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# Changes in the ENSO/SPCZ relationship from past to future climates

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## Abstract

The South Pacific Convergence Zone (SPCZ) is the main climate feature of the Southwest Pacific. It is characterized by a band of intense convective rainfall extending from the western Pacific warm pool to French Polynesia. Strong precipitation gradients within the SPCZ make local hydrologic conditions very sensitive to small displacements of this rainfall band, as those caused by El Niño and La Niña events. The associated rainfall fluctuations strongly impact the vulnerable Southwest Pacific countries. They are recorded in environmental indicators such as corals, used as proxies of past evolution of the El Niño/Southern Oscillation (ENSO). Here we analyze a set of paleoclimate and future climate simulations and present evidence that changes in the background tropical state largely control the mean SPCZ location. In contrast, changes in the background tropical state do not di-

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rectly control the interannual variability of the SPCZ location. We show that changes in the interannual variability of the SPCZ location cannot be directly imputable to changes in the ENSO amplitude, or rather the relationship between ENSO and the SPCZ location varies from one climate to another. We thus demonstrate that the teleconnection mechanisms inferred from the modern climate cannot be directly extrapolated to other climates. This study therefore calls for a cautious interpretation of climate reconstructions from environmental indicators in the Southwest Pacific with regard to ENSO variations.

*Keywords:*

SPCZ, ENSO, variability, interannual, teleconnection, paleoclimates

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## 1. Introduction

2 The South Pacific Convergence Zone (SPCZ) is a band of low level con-  
3 vergence and convective precipitation extending from Papua New Guinea  
4 south-eastward towards French Polynesia (Vincent, 1994). It is fully devel-  
5 oped during the austral summer from November to March (NDJFM).

6 The western portion of the SPCZ, considered as a "*true tropical con-*  
7 *vergence zone*" by Kiladis et al. (1989), extends zonally over the western  
8 Pacific warm pool. Its location is governed by underlying Sea Surface Tem-  
9 perature (SST) distribution and monsoon systems, especially the Australian  
10 monsoon (Kiladis et al., 1989). The eastern portion of the SPCZ has a south-  
11 eastward diagonal orientation. Takahashi and Battisti (2007) suggest that  
12 this diagonal orientation originates from the streamlines orientation of the  
13 southeasterly trade winds in the so-called dry zone of the southeastern Pa-

14 cific. They also state that the spatial geometry of this dry zone comes from  
15 the mechanical interaction between the westerly flow of the subtropical jet  
16 and the Andes. Since then, other studies have highlighted the role of large-  
17 scale SST gradients on the existence and orientation of the SPCZ (Vincent,  
18 1994; Widlansky et al., 2011, 2013).

19 At the interannual time scale, the SPCZ location is modulated by the El  
20 Niño/Southern Oscillation (ENSO). ENSO results from ocean-atmosphere  
21 coupling in the tropics (Philander, 1989). It influences tropical Pacific SST  
22 and winds, and thereby acts to displace the SPCZ. In particular El Niño  
23 and La Niña events respectively lead to northward and southward shifts  
24 of the SPCZ (Folland et al., 2002; Trenberth, 1976). This leads to severe  
25 droughts and floods (Kumar et al., 2006), a displacement of the tropical  
26 cyclone prone region, and an increase in coral bleaching and human diseases  
27 in the Southwest Pacific (Vincent et al., 2011; Glynn, 1984).

28 Environmental paleo-indicators such as fossil corals or giant clams record  
29 the past interannual rainfall variability and are the main high resolution  
30 paleo-datasets in the tropical Pacific (Corrège et al., 2000; McGregor and  
31 Gagan, 2004; Tudhope et al., 2001; Duprey et al., 2012; Cobb et al., 2013;  
32 Lazareth et al., 2013; Elliot et al., 2013). On the western side of the Pa-  
33 cific basin, most of them are located within the SPCZ area (see Fig.1). The  
34 present-day relationship between the amplitude of ENSO and the one of the  
35 SPCZ variability found from observations have led scientists to consider the  
36 amplitude of signals derived from these high resolution records as a proxy  
37 of ENSO amplitude in the past (Corrège et al., 2000; McGregor and Gagan,  
38 2004; Tudhope et al., 2001; Elliot et al., 2013). However, a recent study

39 suggests that the SPCZ shifts will be frequently more extreme in the future,  
40 despite no apparent consensus of changes in ENSO amplitude (Cai et al.,  
41 2012). This result raises the question whether changes in the SPCZ vari-  
42 ability derived from past coral records can be directly interpreted as changes  
43 in ENSO amplitude in different paleo-climates. It calls for a better under-  
44 standing of the sensitivity of the ENSO-SPCZ relationship to the background  
45 climate state.

46 In the present study, we consider four radically different climates sim-  
47 ulated by seven Coupled General Circulation Models (CGCMs) from the  
48 Coupled Model Intercomparison Project phase 5 (CMIP5) (Taylor et al.,  
49 2012). Here, the control runs are the unperturbed pre-industrial simulations  
50 (PI) with greenhouse gas concentrations, aerosols and land use fixed to 1860  
51 conditions. We then consider the case of a warmer future climate in response  
52 to CO<sub>2</sub> forcing by using idealized simulations forced with four times the pre-  
53 industrial levels of CO<sub>2</sub> (4xCO<sub>2</sub> hereafter). The two other experiments come  
54 from the Paleoclimate Modeling Intercomparison Project phase 3 (PMIP3)  
55 (Braconnot et al., 2012b). The Last Glacial Maximum experiment (LGM,  
56 21 ky BP) simulates the cold and dry climate in response to extended ice  
57 sheet and lower CO<sub>2</sub> that prevailed 21 ky ago. The Mid-Holocene experiment  
58 (MH, 6 ky BP) simulates the change in the seasonal phase and amplitude pre-  
59 vailing 6 ky ago. It is induced by a change in the Earth's precession combined  
60 with increased obliquity that reduces insolation in the Tropics and enhances  
61 the inter-hemispheric insolation contrast during austral summer. Depend-  
62 ing on the model and climate period considered, simulation lengths range  
63 from 100 to 1000 years. They are provided in Table 1 for the seven CGCMs

64 (IPSL-CM5A, CNRM-CM5, FGOALS-g2, MIROC-ESM, MPI-ESM-P, MRI-  
65 CGCM3, CCSM4) for which outputs for the 4 periods considered are available  
66 in the international database.

## 67 **2. Analyses of pre-industrial, paleo and future climates**

68 We first discuss the background climate state's control of the mean lo-  
69 cation of the SPCZ. The SPCZ simulated for the PI climate by the seven  
70 CGCMs exhibit a meridional tilt as observed (Fig.1). The tilt is typically  
71 underestimated compared to observations. In addition, CGCMs generally  
72 exhibit equatorial cold SST associated with the equatorial upwelling that  
73 extends too far west along the equator. These biases are common to most  
74 CGCMs (Brown et al., 2012) and might affect the interpretation of the results  
75 as discussed later.

76 The eastern portion of the SPCZ has been shown to be more influenced  
77 by the Pacific SST gradients and atmospheric circulation than the western  
78 portion (Vincent, 1994; Kiladis et al., 1989; Takahashi and Battisti, 2007;  
79 Widlansky et al., 2011, 2013). As we are interested in the large-scale features  
80 of the SPCZ-ENSO teleconnection, we focus our discussion below on the  
81 eastern portion of the SPCZ. Following Vincent et al. (2011), the SPCZ  
82 position is characterized by the location of the maximum NDJFM SPCZ  
83 precipitation over 170°W-150°W (refer to latE index hereafter).

84 The Southwest Pacific mean state is characterized in this study by the  
85 meridional SST gradient between the north of the SPCZ (5°S-10°S) and the

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<sup>1</sup>For the other trace gases and boundary conditions see Braconnot et al. (2012b)

Table 1: Main forcings applied in each experiment, and number of years used in each experiment and model. For the 4xCO2 experiment, we remove the initial stabilization part of the simulation for each model, based on the NIÑO3 SST time series (the NIÑO3 index is defined as the average SST over 150°W-90°W, 5°N-5°S).

<i>Simulation</i>	Pre-industrial	MH (6 ky)	LGM	4xCO2
<i>Main forcings</i> <sup>1</sup>	CO <sub>2</sub> : 280 ppm	6 ky astronomical parameters (Berger, 1978)	CO <sub>2</sub> : 180 ppm, and northern ice sheet	CO <sub>2</sub> : 280x4=1120 ppm
<i>Length of simulation (years)</i>				
<i>Models:</i>				
IPSL-CM5A	1000	500	200	300
CCSM4	1051	301	101	126
CNRM-CM5	850	200	200	135
FGOALS-g2	900	685	100	193
MIROC-ESM	630	100	100	125
MPI-ESM-P	1156	100	100	125
MRI-CGCM3	500	100	100	130

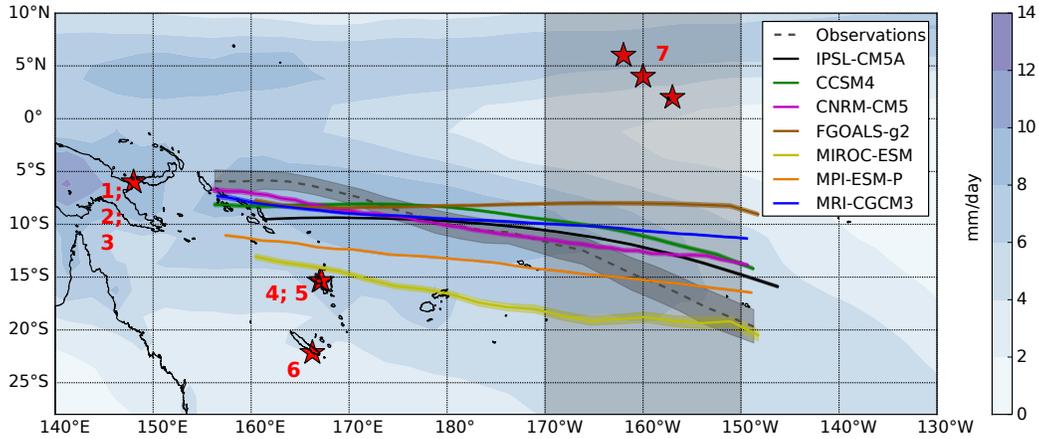


Figure 1: **The SPCZ in the seven models and observations.** Color shading shows the November to March (NDJFM) average precipitation as observed from 32 years of satellite dataset (Adler et al., 2003). Lines indicate the mean NDJFM SPCZ positions for the PI experiment of each CGCM and for observations, and colored shaded bands around indicate 90% confidence interval on the SPCZ position, computed with bootstrap resampling (see methods). Grey shaded vertical band defines the eastern portion of the SPCZ (170°W-150°W). Red stars indicate locations of corals and giant clams and the red numbers link them to the corresponding references: 1-McGregor and Gagan (2004); 2-Tudhope et al. (2001); 3-Elliot et al. (2013); 4-Corrège et al. (2000); 5-Duprey et al. (2012); 6-Lazareth et al. (2013); 7-Cobb et al. (2013).

86 equatorial region (0°-5°S) averaged between 155°E and 120°W. In the ob-  
 87 servations (Rayner, 2003; Adler et al., 2003), this gradient is about 0.8°C  
 88 on average and corresponds to a latE index around 15°S (Fig.2a). It has  
 89 been shown to be strongly related to the location of the SPCZ in present  
 90 and future climates, as it is a key indicator of the wind and related humidity  
 91 convergence from the equator to the SPCZ (Cai et al., 2012). Fig.2a shows  
 92 that the mean meridional SST gradient is significantly anticorrelated with  
 93 the mean latE index across all periods and models. The SPCZ thus tends to

94 be shifted northward (southward) when the meridional SST gradient weak-  
95 ens (strengthens). This is what is usually observed during El Niño events:  
96 in response to equatorial warming—and more generally to a reduction of the  
97 SST gradient between the equator and the off-equatorial band—wind diver-  
98 gence above the equator decreases, slightly shifting northward the maximum  
99 moisture convergence and subsequently the SPCZ (Vincent et al., 2011). The  
100 same mechanism applies for an increase of the SST gradient as during a La  
101 Niña event. Note that Fig.2a also highlights that CGCMs underestimate  
102 the SPCZ tilt despite their tendency to simulate a larger than observed SST  
103 gradient in the PI simulations.

104 Our results show that the relationship between SST gradient and SPCZ  
105 position typically holds when considering individual CGCM changes from  
106 one climate to another (Fig.2b, c). In particular all the 4xCO2 simulations  
107 exhibit a reduced meridional SST gradient compared to PI (Fig.2b). This is  
108 due to the enhanced warming of the equator, as shown in previous studies  
109 for future climate projections (Xie et al., 2010; Liu et al., 2005). A corre-  
110 sponding northward shift of the SPCZ is simulated for 6 models out of 7  
111 (Fig.2c), as the moisture convergence is shifted towards the equator. Results  
112 from the MH experiment mirror those from the 4xCO2 simulations, with an  
113 increased meridional SST gradient in 6 models out of 7 in response to the  
114 reduced austral summer insolation forcing in the tropics and the differential  
115 hemispheric insolation during the MH (Fig.2b). The strengthened SST gra-  
116 dient is associated with a southward shift of the SPCZ for the corresponding  
117 models (Fig.2c), and is in agreement with Mantsis et al. (2013) who also  
118 discuss this shift as a direct consequence of SST changes on both sides of

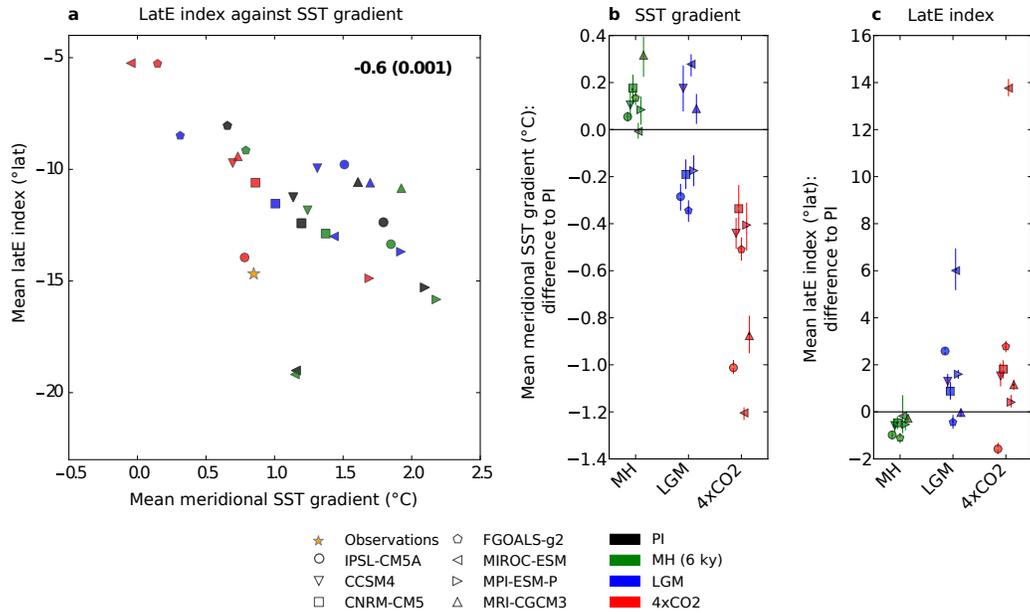


Figure 2: **Changes in the mean eastern SPCZ position and the mean meridional SST gradient in austral summer for all models.** (a) Relationship between the mean NDJFM latE index and the mean NDJFM meridional SST gradient in the model ensemble: values for all simulations and for observations. Numbers in the upper right corner indicate the Pearson correlation coefficient computed by excluding observations and its p-value in parenthesis. (b) Values for the mean NDJFM meridional SST gradient difference to PI for each simulation, in the model ensemble. (c) Same as b for the mean NDJFM latE index. Error bars indicate the 90% confidence interval, computed with bootstrap resampling (see methods).

119 the SPCZ. Additionally, they highlight the role of other contributors: (i)  
120 insolation changes in the mid-Holocene damp the Australian monsoon af-  
121 fecting the western portion of the SPCZ, (ii) deformations of the westerly  
122 flow along the southwestern edge of the SPCZ causes enhanced precipita-  
123 tion in that region due to wave accumulation—see the "graveyard" theory  
124 (Widlansky et al., 2011; Trenberth, 1976). The relationship between the SST  
125 background change and the SPCZ location is however not as clear for the  
126 LGM. For this climate, 5 models out of 7 simulate a northward shift of the  
127 SPCZ compared to PI (Fig.2c), but there is no consensus on the sign of the  
128 change in the meridional SST gradient (Fig.2b). This result echoes the lack  
129 of consensus between model results regarding the LGM Indo-Pacific mean  
130 state (DiNezio et al., 2011).

### 131 **3. Change in the SPCZ variability**

132 Following the analysis of the climatological SPCZ changes in the previous  
133 section, we focus here on the response of the SPCZ variability to ENSO forc-  
134 ing in the different climates (Fig.3). The variability of the SPCZ and ENSO  
135 are inferred from the standard deviations (SD) of the NDJFM averaged latE  
136 and NIÑO3 index (SST average over 150°W-90°W, 5°N-5°S) respectively.  
137 The latE SD is increased in 4 models out of 7 in 4xCO2 (one model gives no  
138 change) and reduced in 6 models out of 7 in the LGM (Fig.3b). However,  
139 models do not correspondingly agree on the changes in ENSO for these two  
140 experiments as illustrated by the NIÑO3 SD change (Fig.3c). It is worth  
141 pointing out the absence of symmetry in the ENSO change between these  
142 two climates, whereas they correspond to opposite signs of CO<sub>2</sub> forcing. In-

143 deed, 5 models simulate the same tendency of ENSO change in response to  
144 both the 4xCO<sub>2</sub> and the LGM forcings. Consequently, the change in the  
145 SPCZ variability in these two climates seems to be independent from the  
146 change in ENSO.

147 The stronger latE SD found in the 4xCO<sub>2</sub> simulations are in line with the  
148 results of Cai et al. (2012) who predict an increase in the frequency of extreme  
149 northward SPCZ shifts in the future, in response to the reduced meridional  
150 SST gradient associated with global warming. The climatological weakening  
151 of the meridional SST gradient indeed makes it easier for this meridional SST  
152 gradient to vanish, a key feature associated with the occurrence of extreme  
153 swings of the SPCZ. Our results are consistent with their statement, as most  
154 of the 4xCO<sub>2</sub> simulations exhibit both a stronger latE SD and a weaker  
155 climatological SST gradient (Fig.3b and Fig.2b).

156 This relationship however does not hold for the past climates, as shown  
157 by the lack of correlation between changes in the latE SD and the mean  
158 meridional SST gradient (Supplementary Fig.A.5). In the radically different  
159 LGM climate, the damped SPCZ variability found in 6 models out of 7  
160 cannot be explained by the mean SST distribution as CGCMs disagree. It  
161 is worth noting that water vapor and convective activity within the SPCZ  
162 region are impacted by the strong cooling that characterizes the LGM period  
163 (not shown), and that this may also affect the SPCZ variability.

164 A similar lack of relationship is found for the MH: 6 models out of 7 agree  
165 on a reduction of the NIÑO3 SD—4 of them significantly—(Fig.3c), in line  
166 with the MH ENSO reduction described in other model studies (Braconnot  
167 et al., 2012a; Luan et al., 2012; Clement et al., 2000; Zheng et al., 2008).

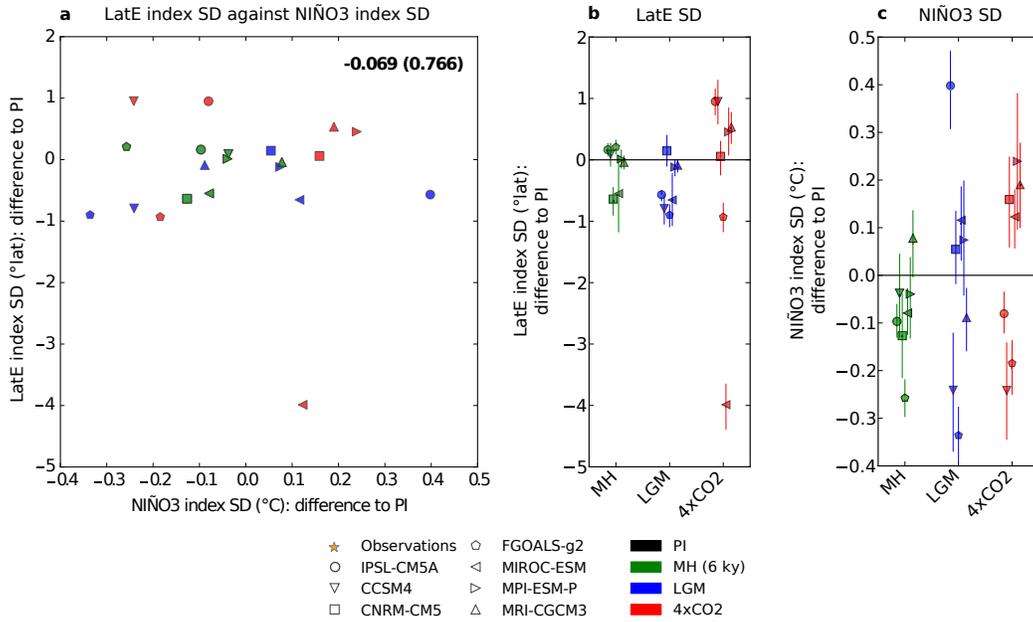


Figure 3: **Changes in the SPCZ position variability and the SST summer variability in the eastern equatorial Pacific for all models.** (a) Relationship between the NDJFM latE index standard deviation (SD) and the NDJFM NIÑO3 index SD in the model ensemble: values for the difference to pre-industrial simulation (PI) for each other simulation of the same model. Numbers in the upper right corner indicate the corresponding Pearson correlation coefficient and its p-value in parenthesis. (b) Values for the NDJFM latE index SD difference to PI for each simulation, in the model ensemble. (c) Same as b for the NDJFM NIÑO3 index SD. Error bars indicate the 90% confidence interval, computed with bootstrap resampling (see methods).

168 Despite the agreement on both ENSO reduction and meridional SST gradient  
169 enhancement (Fig.2b), there is no model consensus about the MH SPCZ  
170 variability (Fig.3b). The above results show that changes in ENSO amplitude  
171 cannot be directly related to changes in SPCZ variability in different climates,  
172 as confirmed by the lack of correlation between the latE SD and NIÑO3 SD  
173 index (Fig.3a).

174 A more in-depth investigation of the relationship between ENSO and the  
175 SPCZ variability for different climates is further provided with the IPSL-  
176 CM5A model (low resolution version IPSL-CM5A-LR) (Marti et al., 2010;  
177 Dufresne et al., 2013). Instead of only considering changes in the NIÑO3 SD  
178 against the latE SD, the long and stable simulations available for this model  
179 (Dufresne et al., 2013; Kageyama et al., 2013) allow us to directly analyze  
180 the relationship between El Niño/La Niña events and identified SPCZ north-  
181 ward/southward shifts. IPSL-CM5A is indeed the only model for which all  
182 simulation lengths provided in the database equal or exceed 200 years, allow-  
183 ing us to select enough El Niño/La Niña events to build robust composites.  
184 In addition, we run a late mid-Holocene (4 ky BP, 4K in the following) sim-  
185 ulation with this model to further assess the role of the insolation forcing.  
186 For each IPSL-CM5A experiment, El Niño, La Niña and normal years are  
187 identified using a common NIÑO3 SST anomaly threshold (Braconnot et al.,  
188 2012a; Luan et al., 2012) (see methods). We use a similar SPCZ shift thresh-  
189 old on the latE index to classify years where the SPCZ location is northward  
190 shifted, southward shifted and neutral. Results are shown in Fig.4. Although  
191 we focus here on IPSL-CM5A, we also classified years as El Niño/La Niña  
192 and northward/southward SPCZ shifts in the simulations of other CGCMs;

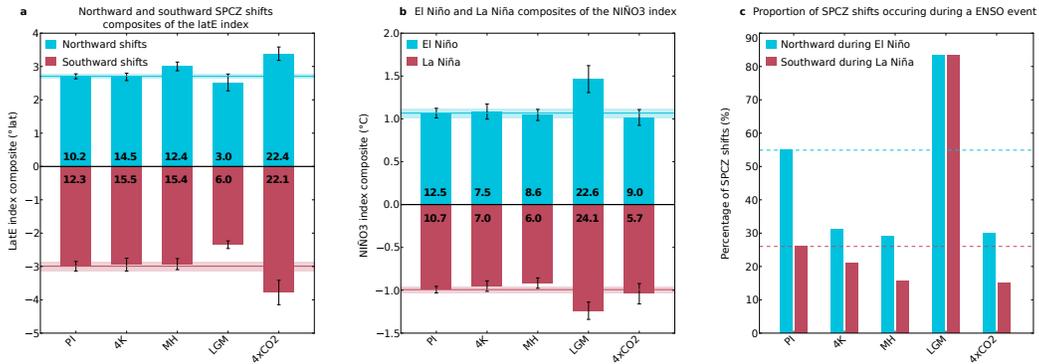


Figure 4: **Changes in frequency and amplitude of SPCZ shifts and ENSO events, and matches between both types of events, with IPSL-CM5A.** (a) Composite values of the NDJFM latE index over selected years of north and south SPCZ shifts, i.e. mean values over these selected years. Error bars indicate the 95% confidence interval, assuming a normal distribution. Blue and red horizontal lines and shaded bands around indicate the PI latE composite and its confidence interval. Numbers indicate the percentage of selected years regarding the length of each simulation. (b) Same as a for the composite values of the NDJFM Niño3 index over El Niño and La Niña years. (c) Percentage of north (south) SPCZ shifts going with El Niño (La Niña) events, regarding total number of north (south) shifts. Horizontal lines indicate PI values.

193 results are detailed in supplementary Fig. B.6 and Fig. C.7.

194 Fig.4a shows that in 4xCO2 and MH experiments, there are more SPCZ  
 195 shifts per century and of larger amplitude than in PI. These changes are  
 196 especially pronounced in 4xCO2 with a doubling of the occurrence of north-  
 197 ward/southward SPCZ shifts per century. Their amplitude is also signifi-  
 198 cantly larger (about 0.5 up to 1°lat at 5% level). The 4K simulation likewise  
 199 gives an increase in frequency but no significant change in amplitude. This  
 200 enhanced SPCZ variability is not consistent with ENSO changes as, in these  
 201 three climates (4xCO2, MH and 4K), the occurrence of El Niño and La Niña

202 events decreases compared to PI (Fig.4b). As a consequence, in these three  
203 climates there are fewer cases where northward (southward) SPCZ shifts are  
204 associated to El Niño (La Niña) events (Fig.4c). In contrast, the IPSL-  
205 CM5A LGM experiment exhibits an opposite situation: SPCZ northward  
206 (resp. southward) shifts are reduced by 70% (resp. 50%), while the number  
207 of El Niño/La Niña events nearly doubles and their amplitude significantly  
208 increases. As a result, the SPCZ movements in this climate are largely driven  
209 by ENSO events (Fig.4c).

#### 210 **4. Conclusions**

211 One of the main conclusions emerging from this multi-model analysis is  
212 that changes in the SPCZ variability cannot be directly inferred from changes  
213 in ENSO. Our analyses show that changes in both ENSO and SPCZ do not  
214 covary between climates and models. They are associated with differences in  
215 the mean spatial structures of the Southwest Pacific, as shown by shifts in  
216 the mean SPCZ location together with the meridional SST gradient changes.  
217 These differences in the mean state may affect the SPCZ variability inde-  
218 pendently from ENSO. Also emerging from this multi-model analysis, in the  
219 4xCO<sub>2</sub> experiment the reduction of the mean meridional SST gradient dis-  
220 places the mean SPCZ northward leading to an increase frequency of shifts.  
221 In the LGM, the SPCZ exhibits a mean northward displacement and its  
222 spatial variability is damped. In the MH and 4K, the increased meridional  
223 SST gradient displaces the mean SPCZ southward and ENSO is reduced, but  
224 these changes may have concurrent effects on the SPCZ spatial variability,  
225 explaining the lack of consensus between models on this point. The change

226 in the SPCZ variability is therefore not primarily determined by ENSO.

227 Our results also stress that the SPCZ response to ENSO influence is likely  
228 to depend on the climate, suggesting that ENSO signature in the Southwest  
229 Pacific is mean-state dependent. All these modifications may impact the sign  
230 and amplitude of El Niño anomalies as recorded in paleo-indicators. Our re-  
231 sults suggest that the El Niño signature on rainfall at a given site was not  
232 necessarily of the same sign or of similar amplitude in past climates than  
233 nowadays. The biased SPCZ location simulated by the CGCMs does not  
234 however allow us to confidently assess the sign and amplitude of El Niño  
235 rainfall anomaly in the past climates at the scale of the Southwest Pacific  
236 islands. In addition, CGCMs biases in the Southwest Pacific region may  
237 contribute to some extent to the lack of agreement on the changes in the  
238 SPCZ-ENSO teleconnection in response to different climate forcings. How-  
239 ever, these caveats are unlikely to affect the main result of the present study,  
240 i.e. the fact that the relationship between ENSO and the SPCZ location  
241 strongly varies from one climate to another, as this result is consistent across  
242 all models.

243 This work then calls for careful interpretation of paleo-data outside the  
244 equatorial Pacific region and for the development of innovative strategies for  
245 model-data comparisons in order to understand the SPCZ variability and its  
246 relationship with ENSO.

## 247 **Methods**

248 *SPCZ position and latE index.* The location of the SPCZ is determined from  
249 the average of rainfall from November to March (NDJFM) at each model

250 grid point. In the region between  $150^{\circ}\text{E}$ - $150^{\circ}\text{W}$  and  $0^{\circ}$ - $30^{\circ}\text{S}$ , the latitude of  
251 the SPCZ corresponds to the latitude of the NDJFM rainfall maximum for  
252 each longitude, where the NDJFM rainfall rate is over 6 mm/day. In the  
253 eastern longitudinal portion  $150^{\circ}\text{W}$ - $142^{\circ}\text{W}$ , the NDJFM rainfall maximum  
254 is only taken within  $11^{\circ}\text{S}$  to  $30^{\circ}\text{S}$ . In Fig. 1, the SPCZ line is smoothed  
255 over 5 longitude grid points. With this classification of the SPCZ, the latE  
256 index is then defined as the average SPCZ latitude over  $170^{\circ}\text{W}$ - $150^{\circ}\text{W}$ . For  
257 each dataset, the mean or climatological SPCZ position is determined by  
258 averaging all positions computed for the individual years.

259 *Meridional SST gradient.* The meridional SST gradient is also computed  
260 from SST average from November to March (NDJFM SST). The meridional  
261 SST gradient is defined as the average NDJFM SST over the southwestern  
262 off-equatorial region ( $10^{\circ}\text{S}$ - $5^{\circ}\text{S}$ ,  $155^{\circ}\text{E}$ - $120^{\circ}\text{W}$ ) minus the average over the  
263 southwestern equatorial region ( $5^{\circ}\text{S}$ - $0^{\circ}$ ,  $155^{\circ}\text{E}$ - $120^{\circ}\text{W}$ ).

264 *Selection of El Niño, La Niña and normal years.* In this study we classify  
265 the different years into El Niño, La Niña or normal years following Braconnot  
266 et al. (2012a). We consider the NIÑO3 index defined as the average NDJFM  
267 SST over the NIÑO3 box ( $150^{\circ}\text{W}$ - $90^{\circ}\text{W}$ ,  $5^{\circ}\text{N}$ - $5^{\circ}\text{S}$ ). For each dataset, a year  
268 is defined as an El Niño (La Niña) year when its NIÑO3 index anomaly is  
269 greater (lower) than the NIÑO3 SD of the PI experiment multiplied by 1.2  
270 (-1.2).

271 *Selection of north, south and neutral SPCZ shifts.* We use NDJFM latE  
272 index as defined above. A year is defined as a north (south) SPCZ shifted  
273 year when its latE index anomaly is greater (lower) than the latE SD of

274 the PI experiment multiplied by 1.2 (-1.2). This criterion is an analogue to  
275 the El Niño/La Niña selection criterion described above (Methods). We also  
276 considered clustering analyses (not shown), but it gave similar results and  
277 we decided to keep the simplest approach.

278 *Bootstrap estimations.* The 90% confidence intervals in Fig. 1 are produced  
279 by bootstrap resampling: for each dataset, 10,000 estimations of the mean  
280 SPCZ position are produced by randomly sampling 10,000 samples in the  
281 original dataset of the same size (1 year = 1 value). The 90% confidence in-  
282 terval consists of the range between the value to which 5% of estimations are  
283 inferior and the value to which 5% of estimations are superior. Concerning  
284 error bars in Fig. 2 and Fig. 3 (panels b and c): for each simulation of each  
285 CGCM, 100 estimations of the variable of interest (mean latE index, mean  
286 meridional SST gradient, latE SD or NIÑO3 SD) are produced by bootstrap  
287 resampling (100 samples of the same size than the original dataset are ran-  
288 domly sampled in the original dataset). We then obtain 10,000 estimations  
289 of the difference between the MH/LGM/4xCO2 and the PI for each CGCM,  
290 by subtracting successively the 100 estimations for the PI to each of the 100  
291 estimations for the MH/LGM/4xCO2. The 90% confidence interval consists  
292 of the percentiles 5-95%.

### 293 **Authors contributions**

294 M.S-L., P.B., J.L. and M.L. coordinated the study and wrote the paper.  
295 M.S.L., M.L. and J.L. developed and performed analyses. O.M. and P.B.  
296 performed paleoclimate simulations. The results and their interpretation

297 were discussed by all authors and all authors contributed to refine the paper  
298 and approved the final article.

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319 **Appendix A. Relationship between the change in the SPCZ vari-**  
320 **ability and the change in the mean SST gradient**

321 Several complementary analyses were done to discuss the relationship be-  
322 tween the change in the SPCZ variability and the change in the mean SST  
323 gradient. Panel **a** of Fig. A.5 shows that the change in the SPCZ variability is  
324 not correlated with the change in the mean meridional SST gradient, in this  
325 set of simulations. However, one particular simulation (4xCO2 for MIROC-  
326 ESM) is an outlier which may degrade the correlation. By excluding it, we  
327 obtain a Pearson coefficient of **-0.453 (p-value=0.045)**, showing a slight  
328 anti-correlation between latE SD change and mean SST gradient change. As  
329 discussed in the text, our results do not exhibit such a relationship between  
330 the reference period (PI) and the other climates, except for the 4xCO2 cli-  
331 mate. This anti-correlation may result from an existing relationship across  
332 models rather than across periods. This is confirmed with the panel **b** show-  
333 ing the absolute values for all simulations of the model ensemble rather than  
334 the difference values to PI. Although no correlation appears, MIROC-ESM  
335 is again an outlier (at least concerning the PI, MH and LGM simulations).  
336 If we exclude this model when estimating the correlation, the Pearson coeffi-  
337 cient value is **-0.545 (p-value=0.006)**, exhibiting an anti-correlation which  
338 is significant given the small p-value.

339 By excluding the outlier MIROC-ESM, it appears that the relationship  
340 between a reduced (strengthened) meridional SST gradient and an enhanced  
341 (damped) SPCZ variability exists from one model to another. This rela-  
342 tionship is not systematically valid from one climate to another. This result  
343 shows that differences between models are larger than differences between

344 the different climates simulated by a particular model. Most importantly, it  
 345 illustrates that applying an external forcing modifies the dominant mecha-  
 346 nisms acting on the SPCZ variability. For example in the 4xCO2 simulation,  
 347 the weakening of the meridional SST gradient acts to increase the SPCZ loca-  
 348 tion variability, but the impact of the meridional SST gradient on the SPCZ  
 349 variability for other climates may be minor compared to other larger changes.  
 350

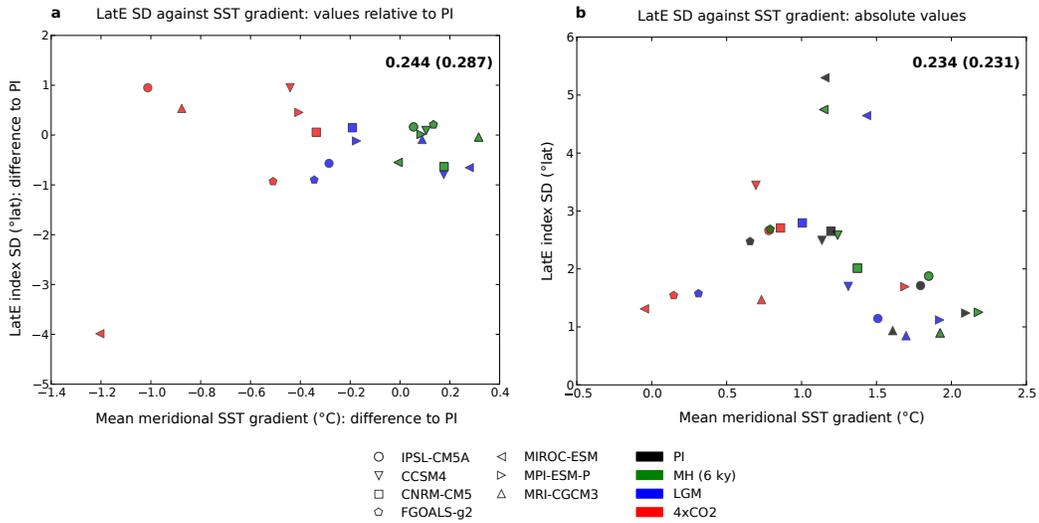


Figure A.5: Relationship between the NDFJM latE index standard deviation (SD) and the mean NDJFM meridional SST gradient in the model ensemble: **(a)** Values for the difference to pre-industrial simulation (PI) for each other simulation of the same model. **(b)** Absolute values for all simulations. Numbers in the upper right corner indicate the Pearson correlation coefficient and its p-value in parenthesis.

351 **Appendix B. Changes in frequency and amplitude of SPCZ shifts**  
352 **and ENSO events, and matches between both types**  
353 **of events, with CNRM-CM5 MPI-ESM-P and MRI-**  
354 **CGCM3**

355 Fig. B.6 is as Fig. 4 (showing IPSL-CM5A results) but for three other  
356 CGCMs CNRM-CM5, MPI-ESM-P and MRI-CGCM3. Results for the re-  
357 maining CGCMs considered in this study are not shown here because there  
358 are too few SPCZ shifts and/or ENSO events selected with our criteria (see  
359 methods) for some of their simulations—in most cases LGM and 4xCO<sub>2</sub>—as  
360 shown by Fig. C.7. For the three CGCMs shown here some simulations are  
361 also very short, which questions the significance of their results and is the  
362 reason why we chose to focus on IPSL-CM5A in the main text.

363 For the three CGCMs presented here—as well as for IPSL-CM5A in the  
364 main text—the matching between SPCZ shifts and ENSO events is modified  
365 across the climates. This suggests that the teleconnection is different.

366 For example, MPI-ESM-P simulates a reduction of the SPCZ shifts fre-  
367 quency in the LGM as well as an amplification of ENSO, resulting in an  
368 increase of the number of SPCZ shifts matching with ENSO events. The  
369 contrary is found for the MH simulation of this model. It is worth pointing  
370 out that in some cases—like the MPI-ESM-P 4xCO<sub>2</sub> and the MRI-CGCM3  
371 LGM simulations—ENSO and the SPCZ variability are both increased or  
372 decreased compared to pre-industrial (PI) but the matching between both  
373 is still modified (although we cannot assure the significance of the results).  
374 Concerning CNRM-CM5, the teleconnection is also slightly modified across  
375 the different simulations. For this model there seems to be an asymmetry be-

376 tween the selection of north and south SPCZ shifts, and between Niño/Niña  
377 events, as they present in most cases an opposite change compared to PI.

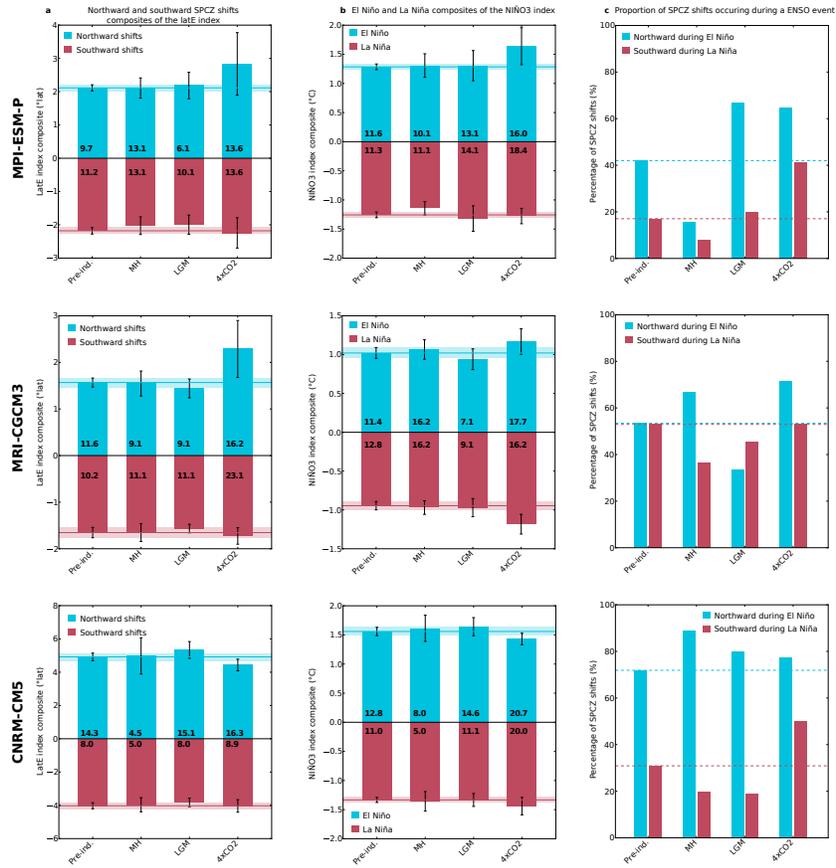


Figure B.6: (a) Composite values of the NDJFM latE index over selected years of north and south SPCZ shifts, i.e. mean values over these selected years. Error bars indicate the 95% confidence interval, assuming a normal distribution. Blue and red horizontal lines and shaded bands around indicate the PI latE composite and its confidence interval. Numbers indicate the percentage of selected years regarding the length of each simulation. (b) Same as a for the composite values of the NDJFM NINO3 index over El Niño and La Niña years. (c) Percentage of north (south) SPCZ shifts going with El Niño (La Niña) events, regarding total number of north (south) shifts. Horizontal lines indicate PI values. Top: CNRM-CM5; middle: MPI-ESM-P; bottom: MRI-CGCM3.

378 **Appendix C. SPCZ shifts and Niño/Niña occurrences as simulated**  
379 **by the models compared to PI**

380 Fig. C.7 shows for the model ensemble the percentage of selected: **a**  
381 SPCZ north shifts, **b** SPCZ south shifts, **c** El Niño events, **d** La Niña events,  
382 regarding the length of each simulation and in difference to pre-industrial  
383 (PI).

384 From this figure, we note that there are few events selected (Niño/Niña  
385 or south/north SPCZ shifts) in each simulation of most models, because in  
386 most cases the simulations are too short (less than 200 years, see Table 1).

387 However, changes in the percentage of selected events (in **a**, **b**, **c** and **d**)  
388 yields the same conclusions as changes in the latE and NIÑO3 index standard  
389 deviations (Fig.3). The only difference occurs in the LGM simulation: while  
390 6 models out of 7 reduce the latE index standard deviation compared to PI, 6  
391 models out of 7 produce less SPCZ north shifts than in PI but only 4 models  
392 also produce less SPCZ south shifts (one gives no change).

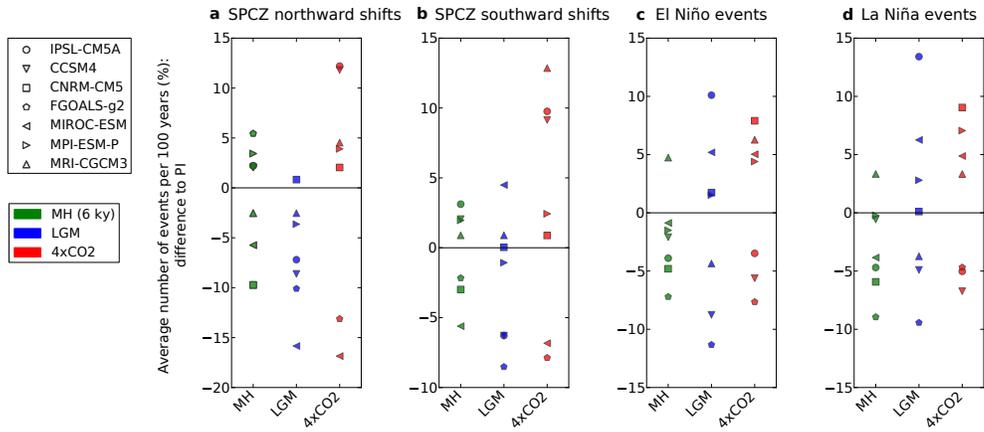


Figure C.7: Differences to PI for each simulation for all models of: **(a)** The percentage of north shifted SPCZ years (i.e. average number of selected years per century); **(b)** the percentage of south shifted SPCZ years; **(c)** the percentage of El Niño years; **(d)** the percentage of La Niña years. See methods for years selection.

393

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