Supplement of Atmos. Chem. Phys., 20, 15461–15485, 2020
https://doi.org/10.5194/acp-20-15461-2020-supplement

Supplement of

Tropical Pacific climate variability under solar geoengineering: impacts on ENSO extremes

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Figures and Captions

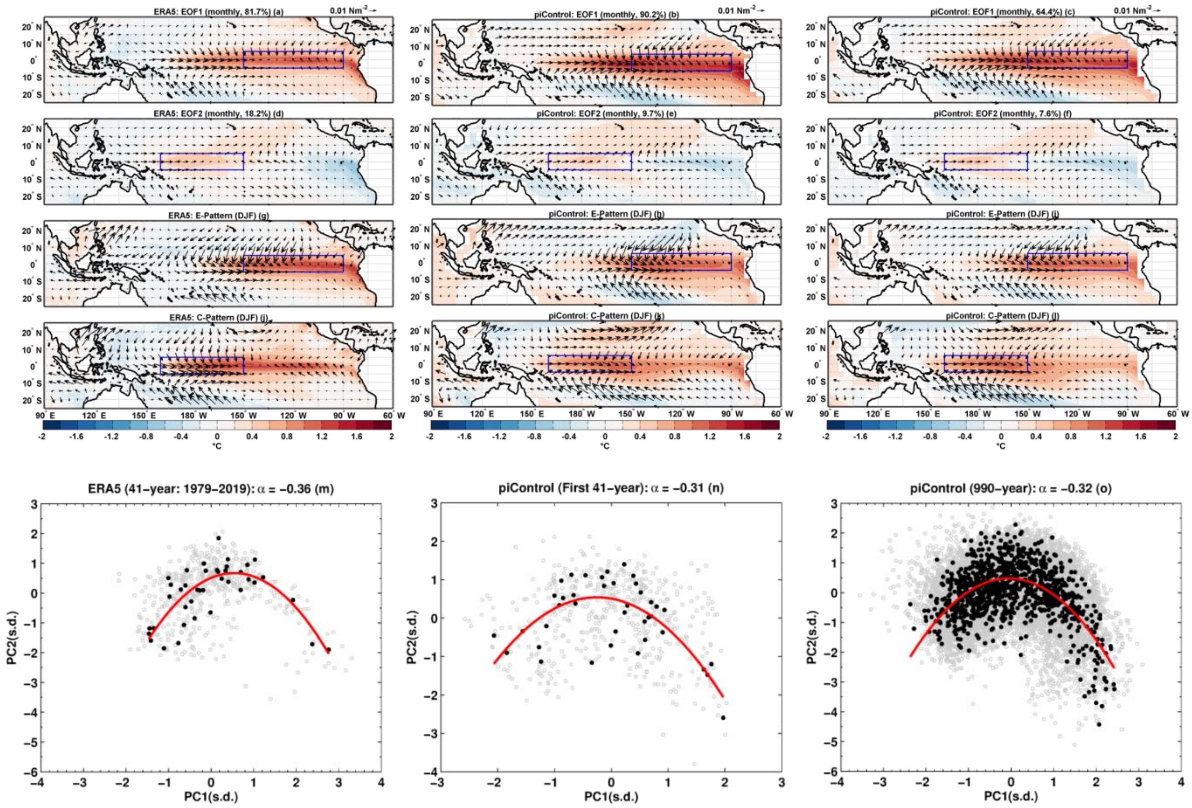

Figure S1. ENSO diversity and nonlinear relationship between PCs. First monthly principal pattern, EOF1, for (a) ERA5 and (b, c) piControl. Second monthly principal pattern, EOF2, for (d) ERA5 and (e, f) piControl. DJF EP pattern for (g) ERA5 and (h, i) piControl. DJF CP pattern for (j) ERA5 and (k, l) piControl. The nonlinear relationship between PC1 and PC2 for (m) ERA5 and (n, o) piControl. The left and the middle panel shows EOF analysis over the 41 years of ERA5 (1979-2019) and piControl. The right panel shows EOF analysis over 990-year of piControl. The blue box indicates the Niño3 (Niño4) region in a-c, and g-i (d-f and j-l). The red line in m-n shows a quadratic fit between PC1 and PC2 averaged over DJF. Grey dots show monthly data whereas black dots indicate data averaged over DJF. EOF analysis is performed over the region 15° N-15° S and 140° E-80° W (Cai et al., 2018). Before analysis and calculating E- and C-index (Takahashi et al., 2011), PC1 and PC2 are normalized by their monthly standard deviations calculated over the corresponding observational and model simulation period.

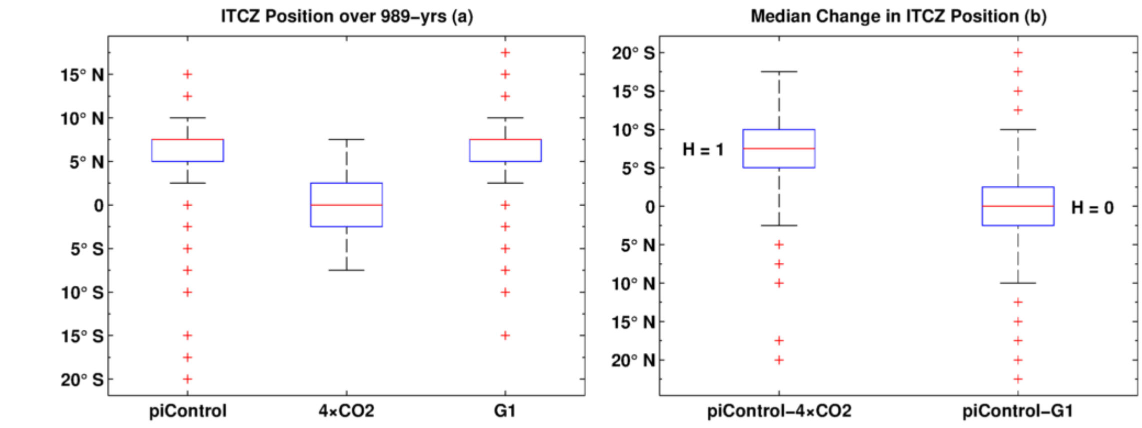

Figure S2. (a) Variability in ITCZ position over the simulated period for piControl, 4×CO_2, and G1. The solid red lines show the media position. (b) Change in position of ITCZ relative to piControl under 4×CO_2 and G1. The red lines show the median change in position relative to piControl. The ITCZ position is calculated by finding the latitude where maximum rainfall occurs. H = 1 indicates that the change is statistically significant at 99 % cl using a non-parametric Wilcoxon rank-sum test.

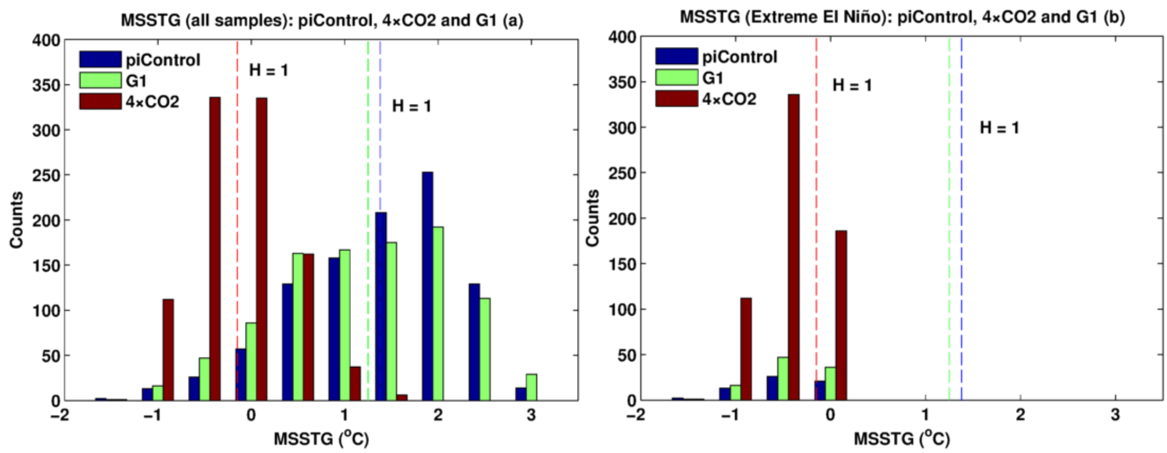

Figure S3. Histogram of MSSTG for piControl, 4×CO_2, and G1 for all samples (a) and for extreme El Niño events. The values are plotted at the centre of each bin with an interval of 0.5 °C. Blue, red, and green vertical lines indicate climatological mean values of MSSTG under piControl (1.38 °C), 4×CO_2 (-0.15 °C), and G1 (1.25 °C), respectively. H = 1 indicates that the shift in the mean is statistically significant at 99 % cl using a non-parametric Wilcoxon rank-sum test.

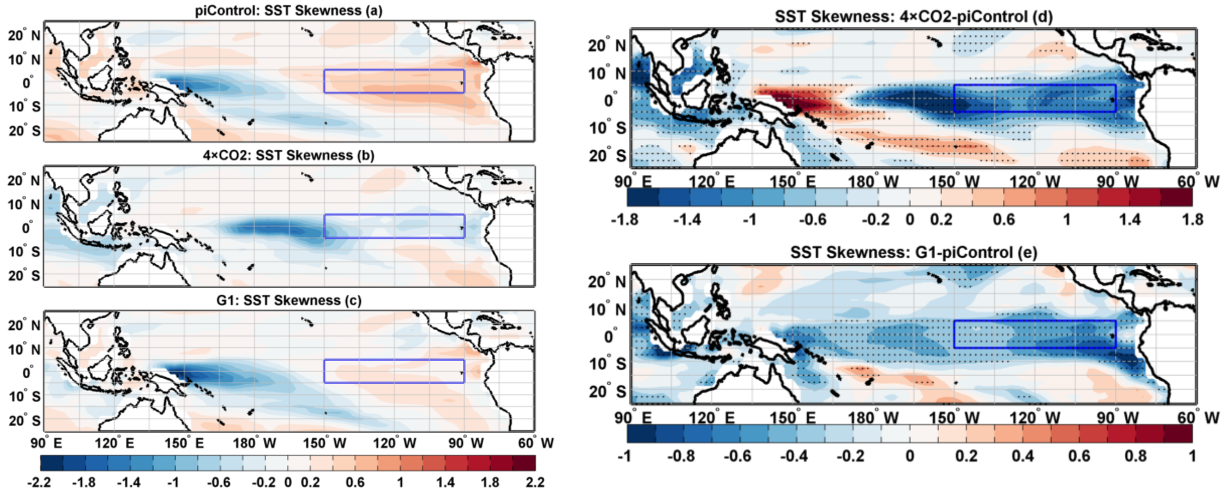

Figure S4. Quadratically detrended SST skewness for (a) piControl (b) 4×CO_2 (c) G1 (d) difference: 4×CO_2-piControl and (e) difference: G1-piControl. Stipples indicate grid points where the difference is statistically significant at 99 % cl using the bootstrap method with 10,000 realizations.

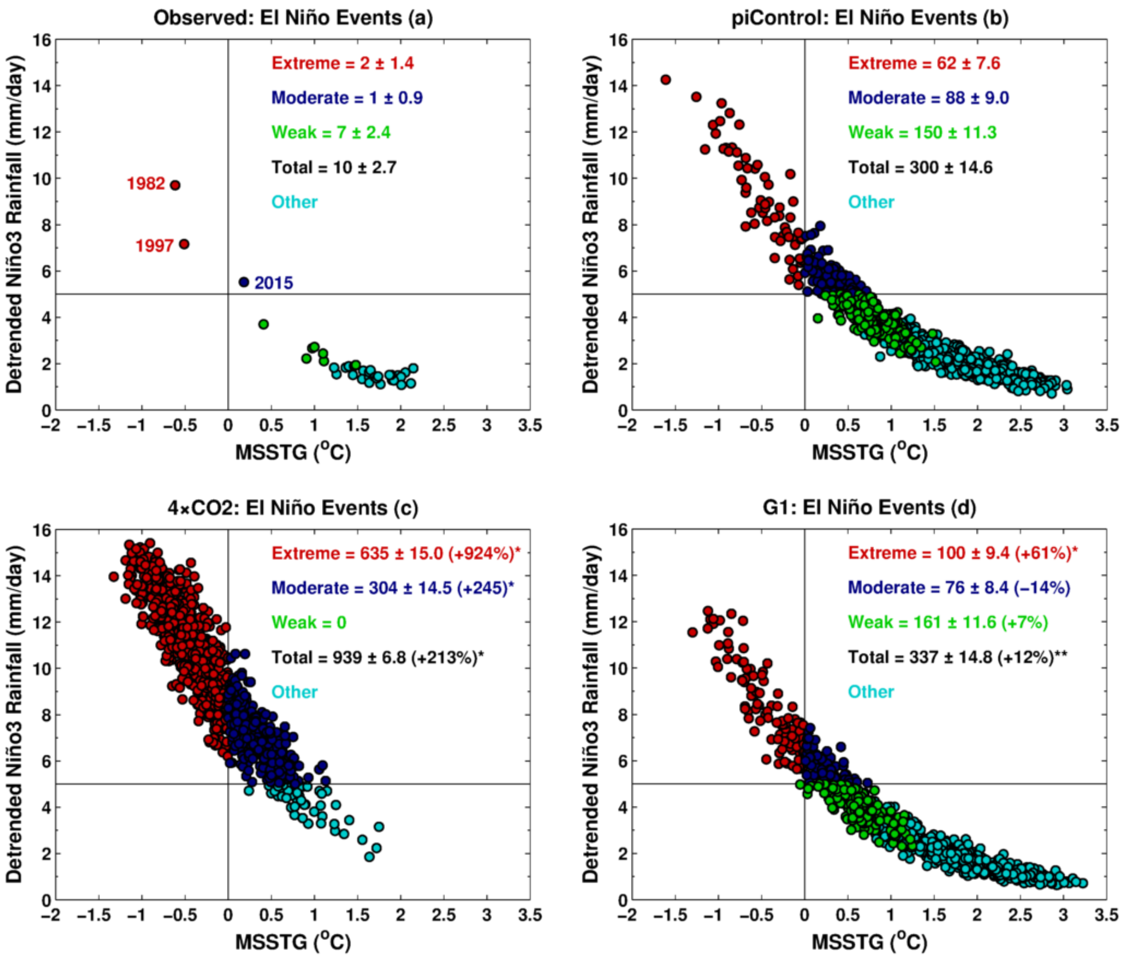

Figure S5. Relationship between MSSTG and quadratically detrended Niño3 rainfall for (a) observations (b) piControl (c) 4×CO_2, and (d) G1. The solid black horizontal line indicates a threshold of 5 mm day^{-1}. A single (double) asterisk indicates that the change in frequency, relative to piControl, is statistically significant at 99 % (95 %) cl. Numbers with a ± symbol indicate s.d. calculated with 10,000 bootstrap realizations. Following Cai et al. (2014), a non-ENSO related trend has been removed from the rainfall time series. Events are classified as: Extreme (Niño3 rainfall > 5 mm day^{-1} and MSSTG < 0), moderate (Niño3 rainfall > 5 mm day^{-1} and MSSTG > 0), weak (Standardized Niño3 SSTs > 0.5 °C and Niño3 rainfall < 5 mm day^{-1}), total is sum of extreme, moderate, and weak events.

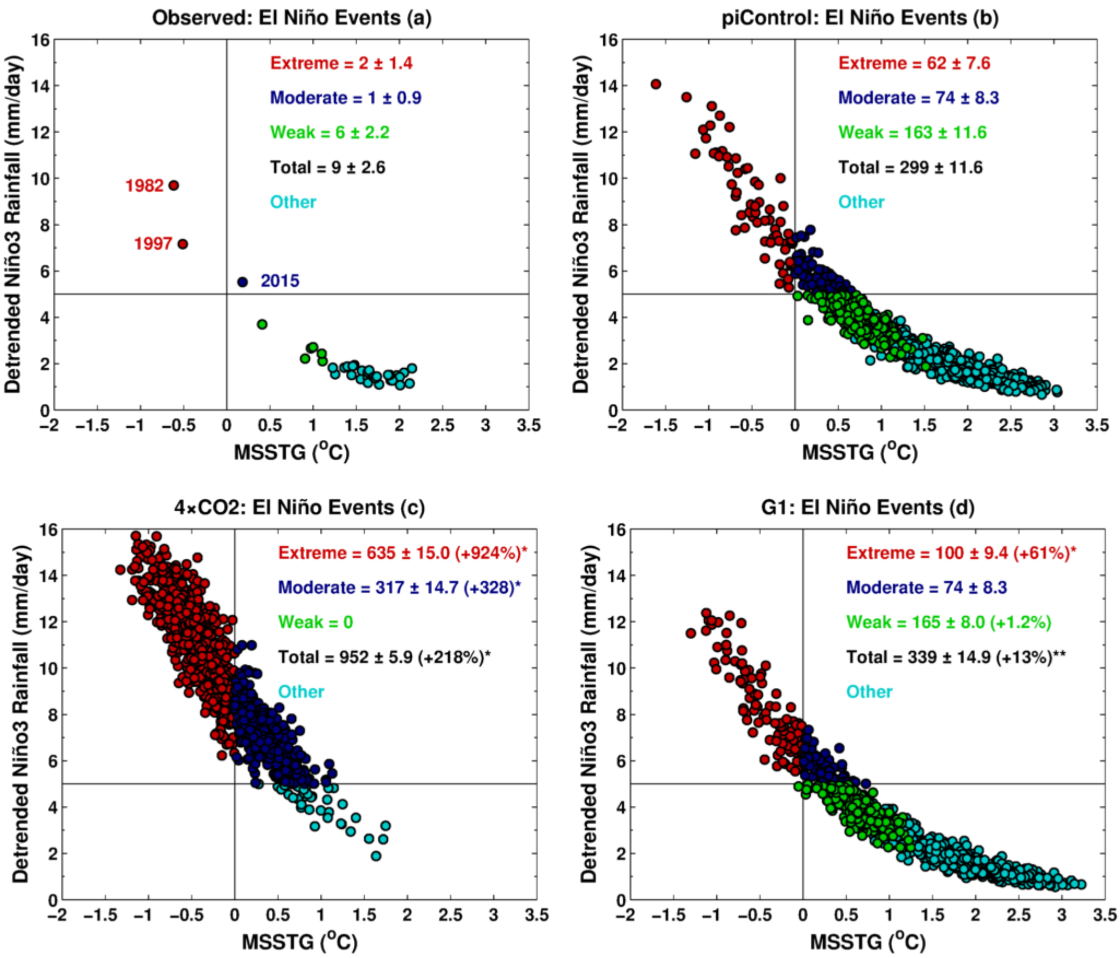

Figure S6. Relationship between MSSTG and linearly detrended Niño3 rainfall for (a) observations (b) piControl (c) $4\times CO_2$, and (d) G1. The solid black horizontal line indicates a threshold of 5 mm day^{-1}. A single (double) asterisk indicates that the change in frequency, relative to piControl, is statistically significant at 99 % (95 %) cl. Numbers with a ± symbol indicate s.d. calculated with 10,000 bootstrap realizations. Following Cai et al. (2014), a non-ENSO related trend has been removed from the rainfall time series. Events are classified as: Extreme (Niño3 rainfall > 5 mm day^{-1} and MSSTG < 0), moderate (Niño3 rainfall > 5 mm day^{-1} and MSSTG > 0), weak (Standardized Niño3 SSTs > 0.5 °C and Niño3 rainfall < 5 mm day^{-1}), total is sum of extreme, moderate, and weak events.

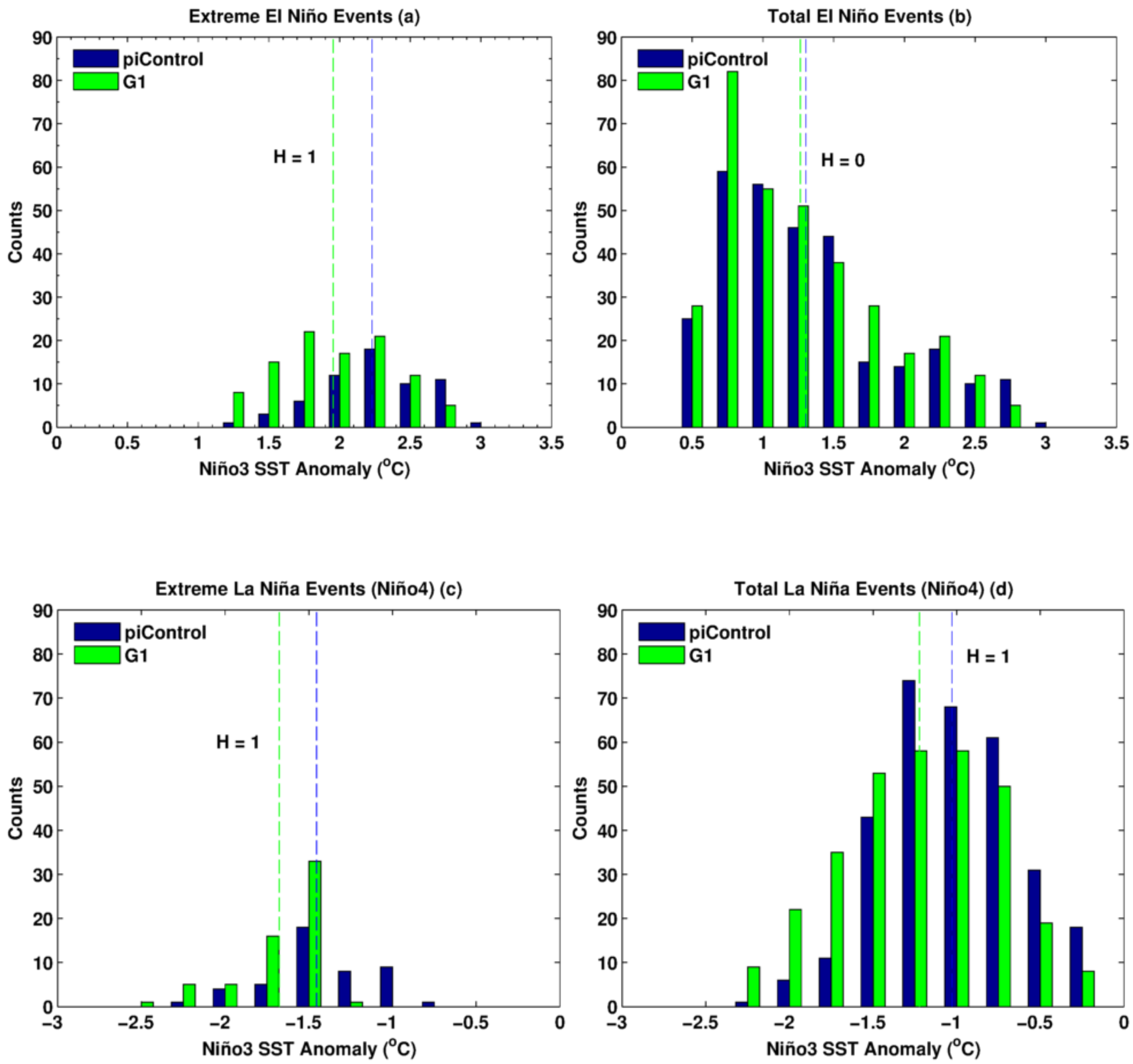

Figure S7. Histograms of quadratically detrended Niño3 SST anomalies calculated for (a) extreme El Niño events (b) total El Niño events (c) extreme La Niña events and (d) total La Niña events. Blue and green vertical lines indicate mean values for piControl and G1, respectively. H = 1 indicates that shift in the mean is statistically significant at 99 % cl using a non-parametric Wilcoxon rank-sum test. Extreme and Total El Niño events are selected based on Niño3 rainfall anomaly of 5 mm/day, as shown in Fig. S6.

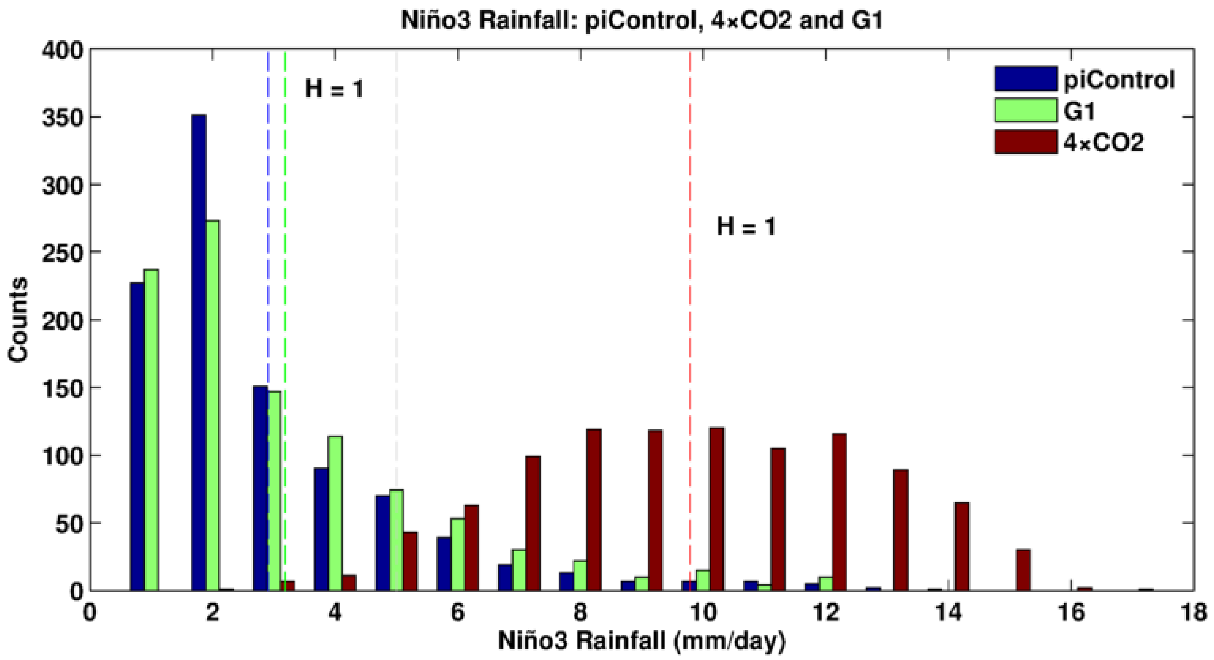

Figure S8. Histogram of Niño3 rainfall for piControl, 4×CO_2, and G1. The values are plotted at the centre of each bin with an interval of 1 mm day^{-1}. Blue, red, and green vertical lines indicate climatological mean values of Niño3 rainfall under piControl (2.9 mm day^{-1}), 4×CO_2 (9.8 mm day^{-1}), and G1 (3.2 mm day^{-1}), respectively. H = 1 indicates that the shift in the mean is statistically significant at 99 (95) % cl for 4×CO_2 (G1) using the non-parametric Wilcoxon rank-sum test. The grey vertical line show threshold of 5 mm day^{-1}.

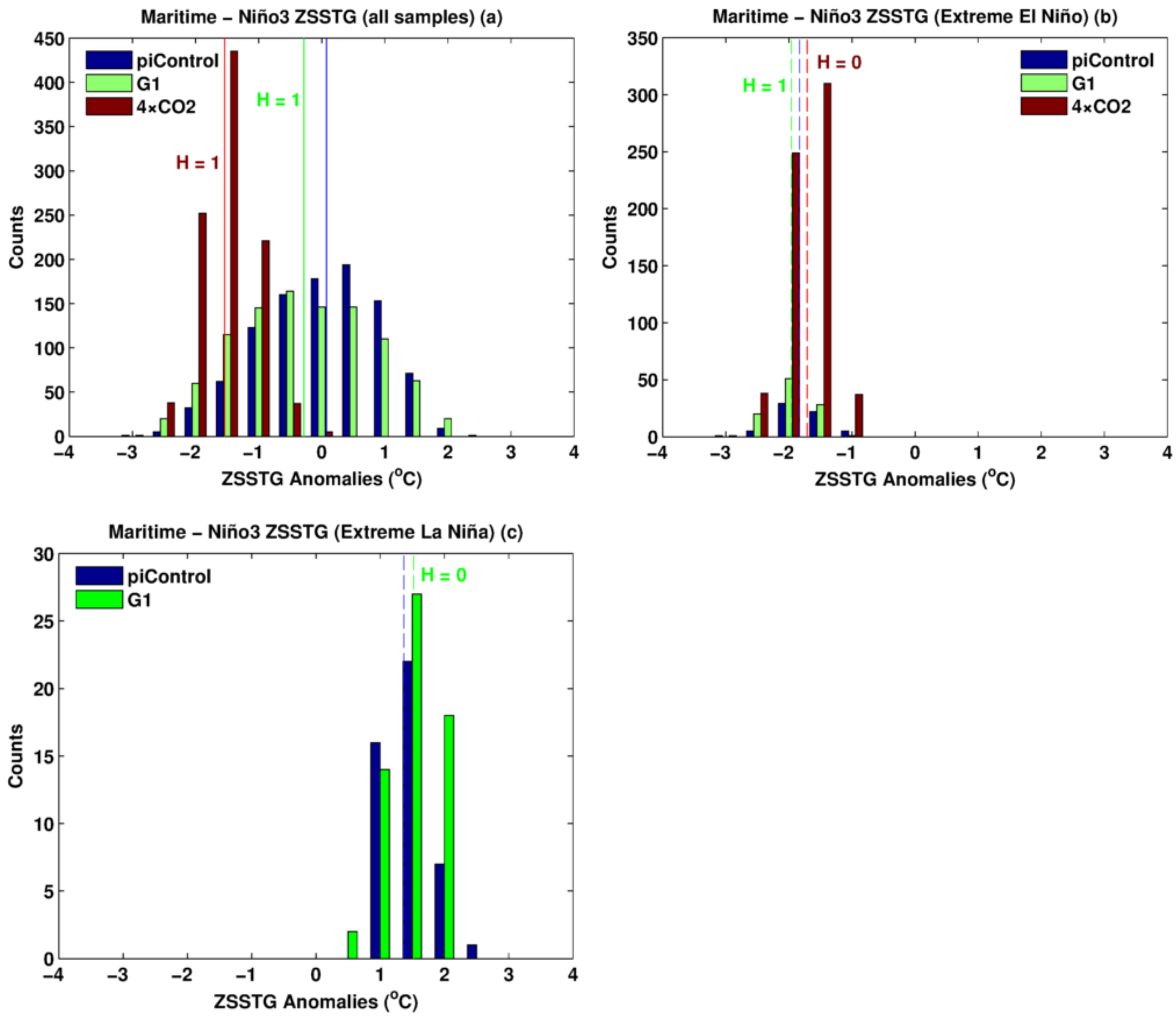

Figure S9. Histogram of ZSSTG anomalies for (a) all samples, (b) extreme El Niño events only, and (c) extreme La Niña events only. The values are plotted at the centre of each bin with an interval of 0.5 °C. In a blue, red, and green solid vertical lines indicate climatological median ZSSTG under piControl (0.07 °C), $4\times CO_2$ (-1.54 °C), and G1 (-0.28 °C), respectively, for all samples. In b, blue, red, and green dashed vertical lines indicate climatological median ZSSTG under piControl (-1.83 °C), $4\times CO_2$ (-1.71 °C), and G1 (-1.96 °C), respectively, for extreme El Niño events. In c, blue, and green dashed vertical lines indicate climatological median ZSSTG under piControl (1.37 °C) and G1 (1.52 °C), respectively, for extreme La Niña events. H = 1 indicates that using a non-parametric Wilcoxon rank-sum test, the shift in the median is statistically significant at 99 (95) % cl in a (b). H = 0 means that the shift in the median is not statistically significant. The ZSSTG is defined as the difference between SST in the Maritime continent (5° N-5° S; 100° E-126° E) and eastern equatorial Pacific (Niño3 region: 5° N-5° S, 150° W-90°W). The anomalies are calculated relative to piControl.

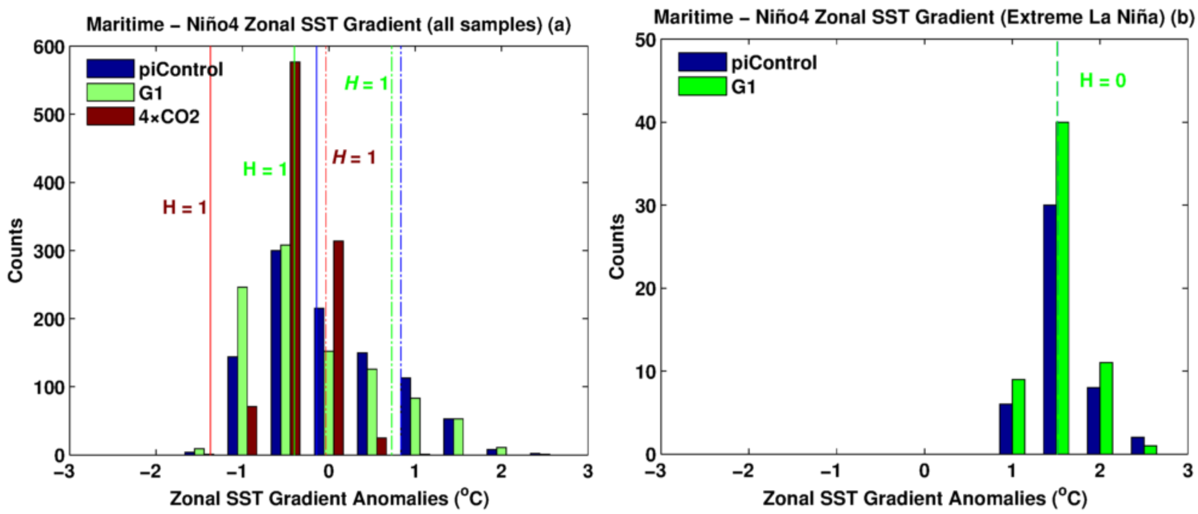

Figure S10. Histogram of ZSSTG anomalies for (a) all samples and (b) extreme La Niña events only. The values are plotted at the centre of each bin with an interval of 0.5 °C. Blue, red, and solid green lines indicate climatological median ZSSTG under piControl (-0.14 °C), 4×CO_2 (-1.37 °C), and G1 (-0.40 °C), respectively, for all samples. Blue, red, and green dash-dotted lines indicate climatological median ZSSTG under piControl (0.84 °C), 4×CO_2 (-0.03 °C), and G1 (0.72 °C), respectively, for all La Niña events. In b, blue, red, and green dashed lines indicate climatological median ZSSTG under piControl (1.52 °C) and G1 (3.35 °C), respectively, for extreme La Niña events. H = 1 indicates that the shift in the median is statistically significant at 99 % cl using the non-parametric Wilcoxon rank-sum test. The ZSSTG is defined as the difference between SST in the Maritime continent (5° N-5° S; 100° E-126° E) and central equatorial Pacific (Niño4 region: 5° N-5° S, 160° E-150° W) (Cai et al., 2015). The anomalies are calculated relative to piControl.

Tables

Table S1. Mean SST (°C) and rainfall (mm day^{-1}) climatology over tropical Pacific (25° N-25° S; 90° E-60° W)

Experiment	Mean ± standard Error	Difference w.r.t. piControl	Std. Dev. 10,000 Realizations	~ Change w.r.t. piControl (%)
piControl	26.52* (4.32)*		0.009 [0.0042]	
4×CO_2	30.42* (4.53)*	+3.9 (+0.21)		+15* (+5)*
G1	26.22* (4.09)*	-0.30 (-0.23)		-1* (-5)*

Key: SST (Rainfall); *99 % cl; **95 % cl

Table S2. Meridional SST Gradient (MSSTG)

Experiment	Mean (°C)	Difference w.r.t. piControl (°C)	Std. Dev. 10,000 Realizations (°C)	~ Change w.r.t. piControl (%)
piControl	1.38*		0.0265	
4×CO_2	-0.15*	-1.53		-111*
G1	1.25*	-0.13		-9*

Key: *99 % cl; **95 % cl

Table S3. Total number of El Niño events (Index > 0.5 s.d.)

Experiment	No. of Events	Difference w.r.t. piControl	Std. Dev. 10,000 Realizations	~ Change w.r.t. piControl (%)
piControl	300 [247]		14.6 [14.6]	
4×CO_2	161 [511]	139 [264]		-46* [+107*]
G1	337 [239]	37 [8]		+12** [-3]

Key: Niño3 [E-Index]; *99 % cl; **95 % cl

Table S4. La Niña events

Experiment	**Index < -1.75** ±s.d. with 10,000 realizations	**-1 > index > -1.75** ±s.d. with 10,000 realizations	**-0.5 > index > -1** ±s.d. with 10,000 realizations	**Index < -0.5** ±s.d. with 10,000 realizations
piControl	[29±5.2]	[105±9.7]	[147±11.1]	[281±14.1]
4×CO_2	[3] (-90 %)*	[82] (-22 %)**	[239] (+63 %)*	[324] (+15 %)*
G1	[22] (-24 %)	[98] (-7 %)	[123] (-16 %)**	[243] (-14 %)**

Key: [C-Index]; *99% cl; **95% cl

Table S5. Mean DJF Heat Flux (hf) Feedback

Experiment	hf feedback or Damping Coefficient (Wm^{-2}/°C)	Difference w.r.t. piControl (Wm^{-2}/°C)	Std. Dev. 10,000 Realizations (Wm^{-2}/°C)	~ Change w.r.t. piControl (%)
ERA5	-14.59			
piControl	-14.70		0.52	
4×CO_2	-21.90	+7.19		+48*
G1	-14.85	+0.15		+1.0

*99% cl; **95% cl; Calculation period: ERA5 (41-yrs); HadCM3L (990-yrs)

Table S6. Mean DJF Bjerknes (BJ) Feedback

Experiment	BJ feedback (10^{-2} $Nm^{-2}/^oC$)	Difference w.r.t. piControl (10^{-2} $Nm^{-2}/^oC$)	Std. Dev. 10,000 Realizations ($Wm^{-2}/^oC$)	~ Change w.r.t. piControl (%)
ERA5	3.3			
piControl	3.3		0.0091	
4×CO_2	2.2	-1.1		-33*
G1	3.5	+0.2		+6*

*99% cl; **95% cl; Calculation period: ERA5 (41-yrs); HadCM3L (990-yrs)

Table S7. Mean DJF Ocean Stratification

Experiment	Stratification (ºC)	Difference w.r.t. piControl (ºC)	Std. Dev. 10,000 Realizations (ºC)	~ Change w.r.t. piControl (%)
piControl	2.28*		0.0331	
4×CO_2	5.06*	+2.78		+122*
G1	2.37*	+0.09		+4**

*99% cl; **95% cl

Equations

$$S = \left[\frac{1}{n-1}\right]\frac{\sum_i^n (X_i - \bar{X})^3}{\sigma^3}$$ …………………………………… (S1; Ghandi et al., 2016)

Where

S = skeness

n = sample size

X_i = sample ith observation

$\bar{X}$ = sample mean

σ^3 = sample standard deviation

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