{'} + \frac{H_1}{2H_2} H \frac{\alpha}{b^2}(T_1 - T_2)$$

Sun 1997

Regime Transitions in Response to an Increasing Radiative Heating

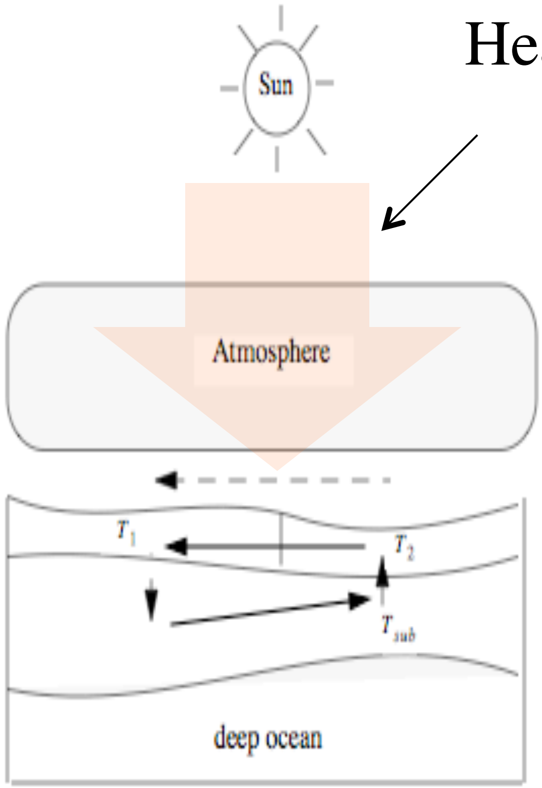


Sun 1997

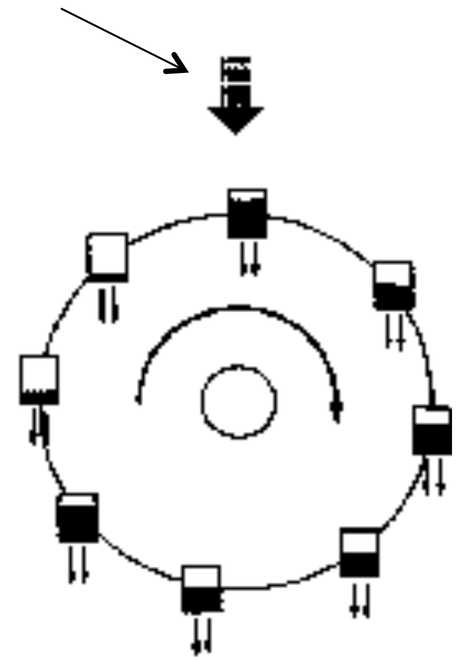
Why and How Intensity of Heating Matter:
A Close Analogy with the Malkus's Waterwheel

Heat Flux

Water Flux



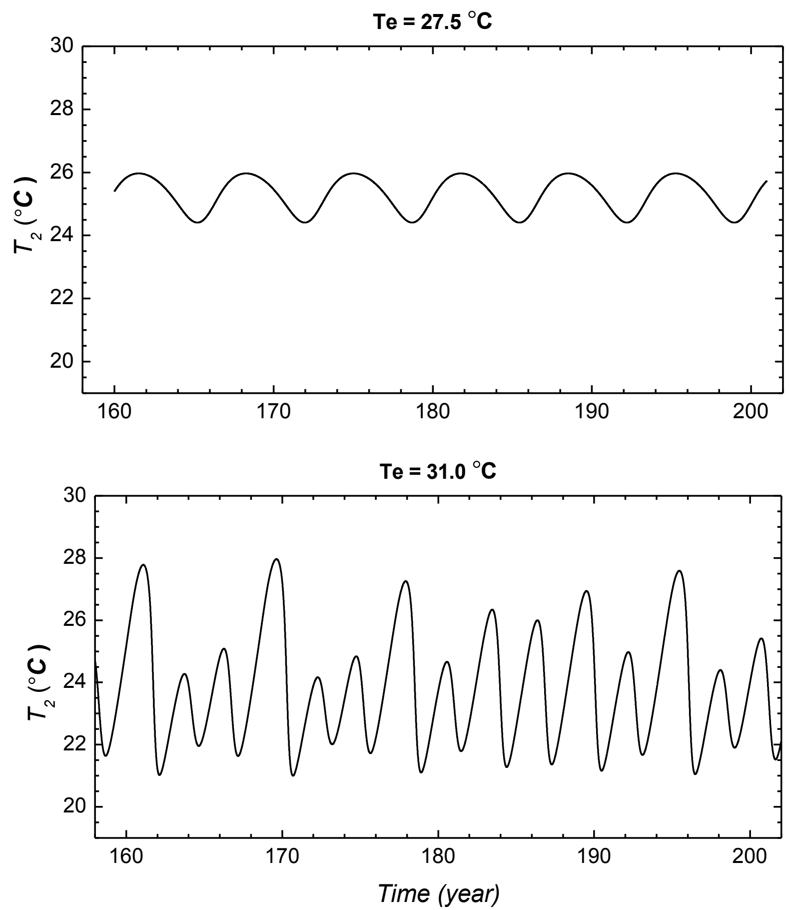
Sun 1997



Strogatz 1994

Intensity of heating matters because the inertia of the resulting circulation matters. Strong inertial causes the system to overshoot.

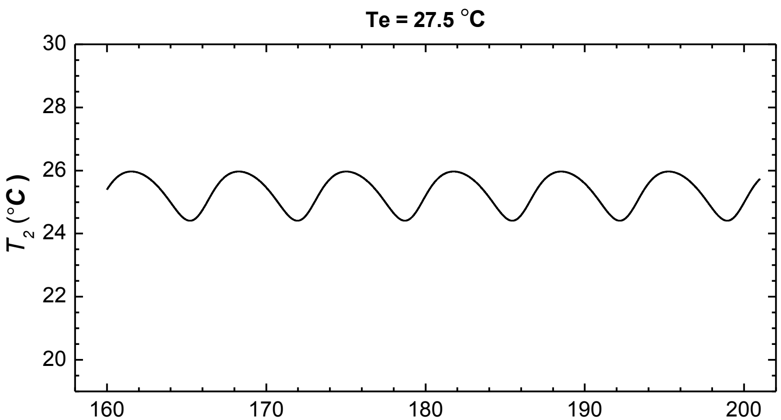
Pattern and Amplitude of Oscillation in the Model of Sun (1997) under Different Intensities of Radiative Heating

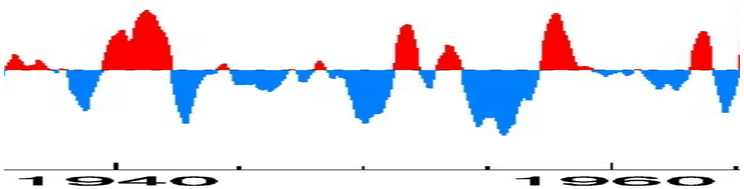


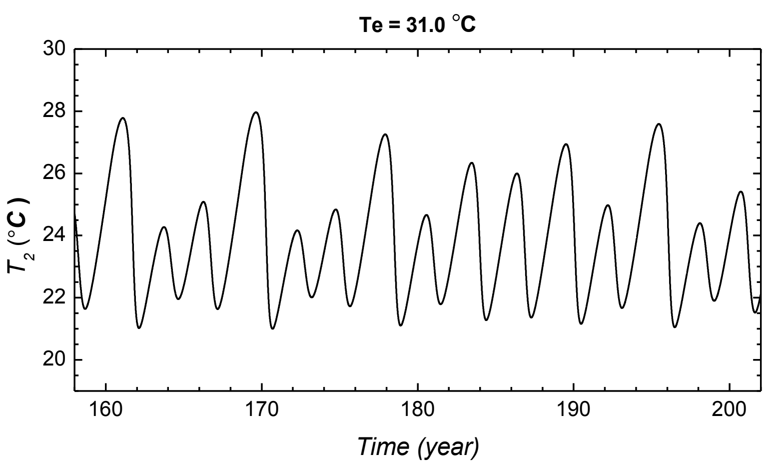
Liang, J., X.-Q. Yang, and D.-Z. Sun 2012, J. Climate, 25, 7590-7606.

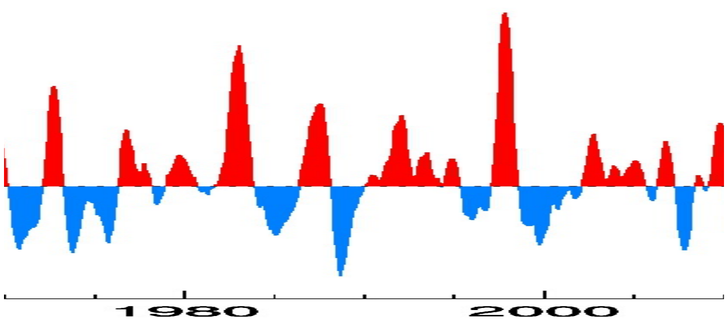
Pattern and Amplitude of Oscillation under Two Different Intensities of Radiative Heating (Model)

Pattern and Amplitude of Oscillation over 1940-1970 and the later Period 1970-2000

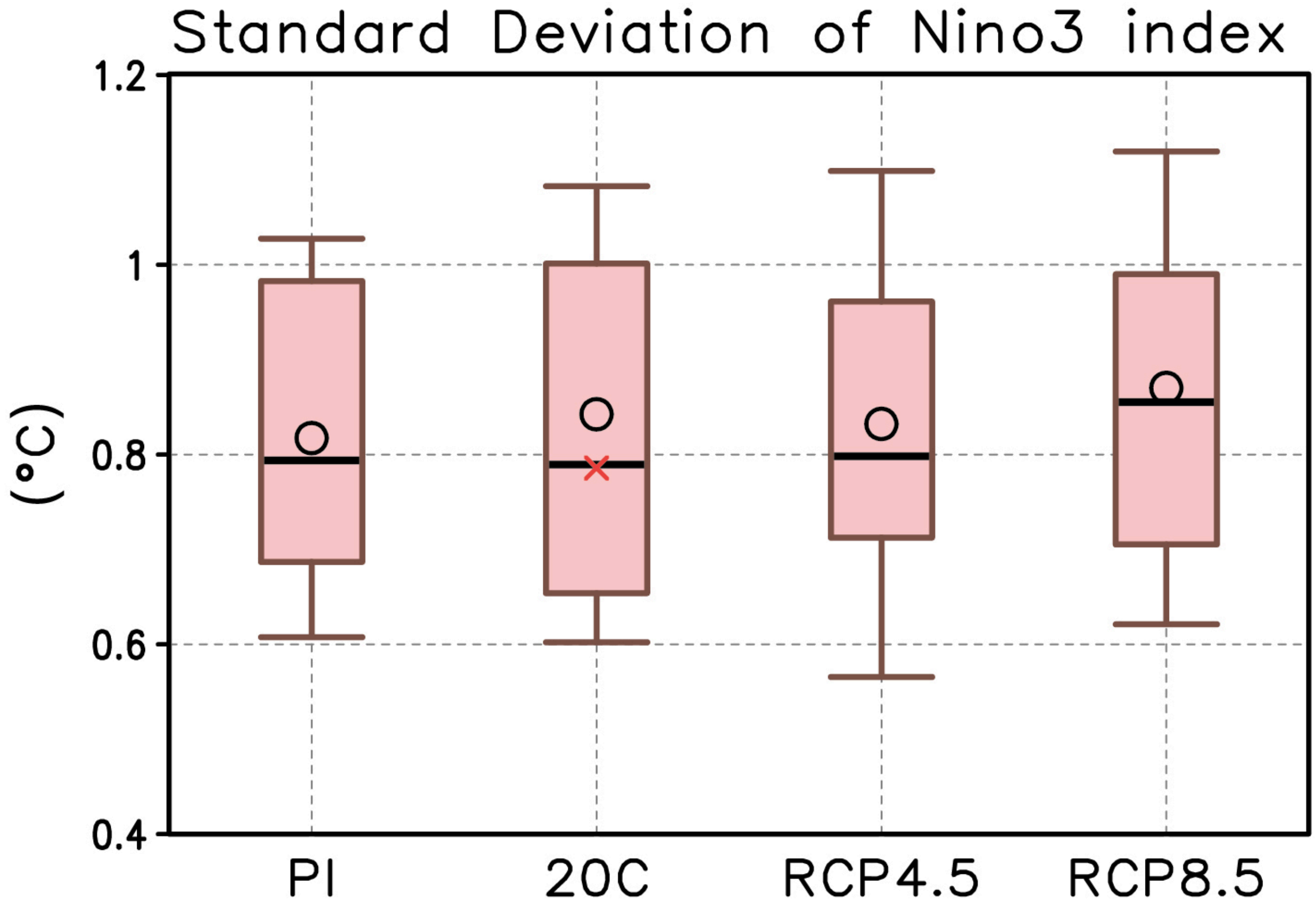








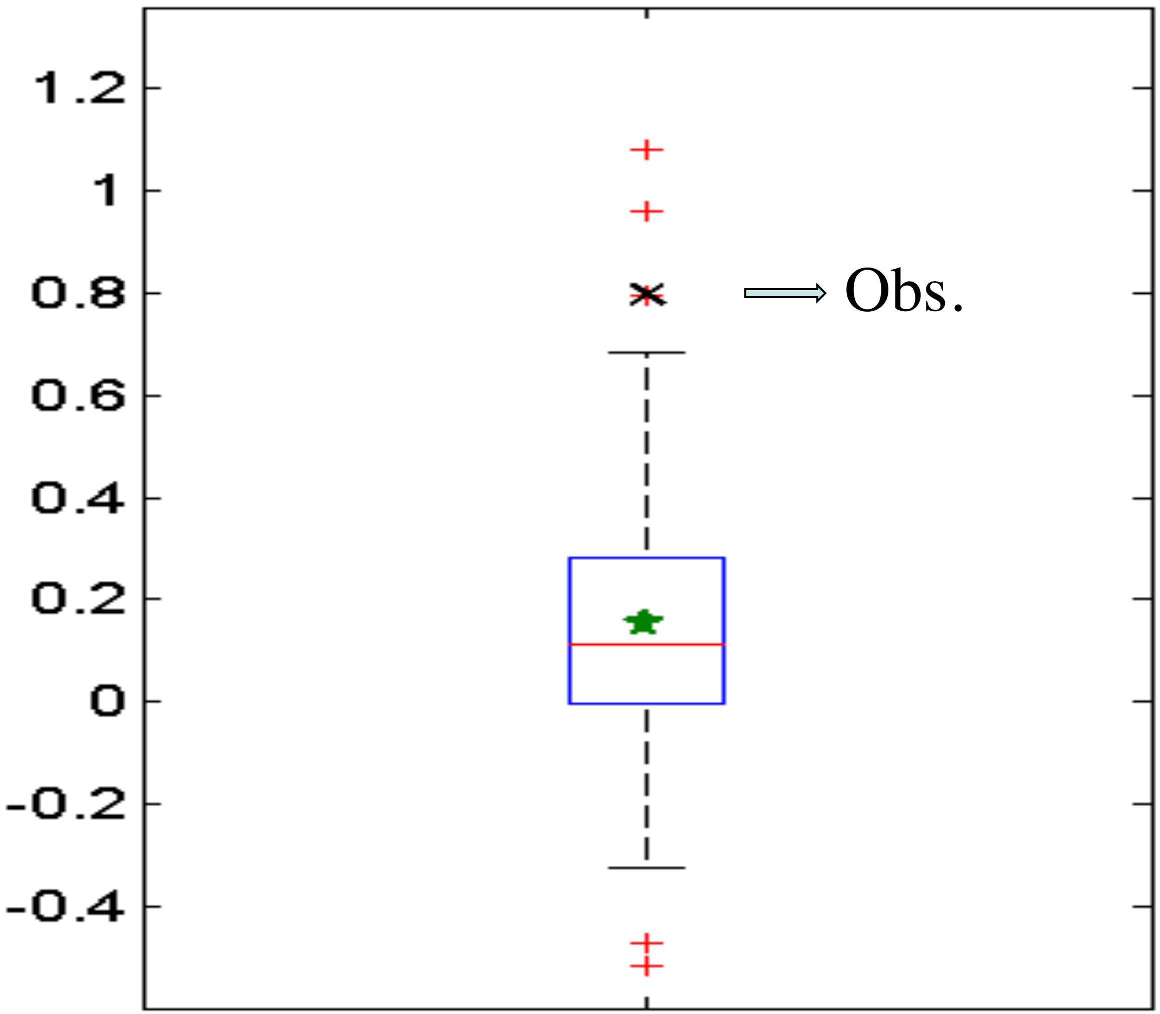
Response of ENSO to a Higher CO2: CMIP5 Results



IPCC AR5

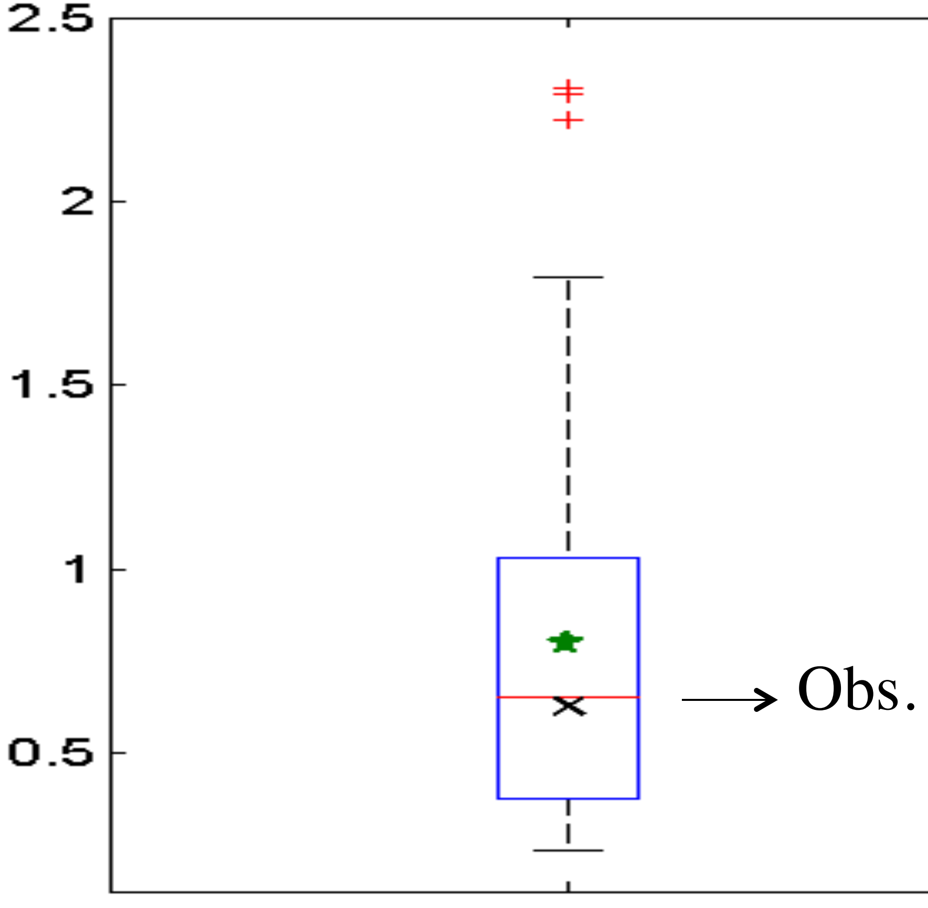
ENSO Asymmetry in CMIP5 Models

Box plot for Skewness



ENSO Amplitude in CMIP5 Models

Box plot for variance



Methodology: Dividing Models into 7 Groups

- **Criteria:**
- Diff = Var(i) – Var(j) **(Rcp85-historial run or Rcp45-historical run)**
- Vc: STD of the 16-year moving variance of the historical run for each model

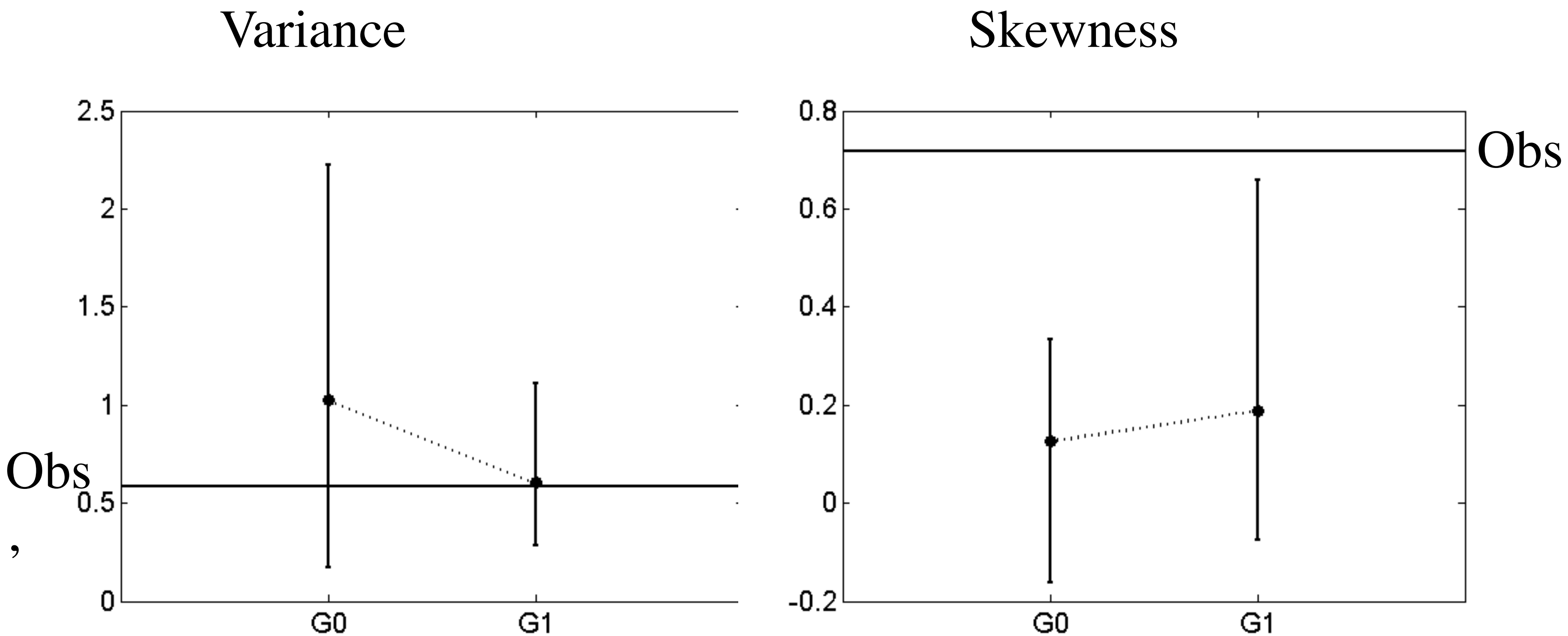
- If Diff > 1 Vc in Run/Model A: A is Indexed 1;
- If Diff < -1 Vc in Run/Model A: A-> -1;
- else, 0

	Rcp45 & His	**Rcp85 & His**
Group 0	0	0
Group 1	1	1
Group 2	-1	-1
Group 3	0	1
Group 4	0	-1
Group 5	1	0
Group 6	-1	0

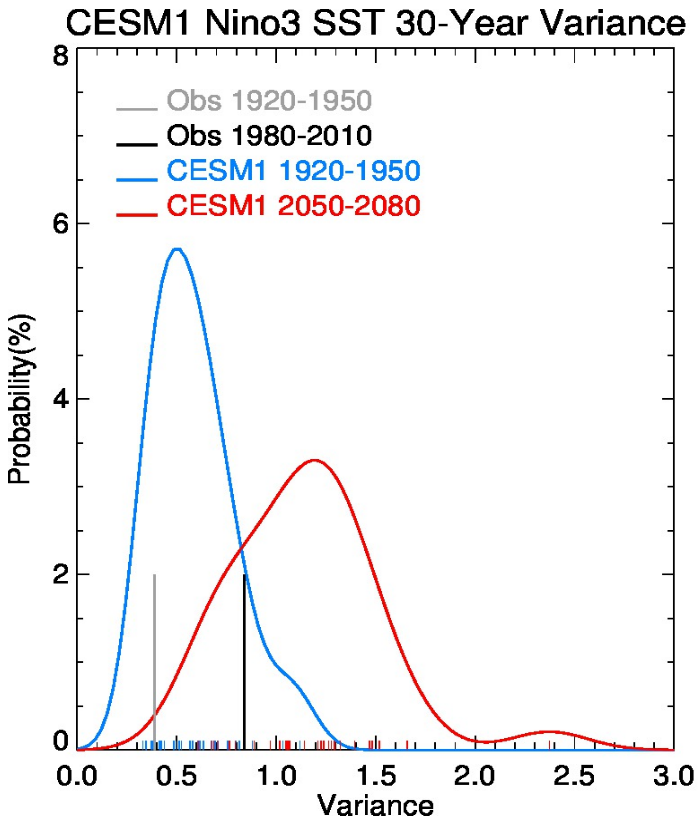
Table 1 number of models (or runs) in each group

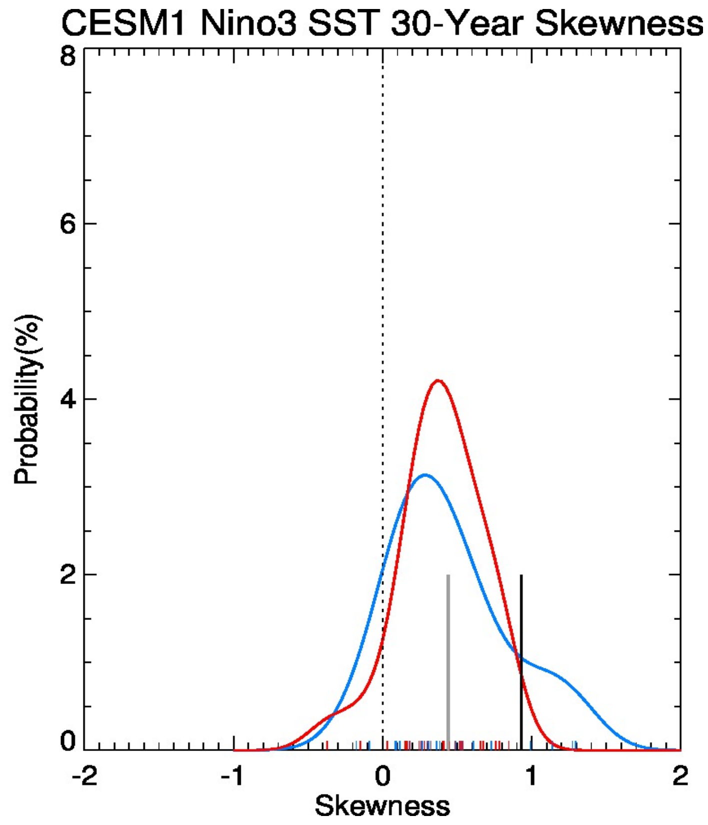
Group	All runs		Ensemble runs	
	No. of runs	Percent	No. of models	Percent
G 0	21	28%	9	25%
G 1	20	26.67%	11	30.56%
G 2	7	9.33%	4	11.11%
G 3	9	12%	4	11.11%
G 4	8	10.67%	3	8.33%
G 5	6	8%	2	5.56%
G 6	4	5.33%	3	8.33%

Variance and Skewness in the Two Largest Groups



Response of ENSO to a Higher CO2: Results from CESM1





Differences Between CESM1 and CCSM4

Table-1 Nino3 SST Statistics

	Variance	Skewness	Sample Size
CCSM4 Y1850	0.90	0.30	2100 years
CCSM4 Y2000	0.84	0.34	2100 years
CCSM4 1920-1990	0.98	0.38	70×5 years
CCSM4 2010-2080	0.69	0.34	70×5 years
CESM1 Y1850	0.68	0.64	1100 years
CESM1 Y2000	1.39	0.59	510 years
CESM1 1920-1990	0.80	0.73	70×30 years
CESM1 2010-2080	1.16	0.54	70×30 years

Summary

- Stability analysis of a lower order model suggests that the very existence of an oscillating regime requires a sufficiently strong radiative heating. Further increases in the intensity of heating results in stronger and more asymmetric oscillation.

- A common deficiency in the State-of-the-Art Models collected in CMIP5 is noted: they fail to produce strongly asymmetric oscillation as that had occurred in the observations, even when the amplitude of the oscillation in the models is as strong as or even much stronger than the observations.

- While on average, results from CMIP5 models seem to suggest a muted response of ENSO to a high CO2, but models that have a consistent response to different levels of increase of CO2 tend to produce a positive response. ENSO in these models are found to be more comparable to the observations in amplitude and asymmetry.

- The newest NCAR climate model—CESM1—is found to produce a positive response of ENSO to higher CO2. The amplitude ENSO in CESM1 is weaker than in its immediate predecessor (CCSM4) while the asymmetry is stronger.

Further Studies

- Why do the state-of-the-art models fail to produce highly asymmetric oscillation as we have observed?
- Why do models tend to have a more sensitive response in the zonal SST contrast in the mean?
- How do we know whether a state-of-the-art models is in the same dynamic regime with the observations?

Why Do We Have El Nino?

- ✓ Consequence of the way that equatorial waves passage and reflect in a bounded basin.
- ✓ The existence of a positive feedback—the Bjerknes feedback—that enables a self-propelled growth of a SST anomaly.

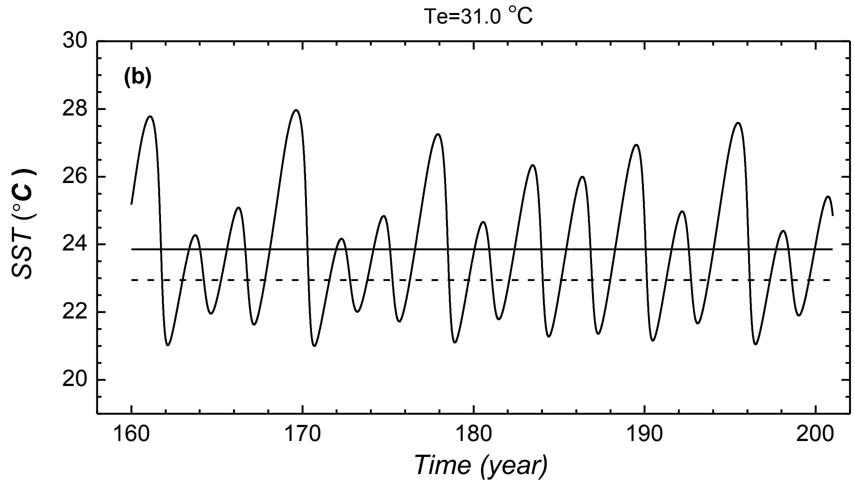
- ✓ The strengthening/weakening equatorial zonal wind results in accumulation/depletion of heat content in the equatorial upper ocean

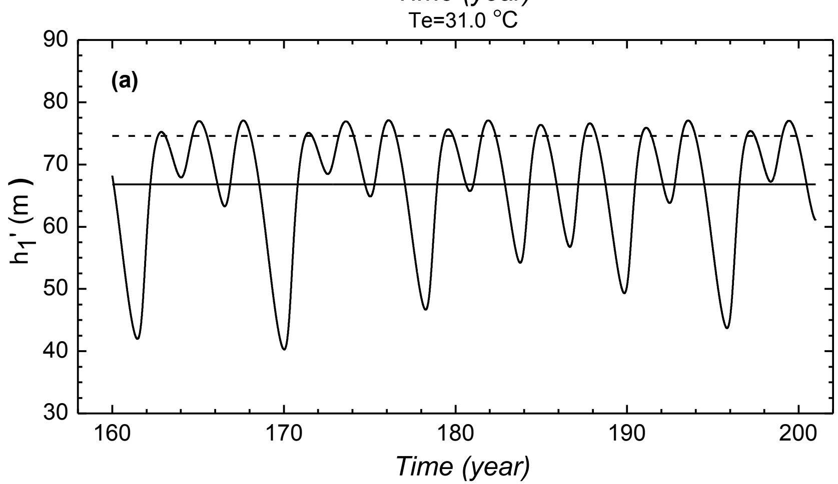
***All true, but these processes will not produce El Nino unless the radiative heating over the equatorial Pacific is sufficiently strong*.**

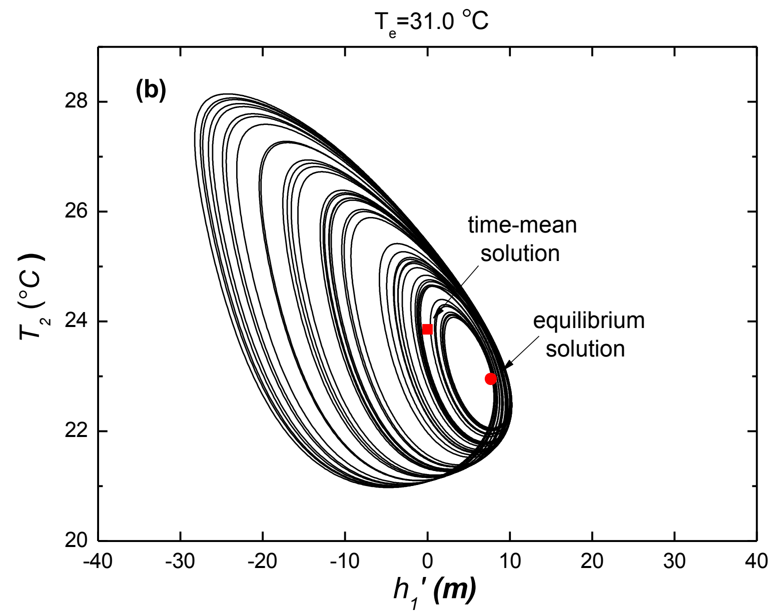
Why Do We Have El Nino?

- More Specifically, the coupled tropical ocean-atmosphere system has two equilibrium states: One is characterized by a zonally symmetric state with no zonal SST contrast between the western and eastern Pacific, and one is zonally asymmetric state with strong zonal SST contrast between the two sides of the basin.
- When the heat flux is sufficient strong, both of the equilibrium states become unstable, resulting in an unsteady behavior of the system that is characterized by a recurrent relaxation of the latter state towards the former state.

Asymmetry in the Oscillation in the Model of Sun (1997)

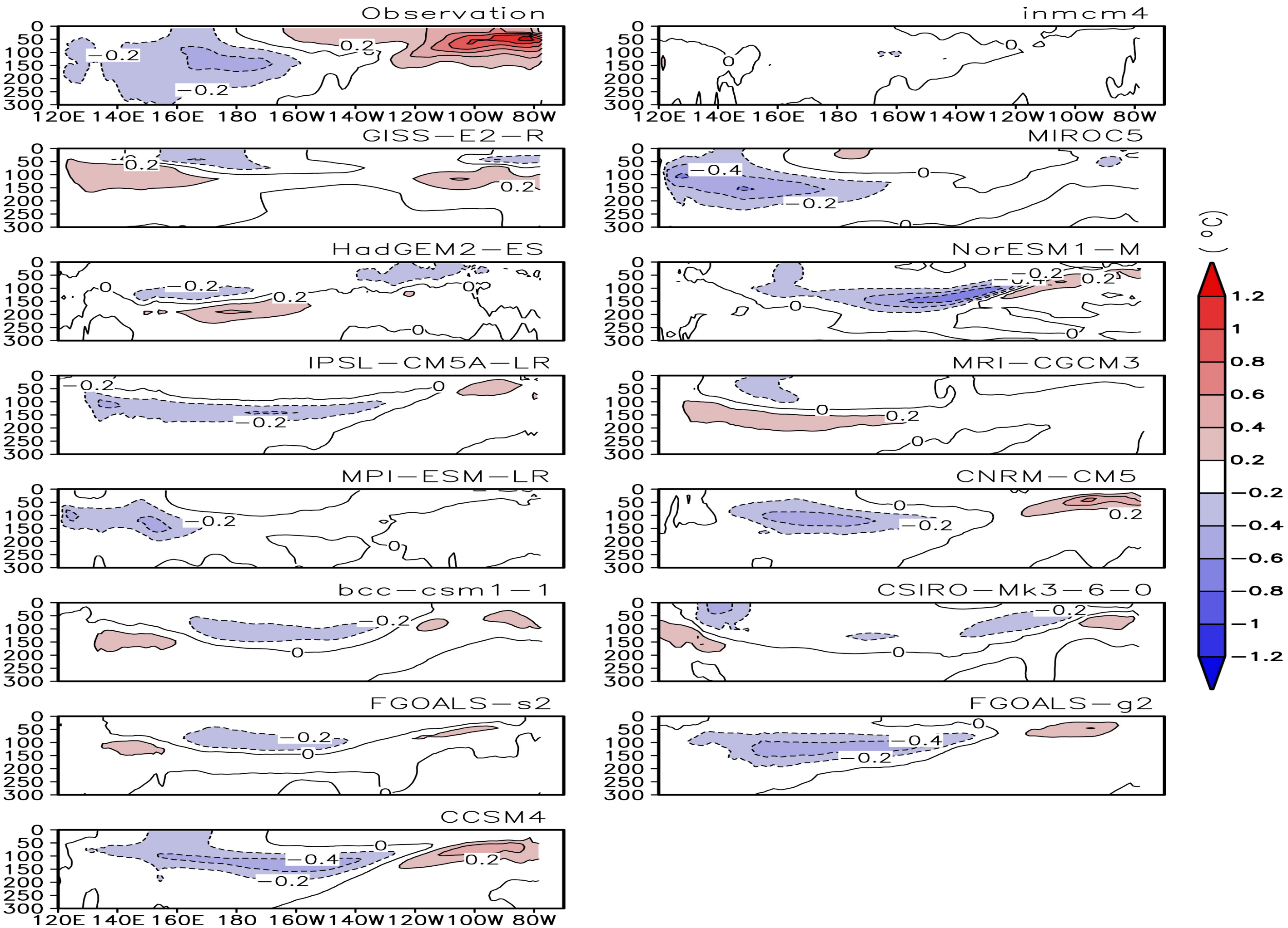






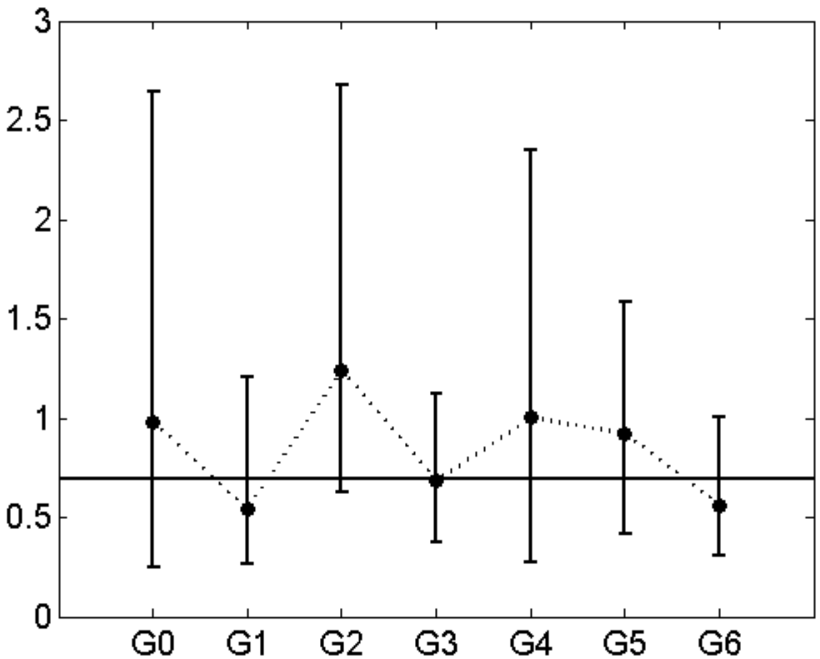
Liang, J., X.-Q. Yang, and D.-Z. Sun, 2012, J. Climate, 25, 7590-7606.

ENSO Asymmetry in Models and Obs.



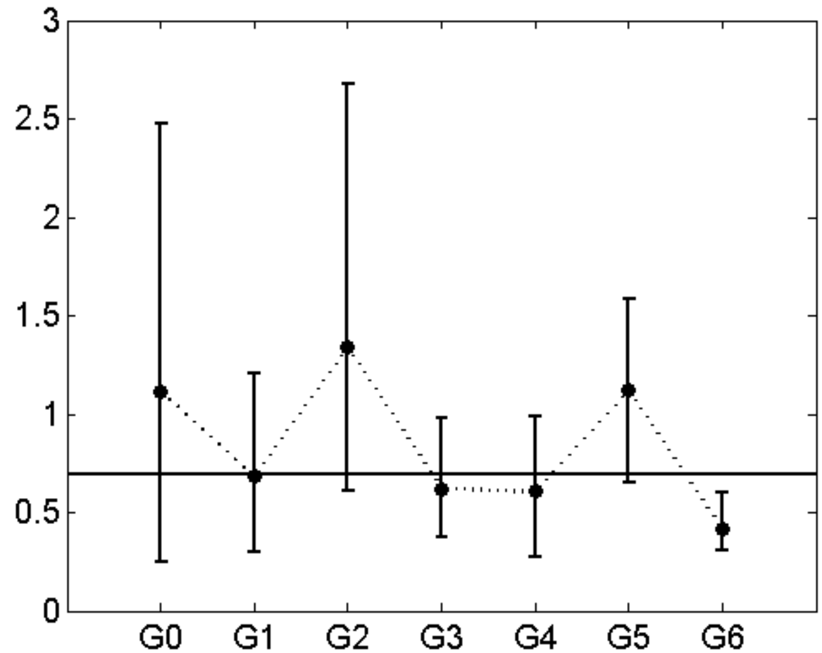
Group mean variance

All runs



0.981	0.538	1.243	0.684	1.001	0.921	0.563

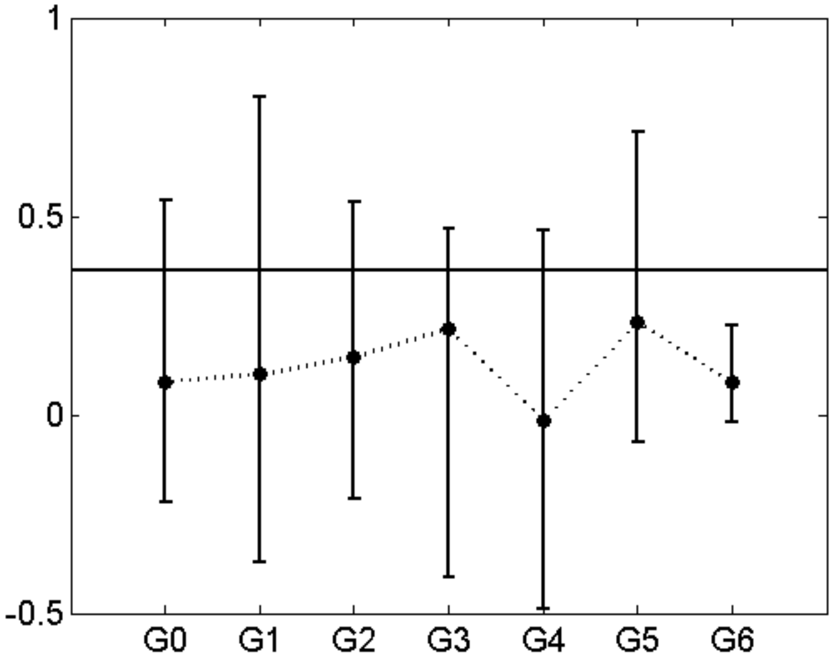
Ensemble



1.112	0.681	1.340	0.618	0.608	1.118	0.416

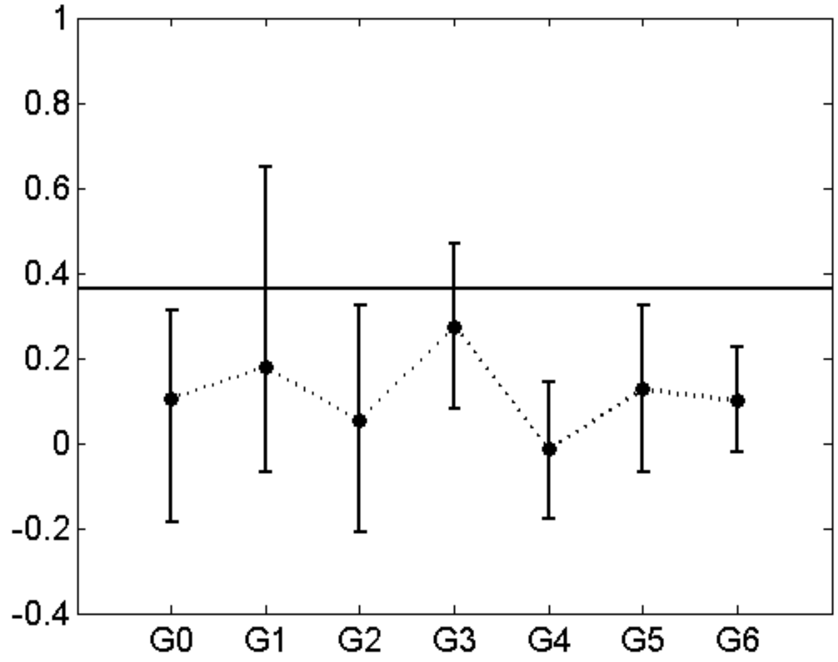
Group mean skewness

All runs



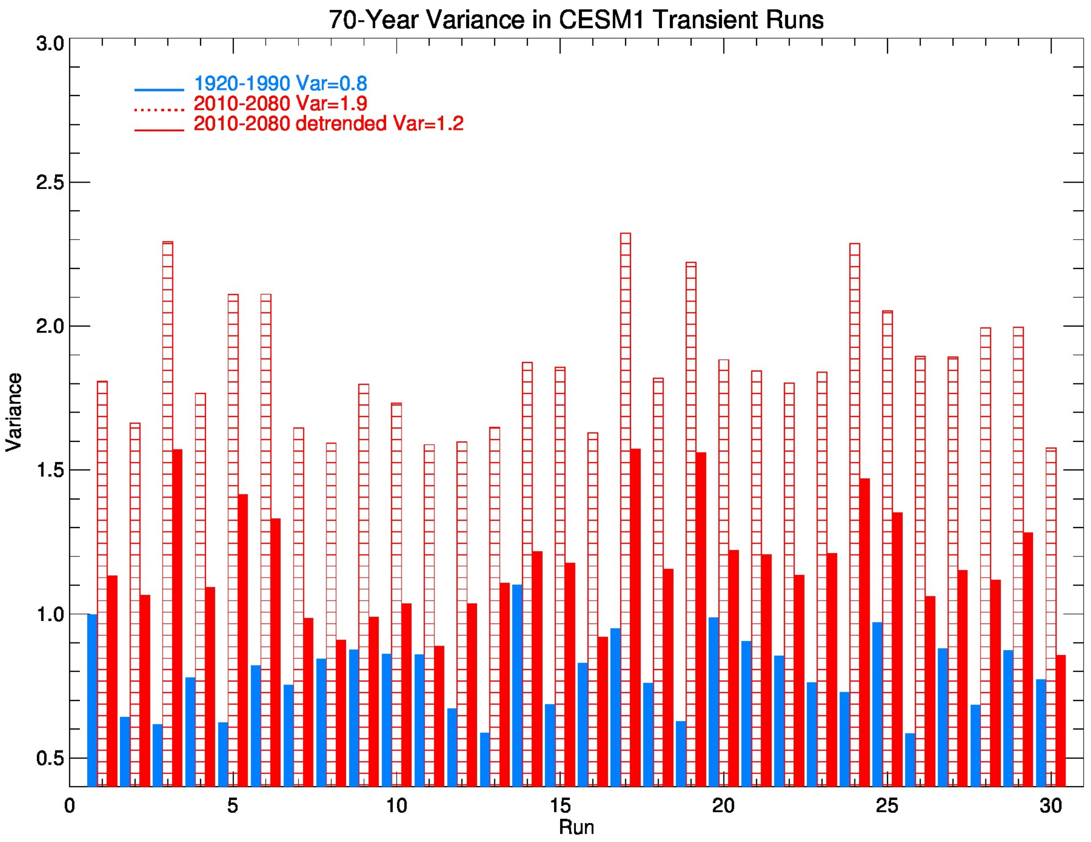
0.083	0.102	0.143	0.215	-0.015	0.233	0.080

Ensemble

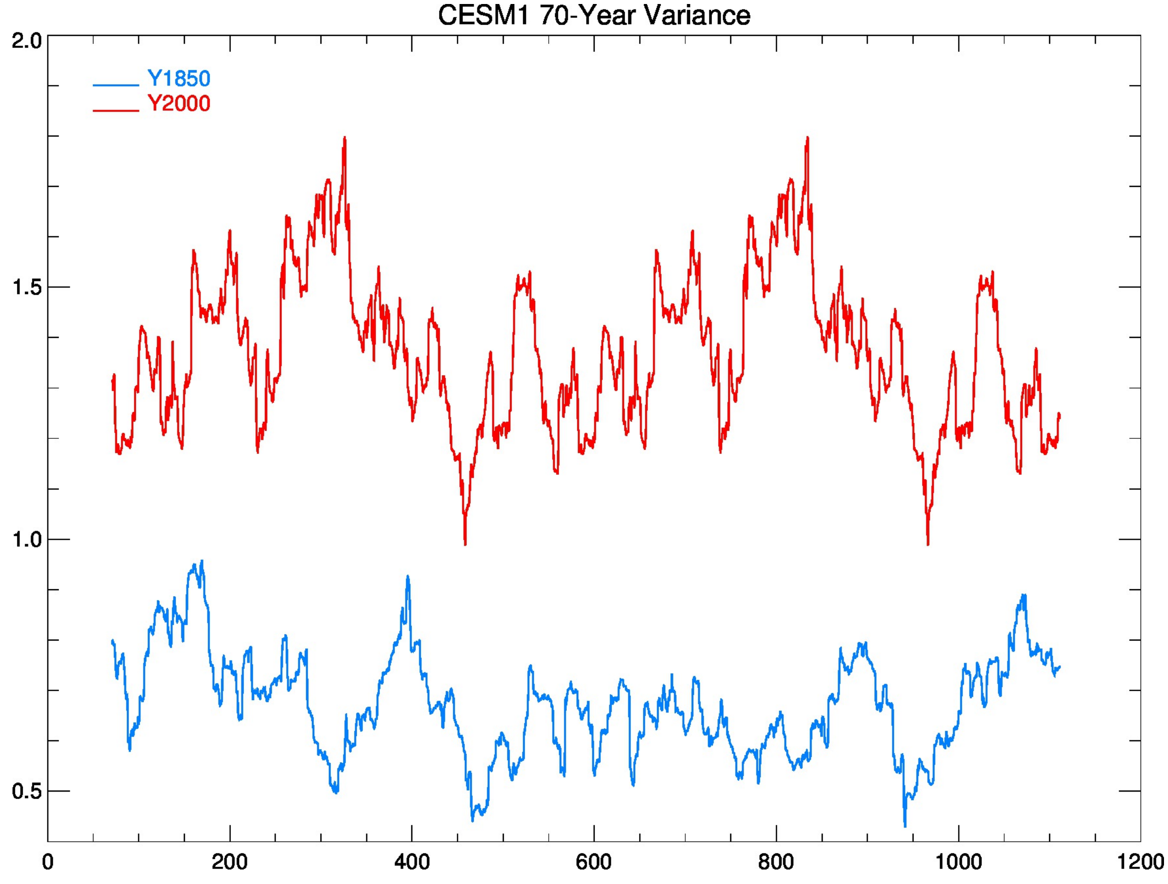


0.106	0.179	0.052	0.273	-0.015	0.126	0.099

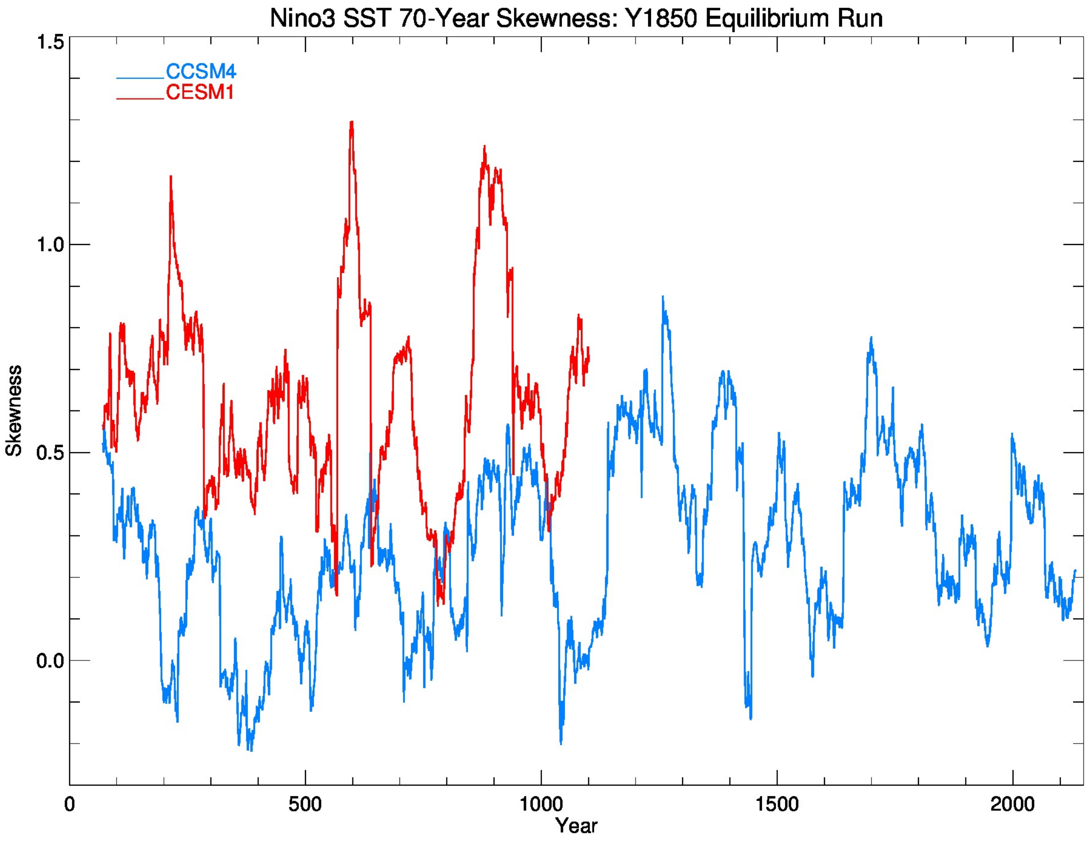
Results from an ultra-long ensemble run of CCSM4 and CESM1



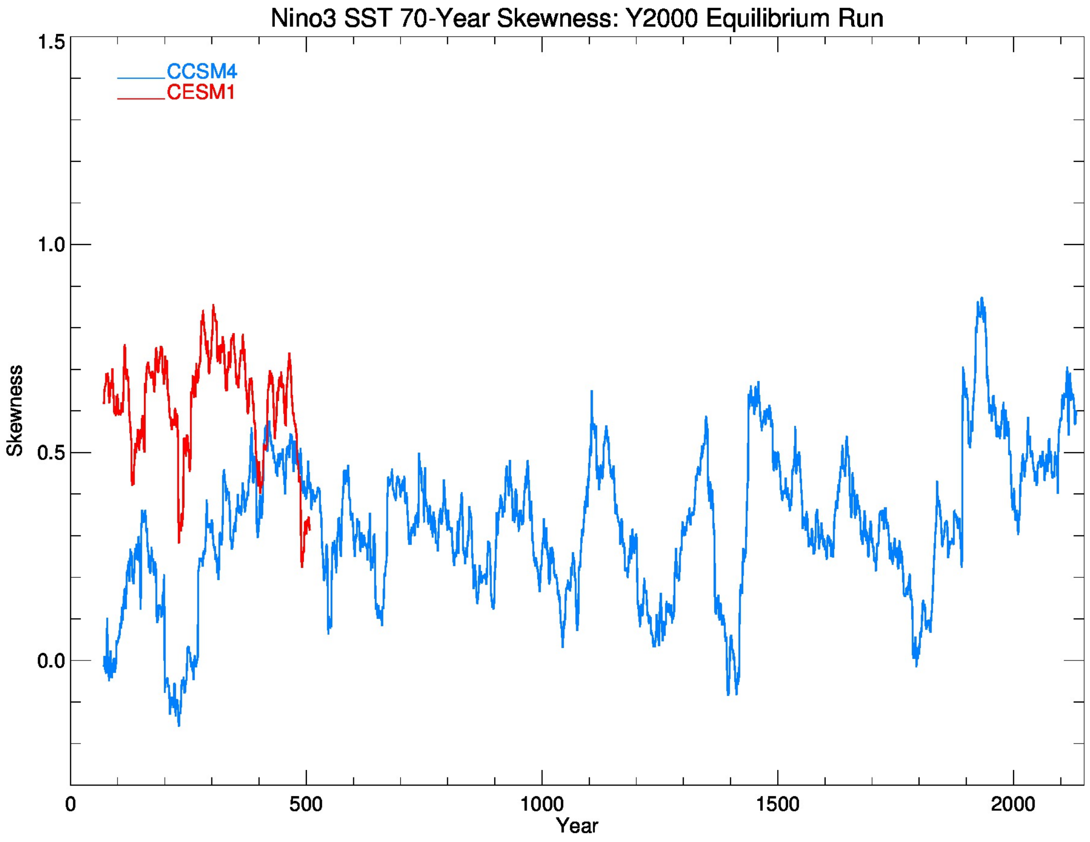
Results from CESM1



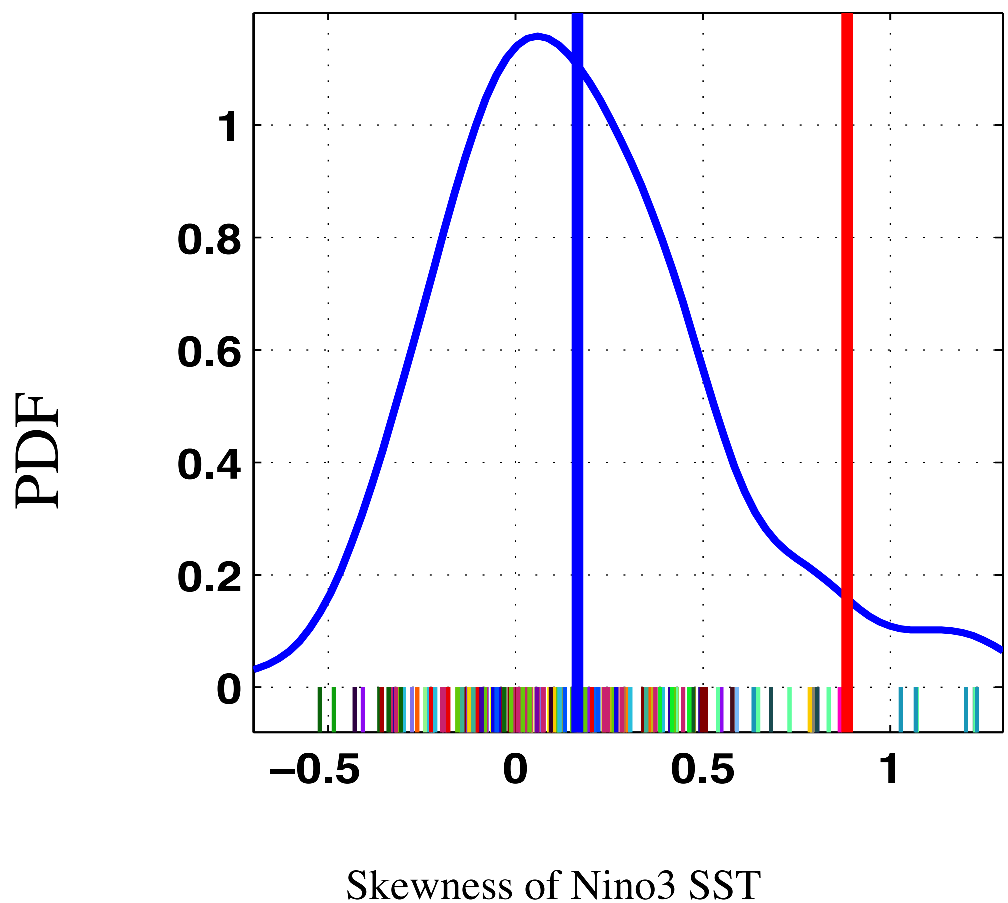
Results from an ultra-long ensemble run of CCSM4 and CESM1



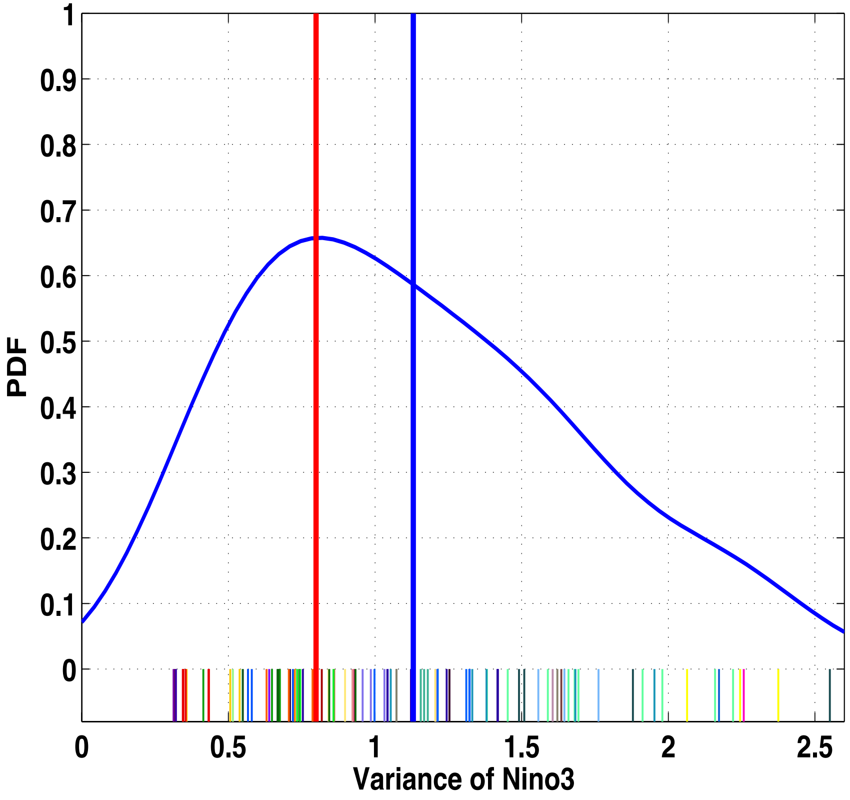
Results from an ultra-long ensemble run of CCSM4 and CESM1

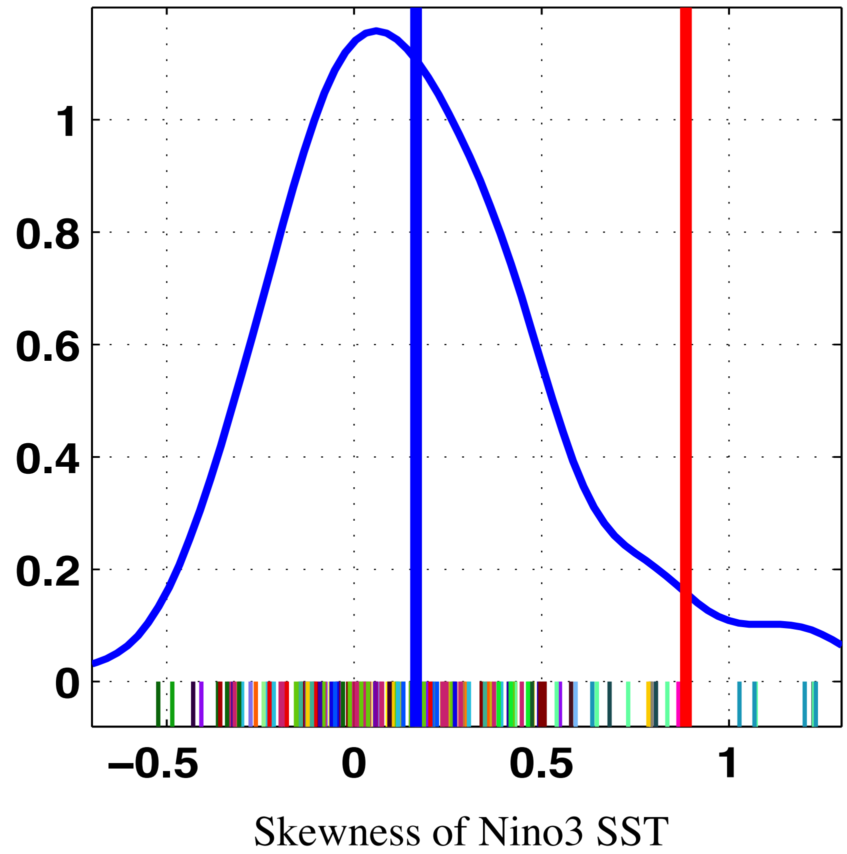


ENSO Asymmetry in CMIP5 Models (20C)



ENSO Amplitude and Asymmetry in CMIP5 Models (20C)



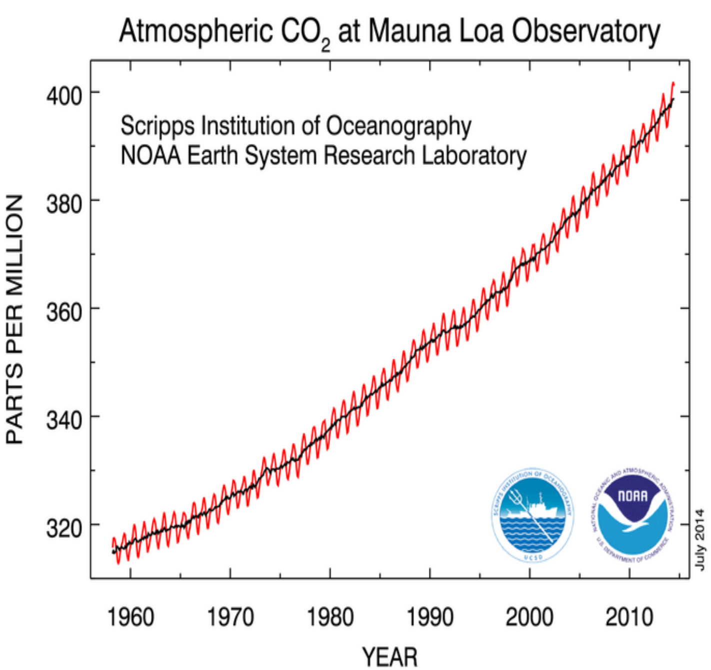


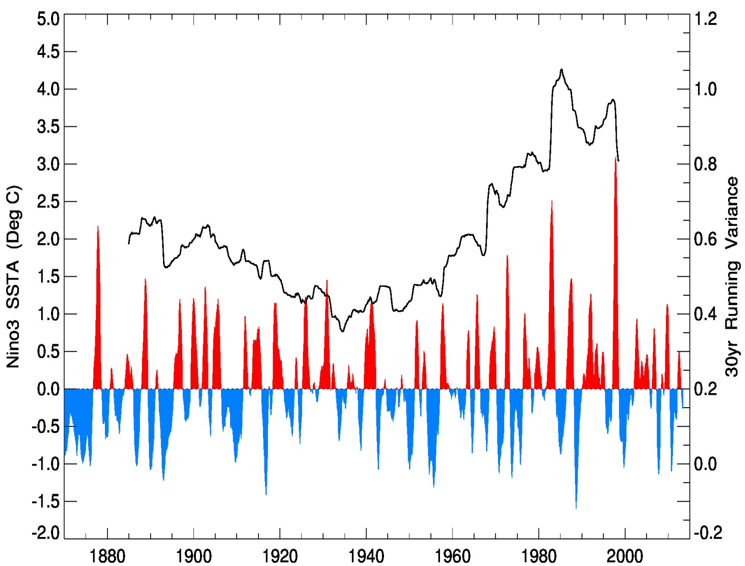
Does Higher CO2 Concentration Cause Stronger El Nino Events?

Is there a Case for a More Affirmative Answer than What is Stated in IPCC AR5?

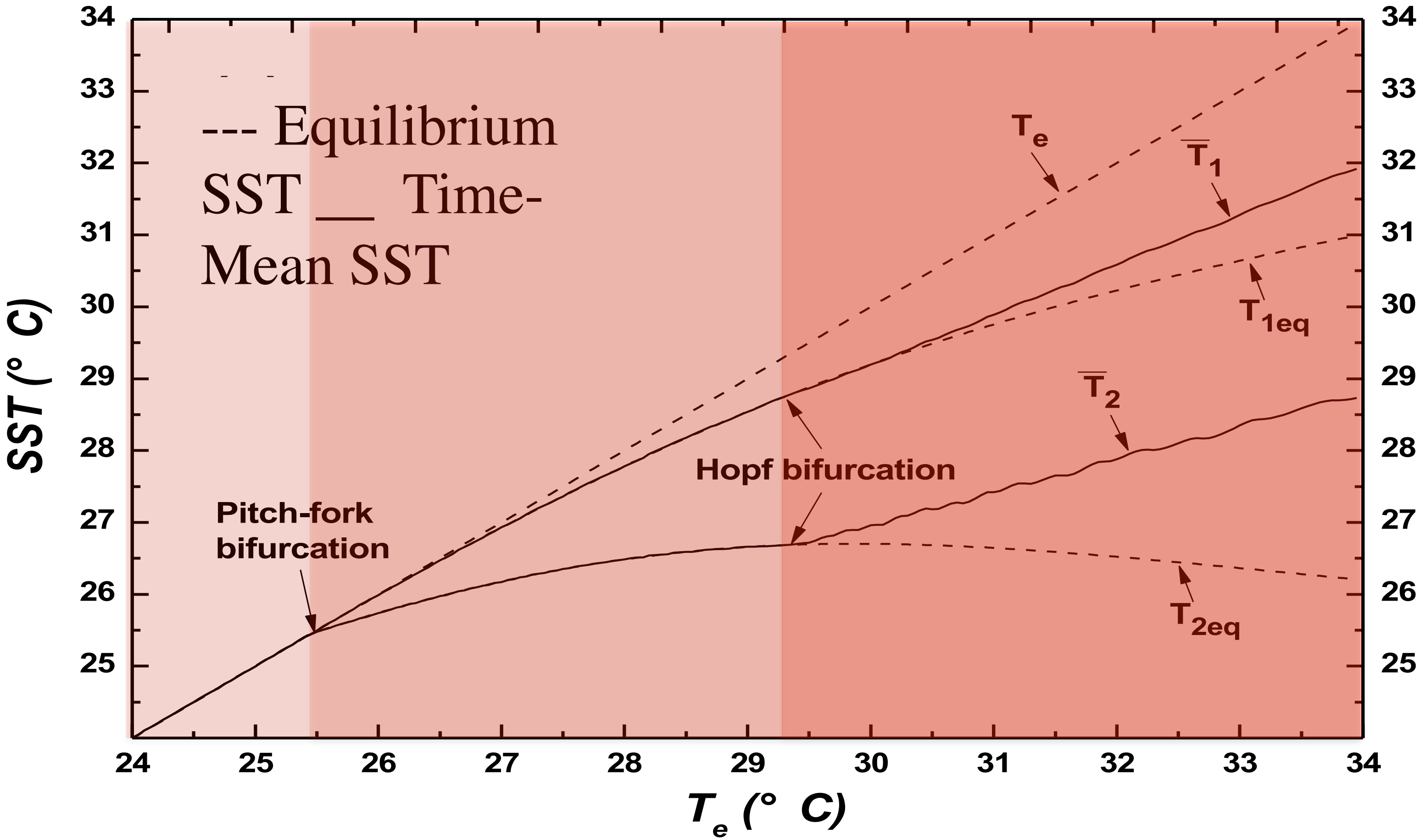
De-Zheng Sun, Xiao-Wei Quan, Jiabing Shuai, and Martin Hoerling

CIRES, University of Colorado &
Earth System Research Laboratory, NOAA





Equilibrium State Versus Time-Mean State



Liang et al. 2012

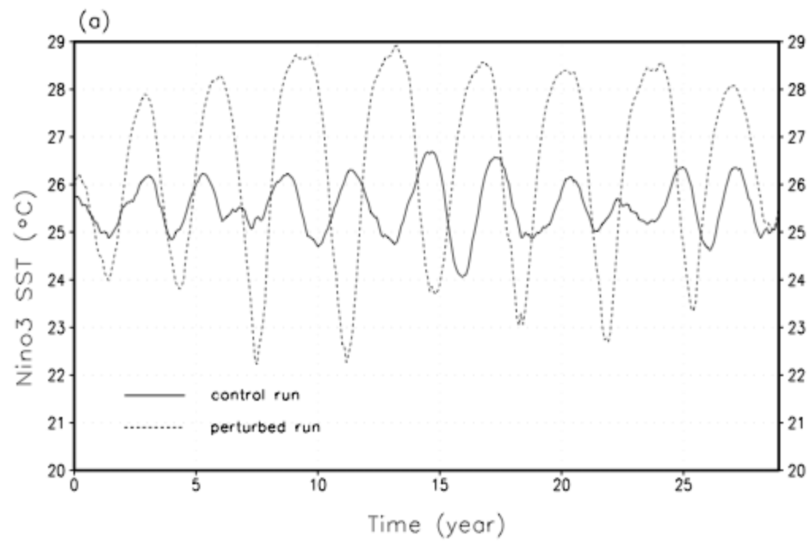
Results From a Hybrid Coupled Model

- Atmospheric component: empirical, $F_s \sim SST_p - SST$, $\tau^x \sim SST_E - SST_w$
- Ocean component: The NCAR Pacific basin model (Gent and Cane 1989)

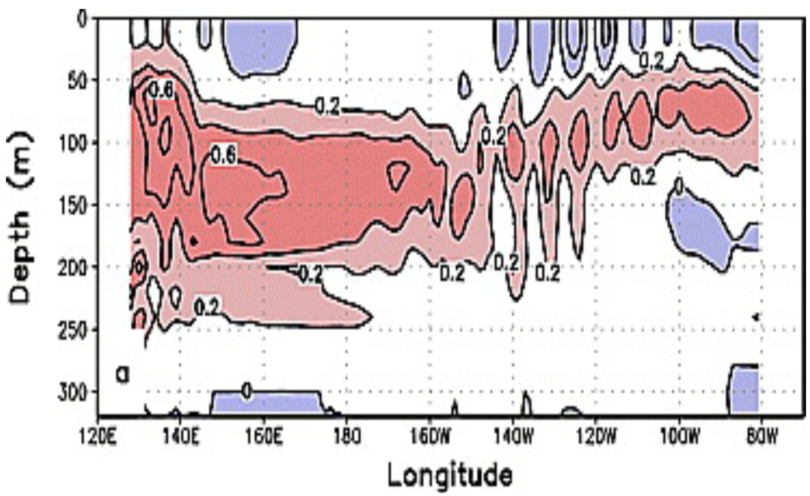
Sun, D.-Z., 2003, *J. Climate*, **16**, 185-205

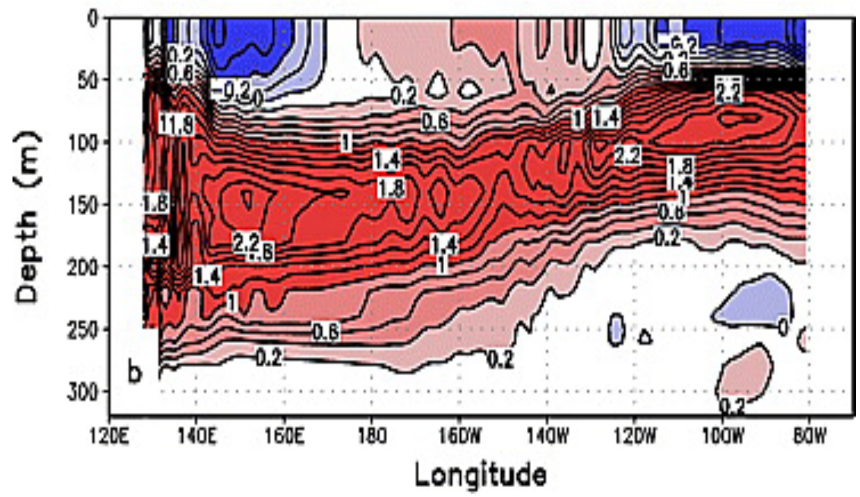
Response to An Increase

in the Radiaitive Heating



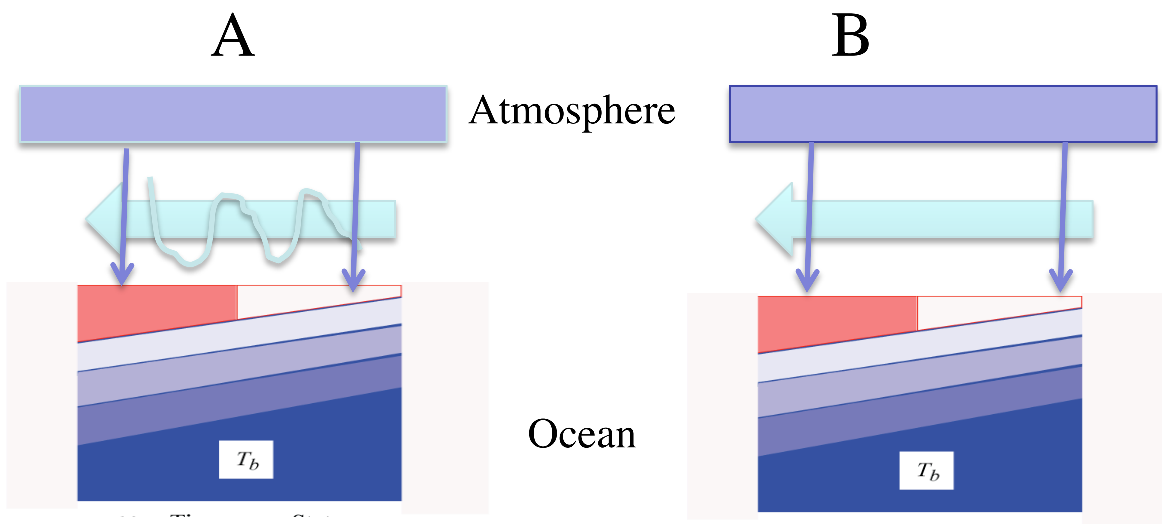
Effect of ENSO variance onto the mean state





Sun and Zhang, 2006, GRL, Vol. 33, L07710, doi:10.1029/2005GL025296

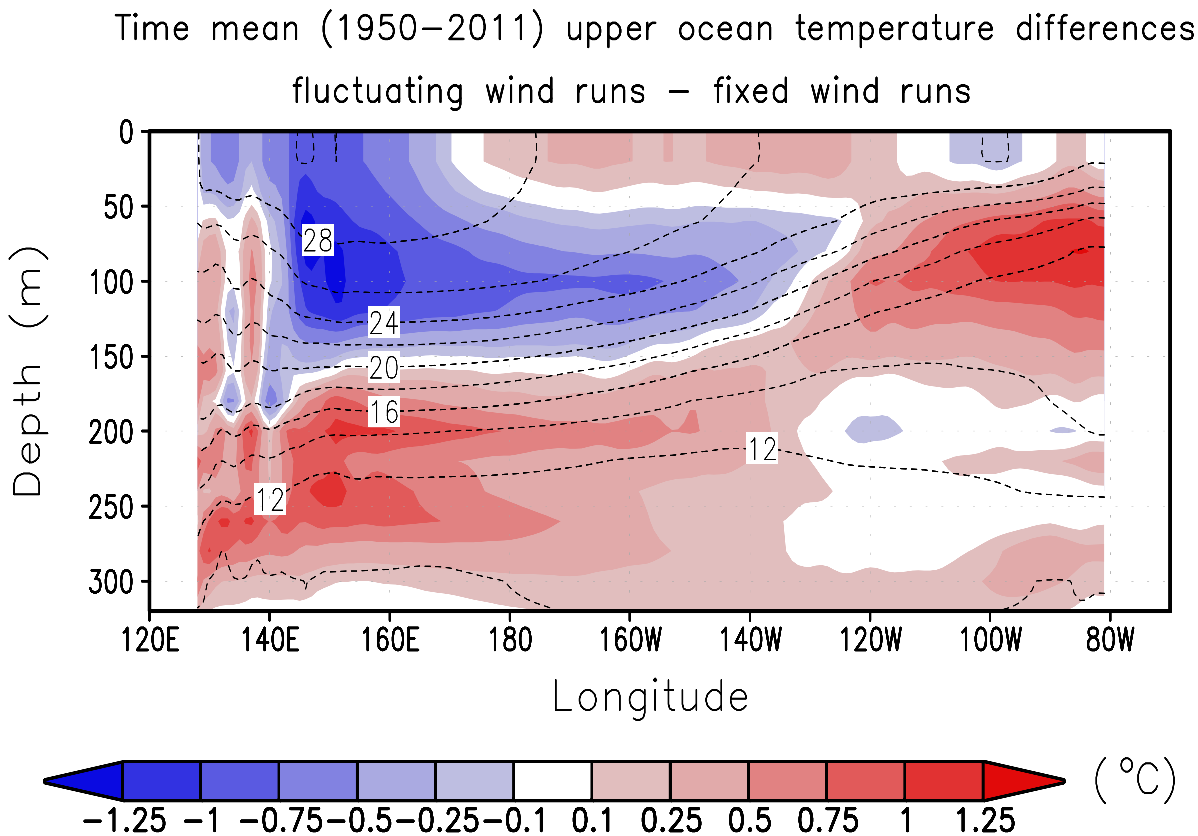
Forced Ocean GCM Experiments with and without ENSO in the Surface Forcing



- The long-term mean winds are identical for A and B, but A has interannual variations and B does not.

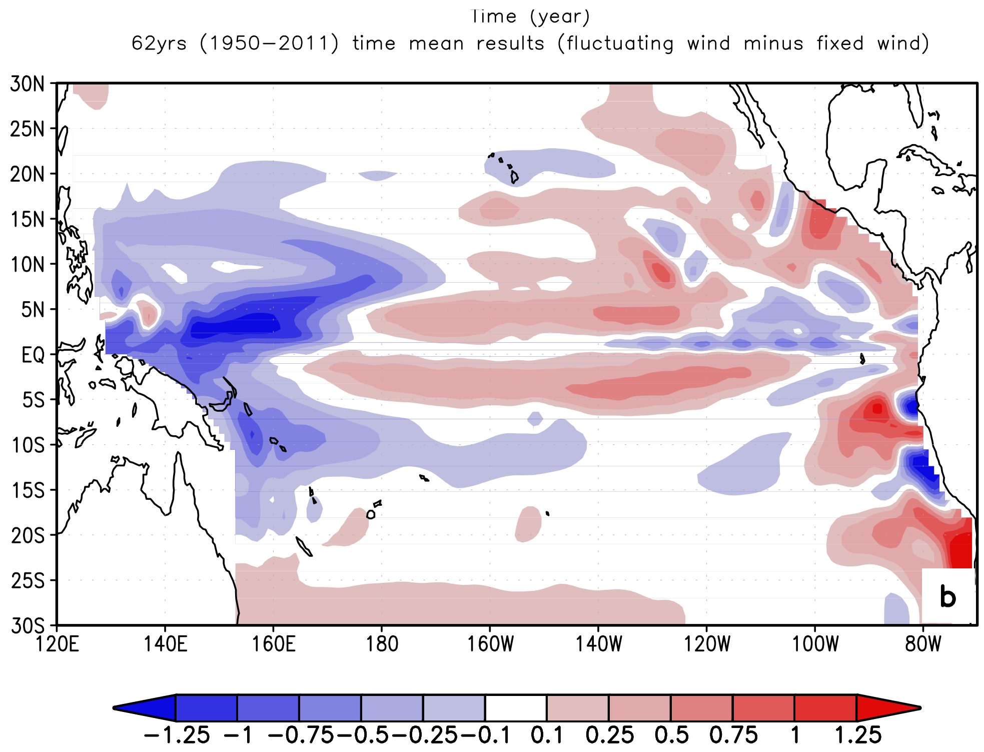
- The thermal BCs for A and B are identical-- both are restored to a prescribed potential SST

Upper T Difference Between Experiments with/ without ENSO



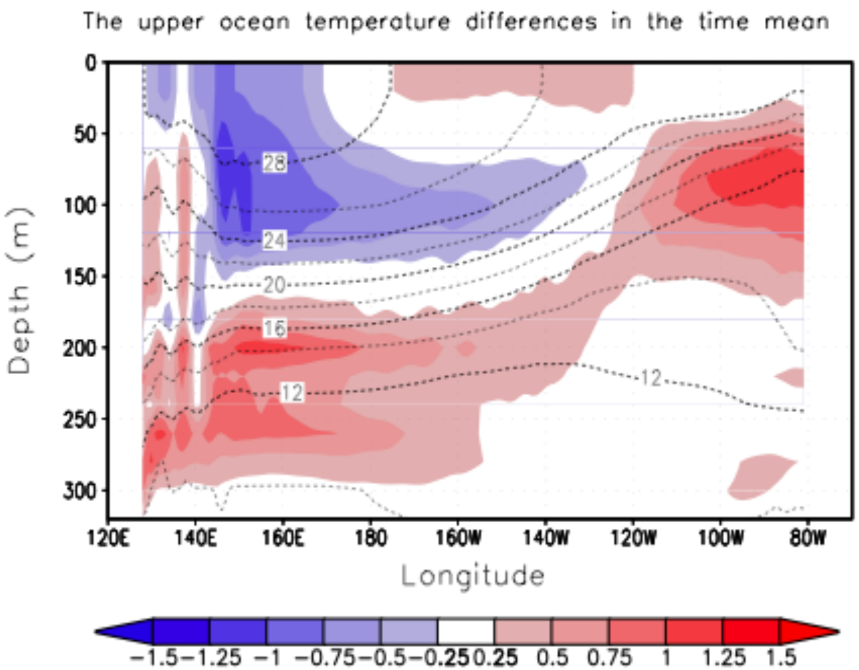
Sun et al. 2014, J. Climate, 27, 2545-2561

SST Difference Between Experiments with/without ENSO

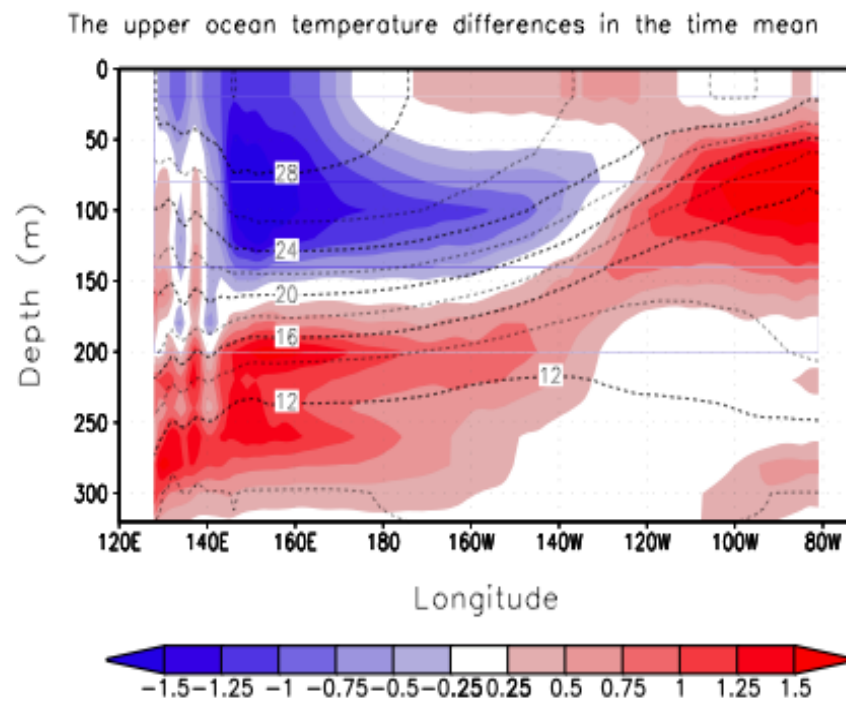


The Time-Mean Effect of ENSO on the Upper Ocean T: Sensitivity to the amplitude of ENSO

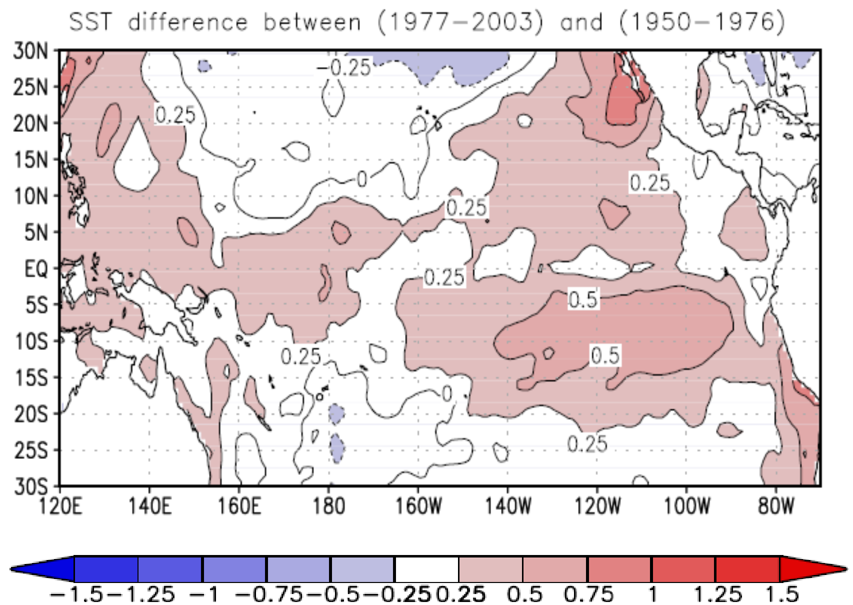
τ'

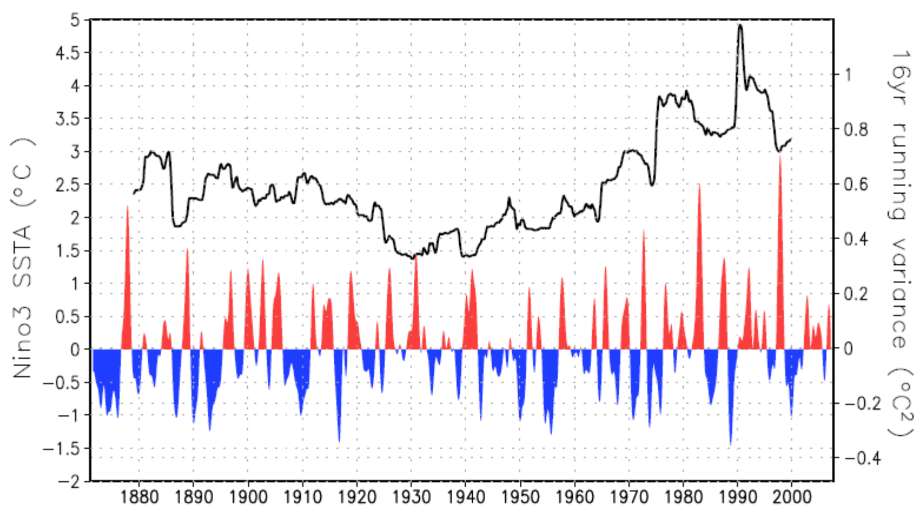


$1.5\tau'$

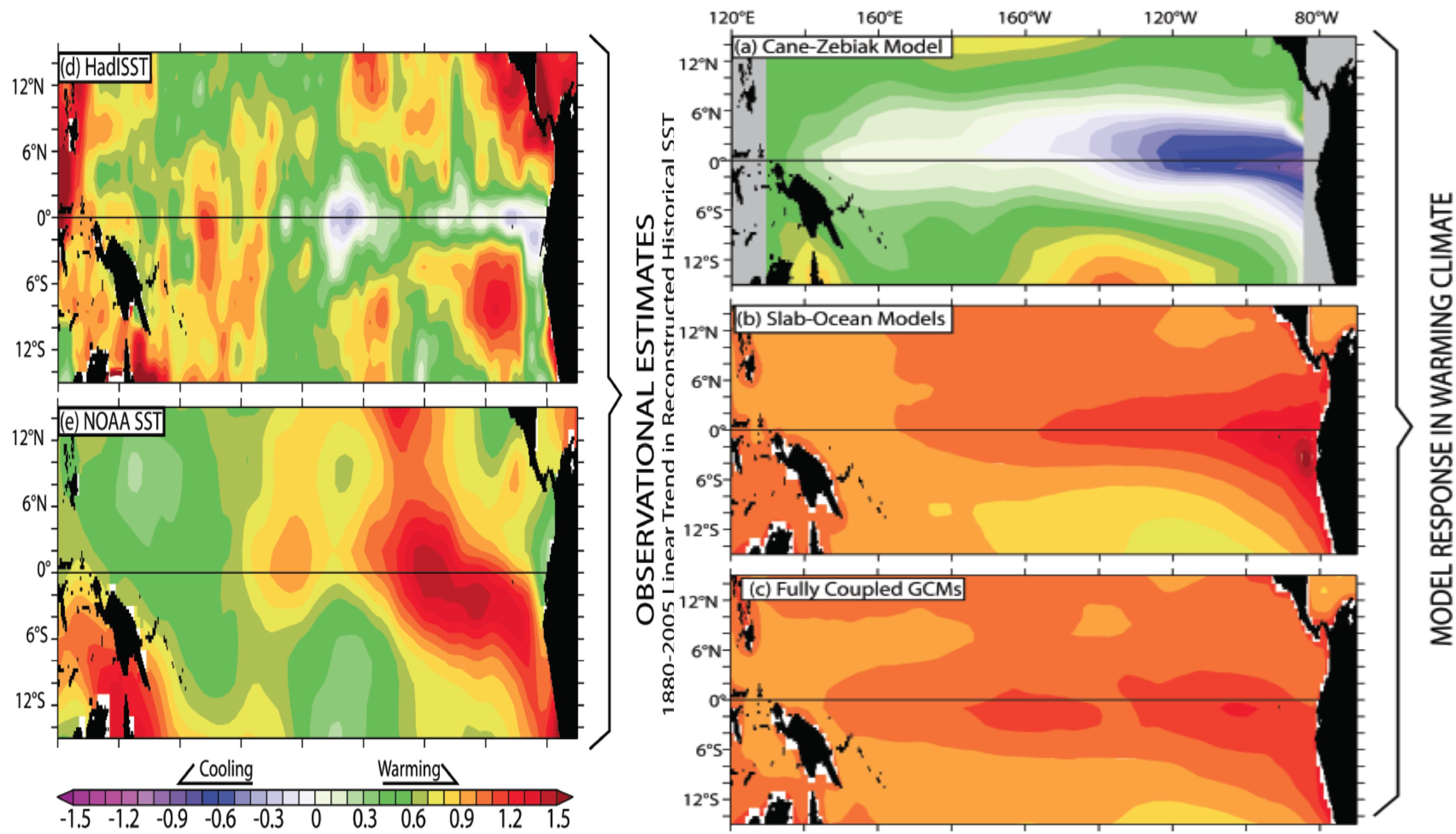


A Cause or A Consequence?





Why no trend has shown up in the zonal SST contrast in the observations?



Vecchi et al.

Equilibrium State Versus Time-Mean State

The System: $$\frac{dA}{dt} = f(A,\lambda)$$

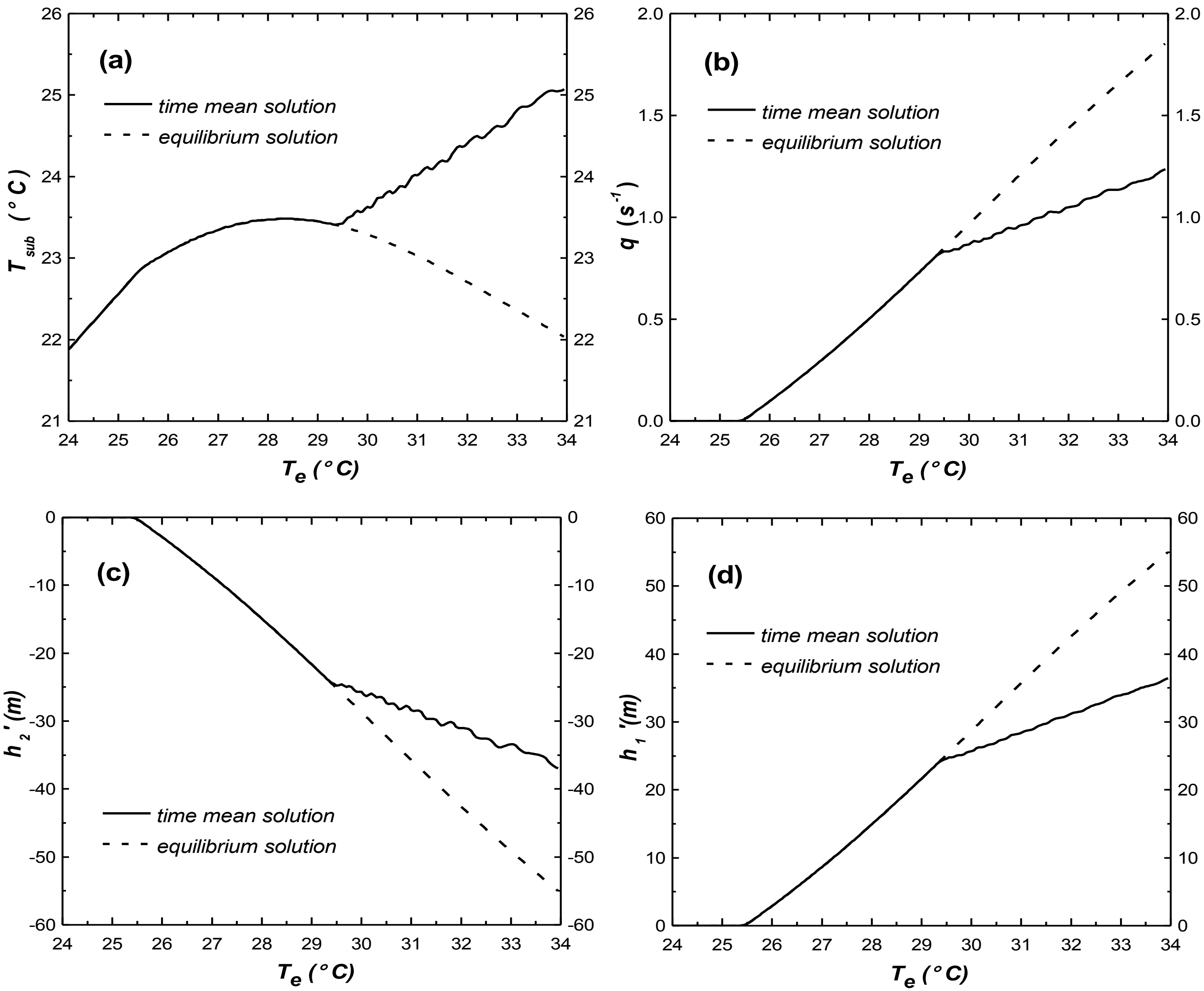
Equilibrium State: $$f(A_0,\lambda) = 0$$

Time Mean State: $$\overline{f(\bar{A}+A',\lambda)} = 0$$

$$f(A_0,\lambda) + \tfrac{\partial f}{\partial A}\overline{(\bar{A}+A'-A_0)} + \tfrac{\partial^2 f}{\partial^2 A}\overline{(\bar{A}+A'-A_0)^2} + \ldots = 0$$

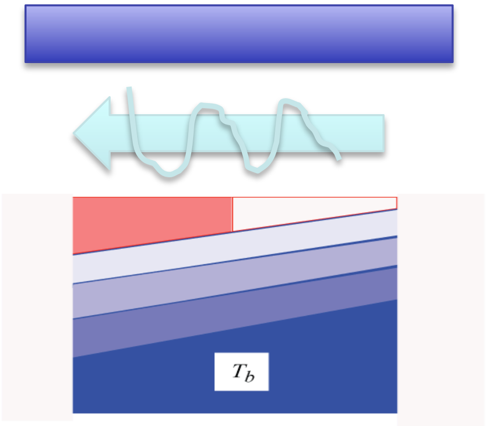
When $f(A,\lambda)$ Is nonlinear $\bar{A} \neq A_0$

Tsub, q, h1, and h2 as a function of T_e.

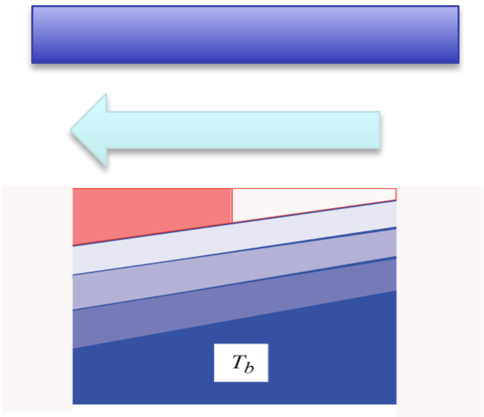


Forced Ocean GCM Experiments with and without ENSO in the Forcing

A



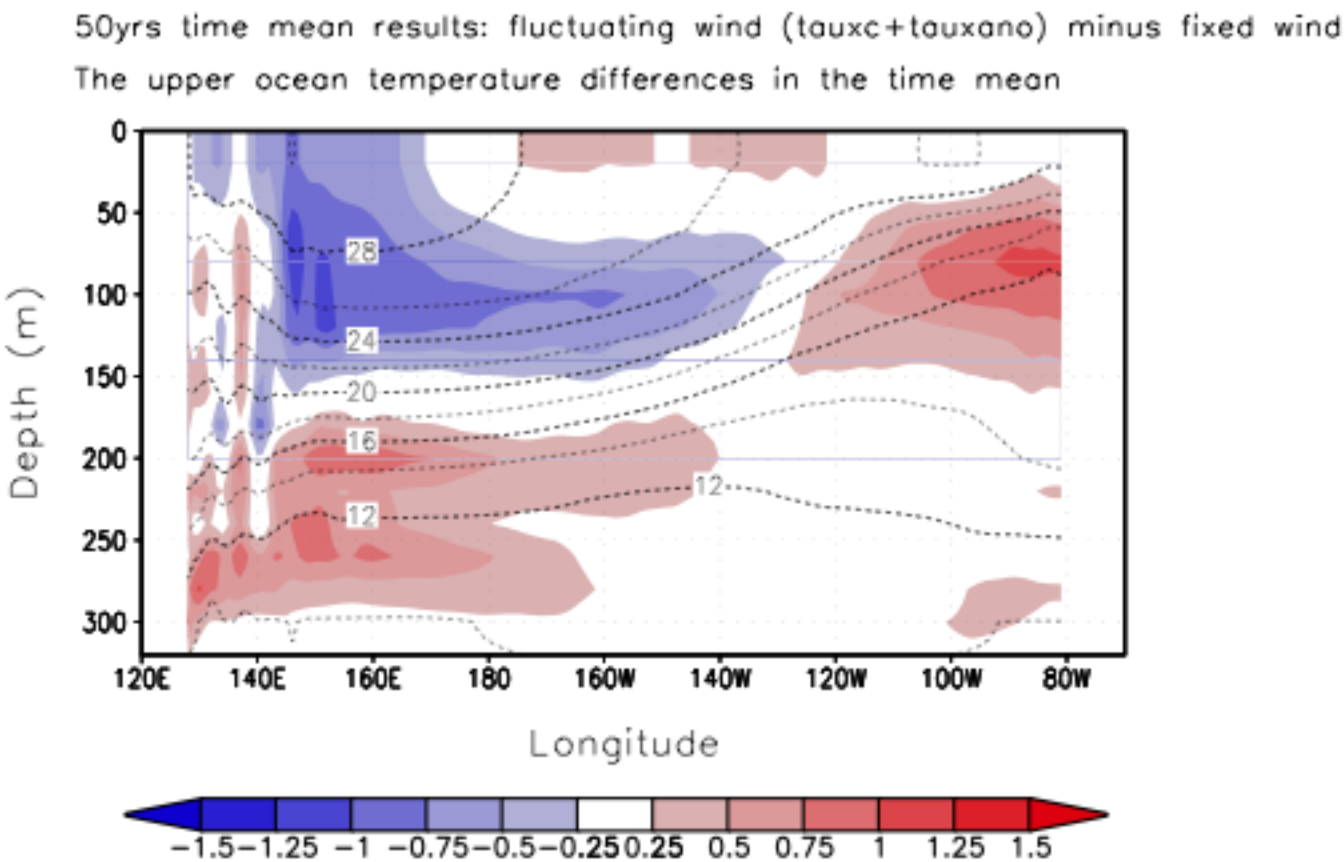
B



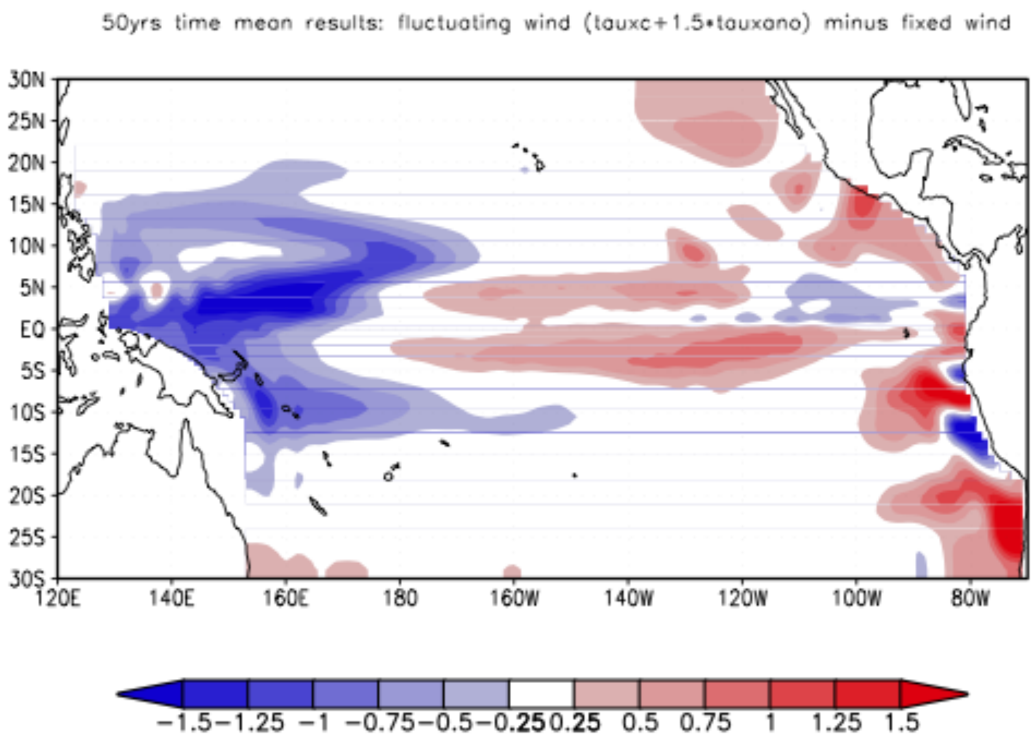
- The long-term mean winds are identical for A and B, but A has interannual variations and B does not.

- The thermal BCs for A and B are identical-- both are restored to a prescribed potential SST

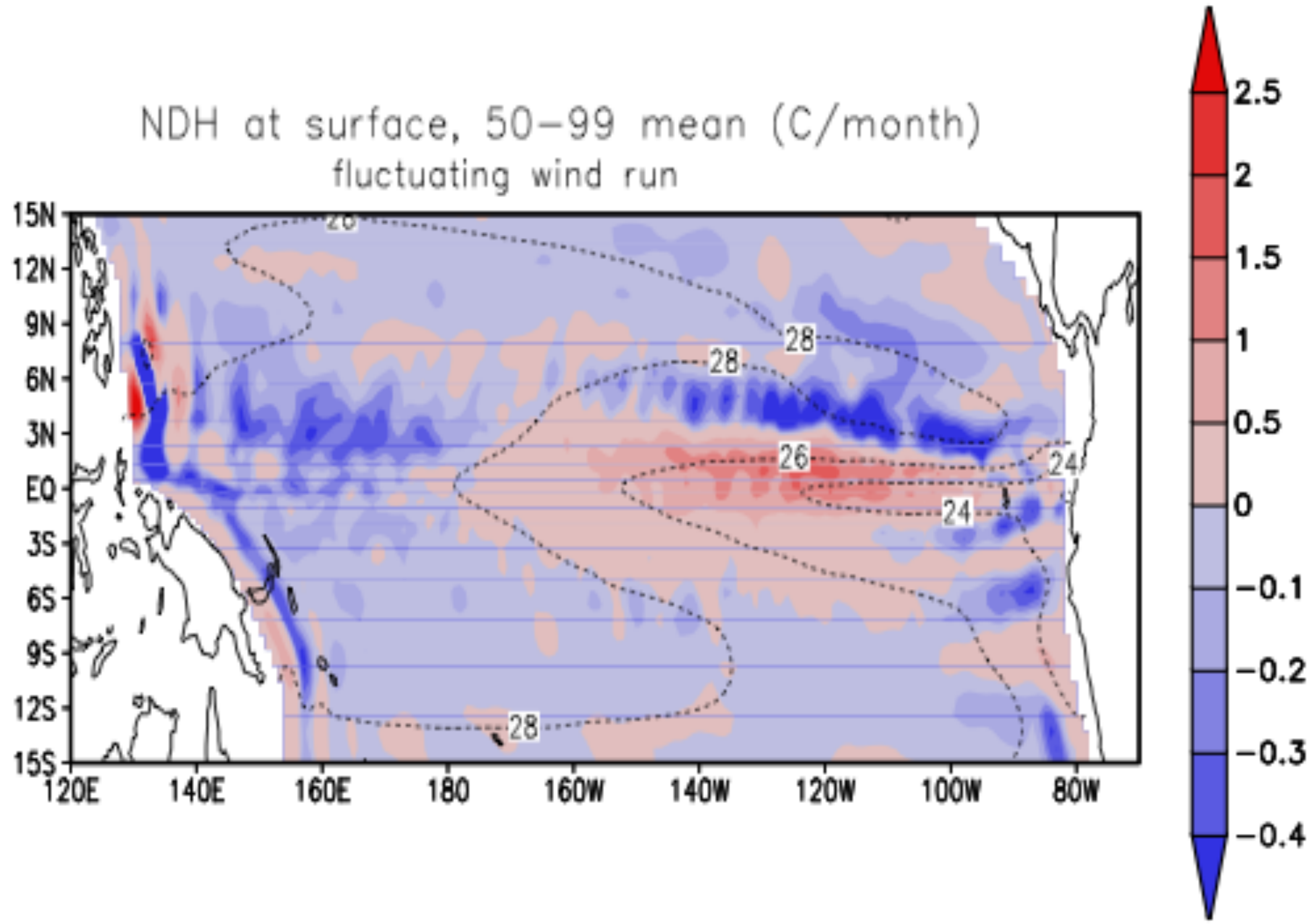
Upper T Difference Between Experiments with/without ENSO



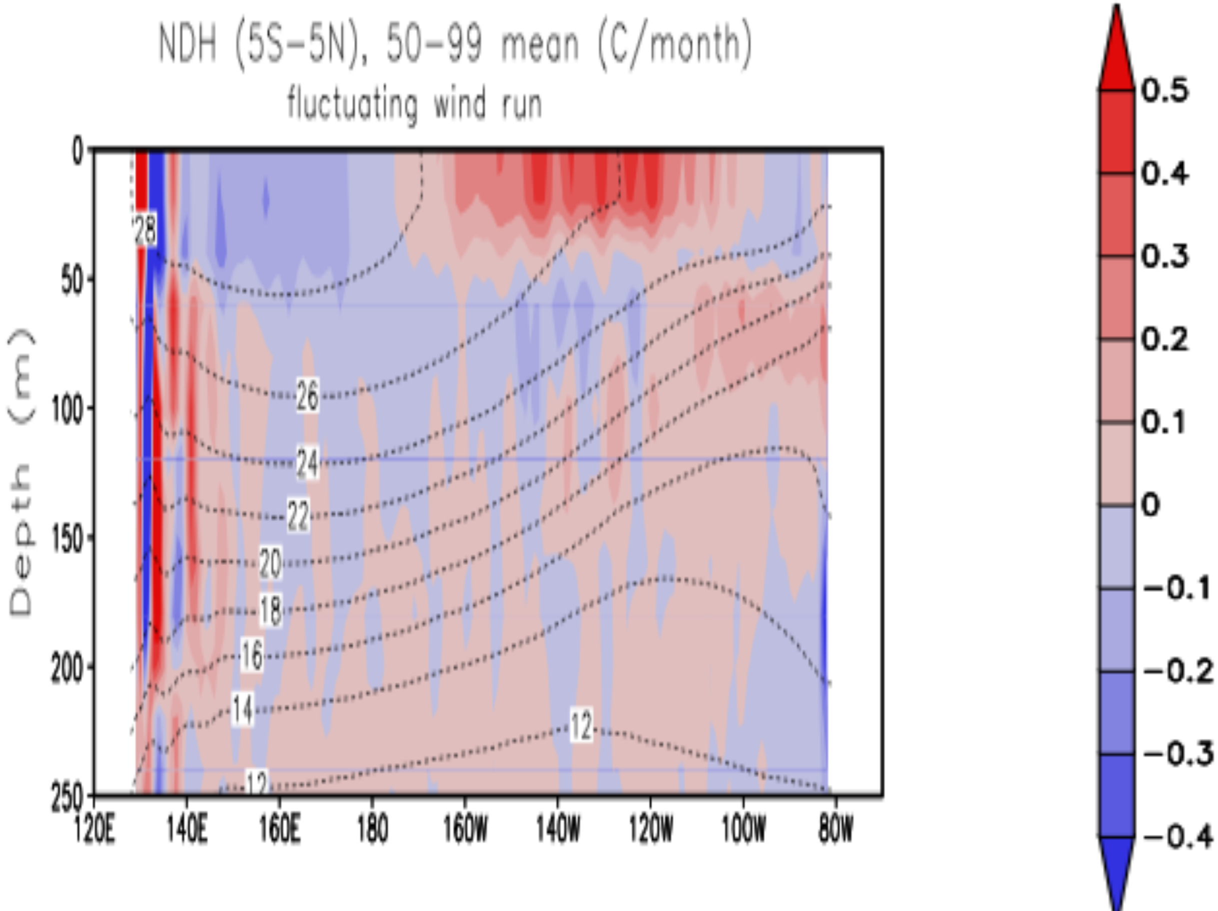
SST Difference Between Experiments with/without ENSO



The Heating From ~~ENSO~~ Events
$V'T'$



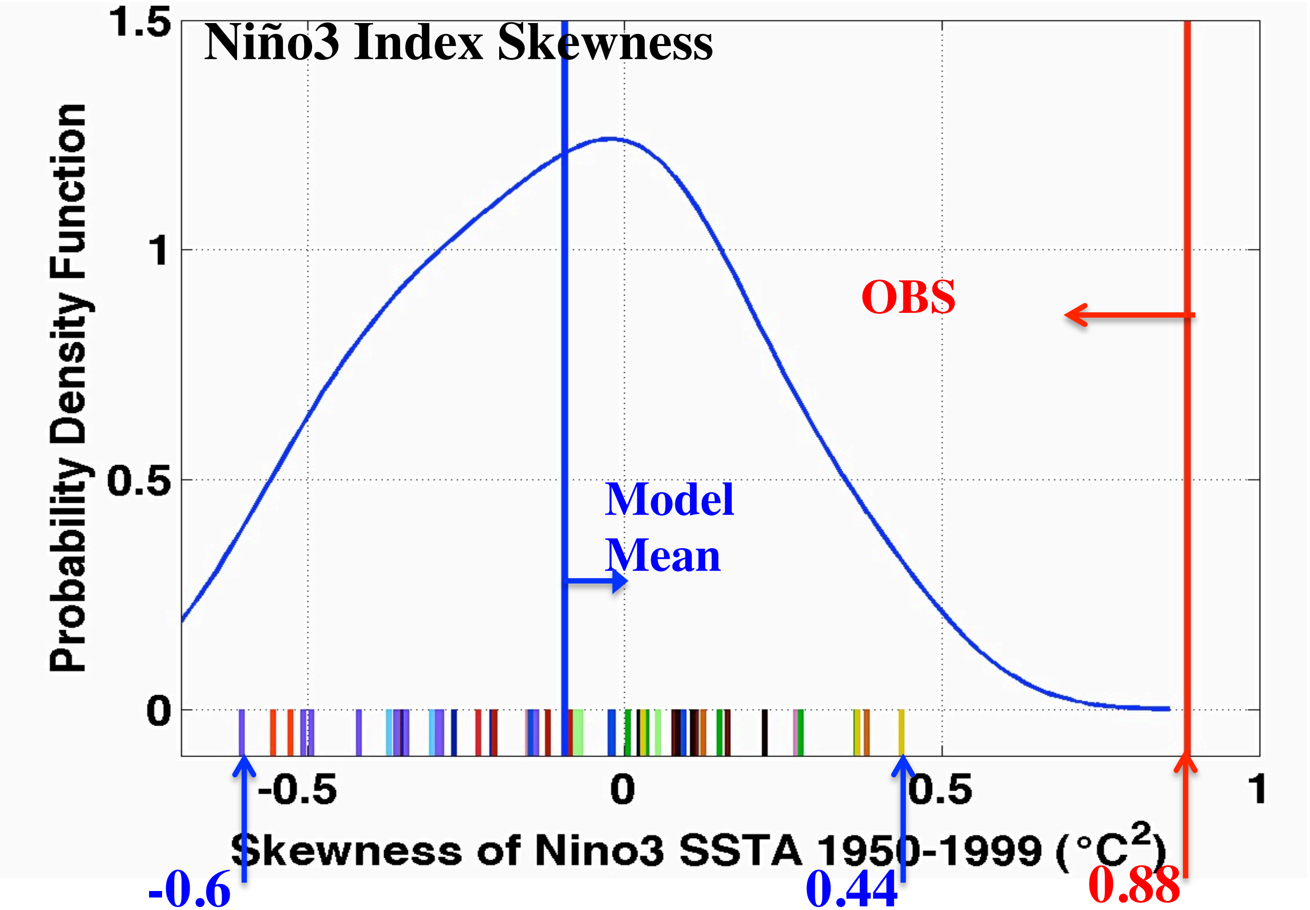
The Heating From ~~ENSO~~ Events $V'T'$



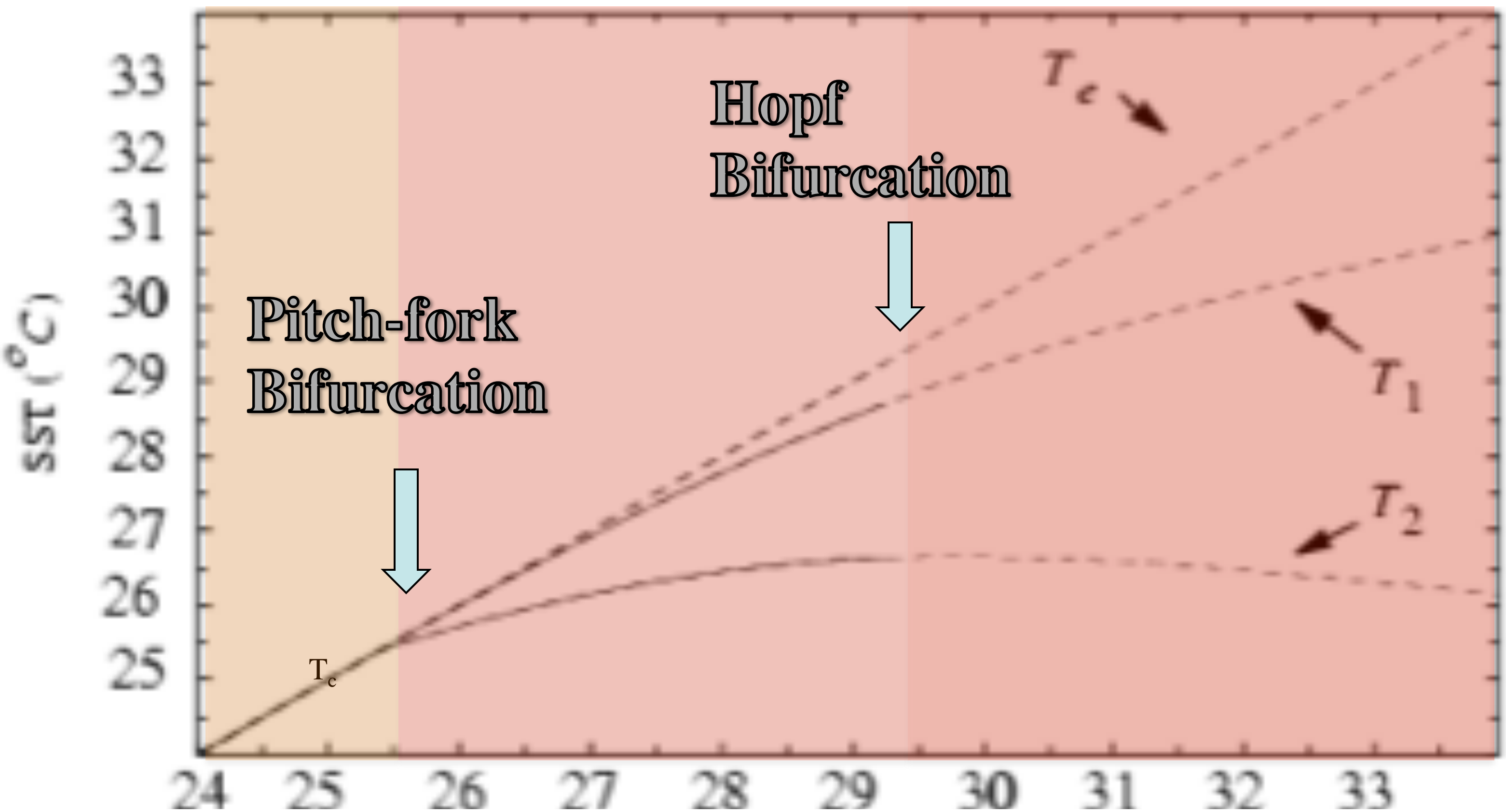
Key Results From Forced Ocean GCM Experiments

- ENSO events collectively warm the tropical eastern Pacific
- ENSO events collectively cool the warm-pool
- The spatial pattern of the effect of ENSO events resembles to the decadal warming in the tropical Pacific
- The effect of ENSO events increases with increases in the level of ENSO activity.

ENSO Asymmetry in IPCC AR4 Models



Regime Transitions in Response to an Increasing Radiative Heating



Radiative-Convective Equilibrium SST Te (°C)

Sun ,1997, Geophys. Res. Lett., 24, 2031-2034.

The Scientific Basis For Our View

(1) Insights from an analytical model

Sun 1997, Sun 2000, Timmerman and Jin 2001, Liang et al. 2012

(2) Results from a hybrid model

Sun 2003, Sun et al. 2004, Sun and Zhang 2006, Yu and Sun 2009

(3) Results from forced ocean GCM experiments

Ogata et al. 2013, Sun et al. 2014, Hua et al. 2014

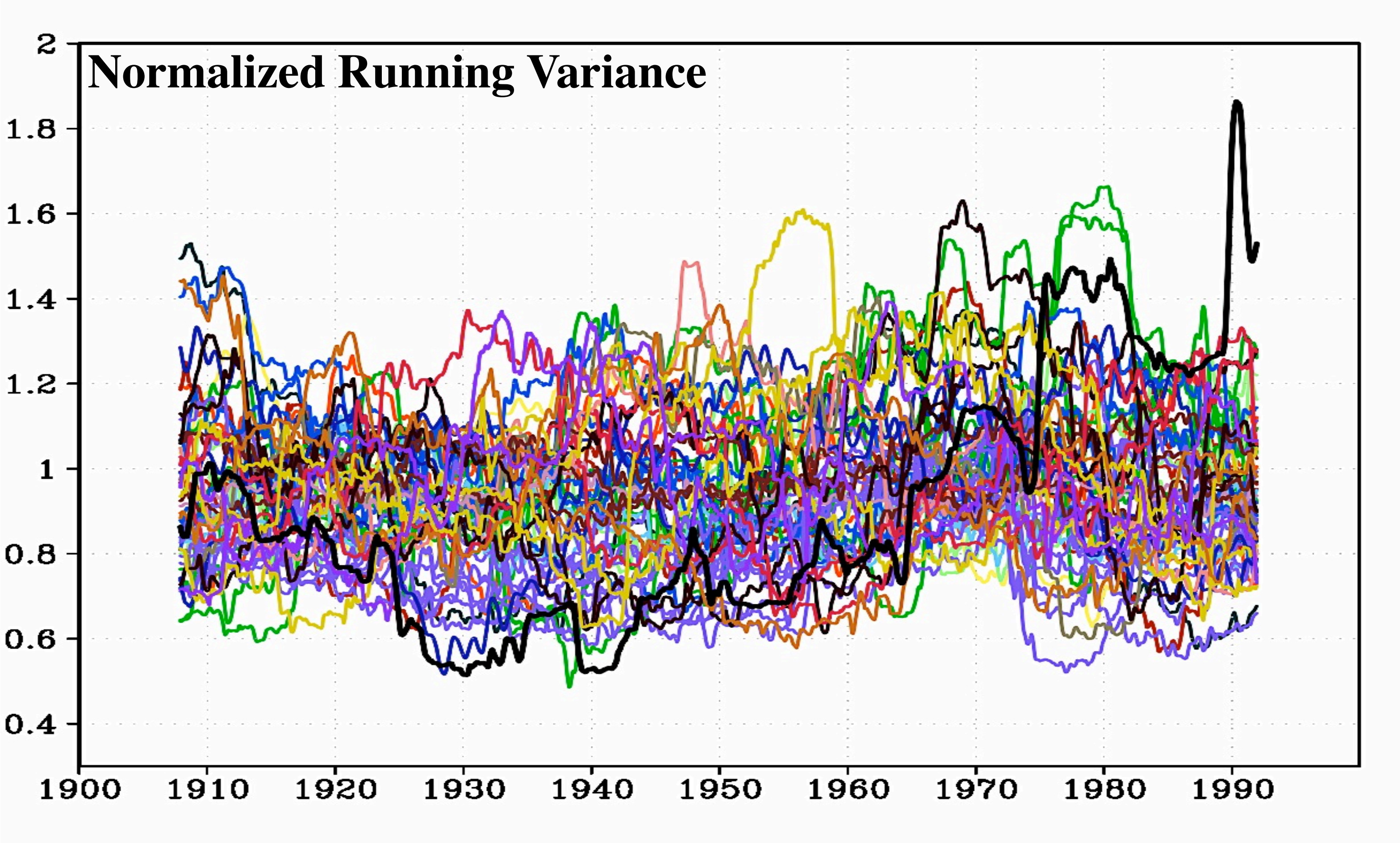
(4) Results from an analysis of CMIP models

Sun et al. (2014) (in preparation)

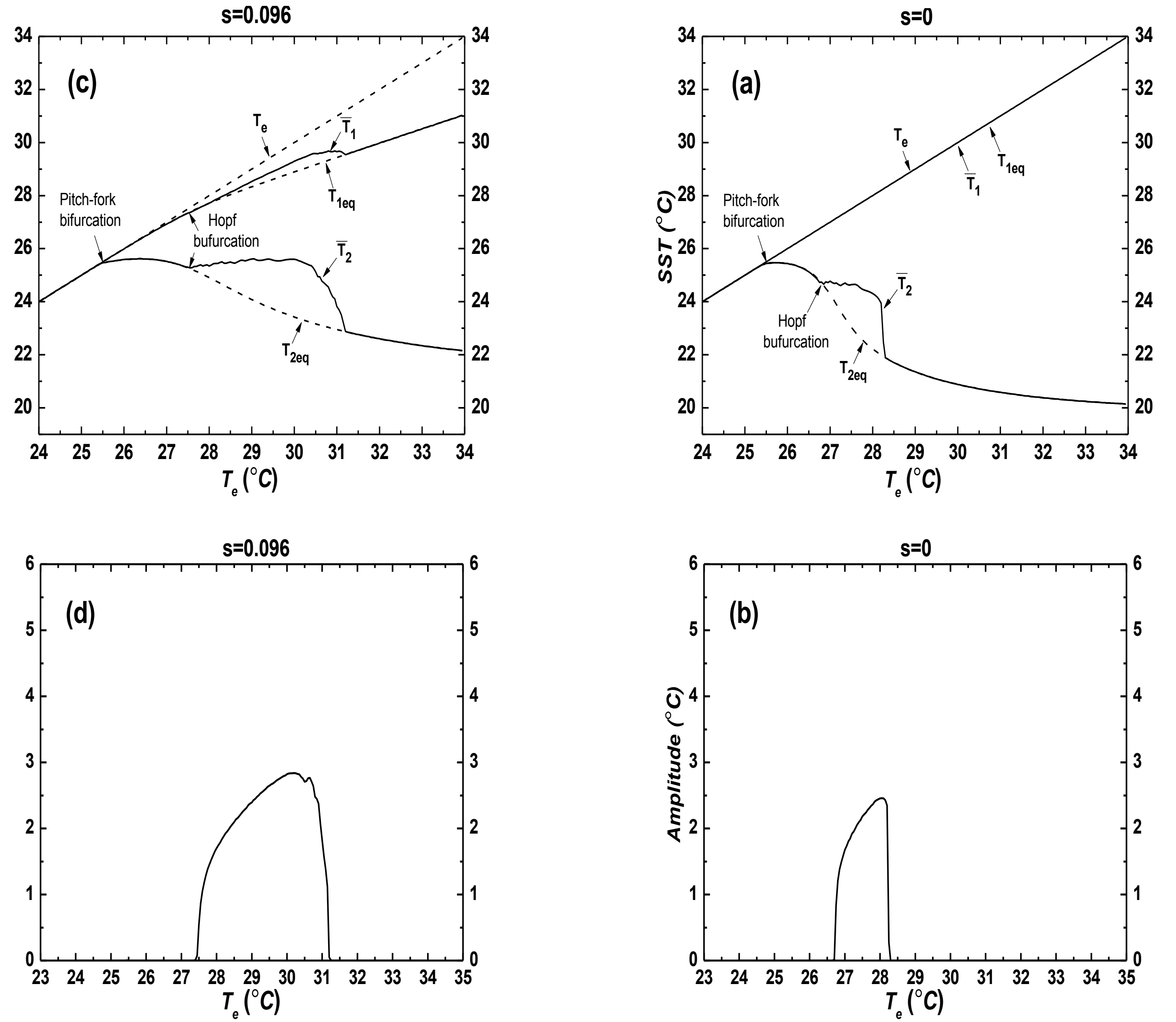
(5) Results from the newest NCAR Climate Model-CESM

Sun et al. (2014) (in preparation)

Variations in the Level of ENSO activity in the IPCC AR4 Models

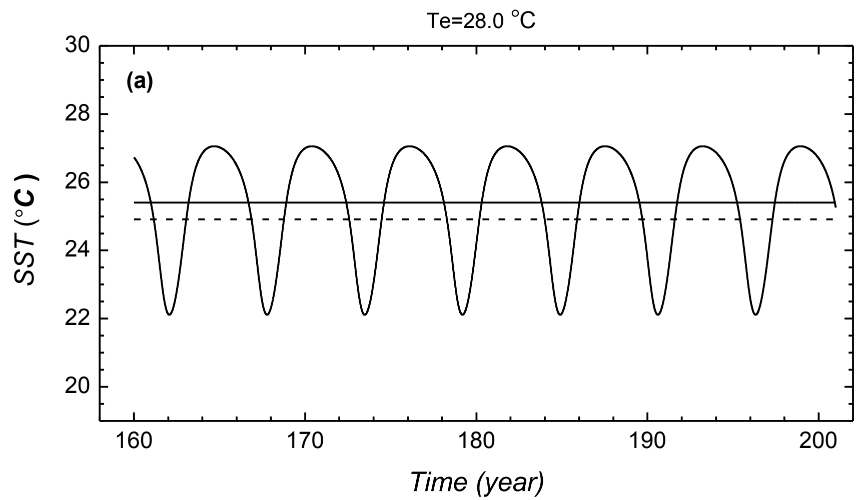


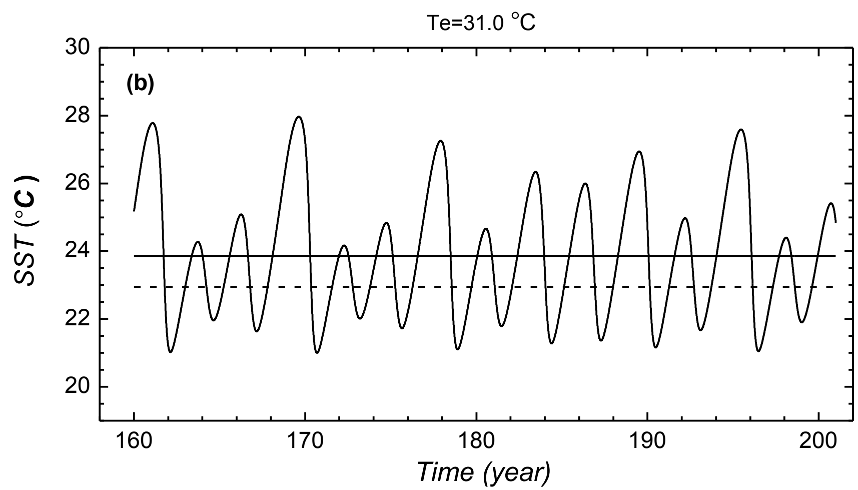
Tropical Pacific Climate as a Function of T_e



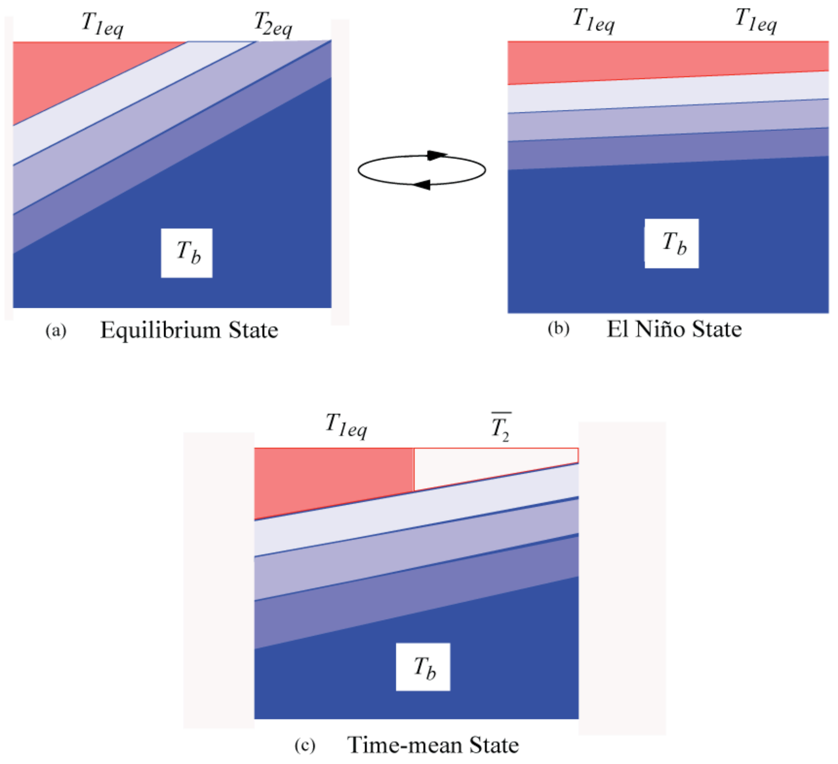
Asymmetry in the Oscillation

Time series of T_2 when T_e=28.5°C and T_e=31°C

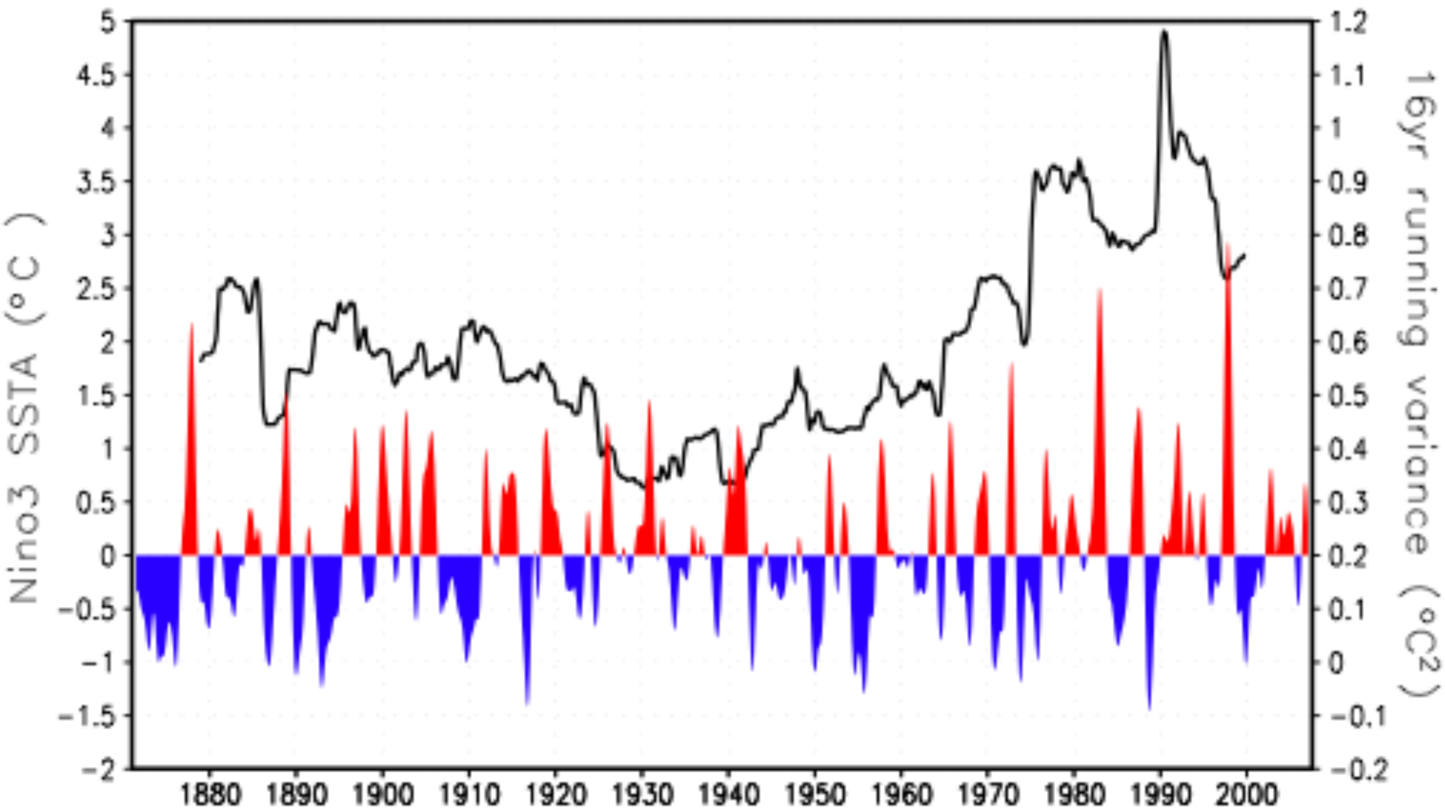




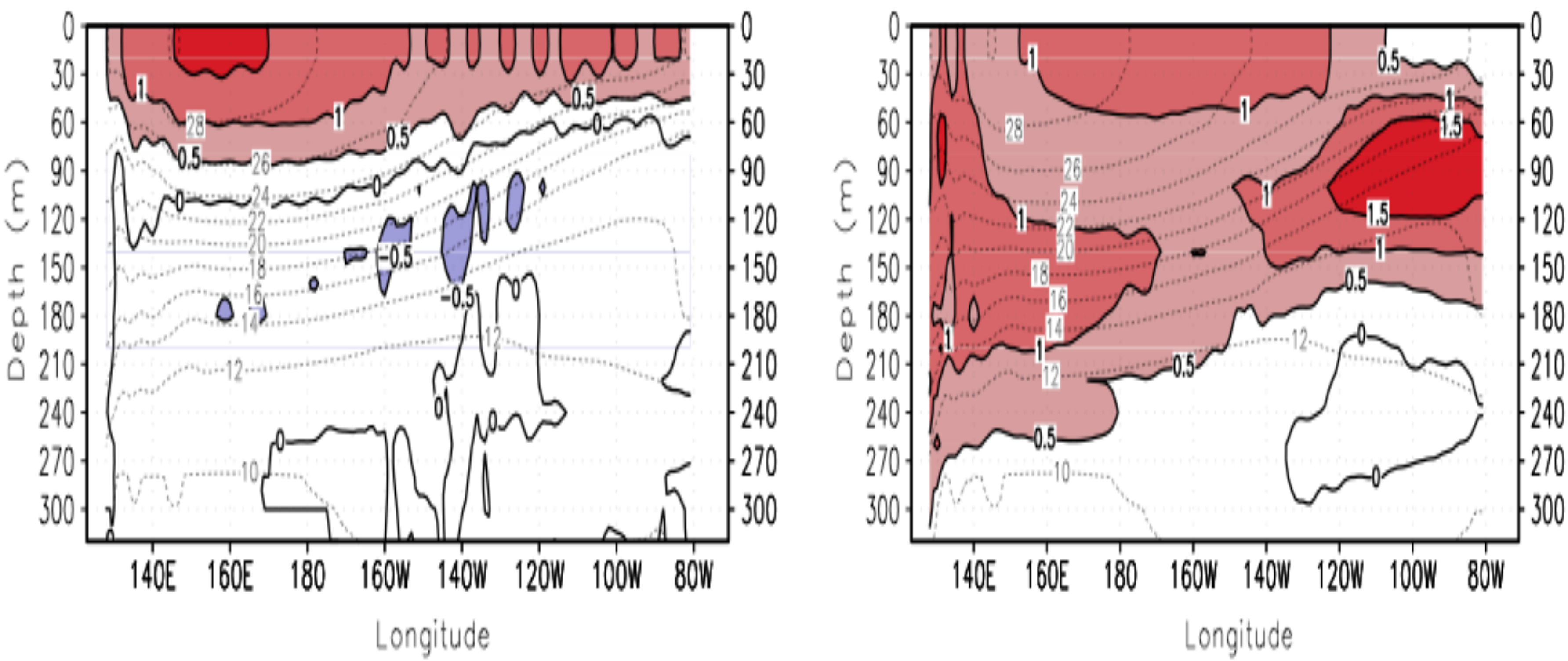
A schematic illustration of the simple advective model



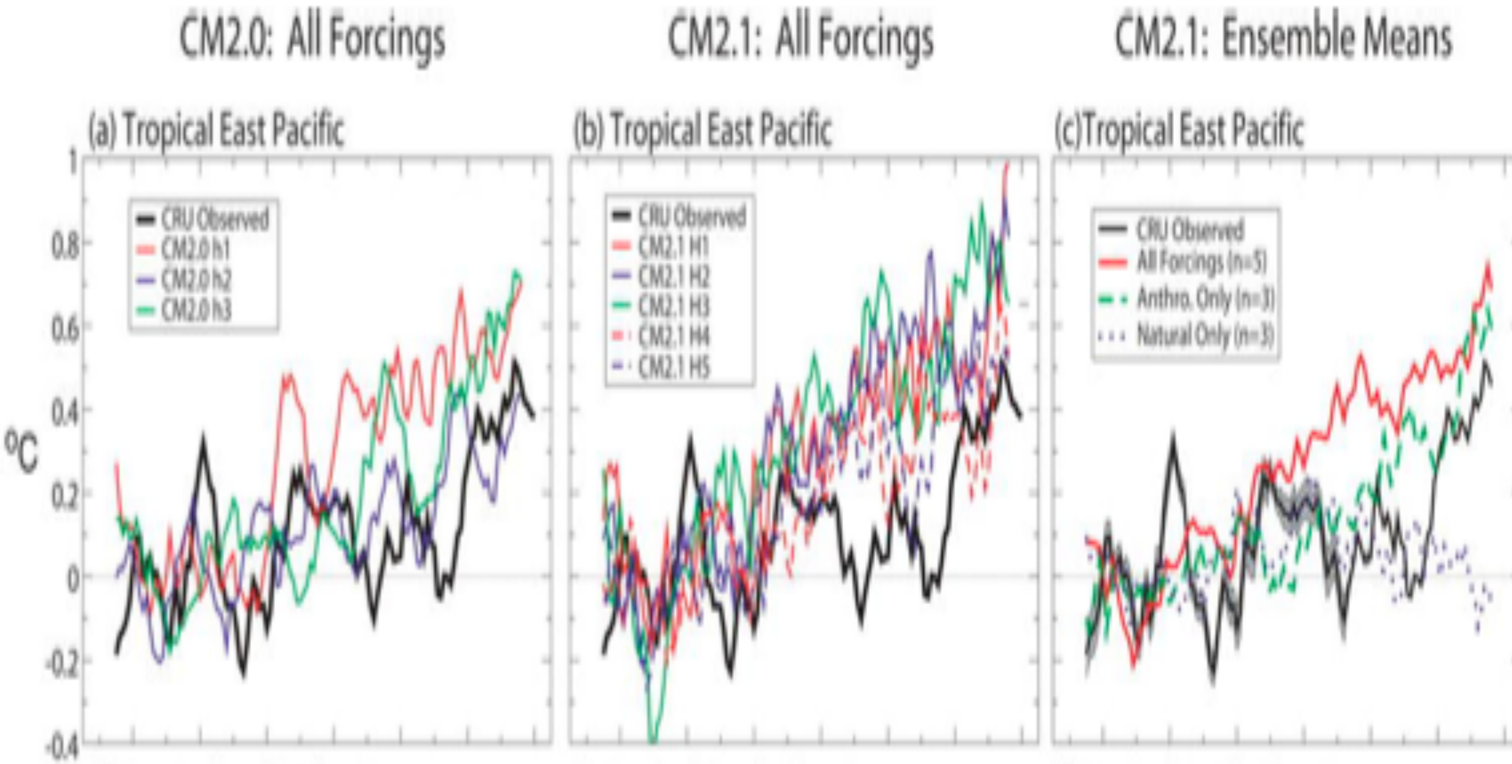
Observations: Nino3 SST



ENSO and Heat Uptake of the Tropical Pacific

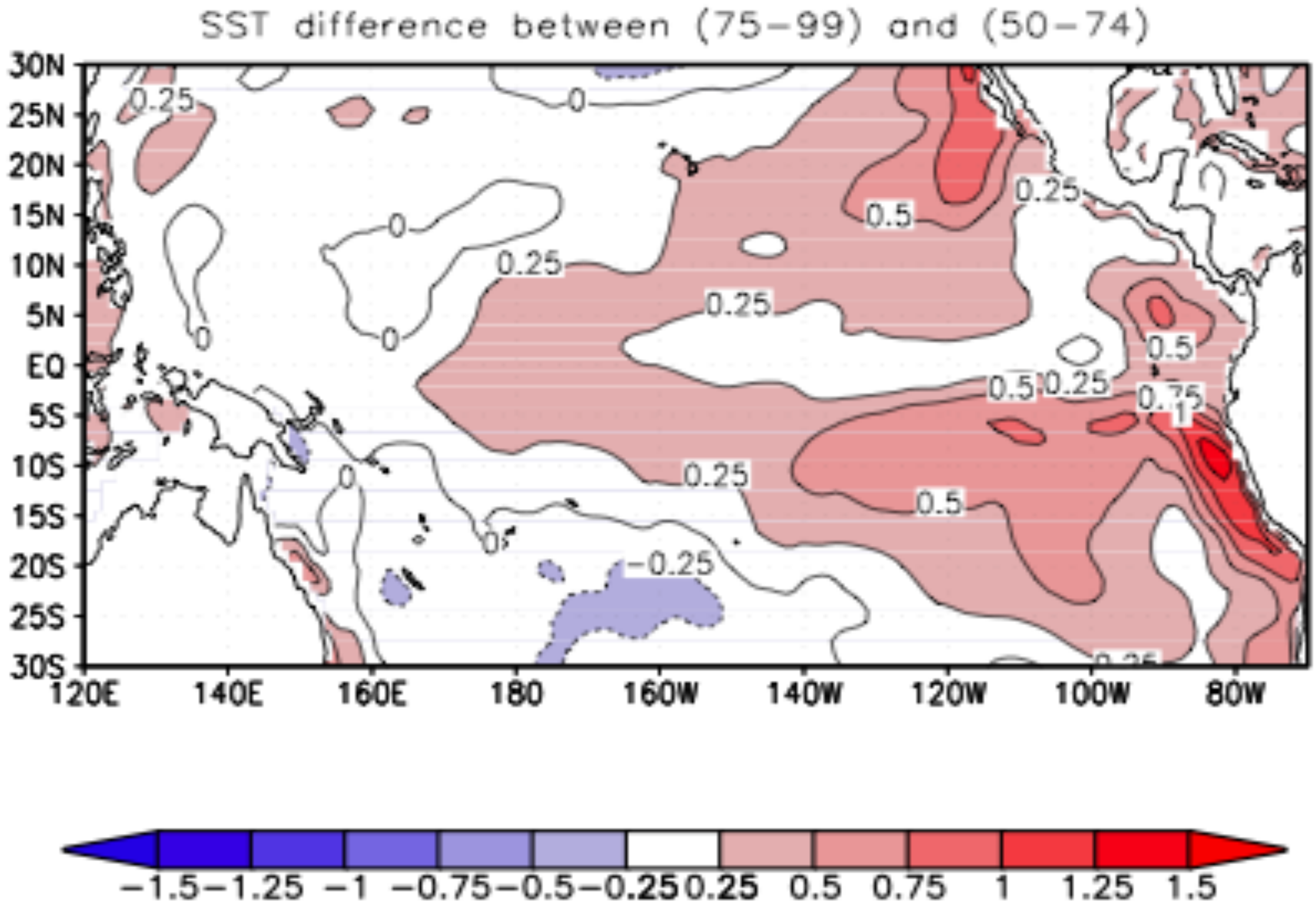


Eastern Pacific SST over the last century: Observed and Modeled

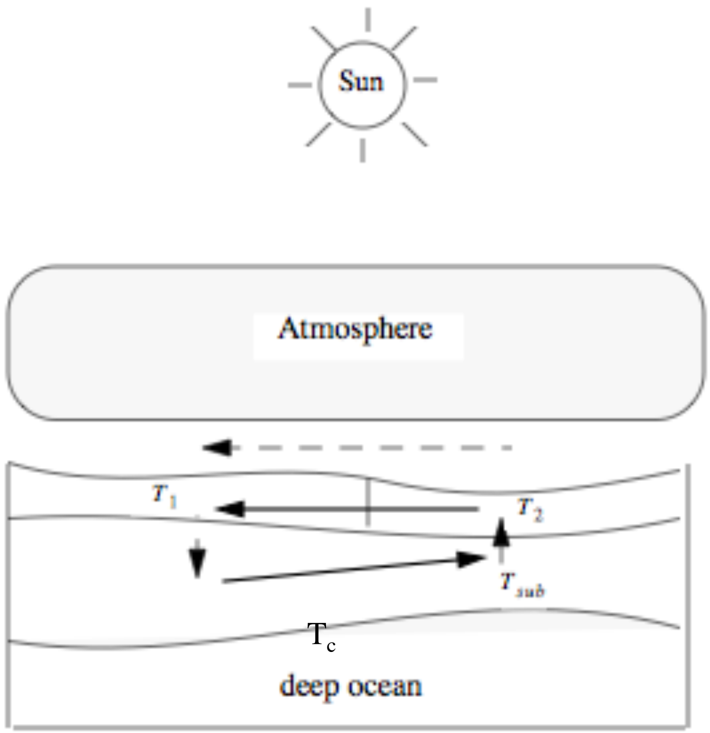


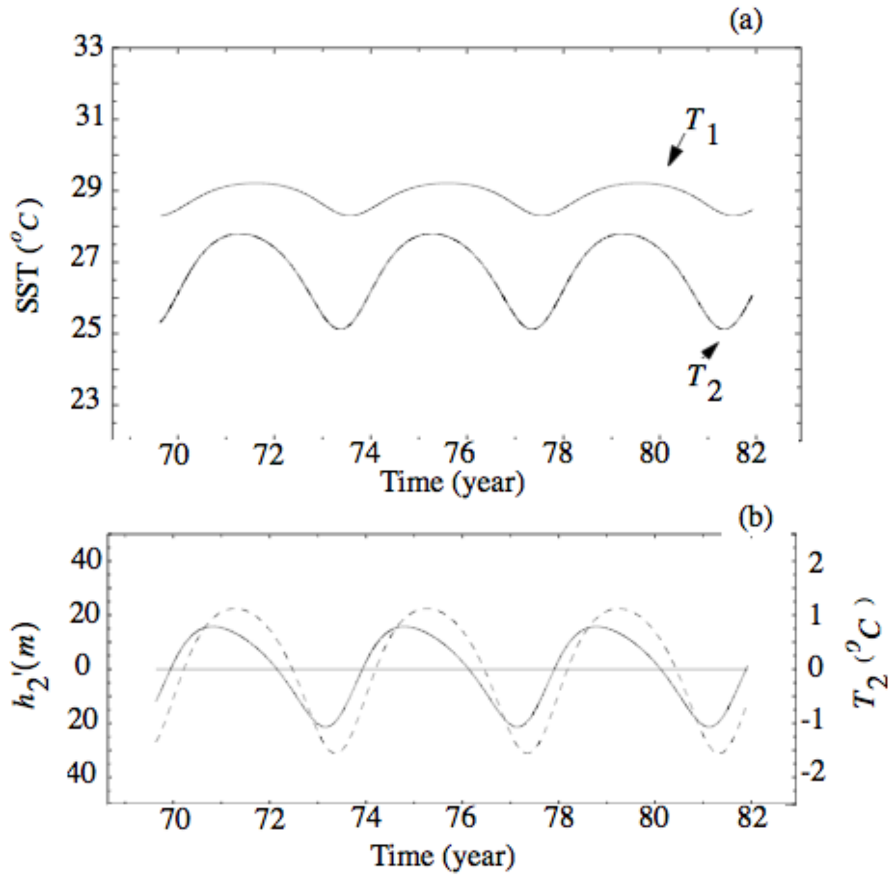
From Knuston et al. 2006

Pattern of Changes in SST



Theory: Insights From an Analytical Model





Sun ,1997, Geophys. Res. Lett., 24, 2031-2034.

Feedback from ENSO onto the mean state

Response of Tw-Tc with and without ENSO

From Tropical Heating Experiments

perturbation type	experiment type	change of Tw (°c)	change of Tc (°c)	change of Tw-Tc (°c)
Pair I (5°S-5°N)	No ENSO	1.03	0.0050	1.02
	With ENSO	0.81	0.76	0.053
Pair II (10°S-10°N)	No ENSO	1.38	0.036	1.34
	With ENSO	0.97	0.83	0.14
Pair III (15°S-15°N)	No ENSO	0.95	0.24	0.71
	With ENSO	0.55	0.63	-0.085

Sun and Zhang, 2006, GRL, Vol. 33, L07710, doi:10.1029/2005GL025296