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

Marion Saint-Lu^{a,*}, Pascale Braconnot^a, Julie Leloup^{a,b}, Matthieu Lengaigne^b, Olivier Marti^a

^a*Laboratoire des Sciences du Climat et de l'Environnement (LSCE),
UVSQ/CEA/CNRS, Orme des Merisiers, 91191 Gif-sur-Yvette, France*

^b*Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques (LOCEAN), IRD/UPMC/CNRS/MNHN, 4 place Jussieu, 75252 Paris Cedex 05, France*

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-

*Corresponding author

Email addresses: marion.saint-lu@lsce.ipsl.fr (Marion Saint-Lu), pascale.braconnot@lsce.ipsl.fr (Pascale Braconnot), jllod@locean-ipsl.upmc.fr (Julie Leloup), lengaign@locean-ipsl.upmc.fr (Matthieu Lengaigne), olivier.marti@lsce.ipsl.fr (Olivier Marti)

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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

1. Introduction

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

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

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

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

Environmental paleo-indicators such as fossil corals or giant clams record the past interannual rainfall variability and are the main high resolution paleo-datasets in the tropical Pacific (Corrège et al., 2000; McGregor and Gagan, 2004; Tudhope et al., 2001; Duprey et al., 2012; Cobb et al., 2013; Lazareth et al., 2013; Elliot et al., 2013). On the western side of the Pacific basin, most of them are located within the SPCZ area (see Fig.1). The present-day relationship between the amplitude of ENSO and the one of the SPCZ variability found from observations have led scientists to consider the amplitude of signals derived from these high resolution records as a proxy of ENSO amplitude in the past (Corrège et al., 2000; McGregor and Gagan, 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 CO₂ forcing by using idealized simulations forced with four times the pre-
 53 industrial levels of CO₂ (4xCO₂ 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 CO₂ 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

¹For 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> ¹	CO ₂ : 280 ppm	6 ky astronomical parameters (Berger, 1978)	CO ₂ : 180 ppm, and northern ice sheet	CO ₂ : 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).

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

3. Change in the SPCZ variability

Following the analysis of the climatological SPCZ changes in the previous section, we focus here on the response of the SPCZ variability to ENSO forcing in the different climates (Fig.3). The variability of the SPCZ and ENSO are inferred from the standard deviations (SD) of the NDJFM averaged latE and NIÑO3 index (SST average over 150°W-90°W, 5°N-5°S) respectively. The latE SD is increased in 4 models out of 7 in 4xCO₂ (one model gives no change) and reduced in 6 models out of 7 in the LGM (Fig.3b). However, models do not correspondingly agree on the changes in ENSO for these two experiments as illustrated by the NIÑO3 SD change (Fig.3c). It is worth pointing out the absence of symmetry in the ENSO change between these two climates, whereas they correspond to opposite signs of CO₂ forcing. In-

143 deed, 5 models simulate the same tendency of ENSO change in response to
144 both the 4xCO₂ 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 4xCO₂ 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 4xCO₂ 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 4xCO₂ 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°E - 150°W and 0° - 30°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°W - 142°W , the NDJFM rainfall maximum
 254 is only taken within 11°S to 30°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°W - 150°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°S - 5°S , 155°E - 120°W) minus the average over the
 263 southwestern equatorial region (5°S - 0° , 155°E - 120°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°W - 90°W , 5°N - 5°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

the different climates simulated by a particular model. Most importantly, it illustrates that applying an external forcing modifies the dominant mechanisms acting on the SPCZ variability. For example in the 4xCO2 simulation, the weakening of the meridional SST gradient acts to increase the SPCZ location variability, but the impact of the meridional SST gradient on the SPCZ variability for other climates may be minor compared to other larger changes.

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 4xCO2—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 4xCO2 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 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. 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.

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