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Geophysical Research Letters

Supporting Information for

What controls ENSO-amplitude diversity in climate models?

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Contents of this file

Figures A1 to A9 and Tables A1 to A13.

Additional Supporting Information (Files uploaded separately)

Captions for Data sets A1 to A10.

Introduction

In the following we list the CMIP5 models used in the main analysis (Table A1). We further show the temporal parameter variability within each CMIP5 model and compare it to the intermodel parameter spread across all CMIP5 models (Table A2). We further show the uncertainty of the ReOsc model parameter estimated for SODA and CMIP5 (Table A3). We also show the root-mean-square (RMS) errors between ENSO amplitude as simulated by CMIP5 and that obtained from the ReOsc model integrations with single parameter variation and with co-varying parameters from EOF-1 (Table A4). Furthermore, we show the results obtained for a Kiel Climate Model (KCM) perturbed physics ensemble (Figure A1-A3 and Table A5-A7), of the CMIP5 model selection from *Kim et al.* [2014] (Figure A4-A6 and Table A8-A10) and for the CMIP3 models (Figure A7-A9 and Table A11-A13). At last, the captions of the data sets describe the uploaded data files (Data sets A1 – A10).

CMIP5 model list

Label number	Model
1	ACCESS1-0
2	ACCESS1-3
3	bcc-csm1-1
4	bcc-csm1-1-m
5	BNU-ESM
6	CanESM2
7	CCSM4
8	CESM1-BGC
9	CESM1-FASTCHEM
10	CESM1-WACCM
11	CMCC-CESM
12	CMCC-CM
13	CNRM-CM5
14	CSIRO-Mk3-6-0
15	FGOALS-g2
16	GFDL-CM3
17	GFDL-ESM2G
18	GFDL-ESM2M
19	GISS-E2-H-CC
20	GISS-E2-H
21	GISS-E2-R-CC
22	GISS-E2-R
23	HadCM3
24	HadGEM2-CC
25	HadGEM2-ES
26	IPSL-CM5A-LR
27	IPSL-CM5A-MR
28	IPSL-CM5B-LR
29	MIROC5
30	MPI-ESM-LR
31	MPI-ESM-MR
32	MPI-ESM-P
33	MRI-CGCM3
34	NorESM1-ME
35	NorESM1-M

Table A1 List of CMIP5 models used in the analysis.

CMIP5 model	STD(a_{11})	STD(a_{12})	STD(a_{21})	STD(a_{22})	STD(ξ_T)	STD(ξ_h)
1	0.181	0.016	1.695	0.238	0.135	1.449
2	0.286	0.013	1.415	0.225	0.105	1.109
3	0.206	0.027	1.023	0.189	0.242	1.034
4	0.079	0.051	0.957	0.176	0.235	1.688
5	0.208	0.036	1.420	0.122	0.293	0.792
6	0.197	0.032	1.484	0.189	0.177	0.680
7	0.190	0.026	2.290	0.119	0.149	1.295
8	0.080	0.035	1.054	0.109	0.105	1.145
9	0.116	0.013	0.869	0.111	0.129	1.051
10	0.172	0.029	1.493	0.080	0.275	1.982
11	0.121	0.035	0.962	0.232	0.265	1.811
12	0.128	0.042	2.603	0.185	0.183	0.588
13	0.166	0.033	1.326	0.225	0.179	2.568
14	0.132	0.037	1.189	0.232	0.231	0.893
15	0.307	0.039	2.377	0.180	0.169	1.609
16	0.113	0.017	2.467	0.266	0.181	2.050
17	0.405	0.028	2.855	0.224	0.096	0.539
18	0.145	0.024	1.728	0.090	0.198	2.450
19	0.173	0.026	1.429	0.245	0.172	0.858
20	0.121	0.014	2.126	0.225	0.170	0.346
21	0.304	0.012	1.024	0.237	0.090	0.687
22	0.152	0.044	0.623	0.170	0.101	0.845
23	0.205	0.041	1.425	0.150	0.077	0.740
24	0.432	0.020	2.168	0.124	0.218	1.629
25	0.354	0.065	1.807	0.216	0.318	0.618
26	0.100	0.021	2.370	0.126	0.218	0.524
27	0.222	0.038	1.210	0.294	0.165	1.134
28	0.171	0.027	1.503	0.175	0.145	1.186
29	0.162	0.013	0.983	0.103	0.270	1.200
30	0.159	0.038	2.437	0.142	0.325	1.488
31	0.283	0.021	3.798	0.275	0.141	1.369

32	0.222	0.017	0.980	0.372	0.162	2.348
33	0.300	0.016	1.368	0.113	0.115	0.598
34	0.167	0.023	1.392	0.167	0.227	0.697
35	0.202	0.020	2.777	0.197	0.178	1.518
Ensemble-mean	0.199	0.028	1.675	0.186	0.184	1.215
Intermodel STD	0.457	0.079	2.646	0.302	0.634	3.786
Fraction of mean and intermodel STD	43,55 %	35,44 %	63,30 %	61,59 %	29,02 %	32,09 %

Table A2 Temporal ReOsc parameter variability for each CMIP5 model calculated as the standard deviation over a set of parameters estimated from a moving window with 30 years length and 10 year interval (row 1 – 35), the ensemble-mean over all 35 rows (row 36), the intermodel parameter spread as the standard deviation over all CMIP5 models (entire time period used; row 37) and the fraction of the ensemble-mean temporal variability of the intermodel spread for each parameter (row 38). Units are yr^{-1} for a_{11} and a_{22}, $K\ m^{-1}\ yr^{-1}$ for a_{12}, $m\ K^{-1}\ yr^{-1}$ for a_{21}, $K\ yr^{-1}$ for ξ_T and $m\ yr^{-1}$ for ξ_h .

	a_{11}	a_{12}	a_{21}	a_{22}	ξ_T	ξ_h
SODA	0.24	0.026	2.44	0.27	0.15	1.51
1	0.22	0.024	1.77	0.19	0.10	0.80
2	0.24	0.026	1.66	0.18	0.10	0.73
3	0.24	0.044	1.28	0.23	0.13	0.70
4	0.21	0.046	0.83	0.19	0.17	0.68
5	0.15	0.026	0.91	0.15	0.16	0.92
6	0.17	0.027	1.04	0.17	0.12	0.75
7	0.14	0.021	1.14	0.17	0.11	0.85
8	0.16	0.025	1.21	0.19	0.10	0.76
9	0.15	0.024	1.20	0.19	0.10	0.81
10	0.15	0.023	1.14	0.17	0.13	0.95
11	0.18	0.027	1.11	0.17	0.16	1.04
12	0.25	0.037	1.62	0.24	0.11	0.72
13	0.24	0.033	1.58	0.22	0.16	1.02
14	0.21	0.029	1.38	0.19	0.12	0.78
15	0.18	0.022	1.35	0.16	0.10	0.75
16	0.17	0.025	1.27	0.19	0.12	0.93
17	0.24	0.036	1.79	0.27	0.12	0.87
18	0.16	0.020	1.18	0.15	0.16	1.21
19	0.17	0.020	1.42	0.17	0.09	0.78
20	0.19	0.023	1.67	0.21	0.08	0.71
21	0.21	0.029	1.41	0.19	0.08	0.55
22	0.19	0.027	1.25	0.18	0.08	0.55
23	0.22	0.033	1.12	0.17	0.14	0.71
24	0.34	0.048	1.65	0.24	0.19	0.92
25	0.35	0.056	1.76	0.28	0.19	0.93
26	0.21	0.037	1.22	0.21	0.11	0.65
27	0.18	0.032	1.08	0.19	0.10	0.63
28	0.21	0.032	1.56	0.24	0.10	0.78
29	0.15	0.019	1.04	0.13	0.14	0.96
30	0.22	0.031	1.98	0.27	0.13	1.14
31	0.30	0.036	2.35	0.29	0.14	1.14
32	0.22	0.026	2.01	0.23	0.13	1.14
33	0.27	0.039	1.76	0.26	0.12	0.76
34	0.16	0.020	1.48	0.18	0.11	0.98
35	0.16	0.018	1.63	0.18	0.10	1.01
Ensemble-mean	0.21	0.030	1.42	0.20	0.12	0.85

Table A3 95% confidence interval of all six ReOsc model parameters estimated for SODA, all CMIP5 models and of the CMIP5 ensemble-mean. Units are yr^{-1} for a_{11} and a_{22}, K m^{-1} yr^{-1} for a_{12}, m K^{-1} yr^{-1} for a_{21}, K yr^{-1} for ξ_T and m yr^{-1} for ξ_h.

RMS error	$\mathbf{a_{11}}$	$\mathbf{a_{12}}$	$\mathbf{a_{21}}$	$\mathbf{a_{22}}$	ξ_T	ξ_h
Single parameter variation	1.72	1.39	1.36	1.36	1.23	1.28
All parameter variation (EOF-1)	1.65	-	1.51	1.31	1.23	1.27

Table A4 Root-mean-square (RMS) error of ENSO amplitude as obtained from the ReOsc model integrations with (first row) single parameter variation and (lower row) with co-varying parameters from EOF-1 with respect to the ENSO amplitudes directly derived from the CMIP5 models. No RMS error is given for a_{12} for the co-varying parameters due to infinite ENSO amplitude within the ensembles parameter-range (see main text).

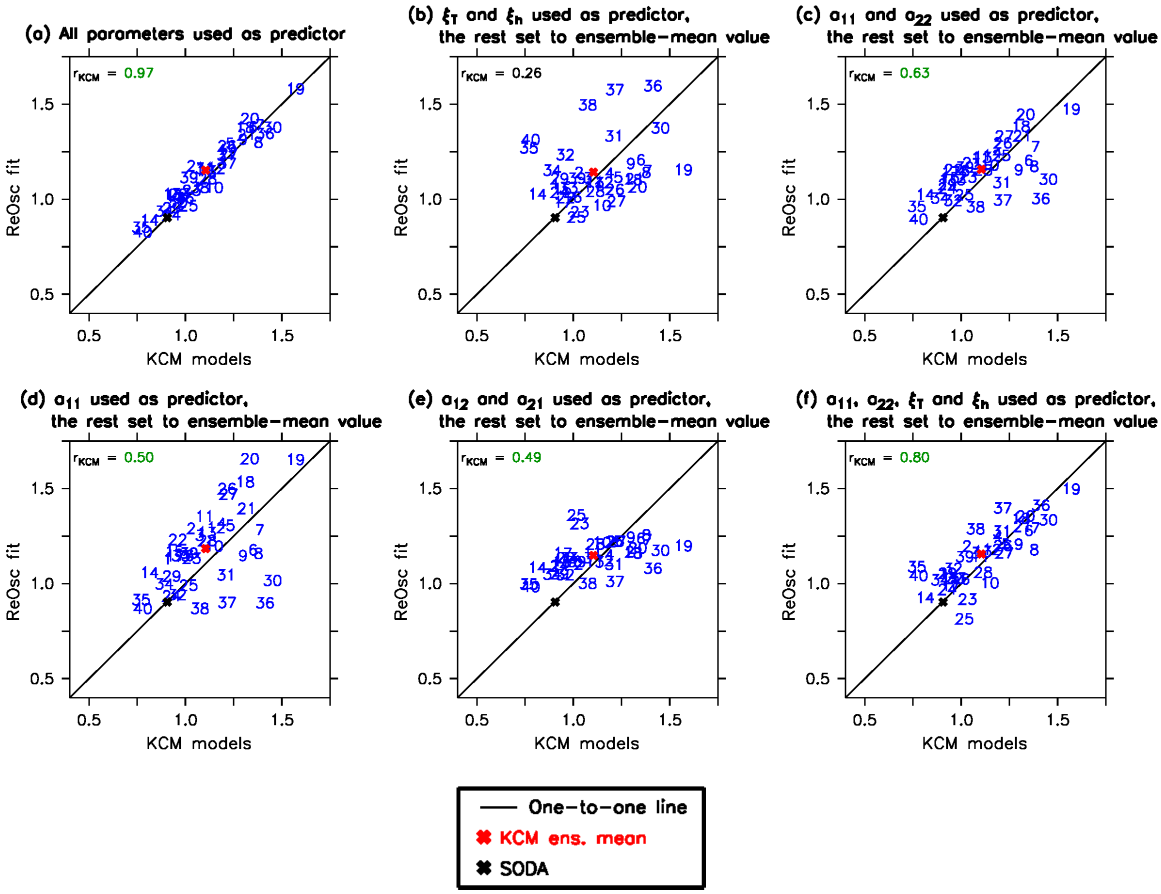

Figure A1 Same as Figure 1 but for the KCM perturbed physics ensemble.

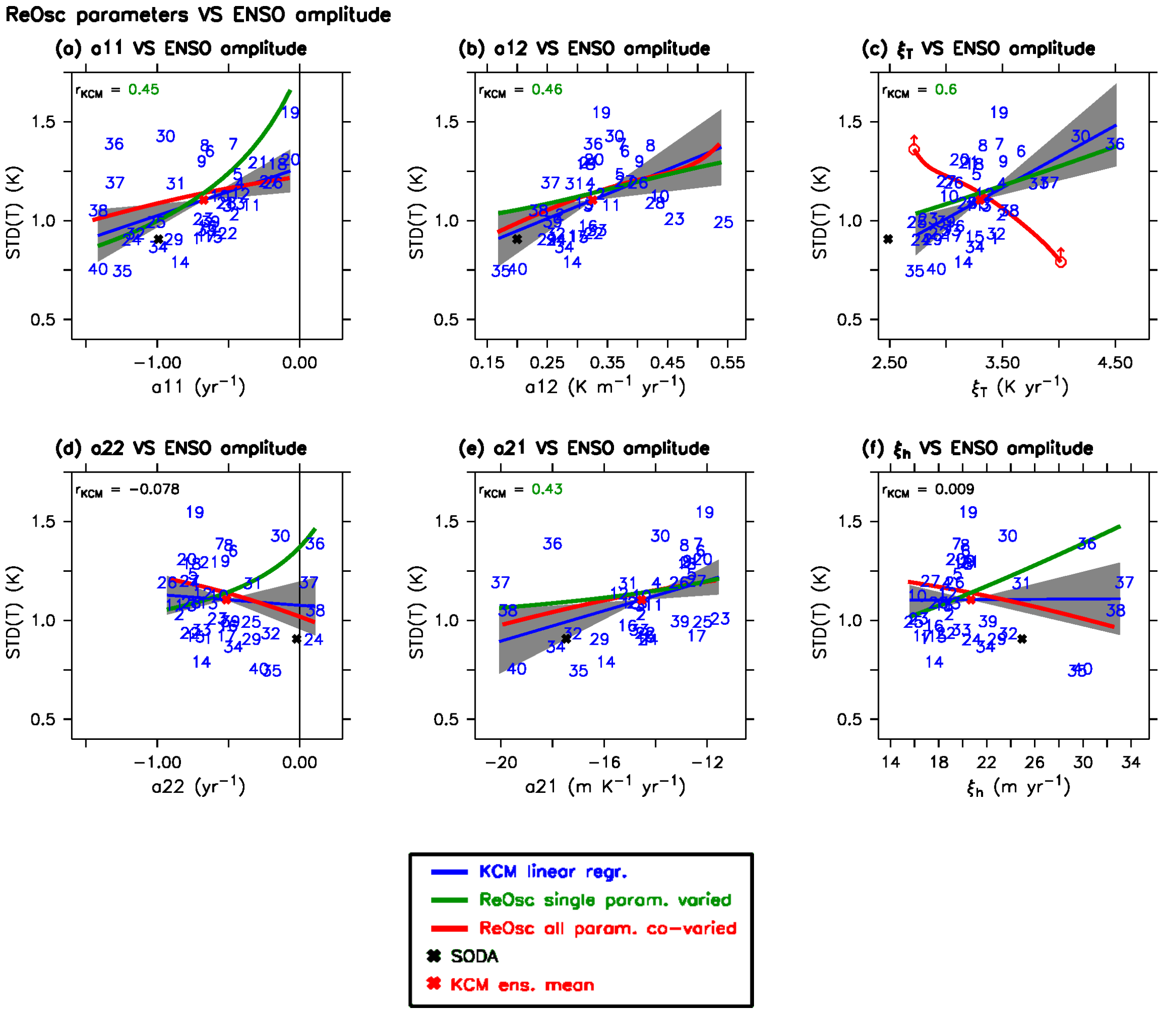

Figure A2 Same as Figure 2 but for the KCM perturbed physics ensemble. Note the different axis scales.

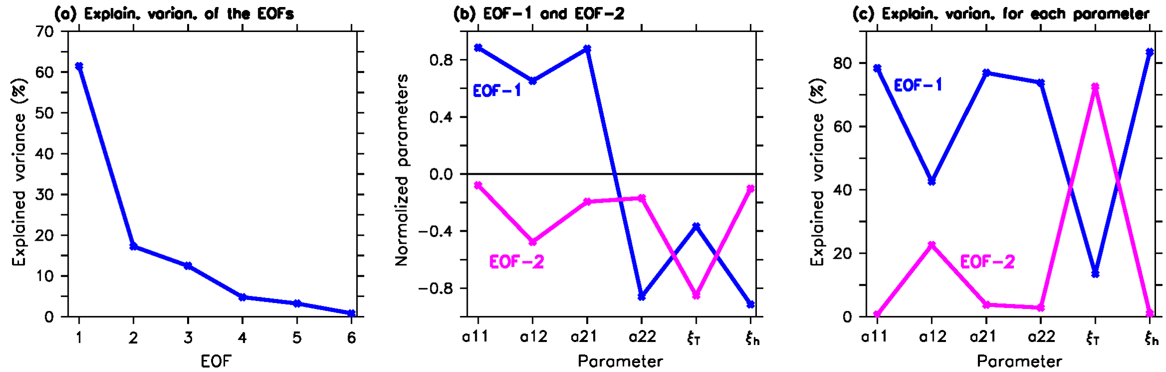

Figure A3 Same as Figure 3 but for the KCM perturbed physics ensemble. Note the different axis scales.

KCM experiment label	Convective mass-flux above level of non-buoyancy	Entrainment rate for shallow convection [10^{-4}]	Convective cloud conversion rate from cloud water to rain [10^{-4}]	Amount of atmospheric vertical levels
1	0.15	3	1	19
2	0.175	3	1	19
3	0.20	3	1	19
4	0.225	3	1	19
5	0.25	3	1	19
6	0.275	3	1	19
7	0.30	3	1	19
8	0.325	3	1	19
9	0.35	3	1	19
10	0.2	1	1	19
11	0.2	2	1	19
12	0.2	4	1	19
13	0.2	5	1	19
14	0.2	6	1	19
15	0.2	7	1	19
16	0.2	8	1	19
17	0.2	9	1	19
18	0.2	3	2.1	19
19	0.2	3	2.5	19
20	0.2	3	3	19
21	0.2	3	4	19
22	0.2	5	4	19
23	0.30	1	4	19
24	0.13	10	4	19
25	0.3	1	1.5	19
26	0.3	10	1.5	19
27	0.2	1	4	19
28	0.35	10	1	19
29	0.3	10	1.5	31
30	0.35	3	1	31
31	0.2	3	1	31
32	0.2	5	1	31
33	0.2	1	4	31
34	0.35	10	1	31
35	0.3	10	1.5	62
36	0.35	3	1	62
37	0.2	3	1	62
38	0.2	5	1	62
39	0.2	1	4	62
40	0.35	10	1	62

Table A5 List of KCM experiments which differ in three atmospheric parameters (column 2-4) and vertical atmospheric resolution (column 5). See *Wengel et al.* [2017] for details.

	a_{11}	a_{12}	a_{21}	a_{22}	ξ_T	ξ_h
a_{11}		0.41	**0.75**	**-0.88**	-0.14	**-0.70**
a_{12}			**0.64**	**-0.34**	-0.03	**-0.58**
a_{21}				**-0.58**	-0.21	**-0.76**
a_{22}					**0.32**	**0.75**
ξ_T						**-0.70**

Table A6 Same as Table 1 but for the KCM perturbed physics ensemble.

RMS error	$\mathbf{a_{11}}$	$\mathbf{a_{12}}$	$\mathbf{a_{21}}$	$\mathbf{a_{22}}$	ξ_T	ξ_h
Single parameter variation	1.35	1.15	1.17	1.49	1.06	1.46
All parameter variation (EOF-1)	1.15	1.12	1.16	1.29	-	1.31

Table A7 Same as Table A4 but for the KCM perturbed physics ensemble.

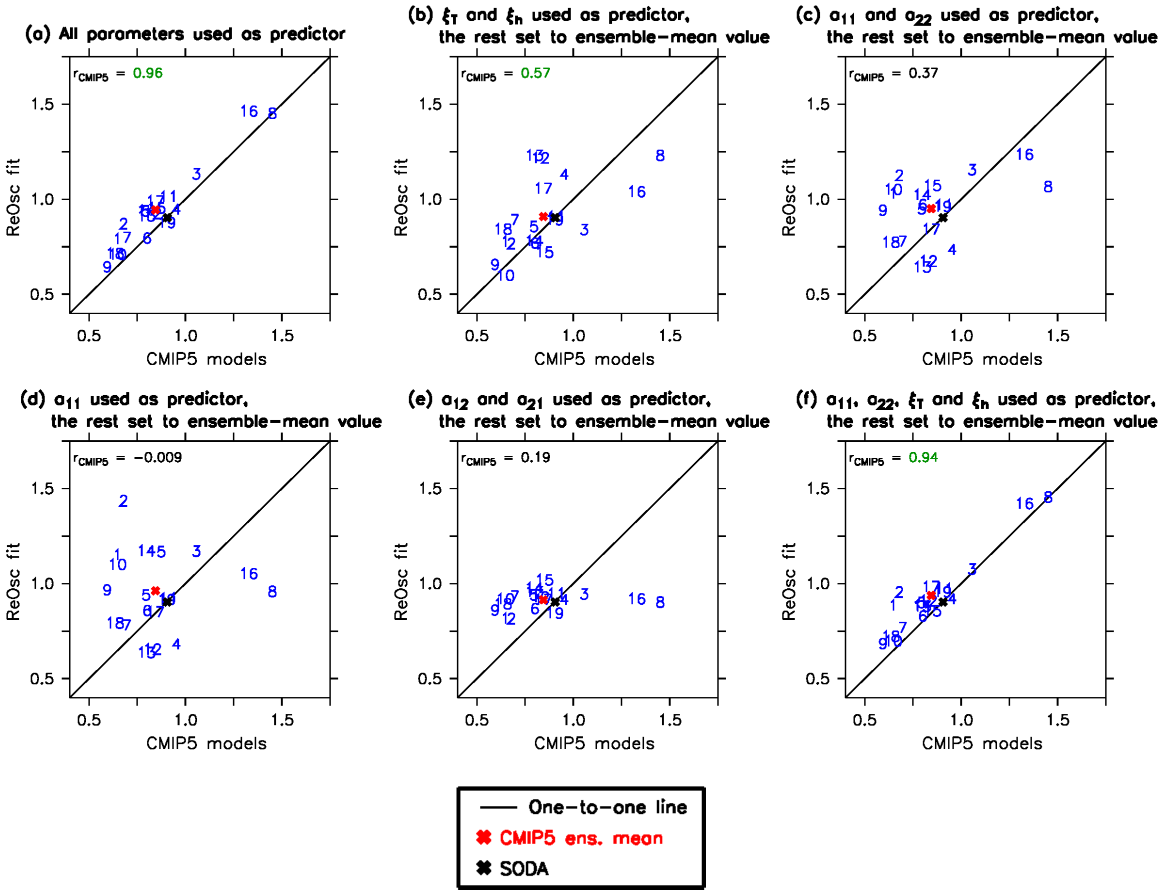

Figure A4 Same as Figure 1 but for the CMIP5 model selection of *Kim et al.* [2014].

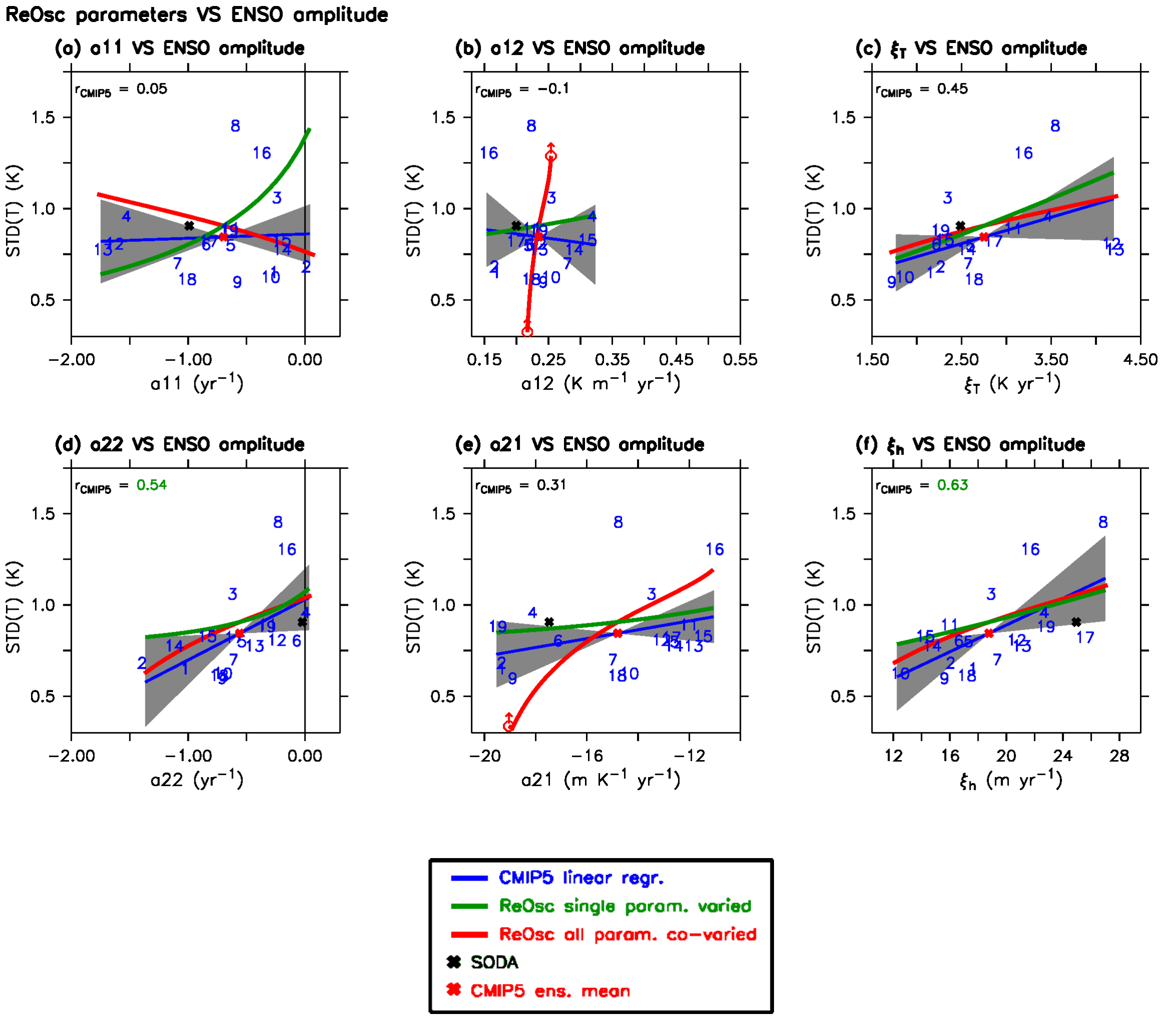

Figure A5 Same as Figure 2 but for the CMIP5 model selection of *Kim et al.* [2014].

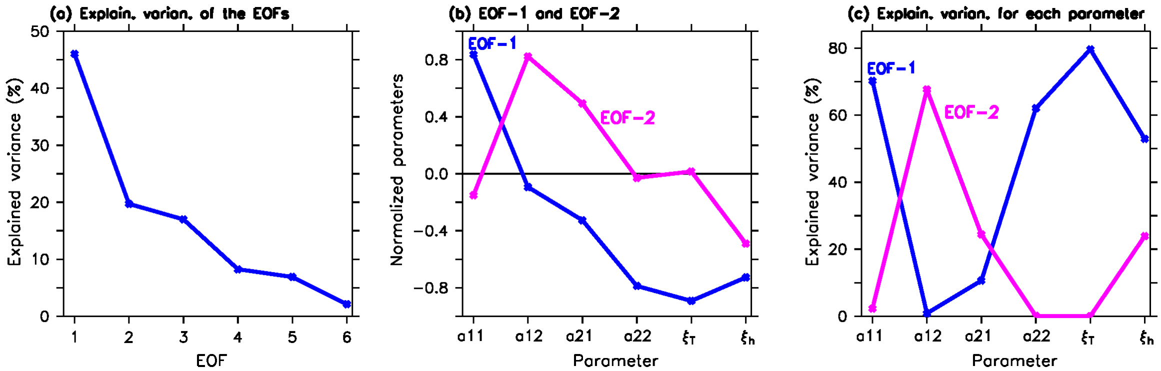

Figure A6 Same as Figure 3 but for the CMIP5 model selection of *Kim et al.* [2014].

Label number	**Model**
1	ACCESA1-0
2	ACCESA1-3
3	CCSM4
4	CNRM-CM5
5	CSIRO-Mk3-6-0
6	FGOALS-g2
7	GFDL-ESM2G
8	GFDL-ESM2M
9	GISS-E2-H
10	GISS-E2-R
11	HadCM3
12	HadGEM2-CC
13	HadGEM2-ES
14	IPSL-CM5A-LR
15	IPSL-CM5A-MR
16	MIROC5
17	MPI-ESM-LR
18	MRI-CGCM3
19	NorESM1-M

Table A8 List of the CMIP5 models from the selection of *Kim et al.* [2014].

	$\mathbf{a}_{11}$	$\mathbf{a}_{12}$	$\mathbf{a}_{21}$	$\mathbf{a}_{22}$	ξ_T	ξ_h
$\mathbf{a}_{11}$		-0.22	-0.11	**-0.59**	**-0.73**	-0.42
$\mathbf{a}_{12}$			0.08	0.12	-0.02	-0.17
$\mathbf{a}_{21}$				0.13	0.42	-0.02
$\mathbf{a}_{22}$					**0.51**	**0.54**
ξ_T						**0.59**

Table A9 Same as Table 1 but for the CMIP5 model selection of *Kim et al.* [2014].

RMS error	$\mathbf{a_{11}}$	$\mathbf{a_{12}}$	$\mathbf{a_{21}}$	$\mathbf{a_{22}}$	ξ_T	ξ_h
Single parameter variation	1.40	1.01	0.96	0.90	0.92	0.83
All parameter variation (EOF-1)	1.07	-	-	0.85	0.89	0.80

Table A10 Same as Table A4 but for the CMIP5 model selection of *Kim et al.* [2014].

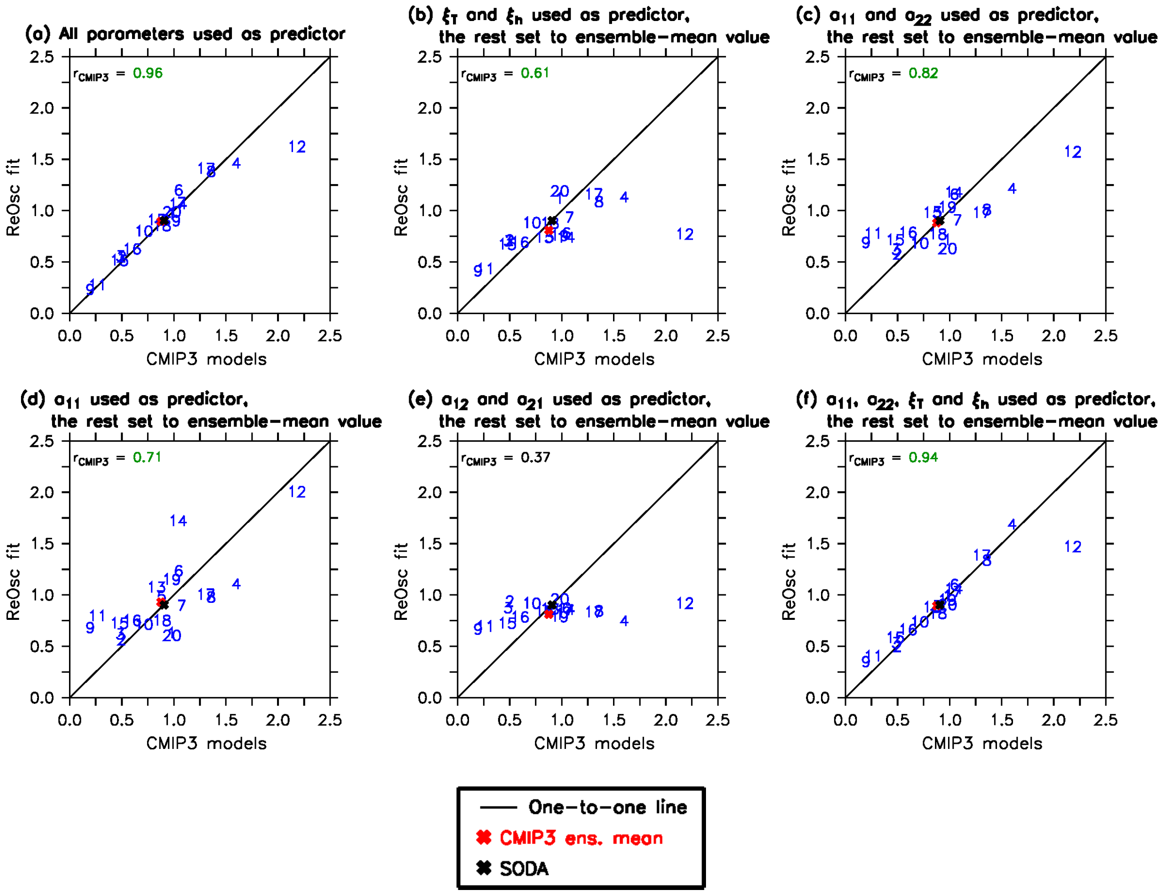

Figure A7 Same as Figure 1 but for the CMIP3 models. Note the different axis scales.

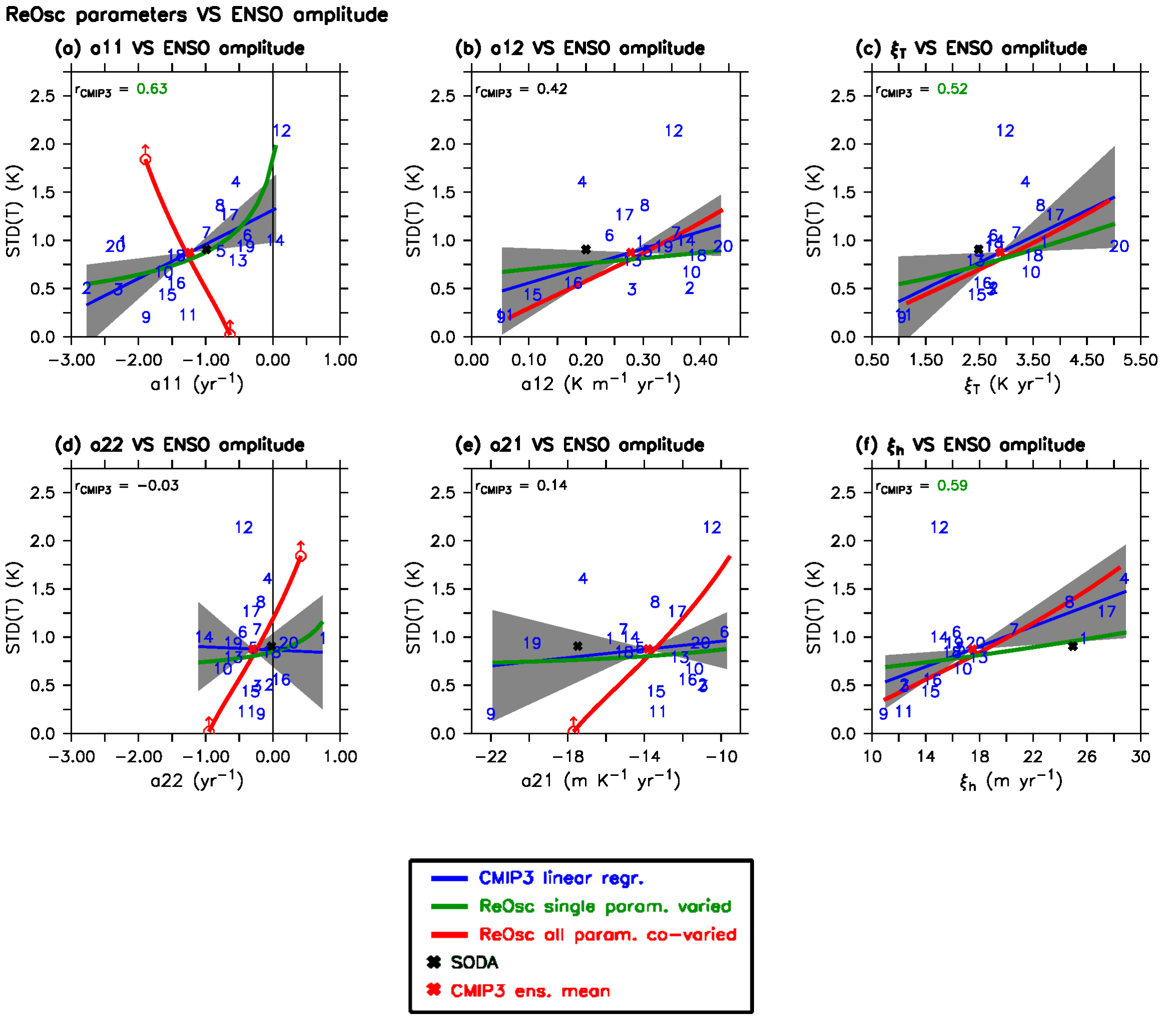

Figure A8 Same as Figure 2 but for the CMIP3 models. Note the very different axis scales.

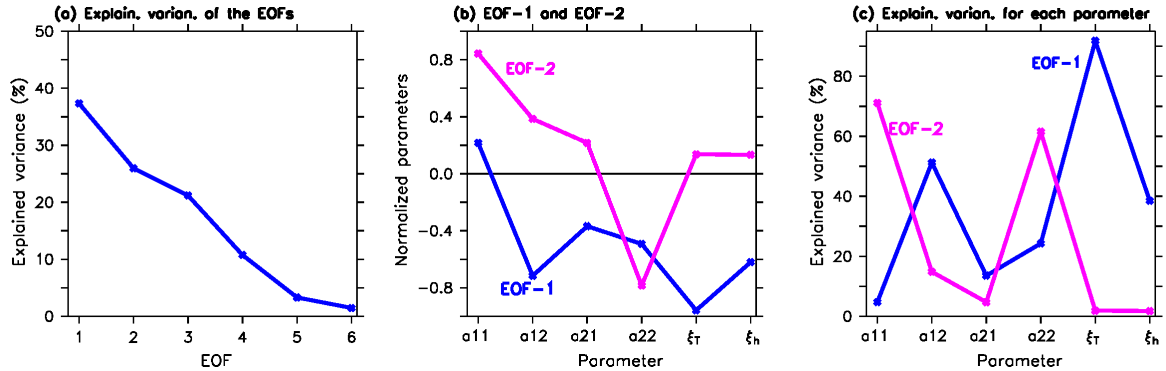

Figure A9 Same as Figure 3 but for the CMIP3 models.

Label number	Model
1	bccr_bcm2_0
2	cccma_cgcm3_1
3	cccma_cgcm3_1_t63
4	cnrm_cm3
5	csiro_mk3_0
6	csiro_mk3_5
7	gfdl_cm2_0
8	gfdl_cm2_1
9	giss_aom
10	giss_model_e_h
11	giss_model_e_r
12	iap_fgoalA1_0_g
13	ingv_echam4
14	ipsl_cm4
15	miroc3_2_hires
16	miroc3_2_medres
17	mpi_echam5
18	mri_cgcm2_3_2a
19	ncar_ccsm3_0
20	ncar_pcm1

Table A11 List of the CMIP3 models.

	$\mathbf{a}_{11}$	$\mathbf{a}_{12}$	$\mathbf{a}_{21}$	$\mathbf{a}_{22}$	ξ_T	ξ_h
$\mathbf{a}_{11}$		0.01	-0.09	**-0.60**	-0.10	0.25
$\mathbf{a}_{12}$				-0.03	**0.72**	0.16
$\mathbf{a}_{21}$				-0.06	0.31	-0.08
$\mathbf{a}_{22}$					0.33	0.33
ξ_T						**0.60**

Table A12 Same as Table 1 but for the CMIP3 models.

RMS error	$\mathbf{a}_{11}$	$\mathbf{a}_{12}$	$\mathbf{a}_{21}$	$\mathbf{a}_{22}$	ξ_T	ξ_h
Single parameter variation	1.48	1.96	2.04	2.08	1.83	1.83
All parameter variation (EOF-1)	-	1.96	-	-	1.78	1.77

Table A13 Same as Table A4 but for the CMIP3 model.

Data Set A1 ENSO amplitudes of the CMIP5 models shown in Figure 1 (horizontal axes) and Figure 2 (vertical axes).

Data Set A2 ENSO amplitudes obtained from integrating the ReOsc model using various parameter combinations of CMIP5 as predictors for ENSO amplitude. Shown in Figure 1 (vertical axes).

Data Set A3 ENSO amplitudes obtained from integrating the ReOsc model using ReOsc parameter as estimated from SODA data. Shown in Figure 1 as black cross (value for vertical axis).

Data Set A4 ReOsc parameters of the CMIP5 models shown in Figure 2 (horizontal axes).

Data Set A5 ENSO amplitude of SODA. Shown in Figure 1 as black cross (value for horizontal axes) and in Figure 2 as black cross (value for vertical axes).

Data Set A6 ReOsc parameters as estimated for SODA data. Shown in Figure 2 as black cross (value for horizontal axes).

Data Set A7 ENSO amplitudes as obtained from integrating the ReOsc model with varying each parameter separately, also including the parameters used for the integration. Shown in Figure 2 by green line.

Data Set A8 ENSO amplitudes as obtained from integrating the ReOsc model with co-varying all parameter, also including the parameters used for the integration. Shown in Figure 2 by red line.

Data Set A9 Linear fit between ENSO amplitude and each parameter and its uncertainty. Shown in Figure 2 by blue line and grey shading, respectively.

Data Set A10 Results of the Empirical Orthogonal Function (EOF) analysis shown in Figure 3. Includes the eigenvalues (Figure 3a), the EOFs (Figure 3b) and the explained variances for each parameter of the first and second EOF (Figure 3c). Also contains the reconstructions, the scaled EOFs for modeling the co-varying effect of the parameters