The Response of ENSO Events to Higher CO_2 Forcing: Role of Nonlinearity

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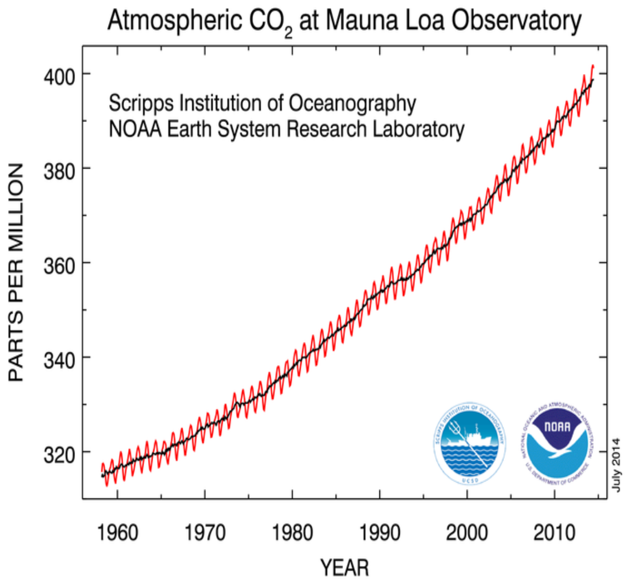
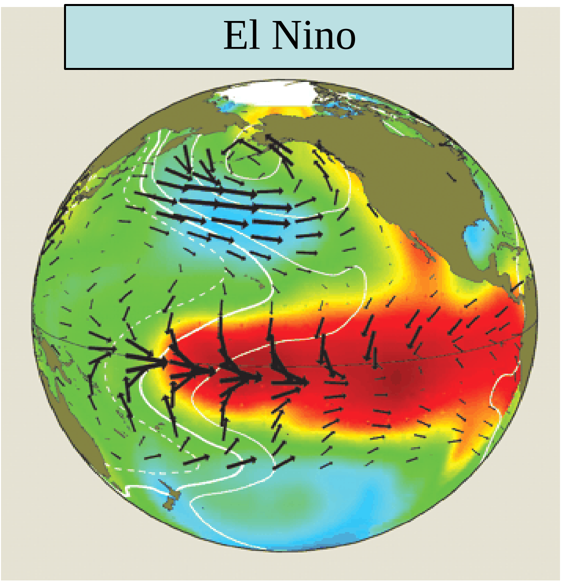
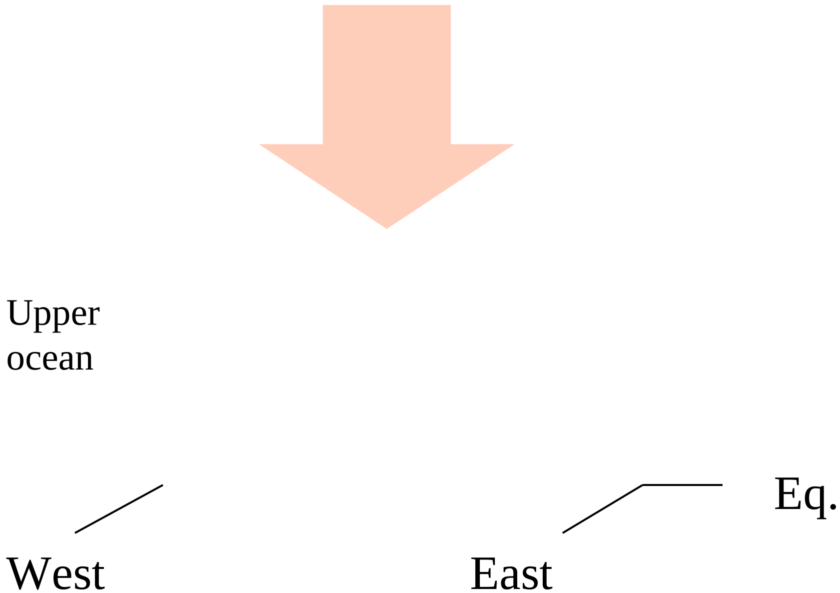




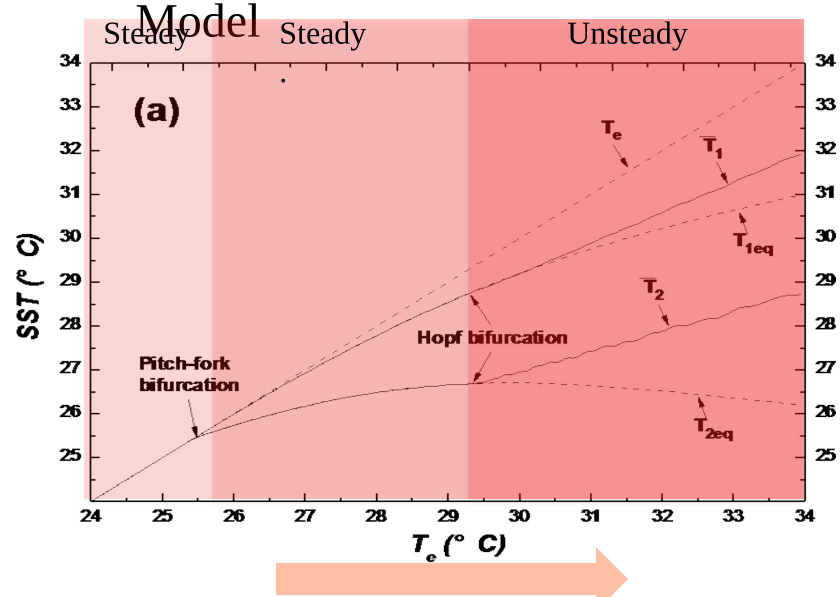
Outline

1. Suggestions From an Analytical but Nonlinear Model
2. The Average Results from IPCC AR5 Models
3. A Common Deficiency in IPCC AR5 Models
4. A New Methodology in Analyzing IPCC AR5 Models
5. The Results From This New Methodology
6. Conclusions

Suggestions From an Analytical but Nonlinear Model



Stability Diagram of The Model



Increasing Radiative Heating

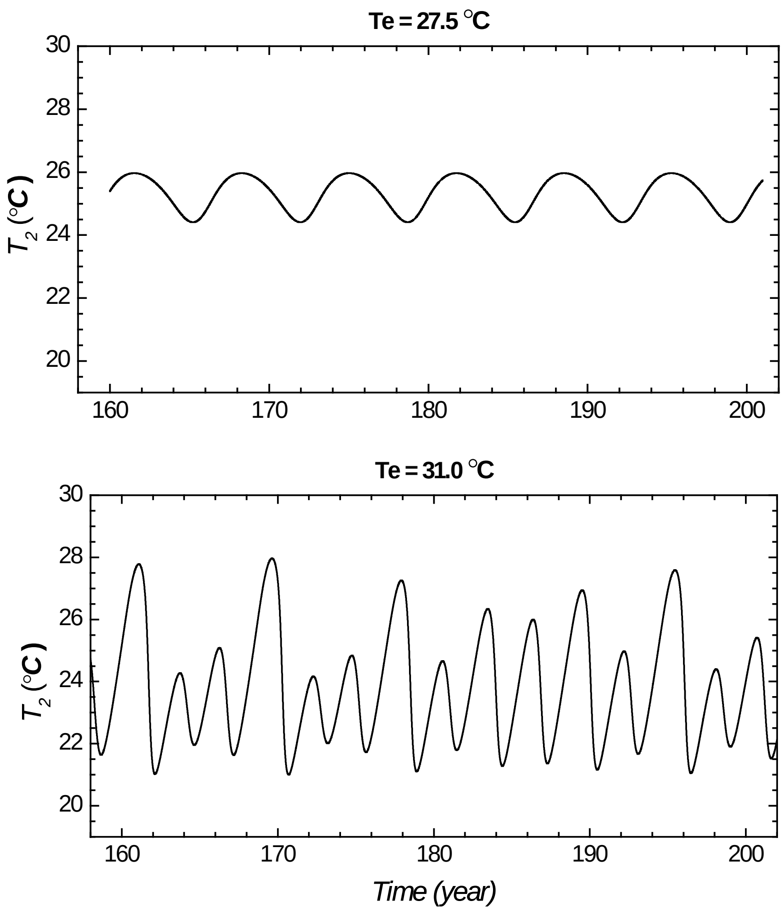
1. The very existence of an oscillating regime is due to a sufficient strong radiative heating: the circulation that is required to balance the radiative heating become so strong that it becomes unstable, resulting in a backlash to the zonally symmetric state which itself is also unstable.

2. ***Further increases in the intensity of radiative heating results in stronger oscillation.***

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

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

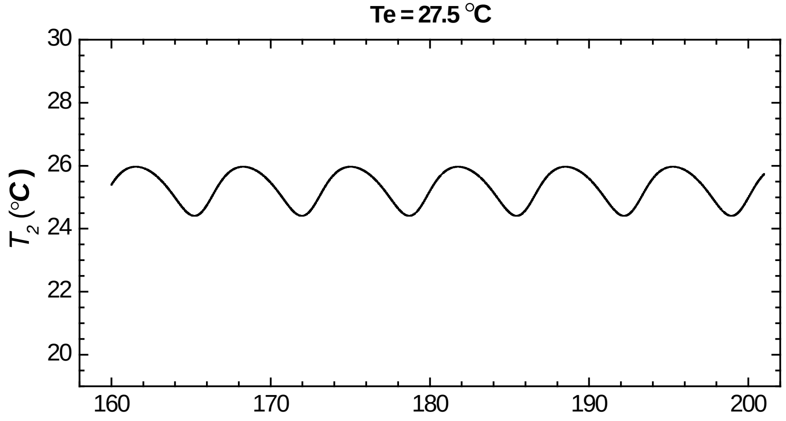
Pattern and Amplitude of Oscillation in the Model of Sun (1997) under Different Intensities of Radiative Heating

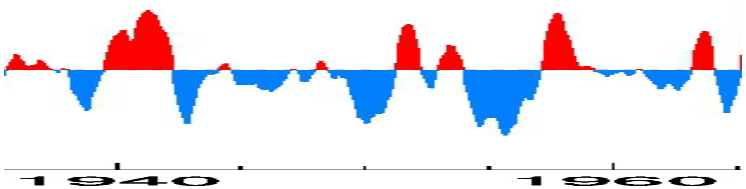


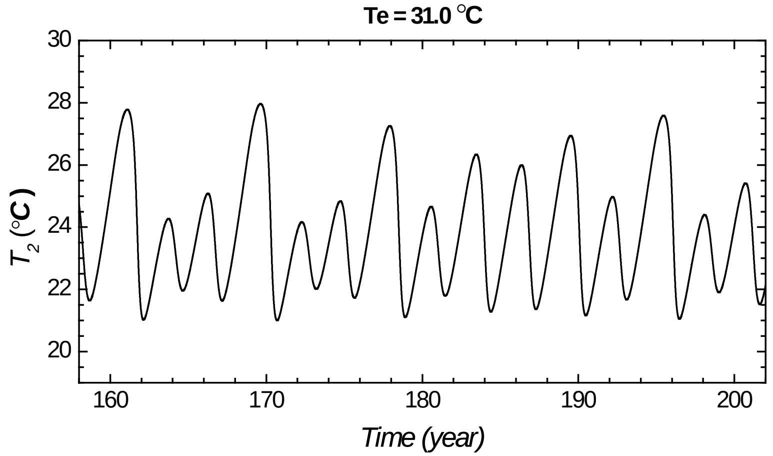
Liang, J., X.-Q. Yang, and D.-Z. Sun 2012, J. Climate, 25, 7590-7606.

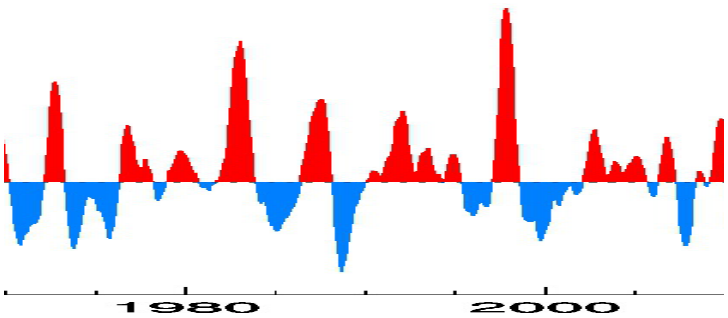
Pattern and Amplitude of Oscillation under Two Different Intensities of Radiative Heating (Model)

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



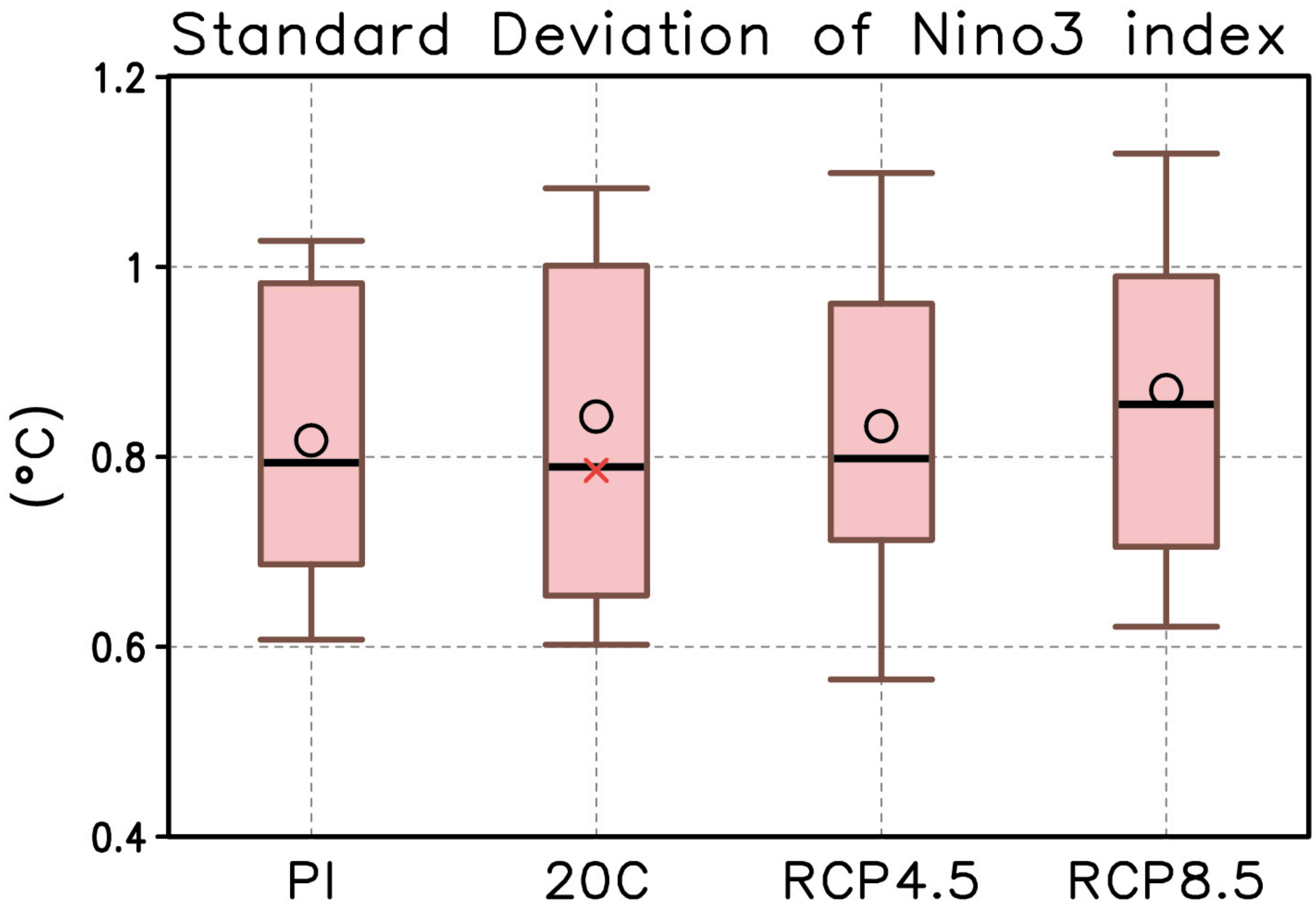






The Results from IPCC AR5

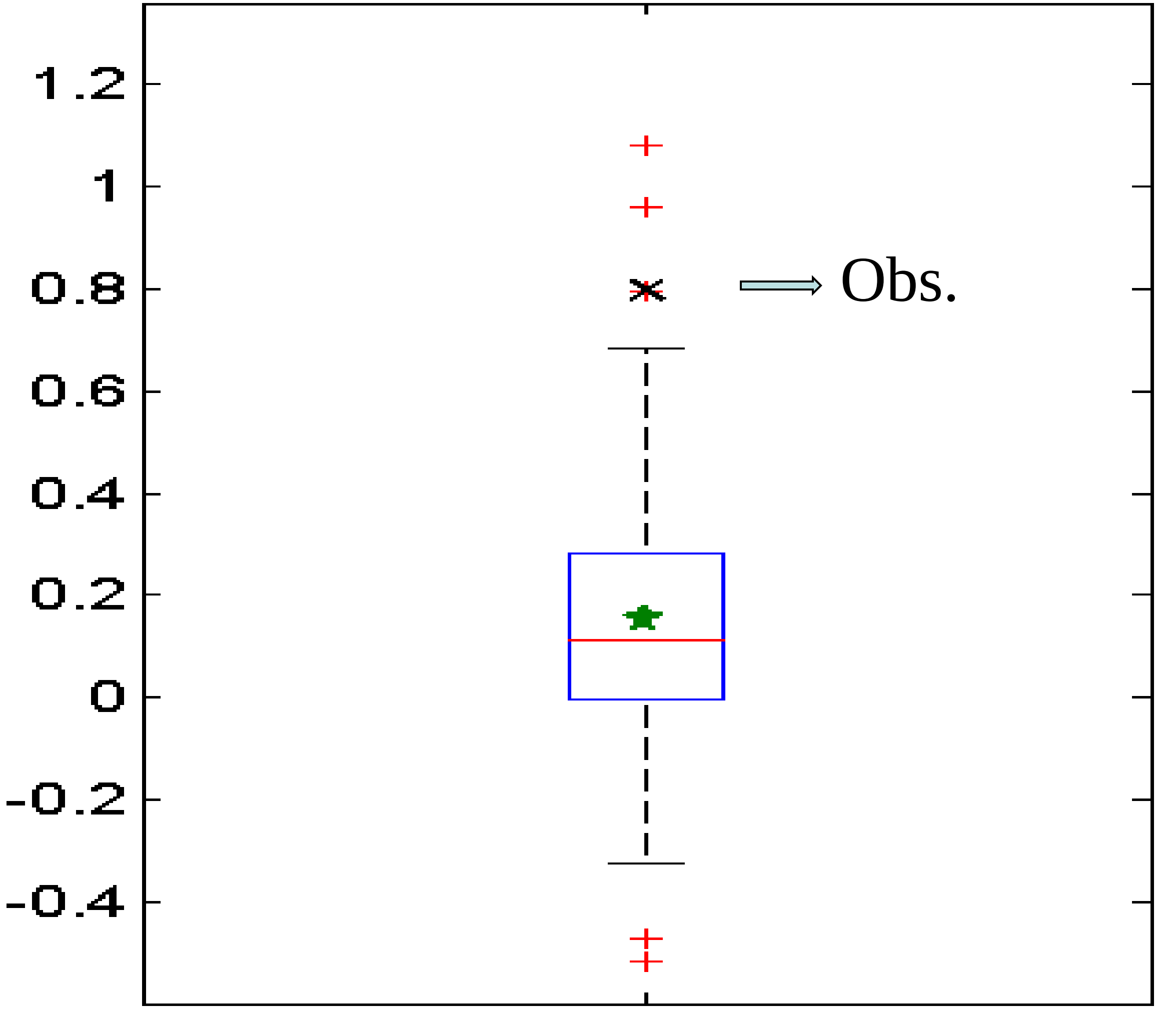
Response of ENSO to a Higher CO2: CMIP5 Results



IPCC AR5

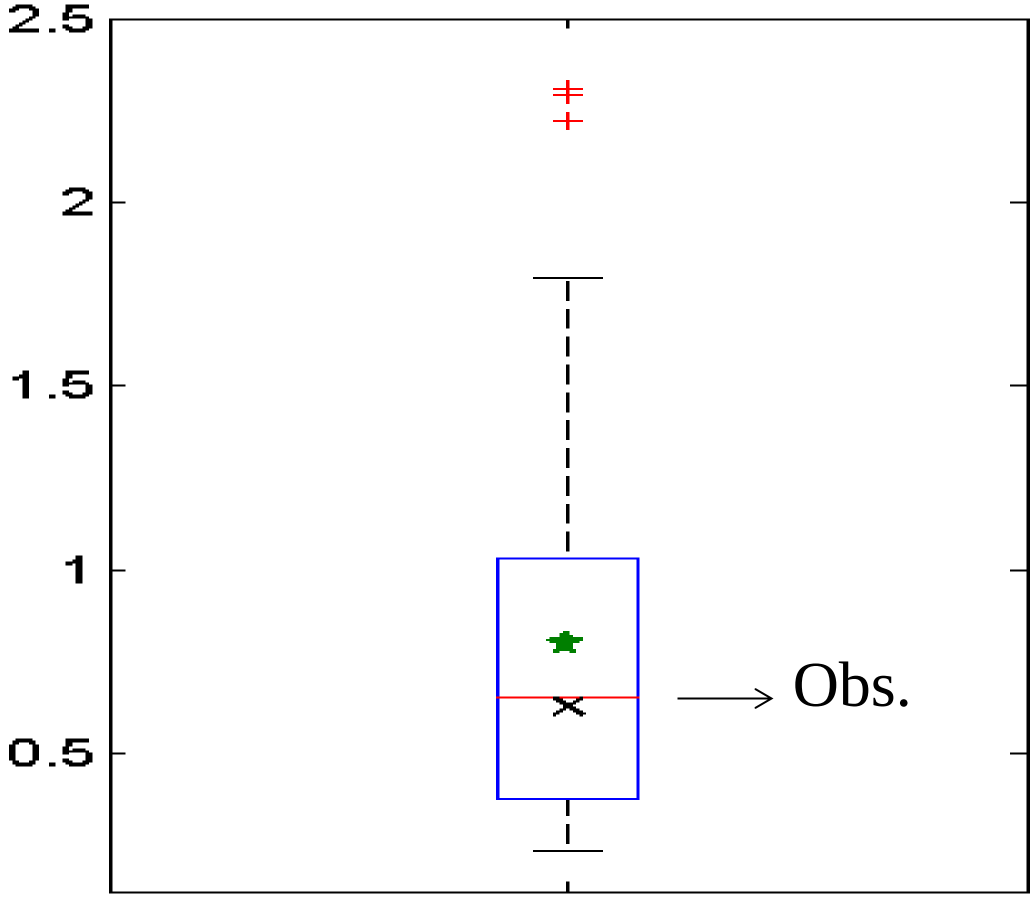
ENSO Asymmetry in CMIP5 Models

Box plot for Skewness



ENSO Amplitude in CMIP5 Models

Box plot for variance



Methodology: Dividing Models into 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

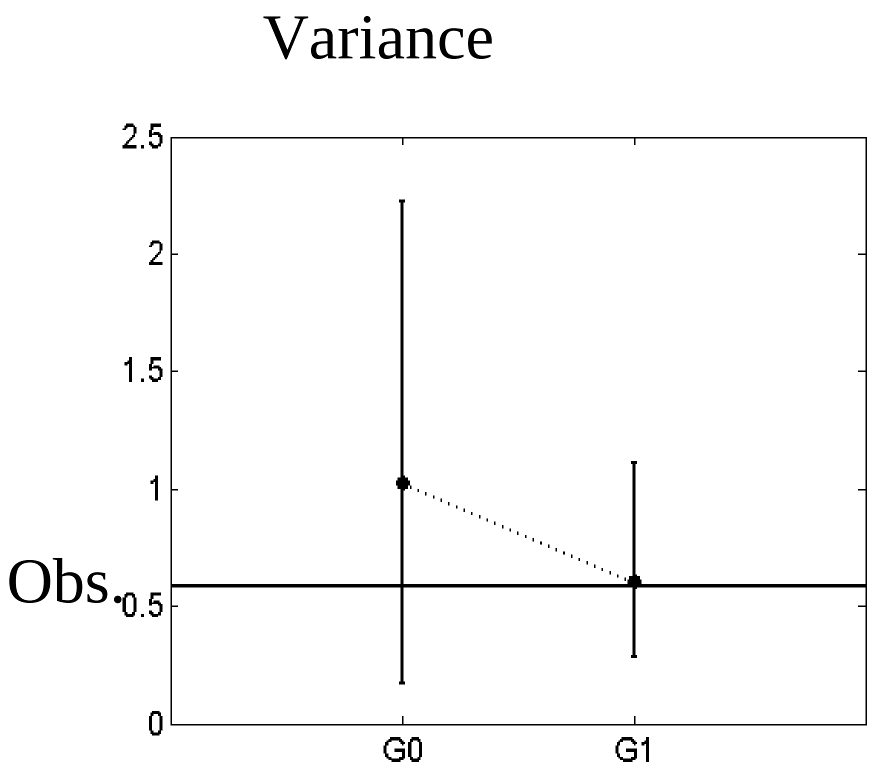
- If Diff > 1 Vc in Run/Model A: A is Indexed 1;
- If Diff < -1 Vc in Run/Model A: A-> -1;
- else, 0

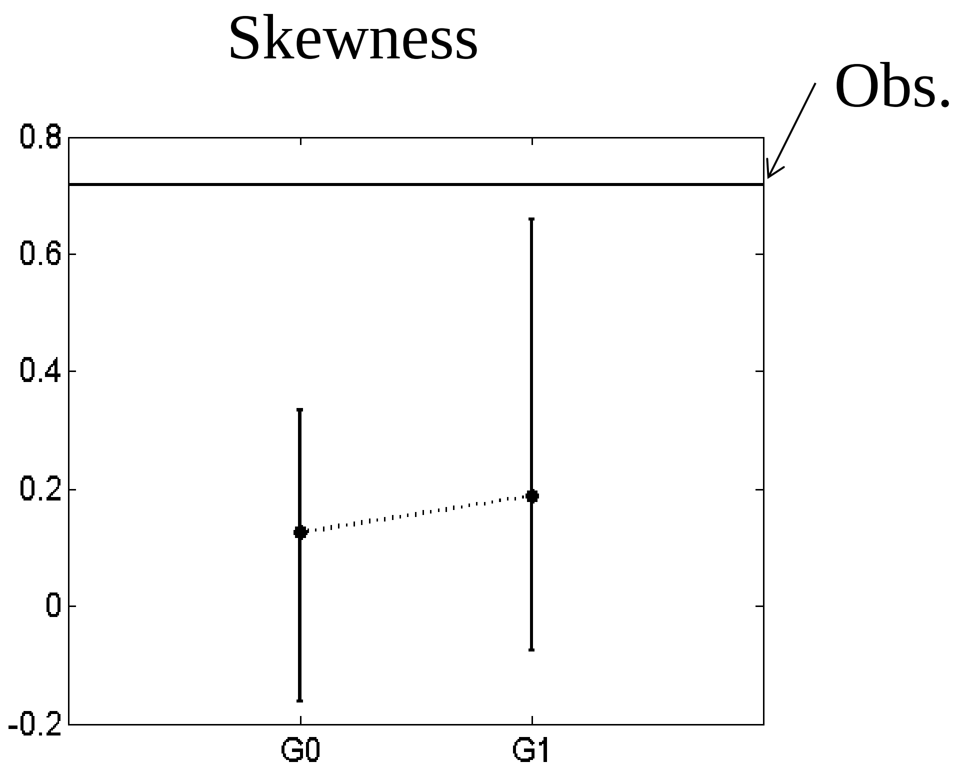
Group	Rcp45 & His	Rcp85 & His
Group 0	0	0
Group 1	1	1
Group 2	-1	-1
Group 3	0	1
Group 4	0	-1
Group 5	1	0
Group 6	-1	0
Group 7	1	-1
Group 8	-1	1

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

Group	By Runs		By Models	
	No. of runs	Percent	No. of models	Percent
G 0	30	39.5%	**11**	**29.7%**
G 1	18	23.7%	**9**	**24.3%**
G 2	7	9.2%	**5**	**13.5%**
G 3	6	7.9%	**3**	**8.1%**
G 4	7	9.2%	**3**	**8.1%**
G 5	3	4.0%	**2**	**5.4%**
G 6	5	6.6%	**4**	**10.8%**

Variance and Skewness in the historical runs of the models in G0 and G1 (by models)





Summary

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

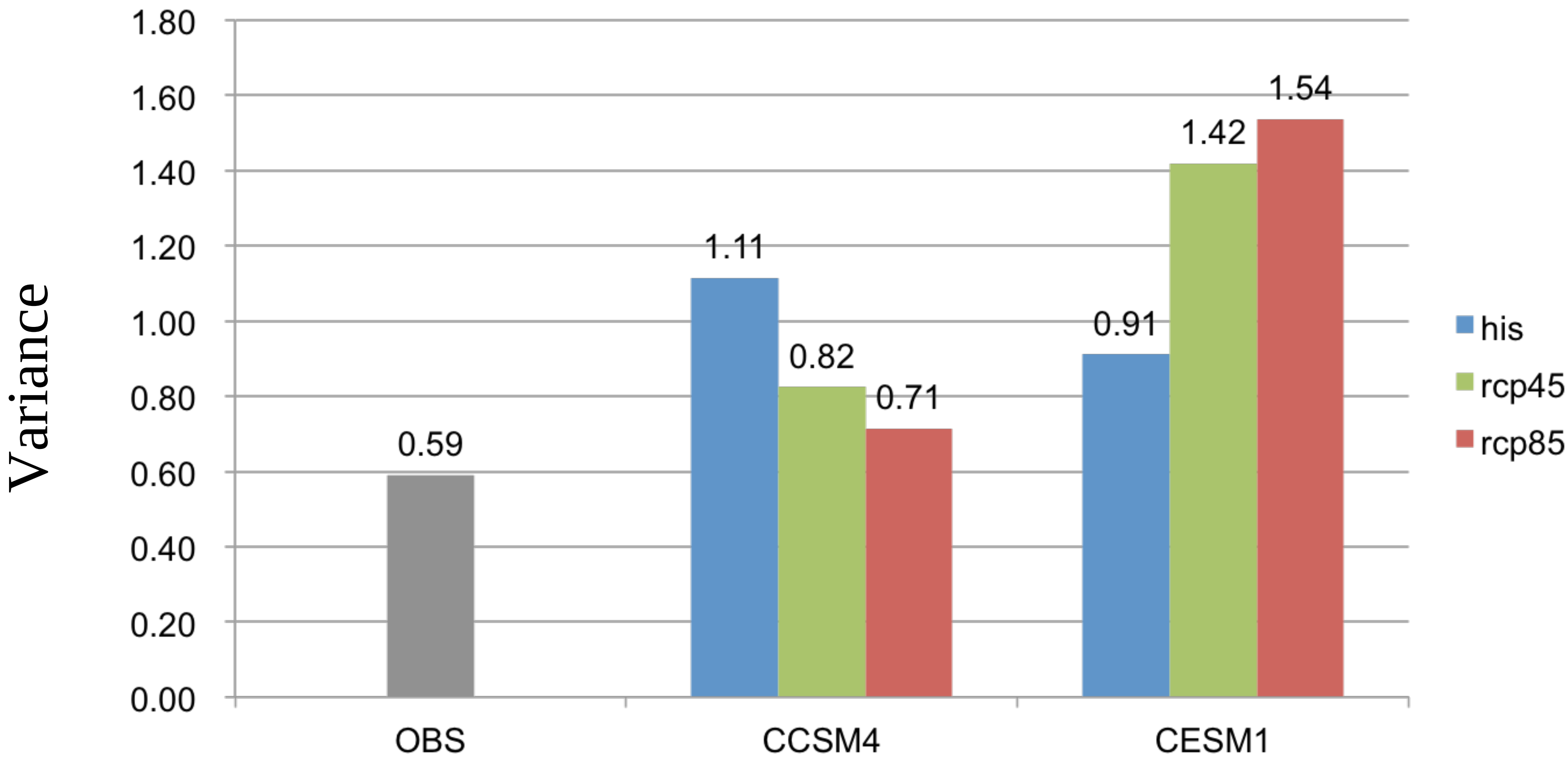
- A common deficiency in IPCC AR5 Models is noted: they fail to produce strongly asymmetric oscillation as that had occurred in the observations, even when the amplitude of the oscillation in the models is as strong as or even much stronger than the observations.

- While on average, results from AR5 models seem to suggest a muted response of ENSO to CO2 increases, but the number of models that predict a consistent positive response of ENSO to different levels of increases of CO2 accounts almost of ¼ of the total models and is comparable to the numbers of models that predict a consistent muted response.

- ENSO simulated in the historical runs of the models that predict a consistent positive response of ENSO are found to be weaker in amplitude and stronger in asymmetry (and are thus more comparable to the observations in amplitude and asymmetry) than ENSO in the models that predict a muted response.

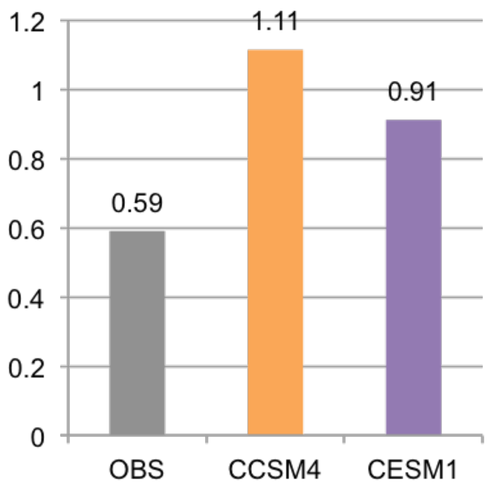
- The results underscore the importance of nonlinearity (and realism of simulated ENSO) in determining the response of ENSO to higher CO2 forcing.

Response of ENSO to Higher CO2 Forcing
Results from Two NCAR Models

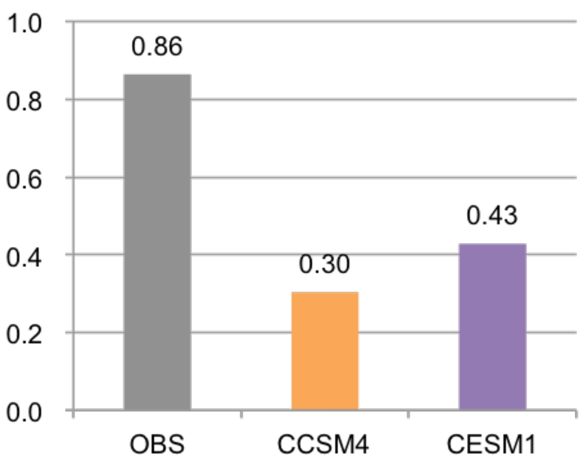


Variance and Skewness of ENSO in Two NCAR Models (filtered data)

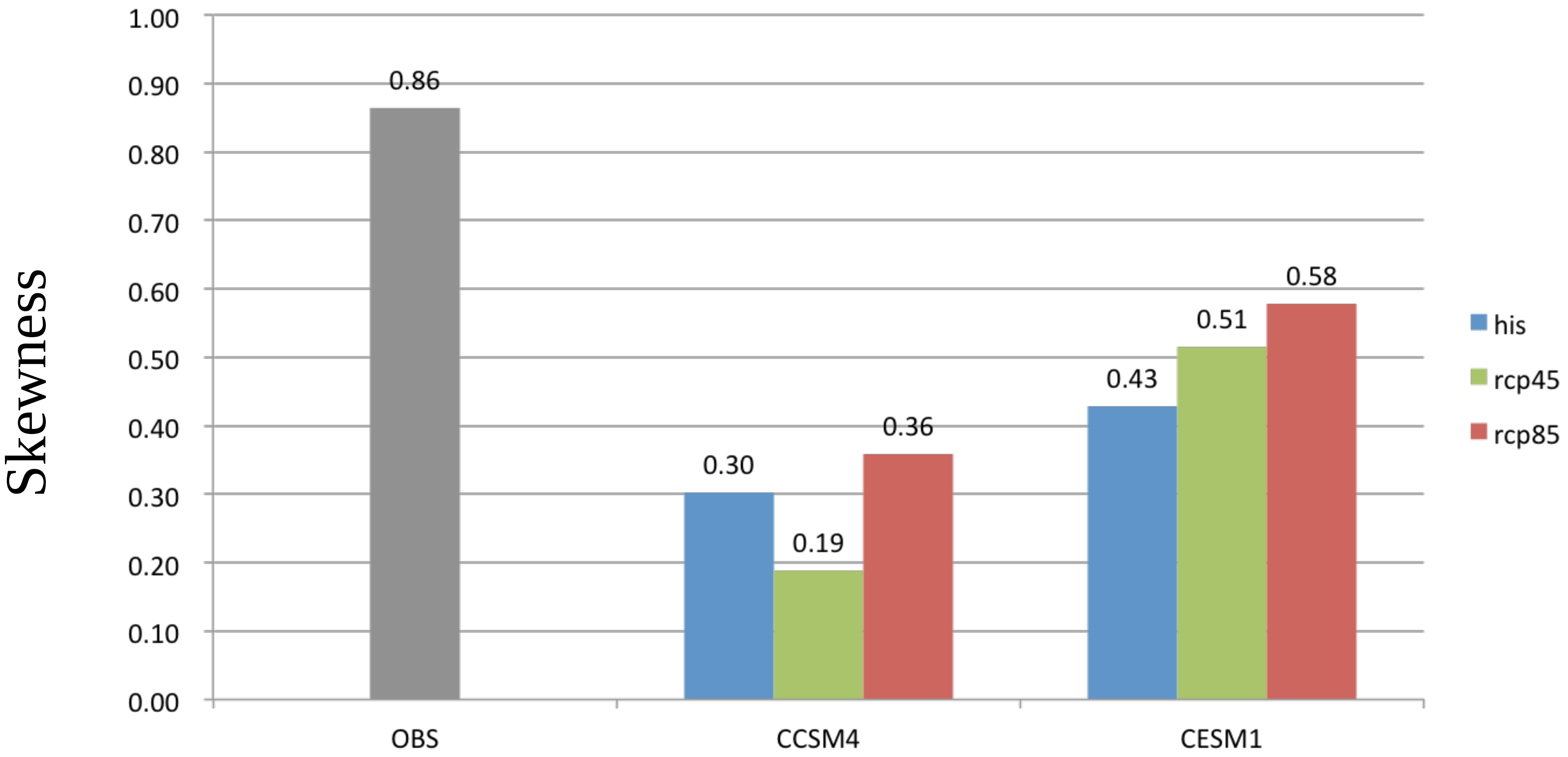
Variance



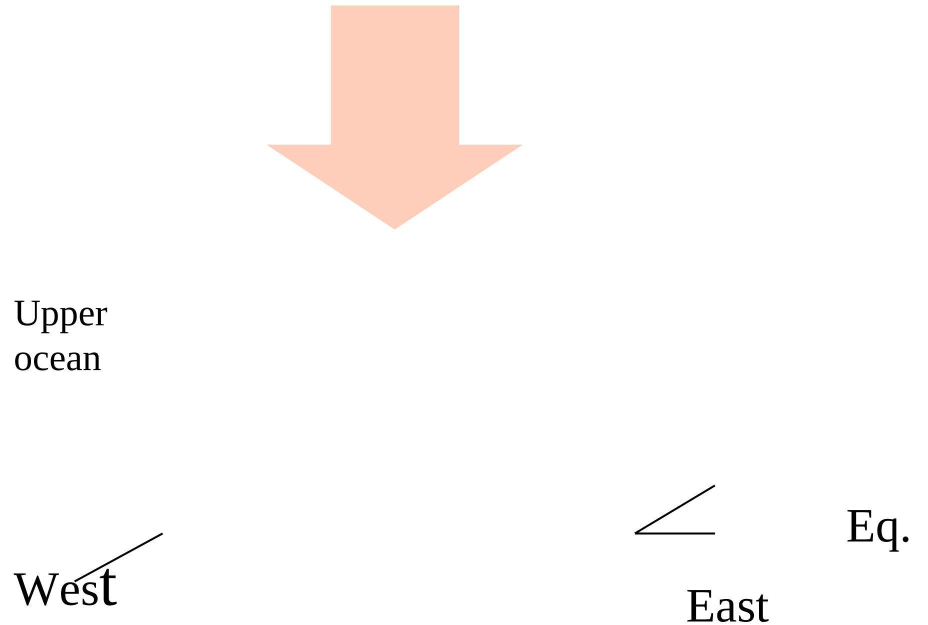
Skewness



Response of ENSO to Higher CO2 Forcing
Results from Two NCAR Models

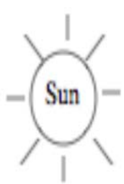


An Analytical Model for the ENSO System



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

An Analytical Model for the ENSO System



West

Eas
t

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

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

Nonlinear term

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

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

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

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

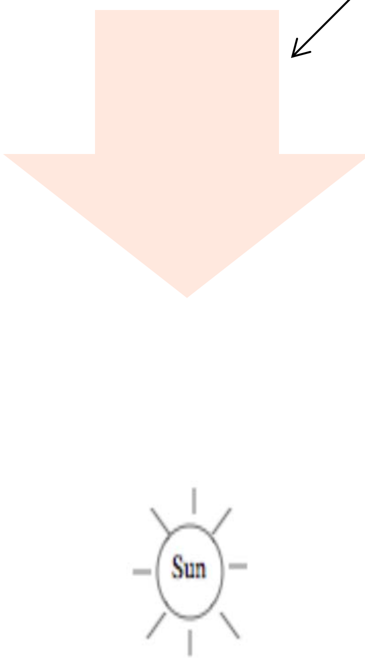
$$\frac{1}{r}\frac{dh_1'}{dt} = -h_1' + \frac{H_1}{2H_2} H \frac{\alpha}{b^2}(T_1 - T_2)$$

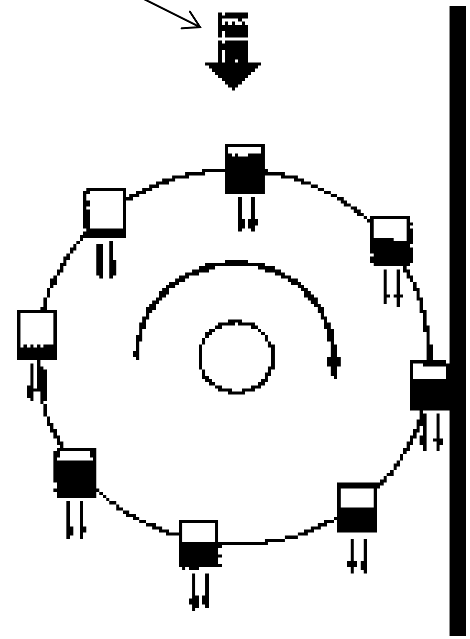
Sun 1997

Why Do We Have ENSO Events?
A Close Analogy with the Malkus's Waterwheel

Heat Flux

Water Flux



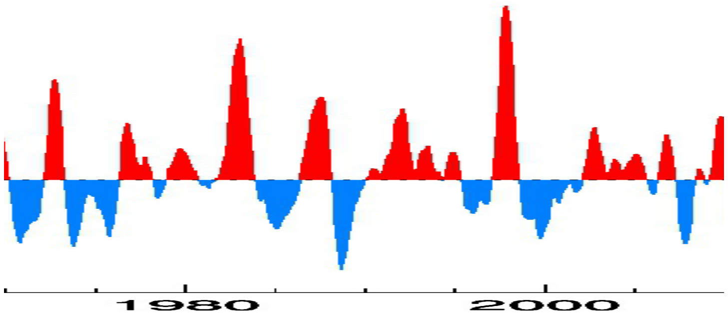


Sun 1997

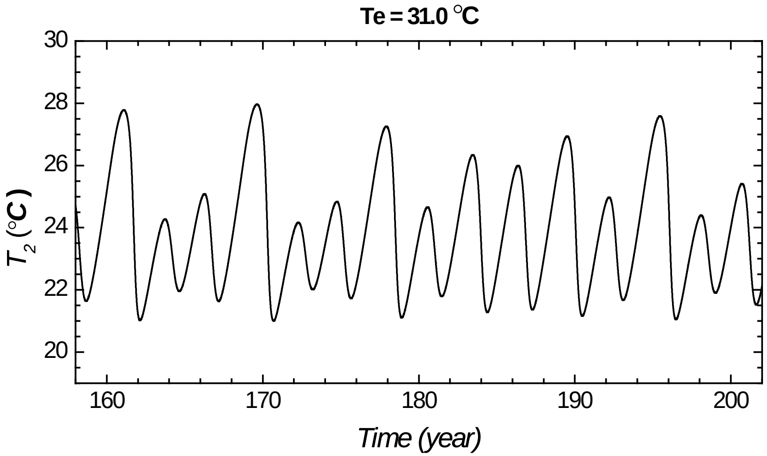
Strogatz 1994

The Model Captures the ENSO Asymmetry

Observed Asymmetry in Variations in Nino3 SST



Simulated Asymmetry in Variations in Eastern Equatorial Pacific SST by a Nonlinear Box Model

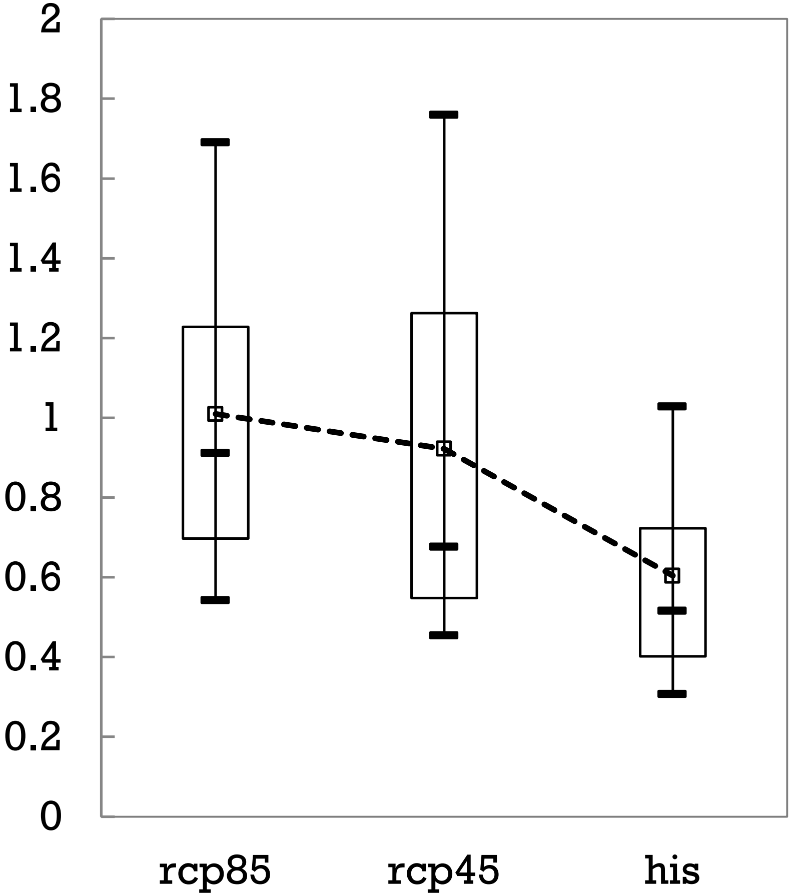


Dependence of Sensitivity on the Amplitude —An Example

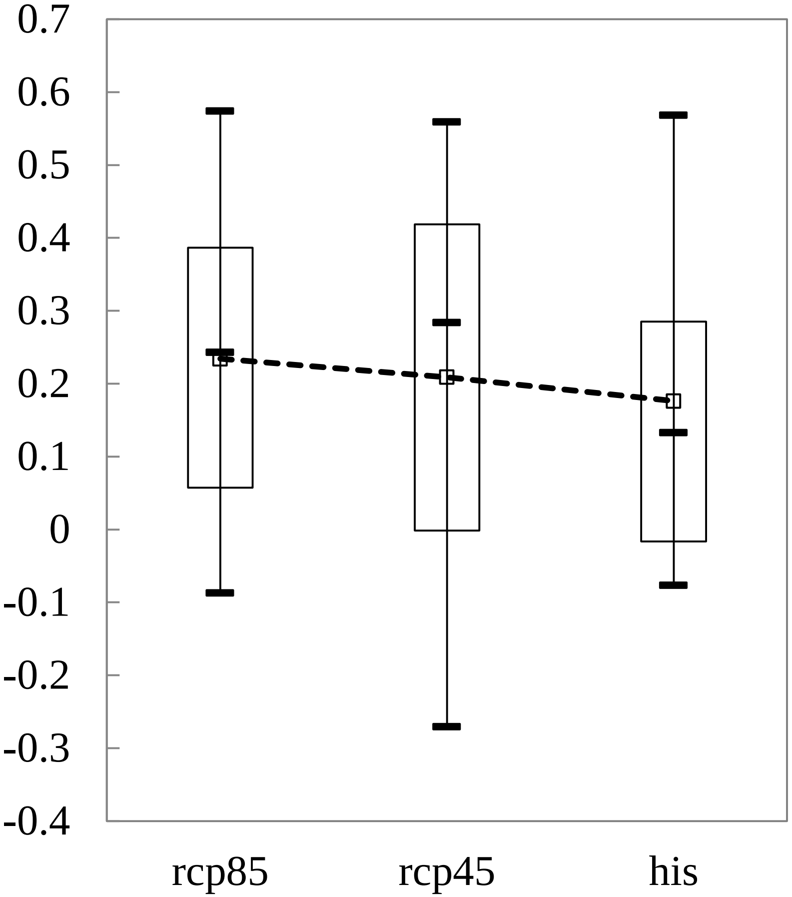
Liang, J., X.-Q. Yang, and D.-Z. Sun 2012, J. Climate, 25, 7590-7606.

ENSO Response To Higher CO2
Results from G1

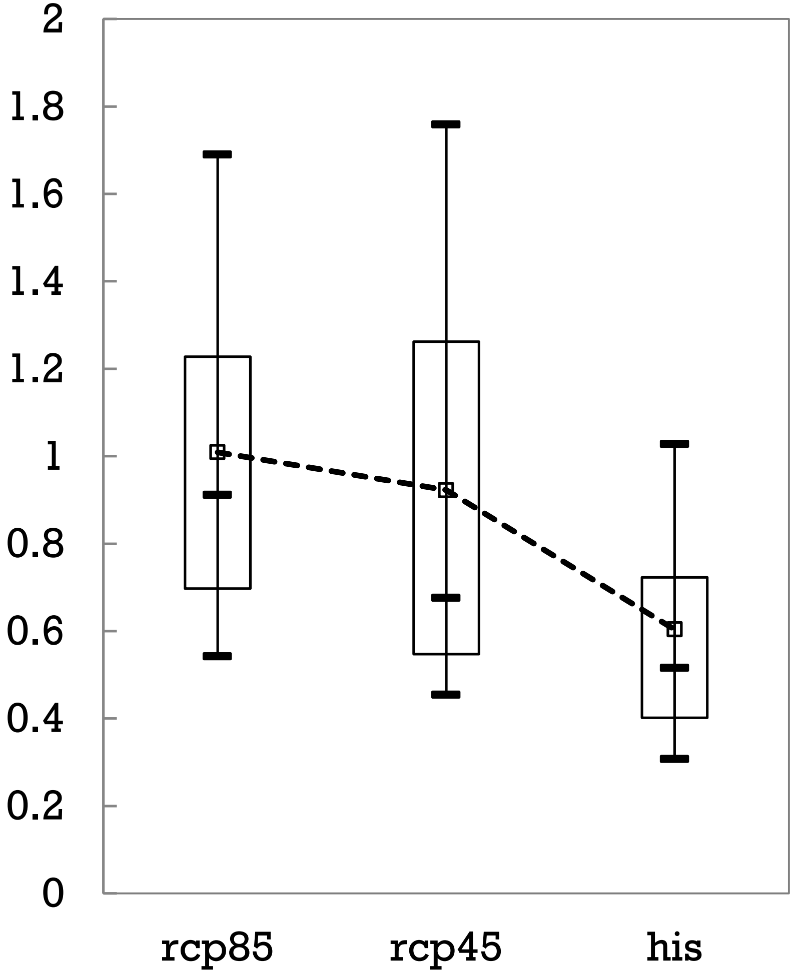
Variance



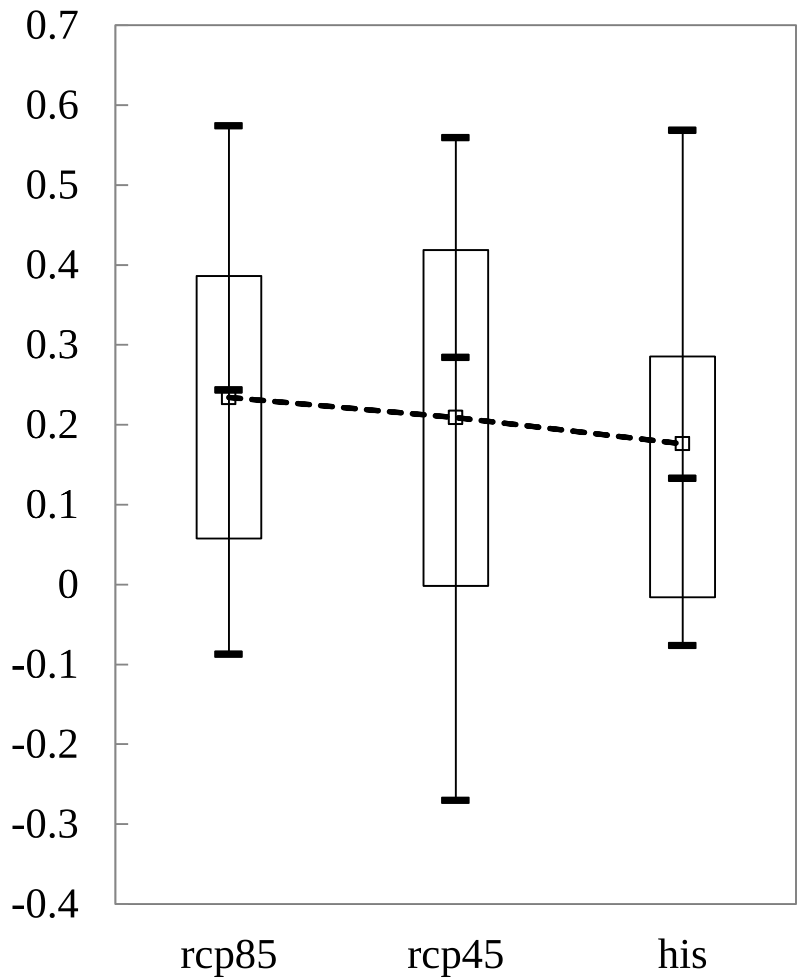
Skewness



ENSO Response to Higher CO2
Results from G1



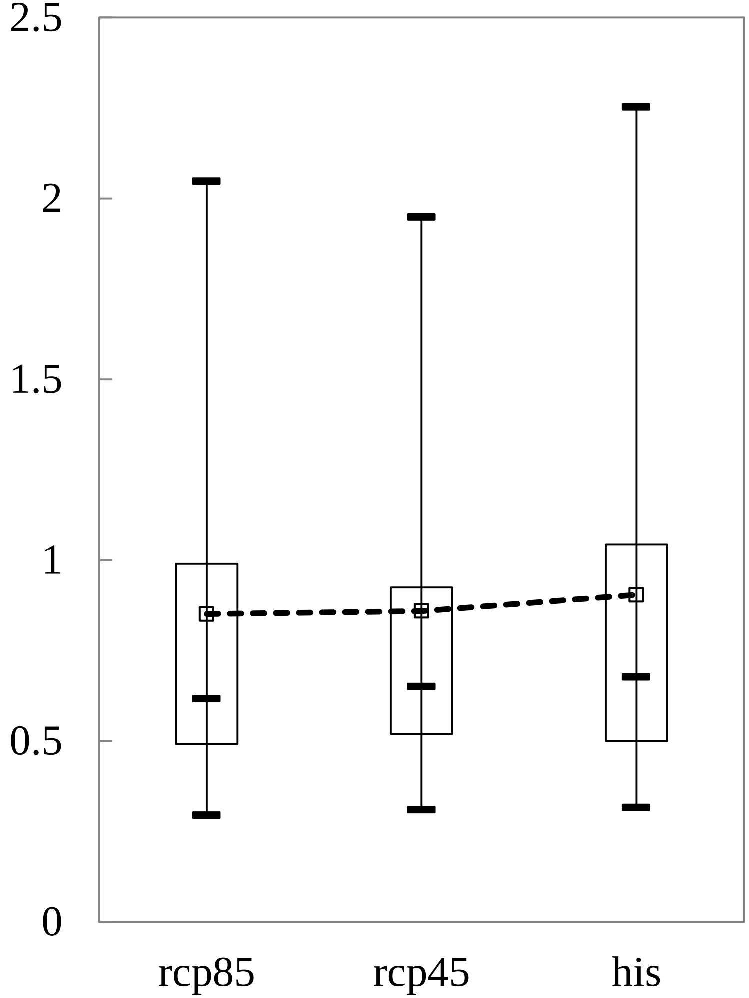
ENSO Skewness Response To Higher CO2 Results from G1



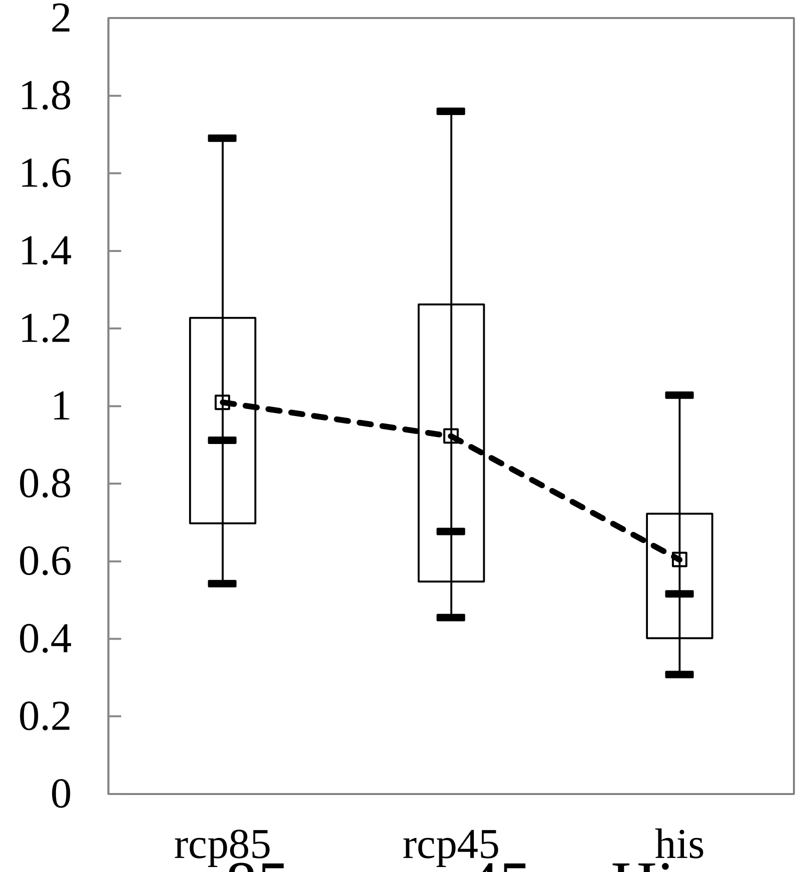
Rcp85 Rcp45 His.

ENSO Response to Higher CO2 Forcing

Results From G0 and G1—Box Plots



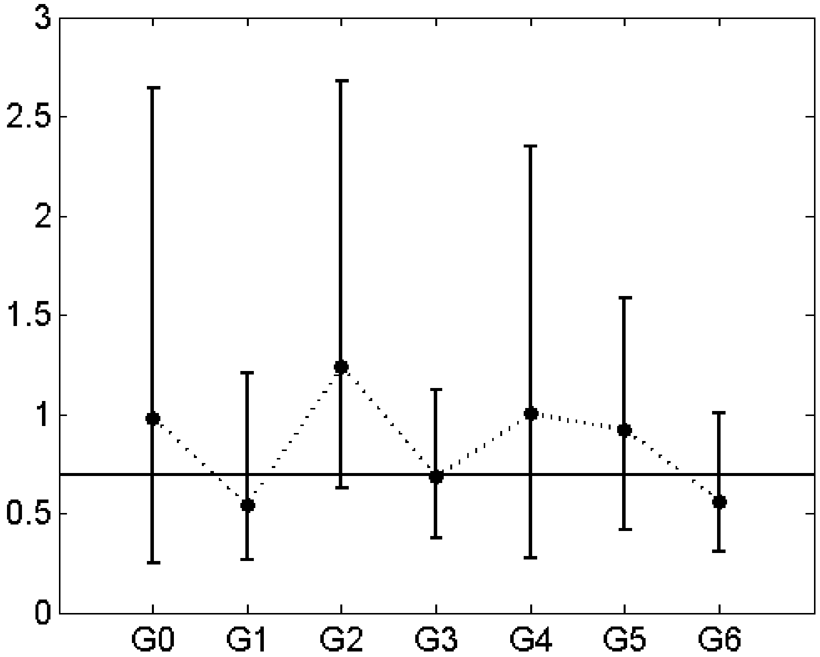
rcp85 rcp45 His.



rcp85 rcp45 His.

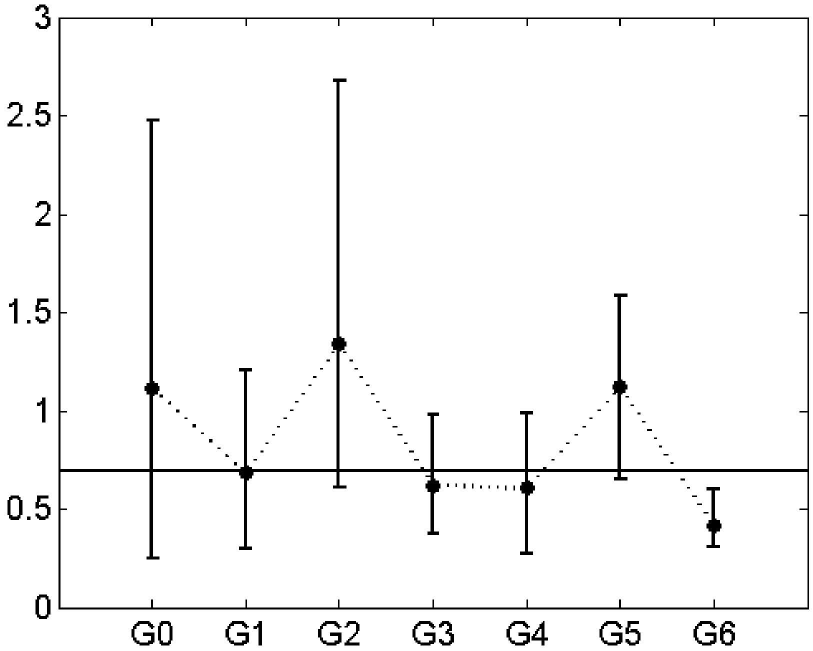
Variances for all groups

By runs



0.981	0.538	1.243	0.684	1.001	0.921	0.563

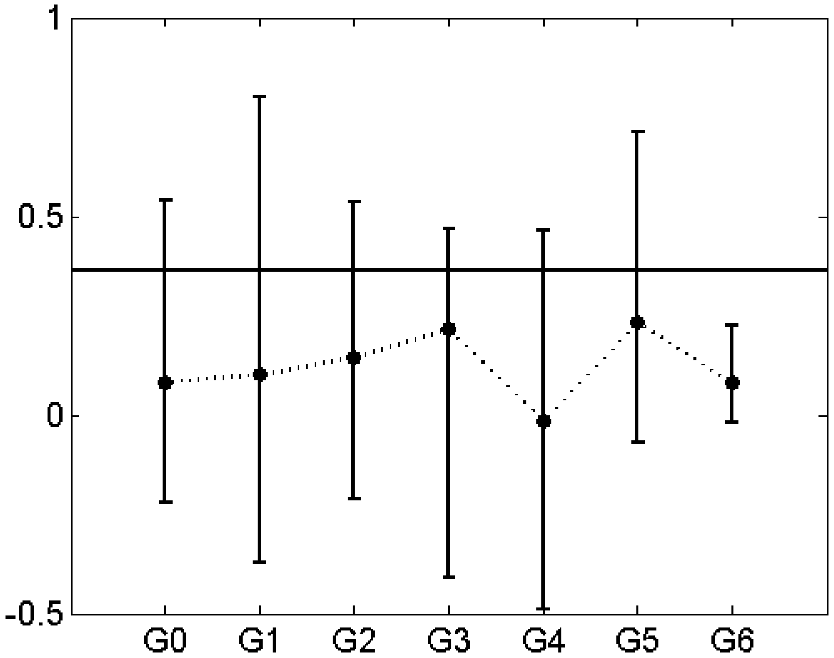
By models



1.112	0.681	1.340	0.618	0.608	1.118	0.416

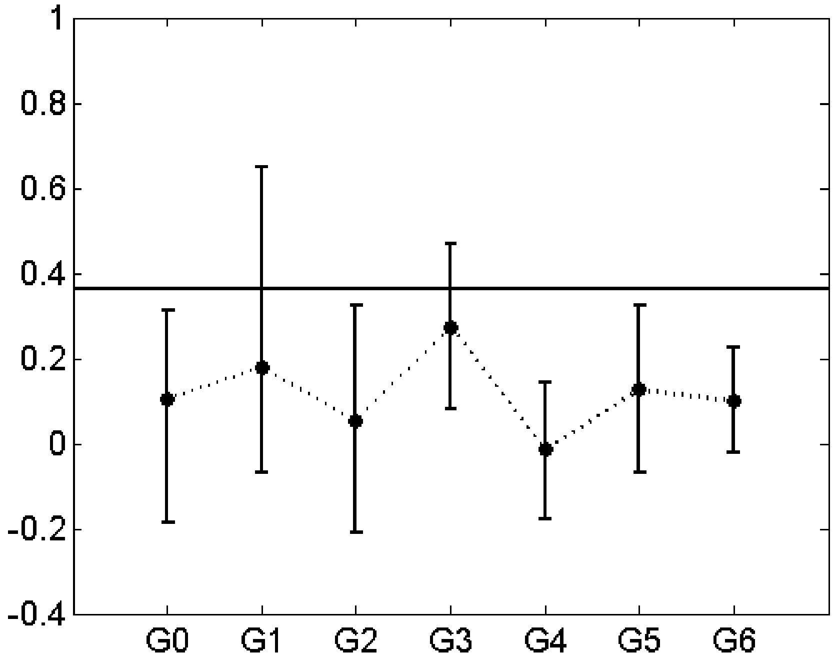
Skewness for all groups

by runs



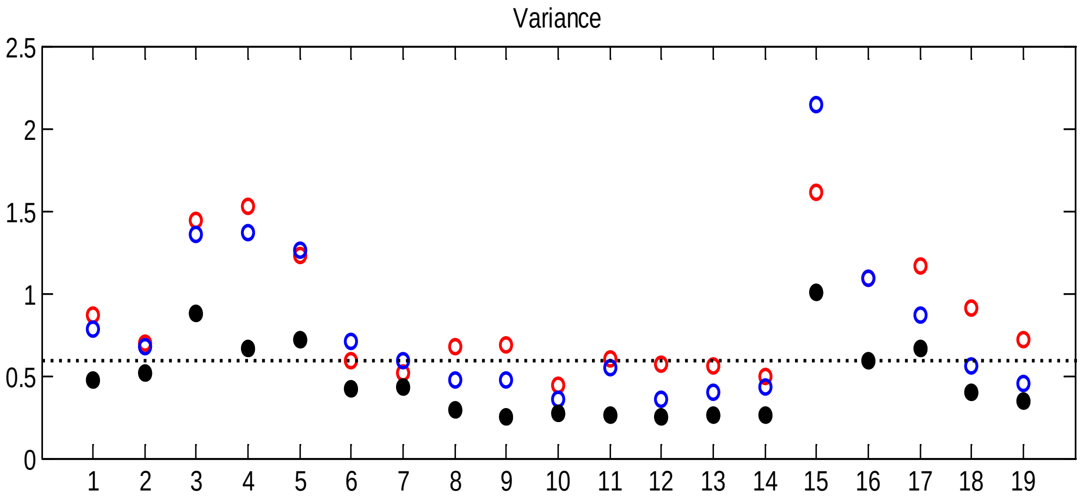
0.083	0.102	0.143	0.215	-0.015	0.233	0.080

By models



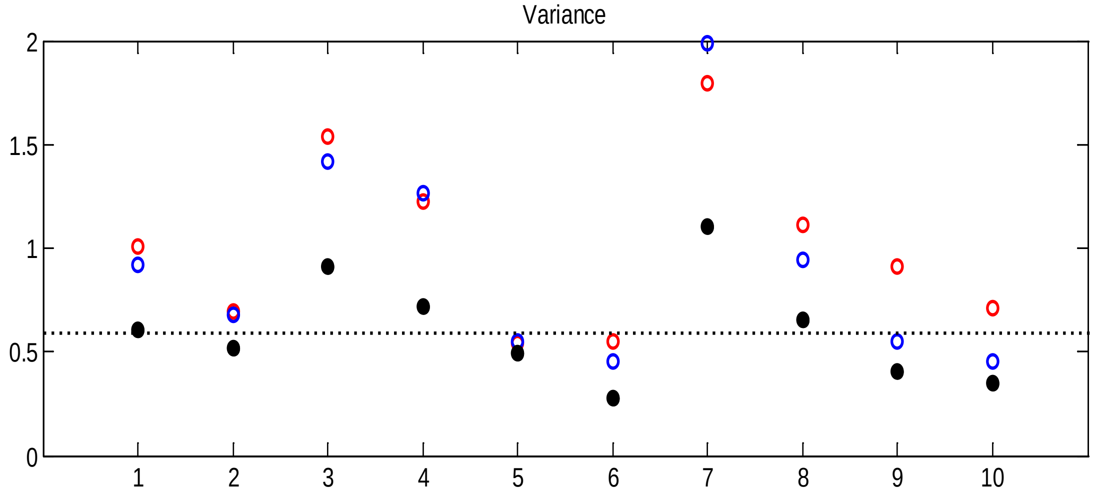
0.106	0.179	0.052	0.273	-0.015	0.126	0.099

Variance Responses from Individual Runs That Fall to G1



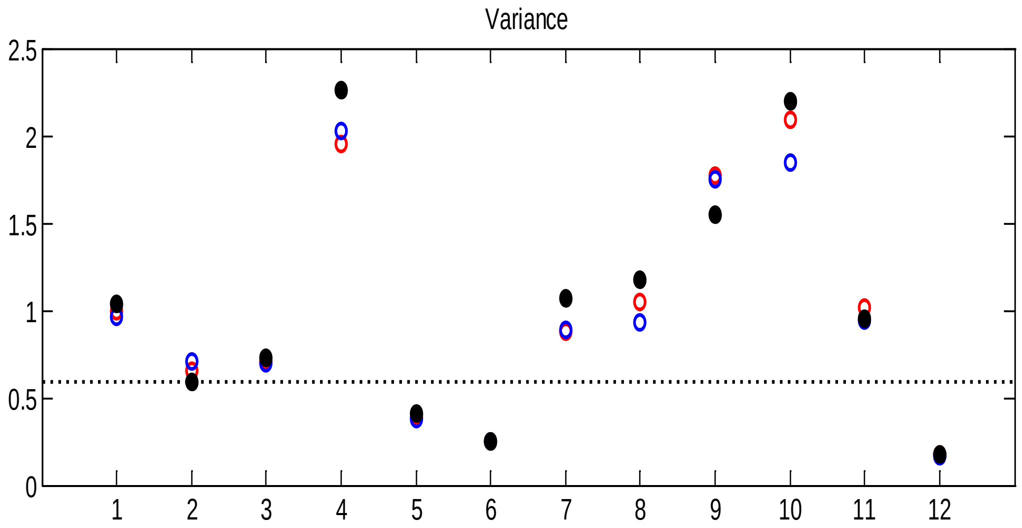
Identifier	**Run Name**
1	Group Mean
2	ACCESS1-3_R1
3	CESM1-CAM5_R1
4	CESM1-CAM5_R2
5	CMCC-CMS_R1
6	CSIRO-Mk3-6-0_R2
7	CSIRO-Mk3-6-0_R4
8	EC-EARTH_R2
9	EC-EARTH_R3
10	EC-EARTH_R6
11	EC-EARTH_R7
12	EC-EARTH_R9
13	EC-EARTH_R10
14	EC-EARTH_R14
15	MIROC5_R3
16	MPI-ESM-LR_R1
17	MPI-ESM-LR_R3
18	MPI-ESM-MR_R1
19	MRI-CGCM3_R1

Variance Response from Individual Models in Group 1 - ensemble



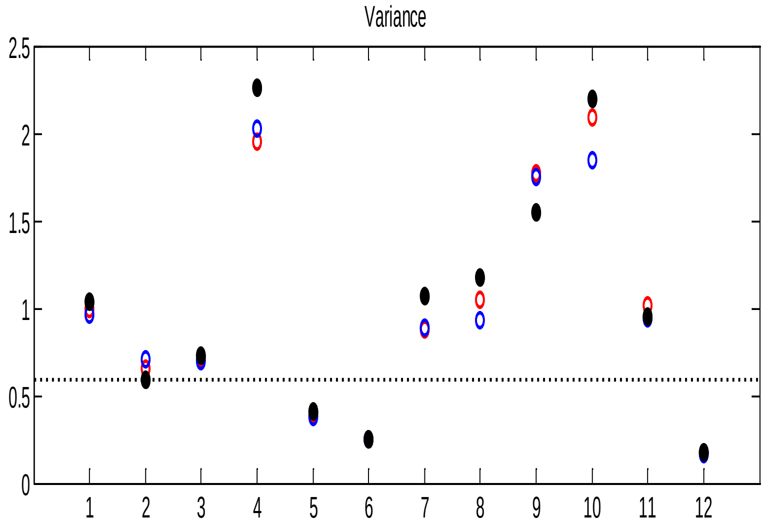
Identifier	**Model Name**
1	Group Mean
2	ACCESS1-3
3	CESM1-CAM5
4	CMCC-CMS
5	CSIRO-Mk3-6-0
6	EC-EARTH
7	MIROC5
8	MPI-ESM-LR
9	MPI-ESM-MR
10	MRI-CGCM3

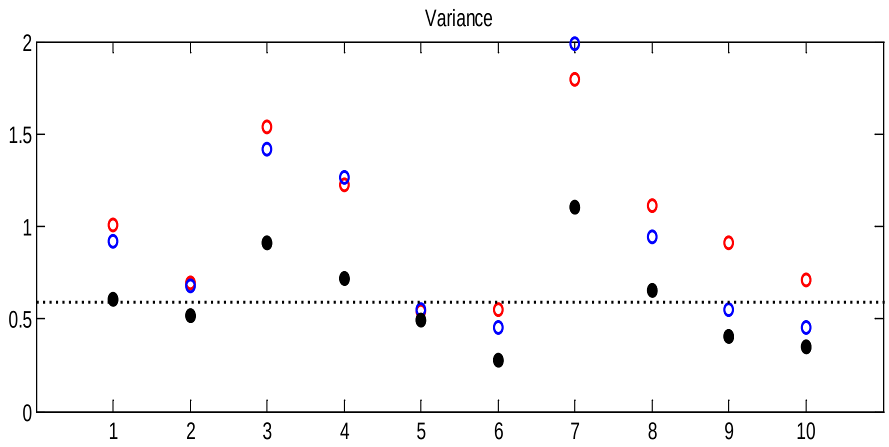
Variance Response from Individual Models from Group 0 - ensemble



Identifier	Model
1	Group Mean
2	ACCESS1-0
3	CESM1-BGC
4	FIO-ESM
5	GISS-E2-H-r1p2
6	GISS-E2-R-r1p3
7	NorESM1-M
8	NorESM1-ME
9	bcc-csm1-1-m
10	BNU-ESM
11	CNRM-CM5
12	MIROC-ESM

Variance Response from Individual Models from G0 (left) and G1(right)

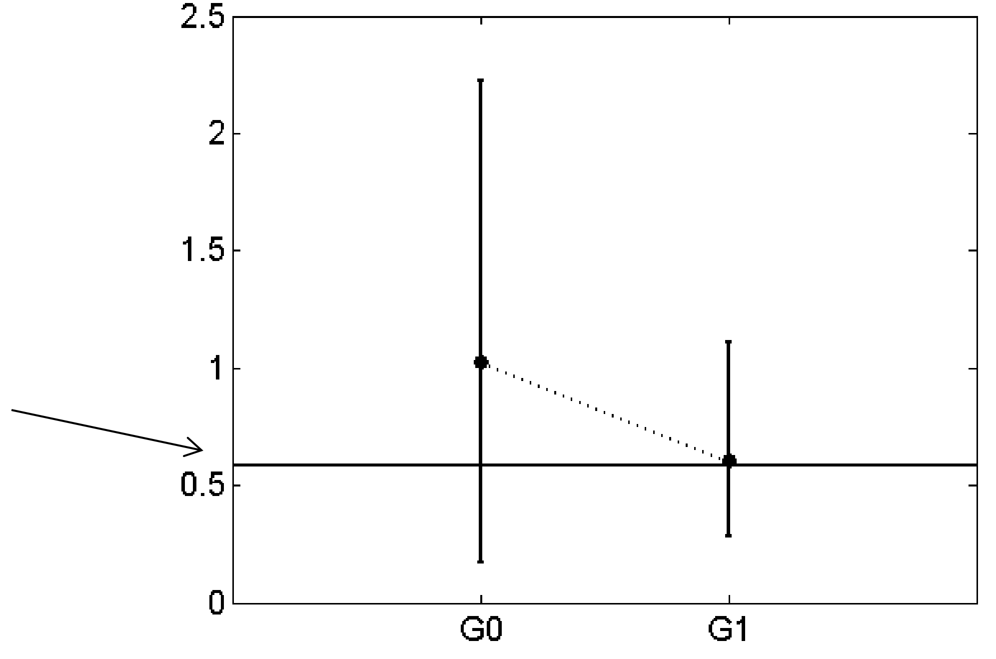




Variances in the Historical Runs of The Models in G0 and G1 (by models)

Variance

Observed Level



Variance and Skewness in the Historical Runs of Models in G1 and G0 (by runs)

Variance

Obs

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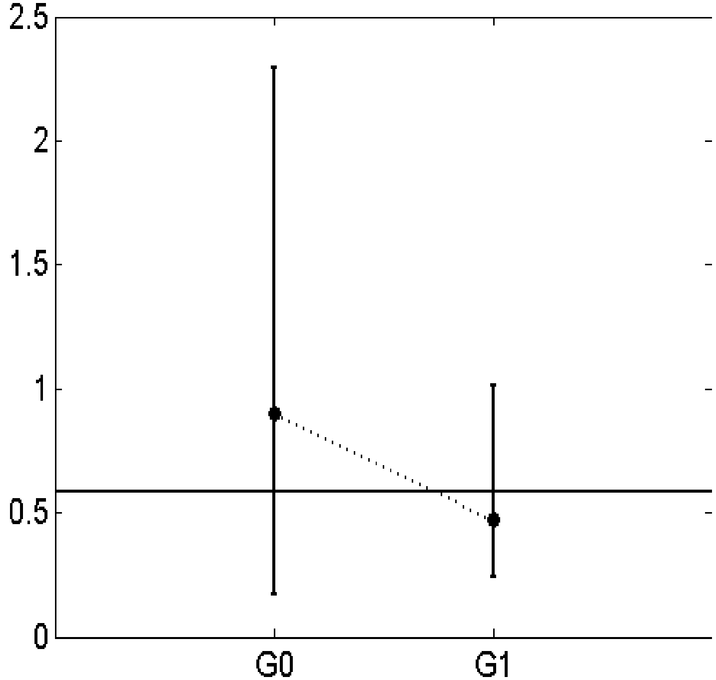
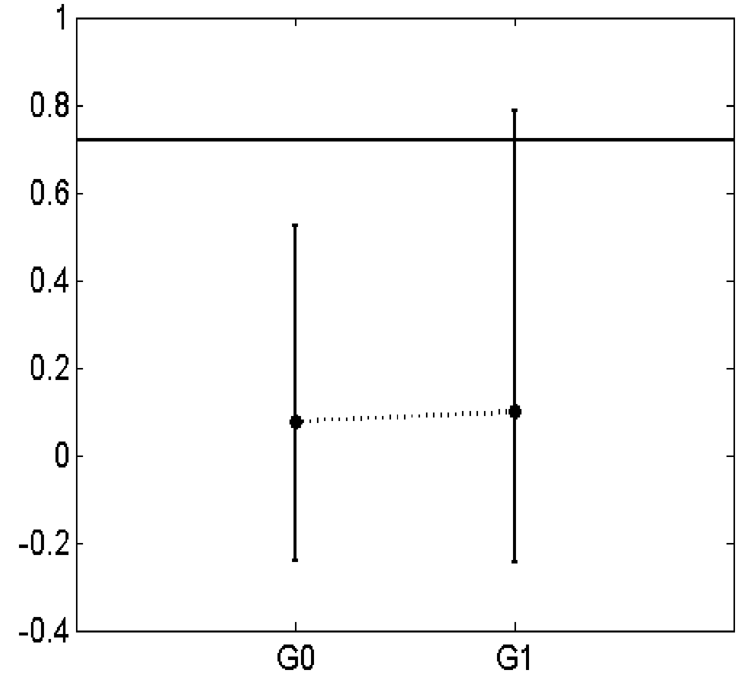
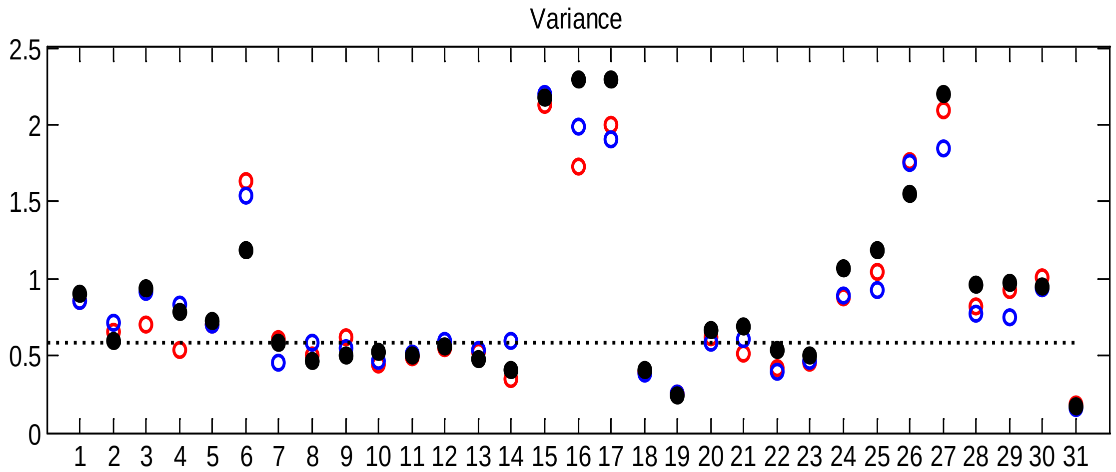


Skewness

Obs.



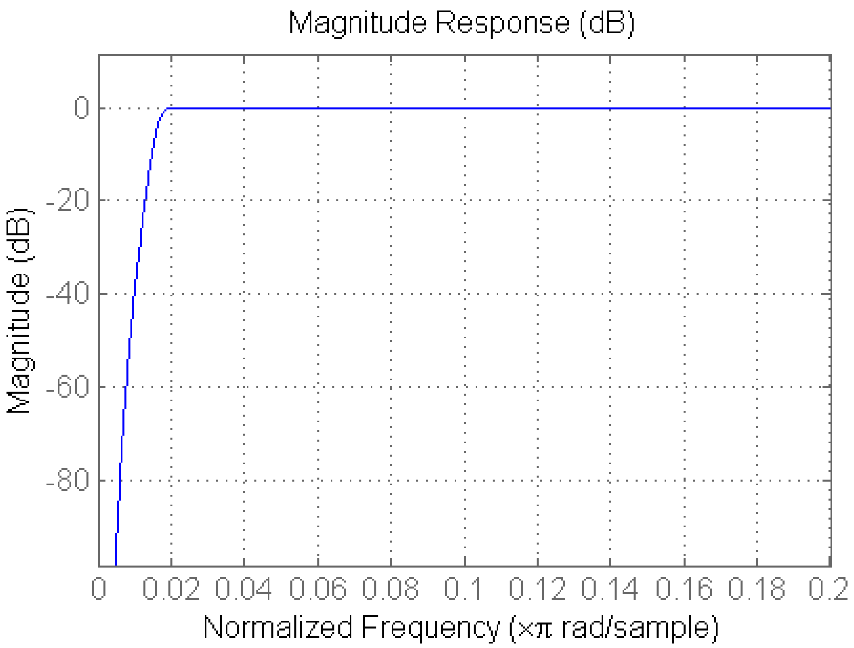
Variance Response from Individual Runs that Fall in G0

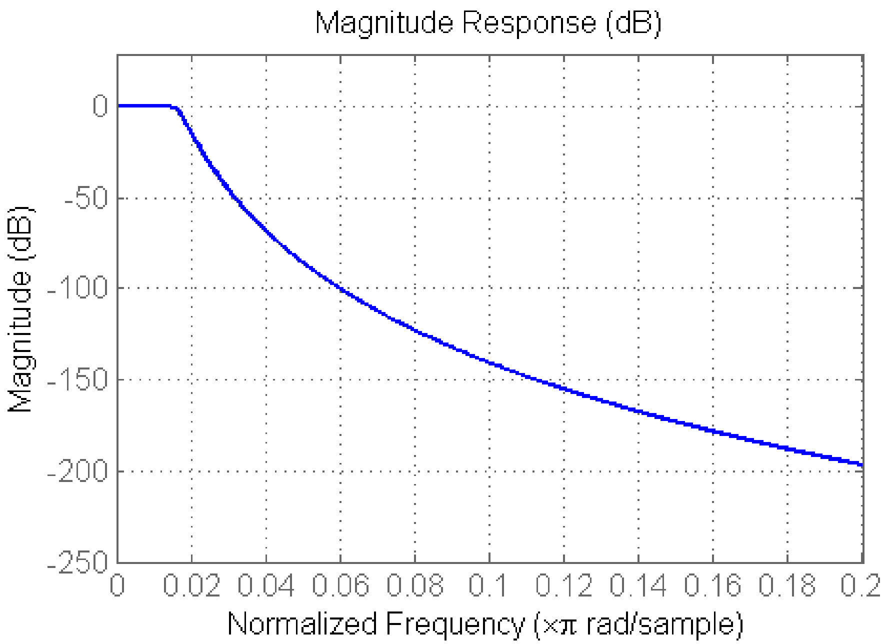


Identifier	Model
1	Group Mean
2	ACCESS1-0_R1
3	CCSM4_R2
4	CCSM4_R4
5	CESM1-BGC_R1
6	CESM1-CAM5_R3
7	CSIRO-Mk3-6-0_R1
8	CSIRO-Mk3-6-0_R3
9	CSIRO-Mk3-6-0_R5
10	CSIRO-Mk3-6-0_R6
11	CSIRO-Mk3-6-0_R7
12	CSIRO-Mk3-6-0_R9
13	CSIRO-Mk3-6-0_R10
14	EC-EARTH_R12
15	FIO-ESM_R1
16	FIO-ESM_R2
17	FIO-ESM_R3
18	GISS-E2-H_R1P2
19	GISS-E2-R_R1P3
20	HadGEM2-ES_R1
21	HadGEM2-ES_R4
22	IPSL-CM5A-LR_R2
23	IPSL-CM5A-LR_R4
24	NorESM1-M_R1
25	NorESM1-ME_R1
26	bcc-csm1-1-m_R1
27	BNU-ESM_R1
28	CanESM2_R1
29	CanESM2_R5
30	CNRM-CM5_R1
31	MIROC-ESM_R1

Filter design

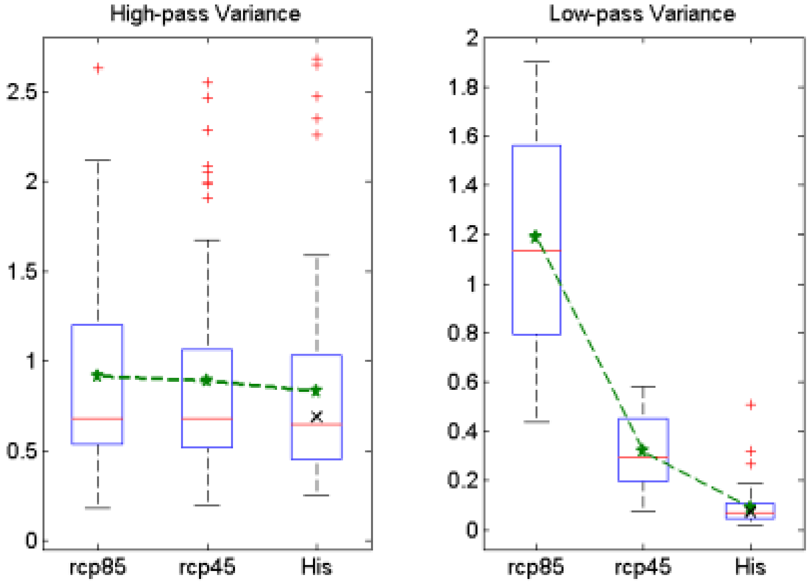
- Butterworth filter
- 10 – year



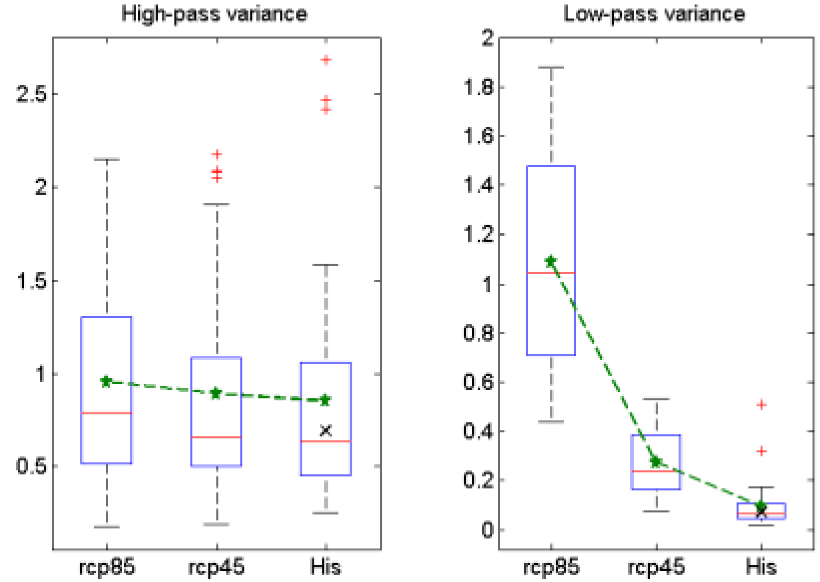


Variance of filtered data

All runs

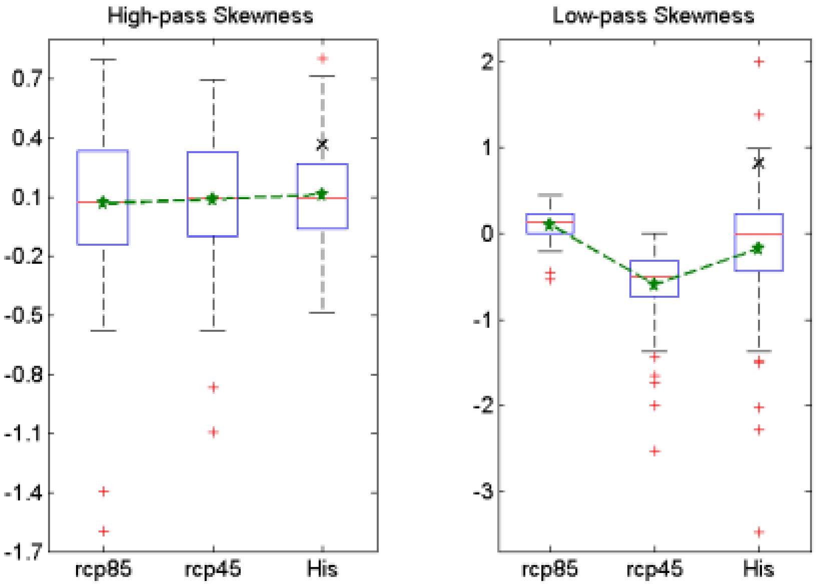


Ensemble

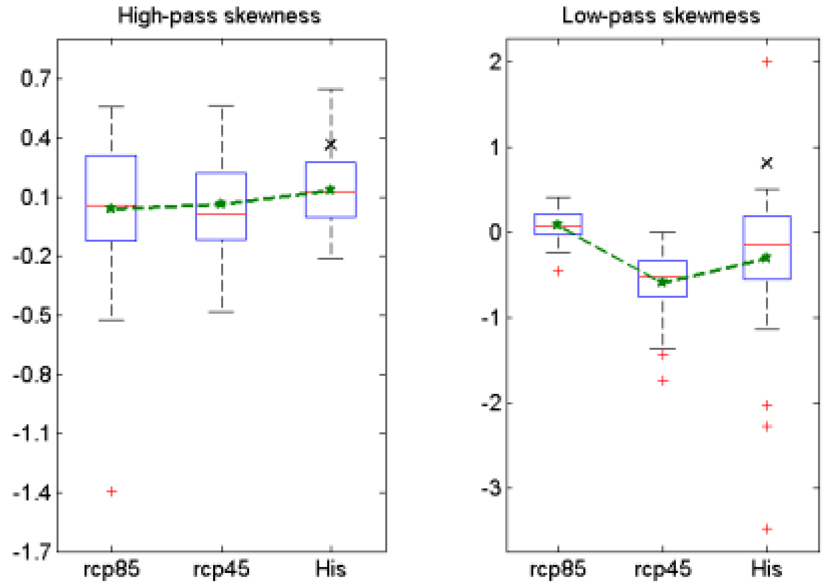


Skewness of filtered data

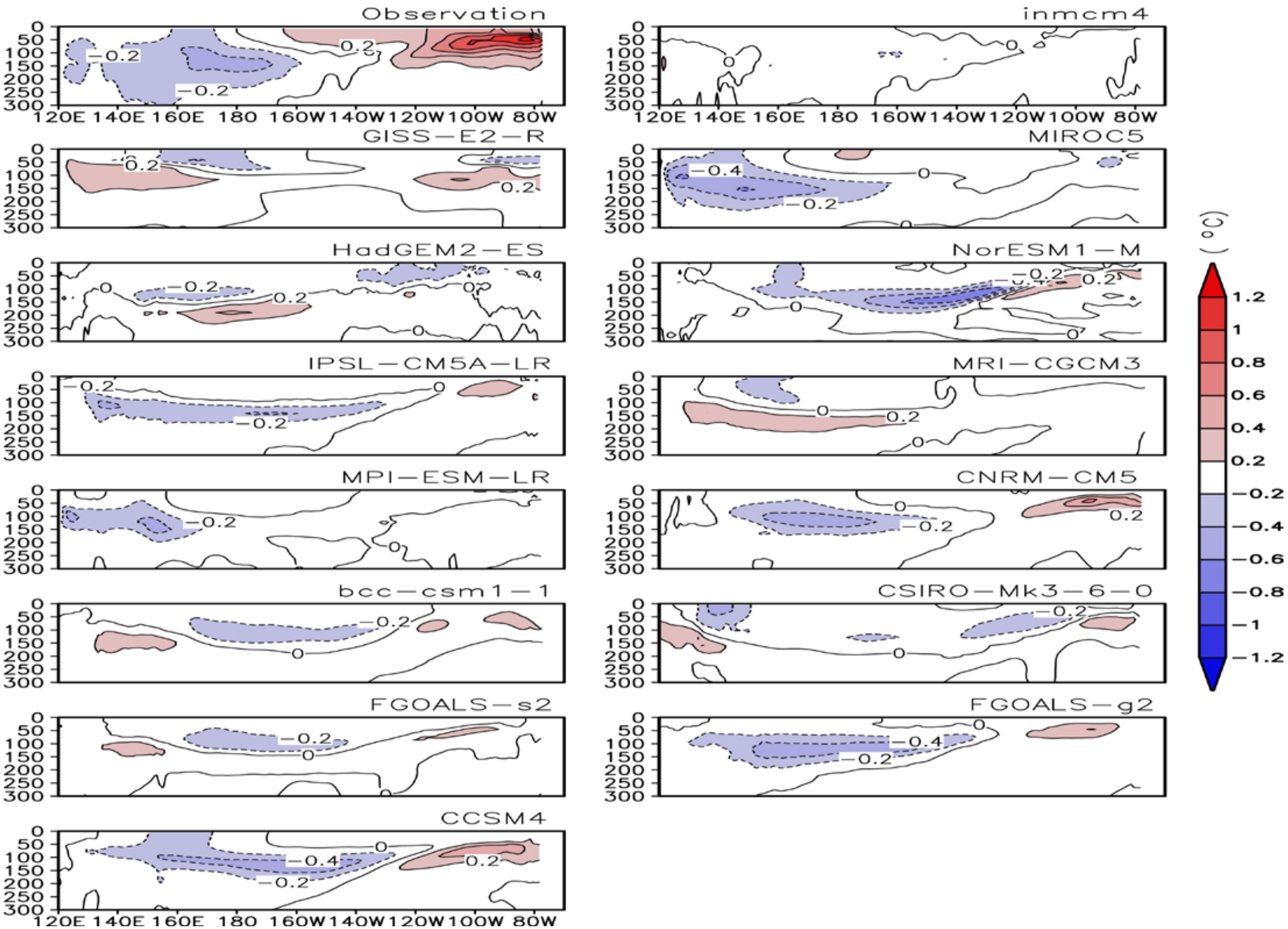
All runs



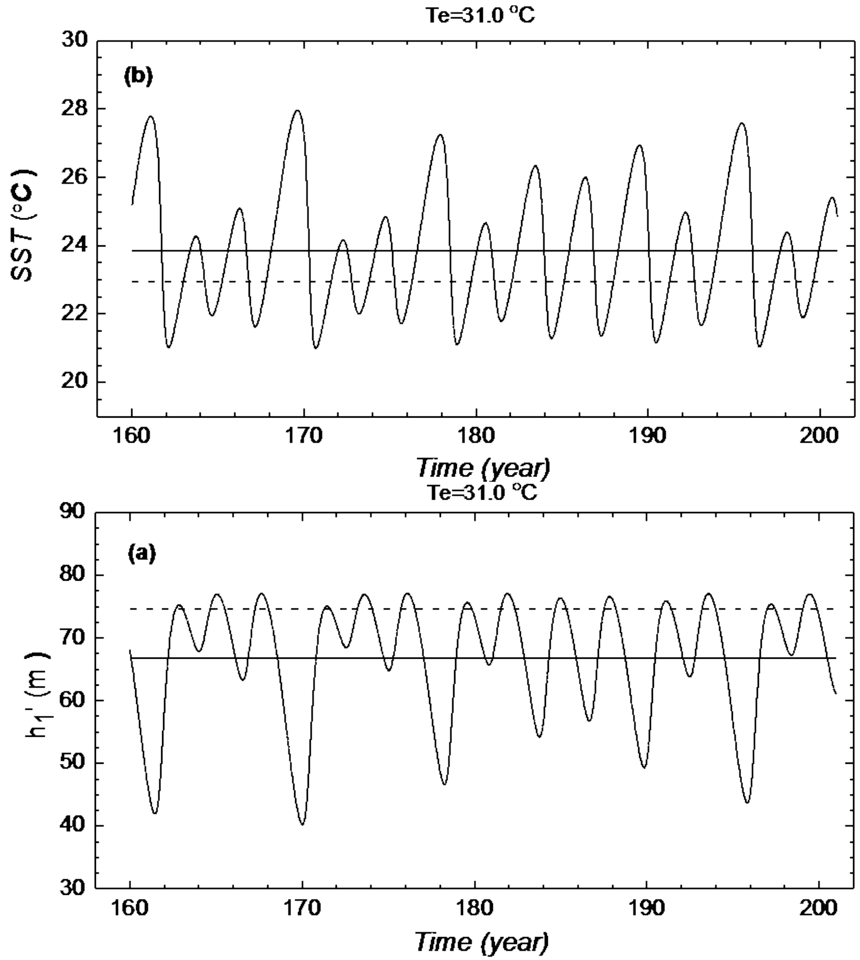
Ensemble

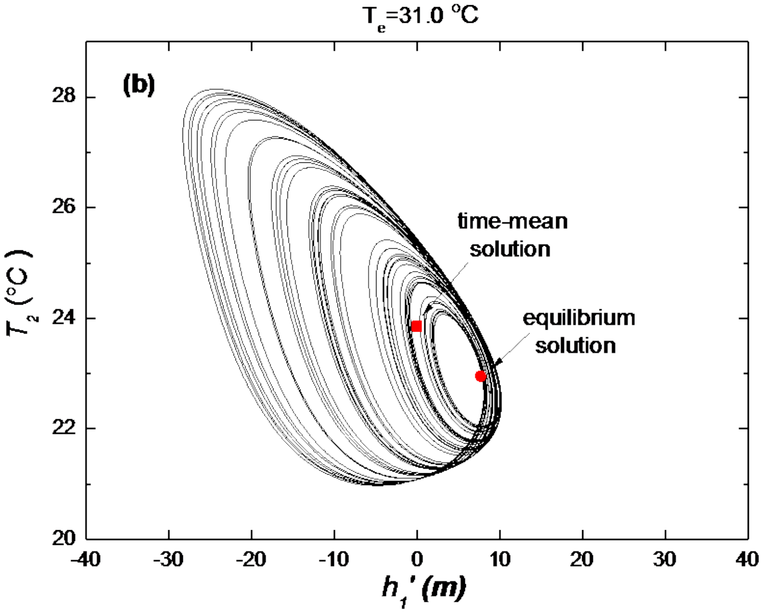


ENSO Asymmetry in Models and Obs.



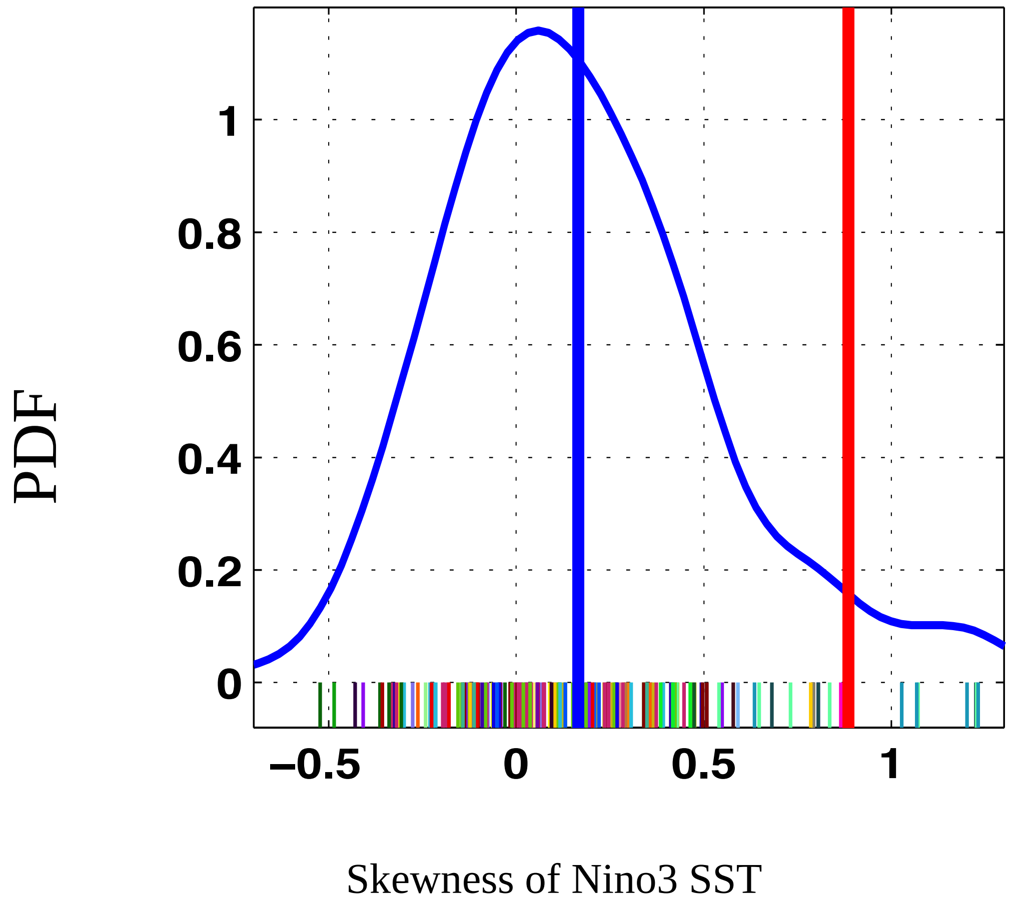
Asymmetry in the Oscillation in the Model of Sun (1997)



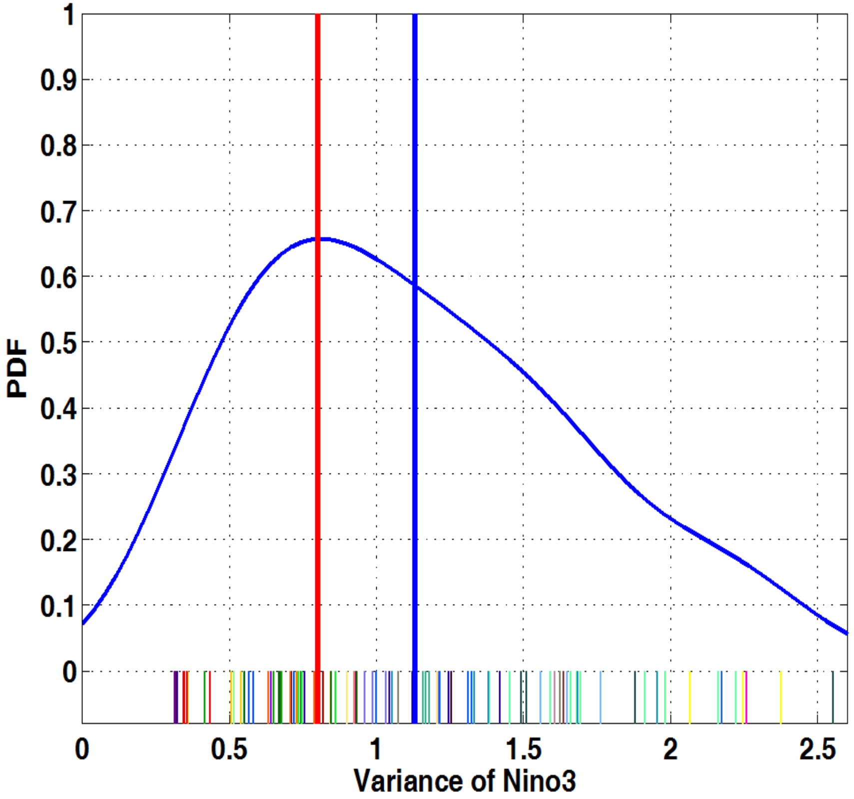


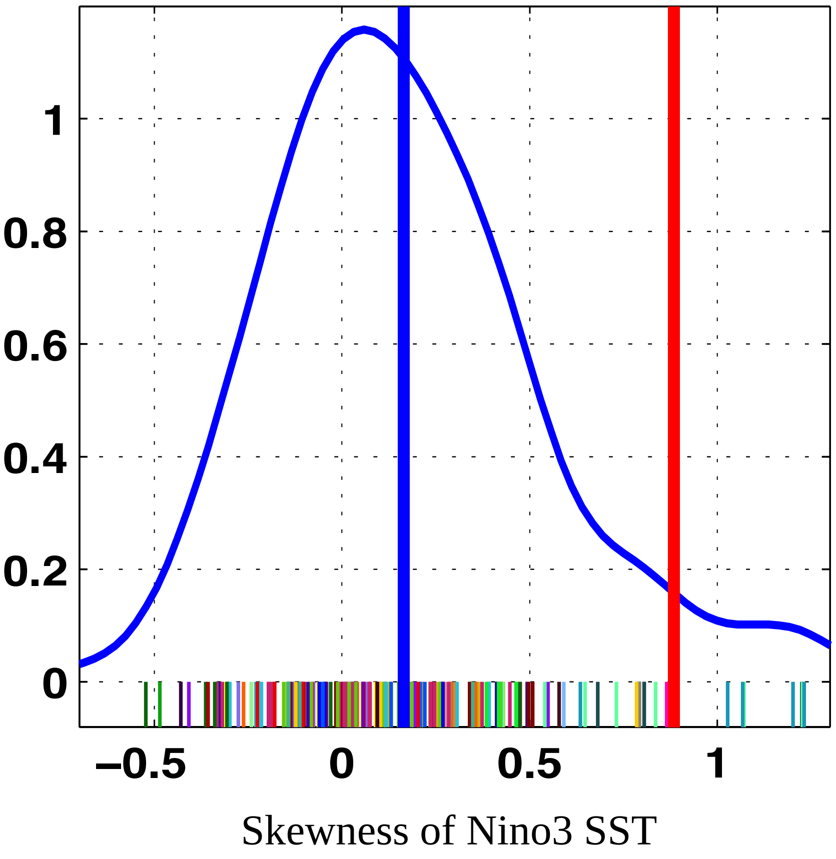
Liang, J., X.-Q. Yang, and D.-Z. Sun, 2012, J. Climate, 25, 7590-7606.

ENSO Asymmetry in CMIP5 Models (20C)



ENSO Amplitude and Asymmetry in CMIP5 Models (20C)





Summary

- 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 1/3 of models that have inconsistent responses to different levels of increase of CO_2.

- Among the models that have a consistent response to different levels of increase of CO2, the two largest groups are the one (G0) that the member models have a muted response and the one (G1) that the member models tend to produce a positive response and the one (G0). The number of models of these two group accounts for respectively 30% and 25% of the total models of CMIP5.

- ENSO events simulated in the historical runs (20C runs) by the models in G1 are found to be weaker in amplitude and stronger in asymmetry than G0 (and thus are more comparable to observations). This result underscores the importance of nonlinearity (and realism of simulated ENSO) in determining the response of ENSO to higher CO2 forcing.