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► **To cite this version:**

Cyril Dutheil, Margot Bador, Matthieu Lengaigne, Jérôme Lefèvre, Nicolas Jourdain, et al.. Impact of surface temperature biases on climate change projections of the South Pacific Convergence Zone. *Climate Dynamics*, 2019, 53, pp.3197-3219. 10.1007/s00382-019-04692-6 . hal-02401413

**HAL Id: hal-02401413**

**<https://hal.science/hal-02401413>**

Submitted on 12 Dec 2019

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# Impact of surface temperature biases on climate change projections of the South Pacific Convergence Zone

Cyril Marcel Dutheil<sup>1</sup>, Bador M.<sup>2</sup>, Lengaigne M.<sup>3</sup>, Lefevre J.<sup>1</sup>, Jourdain N.C.<sup>4</sup>, Vialard J.<sup>3</sup>, Jullien S.<sup>5</sup>, Peltier A.<sup>6</sup>, and Menkes C.<sup>1</sup>

<sup>1</sup> IRD (Institut de Recherche pour le Développement)-Sorbonne Universités (UPMC, Université Paris 06)-CNRS-MNHN-IPSL, LOCEAN Laboratory, IRD Nouméa BP A5, 98848 Nouméa cedex, New Caledonia;

<sup>2</sup> Climate Change Research Centre and ARC Centre of Excellence for Climate Extremes, School of BEES, University of New South Wales, Sydney, New South Wales, Australia.

<sup>3</sup> LOCEAN-IPSL, Sorbonne Universités, UPMC, Université Paris 06, CNRS-IRD-MNHN, Paris, France.

<sup>4</sup> *Univ. Grenoble Alpes / CNRS / IRD / G-INP, IGE, Grenoble, France.*

<sup>5</sup> Ifremer, Univ. Brest, CNRS, IRD, Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, Plouzané, France

<sup>6</sup> Météo France, Nouvelle Calédonie

Corresponding author:

C. Dutheil

IRD Nouméa BP A5

98848 Nouméa cedex

New Caledonia

FRANCE

Email: [cyril.dutheil@ird.fr](mailto:cyril.dutheil@ird.fr)

## **Abstract**

The South Pacific Convergence Zone (SPCZ) is poorly represented in global climate models, with trademark biases such as the “double convergence zones” and an equatorial cold tongue that extends too far westward. Such biases limit our confidence in climate change projections for this region. Here, we first show that simulations using a regional atmospheric model capture the SPCZ mean state and interannual variability well over the 1980-2016 period. We then perform climate change experiments by correcting the model surface and lateral boundary conditions on the basis of their projected changes for 2080-2100, obtained from the RCP8.5 seasonalCMIP5 multi-model mean. We also test a statistical method that corrects the Sea Surface Temperature (SST) projected changes on the basis of present-day biases. This projected SST correction strategy yields a considerably larger southwestern Pacific rainfall reduction (~30%) than

35 in CMIP5 simulations (~7%). Sensitivity experiments indicate that the weak CMIP5 response is due to biases in the  
36 projected CMIP5 SST, which alter future SST gradients, thereby changing the circulation and mitigating the reduction  
37 in south Pacific humidity convergence. While several studies have also shown that CMIP5 models project stronger  
38 SPCZ variability, with more frequent zonal SPCZ events, our experiments do not support this increase in the number of  
39 zonal SPCZ events. Additional simulations with different physical parameterizations yield very similar results,  
40 including the southwestern significant Pacific drying and no increase in the number of zonal SPCZ events.

41

42 **Keywords:** Regional climate models, South Pacific Convergence Zone, Precipitation, Sea surface temperature

43

## 44 **1. Introduction**

45

46 The South Pacific Convergence Zone is the largest convective area of the southern hemisphere in austral  
47 summer (Kiladis et al., 1989; Fig. 1a) and plays a major role in earth's climate (Vincent, 1994; Van der Wiel et al.  
48 2016a). The SPCZ is the main provider of rainfall for a vast majority of South Pacific island nations, where local  
49 hydrological conditions are very sensitive to its displacements (e.g. Alexander et al., 2006; Gouriou and Delcroix, 2002;  
50 Murphy et al., 2015). The location of this rain belt not only strongly constrains the regional hydrological cycle but is  
51 also the breeding ground of South Pacific tropical cyclones (Vincent et al., 2011). The SPCZ exhibits a diagonal  
52 orientation along a north-west/south-east axis, stretching from the Solomon Islands to the central subtropical Pacific  
53 (thick line in Figure 1a; Kiladis et al., 1989; Vincent, 1994), which has been attributed to the equatorward propagation  
54 and the diagonal orientation of eastward propagating Rossby wave trains (Matthews 2012; van der Kiel et al. 2015).  
55 The climatological characteristics of the SPCZ has been related to the underlying sea surface temperature (SST)  
56 gradients (Van der Wiel et al. 2016b). The SPCZ interannual variability affects the frequency of droughts, floods, and  
57 cyclones experienced by vulnerable island countries (Vincent, 1994; Alexander et al., 2006; Kirono et al., 2011;  
58 Vincent et al., 2011). These variations are strongly tied to the El Niño/Southern Oscillation (ENSO), the most energetic  
59 climate mode at interannual timescales. El Niño (resp. La Niña) events tend to induce a north-eastward (resp. south-  
60 westward) displacement of the SPCZ (e.g Folland, 2002; Juillet-Leclerc et al., 2006; Kidwell et al., 2016; Trenberth,  
61 1976), see also Fig. 4). This picture is much more radical during “extreme” El Niño events such as in 1982-1983, 1997-  
62 1998 and 2015-2016, when the SPCZ undergoes an equatorward swing of up to ten degrees of latitude and collapses to  
63 a more zonally oriented structure (e.g, Vincent et al., 2011; Cai et al., 2012). The unusual SPCZ shift and re-orientation  
64 during these extreme El Niños likely arise from the non-linear rainfall response to ENSO-related sea surface  
65 temperature (SST) signals (Chung et al., 2014). These “extreme” events have outsized impacts relative to weaker El  
66 Niños, such as massive drought, food shortage (Kirono et al., 2011) and a considerable reorganisation of cyclogenesis  
67 (Vincent et al., 2011), with an unusual occurrence of cyclones in French Polynesia.

68 Global warming also has the potential to influence the SPCZ rainfall location, intensity or variability,  
69 which would impact the water resources of many South Pacific islands. The detection of such changes in observations  
70 remains uncertain because of the strong aliasing by natural decadal/multi-decadal variability over the past 40 years  
71 (Deser et al., 2010; McGree et al., 2014; Meng et al., 2012; Solomon and Newman, 2012; Tokinaga et al., 2012; Vecchi  
72 et al., 2008). The assessment of the tropical Pacific response to global warming hence heavily relies on climate  
73 projections from the Coupled Model Intercomparison Project (CMIP; Meehl et al., 2007; Taylor et al., 2012). These

74 projections for the late 21<sup>st</sup> century generally depict a robust tropical Pacific SST response to greenhouse warming (see  
75 Fig. 1d, and Fig. 13a in Li et al., (2016)). This response includes a larger warming rate along the equator than in the off-  
76 equatorial central basin (e.g. Cai et al., 2015; Collins et al., 2010; Widlansky et al., 2013) and a robust precipitation  
77 increase in the equatorial Pacific (Fig. 1d, e.g. Watanabe et al., 2014; Li et al., 2016). This warming pattern also drives a  
78 drying of the southeast SPCZ margin in CMIP5 models, attributed to the anomalous transport of dry subtropical air into  
79 the SPCZ region (Widlansky et al., 2013), in response to increased SST meridional gradients in the southeast tropical  
80 Pacific. Within the core of the SPCZ region, west of the dateline, two mechanisms compete in driving the rainfall  
81 changes (Widlansky et al., 2013): the thermodynamical “wet gets wetter” mechanism where increased atmospheric  
82 water vapour content under global warming results in increased rainfall in the SPCZ convective region, and the  
83 dynamical “warmest gets wetter” mechanism where the comparatively weaker warming in the SPCZ region compared  
84 to that in the equatorial region results in anomalous moisture divergence and hence decreased rainfall. This results in a  
85 general tendency for the SPCZ core to dry for moderate tropical warming (~1-2°C), when increased transport of moist  
86 air toward the equatorial warming dominates the local increase of evaporation, and to moisten for stronger tropical  
87 warming (~3°C), when local evaporation, which increases the atmospheric moisture, dominates the dynamical changes  
88 (Widlansky et al., 2013). Finally, despite the absence of consensus on how ENSO-driven SST variability may change in  
89 the future (Collins et al., 2010; Power et al., 2013; Cai et al., 2015), CMIP5 model projections over the 21<sup>st</sup> century do  
90 indicate a consistent intensification of ENSO-related precipitation in the central/eastern equatorial Pacific because  
91 rainfall responds nonlinearly to absolute SST (Power et al., 2013). These climate model projections also display an  
92 increased occurrence of “extreme” El Niño and zonal SPCZ events projected over the 21<sup>st</sup> century because of a  
93 meridional SST gradient reduction in the South Pacific (Cai et al., 2012, 2014) allowing the SPCZ to shift to the north  
94 more easily. As we will see, the regional simulations in our study do not support the increased frequency of zonal  
95 SPCZ in CMIP3-5 projections, described by Cai et al. (2012).

96 While the representation of tropical Pacific climate has slightly improved in CMIP5 relative to CMIP3  
97 models (Bellenger et al., 2014; Grose et al., 2014), these models still exhibit long-standing biases. They indeed  
98 generally produce an excessive cold tongue that extends too far westward (e.g., Li and Xie, 2014; Li et al., 2015;  
99 Mechoso et al., 1995; Zheng et al., 2012; Fig. 1c) and a “double ITCZ” bias (Brown et al., 2011; Grose et al., 2014;  
100 Irving et al., 2011; Niznik et al., 2015; Perkins, 2011), i.e. a tendency for the SPCZ to be too zonal and to extend too far  
101 eastward (Fig. 1 b,c). The southeast SPCZ margin drying projected by CMIP models thus occurs in a region where  
102 these models do not correctly simulate the SPCZ (Fig. 1a,b). The precipitation increase in the equatorial western Pacific  
103 (Fig. 1d) also occurs in a region where most CMIP models exhibit a cold bias (Brown et al., 2013; Grose et al., 2014;  
104 Fig. 1c). Since many aspects of regional climate change depend upon the present-day climatology (e.g., Held and  
105 Soden, 2006; Huang et al., 2013; Matsueda and Palmer, 2011; Xie et al., 2015), these model biases may impair the  
106 reliability of projected future precipitation changes in the SPCZ region. Indeed, Li et al. (2016) showed that the lower  
107 this cold bias, the largest the projected drying in the western Pacific. This clearly indicates an influence of present-day  
108 SST biases on projected precipitation in CMIP5 models (see Fig 12. from Li et al., 2016).

109 A possible strategy to reduce the influence of CMIP biases on climate change projections is to force an  
110 atmosphere-only model with bias-corrected SSTs (e.g. Knutson et al., 2008; Nguyen et al., 2012), i.e. to add the global  
111 warming CMIP5 SST pattern ( $\Delta SST_{GW}$ ) to the present-day observed mean state. Several authors have used this strategy  
112 to assess the sensitivity of the SPCZ response to CMIP mean state biases (Brown et al., 2015; Evans et al., 2016;  
113 Widlansky et al., 2013). Using a global atmospheric model, Widlansky et al. (2013) demonstrated that the biases in

114 CMIP tropical mean SST strongly contribute to the uncertainty of twenty-first-century rainfall projections in the South  
115 Pacific, with a possible future drying of the western SPCZ portion when those biases are corrected. Using a bias-  
116 adjusted SST strategy in a number of Regional Climate Models (RCMs), Evans et al. (2016) showed that these  
117 southwest Pacific regional climate projections were much more sensitive to the choice of the regional climate model  
118 than to the CMIP model used to specify the RCM boundary conditions. Overall, the ensemble of simulations performed  
119 in their study hardly displayed any consensus for projected SPCZ changes, although a majority of ensemble members  
120 projected a drying of the SPCZ, in line with Widlansky et al. (2013).

121 The above bias-correction strategy however does not account for possible biases in the CMIP-projected  
122  $\Delta\text{SST}_{\text{GW}}$ . The present day common cold tongue bias in CMIP5 models may for instance influence the projected  
123  $\Delta\text{SST}_{\text{GW}}$ . A way to alleviate this issue is to use a simple statistical method based on the relationship between CMIP5  
124 present-day biases and projected changes, referred to as “observational constraint” or “emergent constraint” (e.g.  
125 Bracegirdle and Stephenson 2012). This approach reduces the impact of the present-day model biases on the projected  
126 response in the Arctic (e.g. Bracegirdle and Stephenson, 2013) and Indian Ocean (Li et al., 2016; Parvathi et al., 2017).  
127 In the tropical Pacific, Li et al. (2016) applied this “observational constraint” approach to correct CMIP5 projections for  
128 the tropical Pacific based on present-day rainfall bias in the equatorial western Pacific. This strategy yielded a stronger  
129  $\Delta\text{SST}_{\text{GW}}$  in the eastern than in the western equatorial Pacific, and a strong reduction of the inter-model spread in the  
130 model precipitations projections. This method is further described in section 2.2. In the present paper, we will use a  
131 similar method to correct CMIP5 SST projections based on the present-day SST bias, and investigate its impact on  
132 projected SPCZ changes.

133 Using a similar modelling framework as in Brown et al. (2015) and Evans et al. (2016), we investigate  
134 the robustness of the SPCZ response to climate change to i) model physics, ii) present-day SST biases and iii)  
135 correcting the CMIP5-projected SST change  $\Delta\text{SST}_{\text{GW}}$  on the basis of present-day biases. We specifically address the  
136 following questions. What are the expected robust changes in the austral summer SPCZ climatology in response to  
137 anthropogenic forcing? How will these changes alter the interannual SPCZ variability? To answer these questions, we  
138 use the Weather Research and Forecasting (WRF) regional climate model. The paper is organized as follows. Section 2  
139 describes the experimental design. Section 3 provides a thorough evaluation of the SPCZ mean state and variability  
140 simulated by our present-day simulation, and we compare our simulation to a simulation where we applied the CMIP5  
141 SST bias. Section 4 discusses the future changes in the SPCZ mean state and variability derived from our experimental  
142 strategy. We also discuss the sensitivity of our results to the CMIP5 model present-day SST biases and to correcting  
143  $\Delta\text{SST}_{\text{GW}}$  based on emergent constraints. Section 5 investigates the sensitivity of our results to the model physics.  
144 Finally, Section 6 provides a summary and a discussion of our results against previous studies.

145

146

## 147 **2. Experimental design and methods**

148

### 149 **2.1 WRF Regional model configuration**

150

151 The two different model configurations used in this study and detailed in Table 1 are based on the  
152 Weather Research and Forecasting version 3.6.1 regional atmospheric model, which solves compressible, non-  
153 hydrostatic Euler equations with the Advanced Research WRF (ARW) dynamical solver (Skamarock and Klemp,

154 2008). The simulated domain encompasses the tropical Pacific region [101°E-59°W; 26°N-42°S] using a 105 km  
155 horizontal grid spacing and 32 pressure levels. In the following, only a subset of this domain centered on the SPCZ  
156 region is shown (Fig. 1a).

157 This first configuration is based on the study of Lefèvre et al., (2016). It includes the Lin et al., (1983)  
158 microphysics scheme, the Community Atmosphere Model (Collins et al., 2004) for shortwave and longwave radiation,  
159 the UW planetary boundary layer (Bretherton and Park, 2009) with the Monin–Obukhov surface layer parameterization,  
160 and the Noah land surface model (Chen and Dudhia, 2001). The parameterization of subgrid-scale convection is taken  
161 from the Zhang-McFarlane scheme (Zhang and McFarlane, 1995). This configuration will be referred to as the “ZM”  
162 configuration in the following.

163 The second configuration is partly based on Jourdain et al., (2011) and Jullien et al., (2014). The set of  
164 physical parameterizations used is completely different from the ZM configuration with Betts-Miller-Janjić  
165 parameterization for convection (Janjić, 1994), the WRF single-moment three-class microphysics scheme (Hong et al.,  
166 2004), the Rapid Radiation Transfer Model for the longwave and shortwave radiation (Iacono et al., 2008) and the  
167 Yonsei University planetary boundary layer (Noh et al., 2003). This configuration will be referred to as the “BMJ”  
168 configuration in the following.

169

## 170 **2.2 Present-day and climate change experiments**

171 The surface and lateral atmospheric boundary conditions were generated from the multi-model mean  
172 (MMM) of an ensemble of 31 CMIP5 climate models (see Table ; Taylor et al. 2012). For each model, we consider one  
173 simulation covering the historical period and the 21<sup>st</sup> century under the Representative Concentration Pathway 8.5  
174 (RCP8.5) of aerosols and greenhouse gases (GHG) scenario, for which the radiative forcing reaches 8.5 W.m<sup>-2</sup> by 2100  
175 (van Vuuren et al. 2011). When several members were available for a given CMIP5 model, only the first available  
176 ensemble member (referred to r1i1p1 in the CMIP5 naming convention, or r2i1p1 if not available) was considered, to  
177 avoid giving more weight to some models than others in the MMM. The CMIP5 fields used to build the boundary  
178 conditions and the initial state are listed in Table 2. Table 3 provides a summary of the performed simulations, which  
179 are further detailed in the following. It should be noted that the 31 models are not really independent in the sense that  
180 many of them share duplicated codes and common history (Herger et al., 2018; Knutti et al., 2013).

181 A pair of present-day (PD) simulations is performed for each of the two model configurations (ZM and  
182 BMJ), from January 1980 to May 2016. For each of the ZM and BMJ configurations (indicated by subscripts in the  
183 acronyms when needed), a 36-yr present-day simulation (labelled PD\_OBS hereafter) has been designed as a dynamical  
184 downscaling of the NCEP2 reanalysis (NCEP2; Kanamitsu et al., 2002). Surface and lateral boundary conditions are  
185 taken from the 6-hourly outputs of this reanalysis. A second 36-yr present-day simulation uses the same NCEP2  
186 boundary conditions to which the present-day monthly climatological CMIP5 MMM SST bias is added to the observed  
187 SST climatology (labelled PD\_CMIP hereafter). The comparison of this simulation with CMIP5 MMM and CC\_OBS  
188 simulation allows us to test the impact of our model setup, and the impact of the historical CMIP5 SST biases, and will  
189 be discussed in Section 4. SST biases are only applied in the SPCZ region, within [130°E-290°E; 7°N- 30°S], with a  
190 smooth transition to present-day SST near the boundaries of this region. The lateral and sea surface conditions outside  
191 this box remain the same as in PD\_OBS. In all these present-day simulations, the CO<sub>2</sub> forcing is kept constant at a level  
192 representative of the recent period (379ppm).

193 To assess the southwest Pacific response to climate change (CC), we further conduct a set of three future  
194 experiments for each model configuration. For the first two experiments (labelled CC\_OBS and CC\_CMIP), we apply  
195 the climatology of surface and lateral boundary future changes on top of the conditions of PD\_OBS and PD\_CMIP.  
196 These future changes are calculated as the difference between the 2080-2100 and 1989-2009 of MMM monthly  
197 climatologies (Fig. 1d), following the same methodology as in Knutson et al. (2008) and Walsh (2015). We apply a  
198 constant CO<sub>2</sub> forcing representative of the RCP8.5 projections at the end of the 21<sup>st</sup> century (845ppm). The CMIP5  
199 fields used to build the boundary conditions and the initial states are listed in Table 2. This experimental strategy  
200 intentionally assumes no change in variability between the present and future climate for two main reasons. First, the  
201 reported lack of consensus on changes in amplitude of ENSO-related SST signals in future CMIP model projections  
202 (some global climate models showing an increase in the amplitude of ENSO SST variability in the future, others  
203 showing a decrease or, no statistically significant changes; see Bellenger et al. 2014) are an incentive to test the null  
204 hypothesis, i.e. that the ENSO SST variability will not significantly change. Second, Cai et al. (2012) found a consistent  
205 increase in the frequency of zonal SPCZ events despite this lack of consensus and attributed this increase to the changes  
206 in the mean meridional SST gradient in the South Pacific. The present experimental framework that only assume a  
207 mean state change allow examining if the mechanism suggested by Cai et al. (2012) operate in a more realistic  
208 framework (i.e. without CMIP5 mean present-day biases).

209 We apply a constant CO<sub>2</sub> forcing representative of the RCP8.5 projections at the end of the 21<sup>st</sup> century (845ppm). The  
210 CMIP5 fields used to build the boundary conditions and the initial states are listed in Table 2. The third experiment  
211 (CC\_COR), is similar to CC\_OBS experiments, except that we use the CMIP5 SST anomalous pattern (Fig. 1e)  
212 statistically corrected following the method of Li et al. (2016),  $\Delta SST_{COR_{GW}}$ . In order to produce a corrected SST  
213 projection  $\Delta SST_{COR_{GW}}$ , we first assess the statistical relationship between the historical rainfall bias and  $\Delta SST_{GW}$   
214 (Fig. 2) in the equatorial western Pacific (140°E-170°W; 2°S-2°N). We find a significant correlation of -0.56 (p-value =  
215 0.001) between the mean precipitation and  $\Delta SST_{GW}$  across 31 CMIP5 models (Fig. 2), which is consistent with Li et al.  
216 (2016) who found a -0.52 correlation across 24 CMIP5 models (their Figure 6a). This analysis demonstrates that the  
217 drier the present-day west Pacific (and the stronger the cold tongue bias, not shown), the stronger the projected SST  
218 warming in the equatorial western Pacific. We use this linear relation between the mean western equatorial Pacific  
219 present-day precipitation, and  $\Delta SST_{GW}$  to correct  $\Delta SST_{GW}$ , as in Li et al. (2016). The corrected CMIP5 MMM  
220 projection exhibits a weaker western Pacific warming (Fig. 1e). This will modify SST gradients quite significantly in  
221 this region, relative to  $\Delta SST_{GW}$ .

222 In the rest of the manuscript we will refer to the difference between historical CMIP5 climatological  
223 SST, and observed SST as the “*historical CMIP5 SST bias*” and to the difference between  $\Delta SST_{GW}$  and  $\Delta SST_{COR_{GW}}$   
224 as the “ *$\Delta SST_{GW}$  bias*”. (Strictly speaking this last quantity is not bias but an estimated bias).

225

### 226 **2.3 Analysis methods**

227 The SPCZ position at each longitude is taken as the location of the maximum precipitation between the  
228 equator and 30°S, where the precipitations are higher than 6mm.day<sup>-1</sup>. The mean SPCZ slope is calculated as a linear fit  
229 to this SPCZ position between 160°E and 140°W. As in Vincent et al. (2011), we define LatW as the SPCZ latitude  
230 average between 160°E and 180°E, and latE as the SPCZ latitude averaged between 170°W and 150°W. El Niño (La

231 Niña) events are defined as austral summer seasons (December-January-February; DJF) when the DJF Niño3.4 SST  
232 anomaly is greater (lower) than 0.5°C, following NOAA’s index:  
233 [http://www.cpc.noaa.gov/products/analysis\\_monitoring/ensostuff/ensoyears.shtml](http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). We classify El Niño events into two  
234 classes: extreme El Niño events that encompass the three largest events (1982/1983, 1997/1998, 2015/2016) following  
235 Santoso et al. (2017) and moderate El Niño events that gather all the other events.

236 To investigate the relative importance of moisture changes (referred to as “thermodynamical”), and  
237 large-scale atmospheric circulation changes (referred to as “dynamical”) in shaping the pattern of moisture divergence  
238 changes between future and present, we use the same method as discussed in Widlansky et al. (2013) with a simple  
239 decomposition of surface moisture divergence anomalies (the anomaly being the difference between CC\_OBS<sub>ZM</sub> and  
240 PD\_OBS<sub>ZM</sub>) into surface divergence of:

241 - projected moisture changes advected by the mean circulation:  $\delta TH = \nabla \cdot (\bar{u}q')$ (Eq. 1)

242 - mean moisture advected by the projected circulation changes:  $\delta DYN = \nabla \cdot (u'\bar{q})$ (Eq. 2)

243 where  $u$  is the horizontal surface wind vector,  $q$  is the specific surface humidity, the overbar denotes the values from the  
244 present day simulation and primes denote differences between future and present day simulations. The cross terms are  
245 not discussed here as  $\delta TH$  and  $\delta DYN$  dominate the balance in the region of interest (not shown).

246

### 247 **3. Results: Present-day simulations**

#### 248 **3.1 Climatological features**

249 The observed SPCZ persists throughout the year, but reaches its maximum extension during austral  
250 summer (DJF). At this time of the year, the SPCZ extends from 2°S on its western edge to 22°S on its eastern edge and  
251 exhibits a moderate tilt in its western portion (150°E-160°W) and more southeastwardly tilted portion in its eastern  
252 portion (160°W-140°W). The surface winds converge toward the SPCZ (Fig. 3a).

253 The PD\_OBS<sub>ZM</sub> experiment simulates the observed climatological DJF precipitation pattern reasonably  
254 well (Fig. 3b), including the southeastward SPCZ tilt. The surface wind intensity and convergence are correctly  
255 reproduced, resulting in a realistic moisture convergence (not shown). This simulation however exhibits some biases,  
256 including a ~12% underestimation of ITCZ rainfall and a ~30% underestimation of the western equatorial Pacific  
257 rainfall. PD\_OBS<sub>ZM</sub> also overestimates precipitation in the core of the SPCZ. Despite these biases, this simulation  
258 reproduces the location of the observed SPCZ very accurately (yellow and red curves on Figure 3a), a major asset for  
259 the objectives of the present study. In addition, this simulation seems to better reproduce the position of SPCZ than the  
260 other studies using regional models (Evans et al., 2016).

261 These precipitation patterns are further compared to those of the NCEP2 reanalysis (Fig. 3c), which is  
262 used as boundary conditions in the present study. The NCEP2 reanalysis also captures the main observed climatological  
263 precipitation pattern reasonably well. In contrast with PD\_OBS<sub>ZM</sub>, it tends to overestimate ITCZ (~15%) and equatorial  
264 western Pacific (~5%) precipitation. The NCEP2 dataset also exhibits a diagonally oriented SPCZ, although this  
265 reanalysis appears to overestimate the SPCZ tilt in its western portion relative to PD\_OBS<sub>ZM</sub> and CMAP and  
266 underestimate it in its eastern portion. Like PD\_OBS<sub>ZM</sub>, the NCEP2 re-analysis overestimates precipitation in the core  
267 of the SPCZ.



268 A more quantitative assessment of the SPCZ climatological characteristics simulated by PD\_OBS<sub>ZM</sub> (red  
269 circle), NCEP2 (green circle) and the CMIP5 models (boxplot) is provided in Figure 4. Figure 4a clearly illustrates that  
270 all CMIP5 models considerably underestimate the slope of the SPCZ as already reported in past literature (e.g. Brown et  
271 al., 2012), with the historical CMIP5 MMM exhibiting a four times weaker slope than in observations (0.06°S/°E as  
272 compared to 0.26°S/°E for CMAP). This slope varies considerably among individual CMIP5 simulations, ranging from  
273 a completely zonal SPCZ to a more realistic diagonally oriented but still underestimated SPCZ slope of up to 0.14°S/°E.  
274 PD\_OBS<sub>ZM</sub> captures this SPCZ slope far more accurately (0.22°S/°E). The strong underestimation of the SPCZ slope in  
275 historical CMIP simulations largely results from a large northward bias in the location of its eastern portion (Fig. 4b;  
276 9°S for the CMIP MMM, 13.5°S for observations). This location is very well captured in PD\_OBS<sub>ZM</sub> (14°S). The  
277 location of the western SPCZ portion (Fig. 4c) around 8°S is reasonably well captured by PD\_OBS<sub>ZM</sub>, NCEP2 and  
278 CMIP5 simulations. PD\_OBS<sub>ZM</sub> also captures the South Pacific (0-30°S; 150°E-240°E) rainfall pattern accurately (Fig.  
279 4d), with a pattern correlation of 0.96, compared to a correlation ranging from 0.5 to 0.9 for CMIP5 and 0.87 for  
280 NCEP2. Overall, the PD\_OBS<sub>ZM</sub> simulation outperforms all CMIP5 models and behaves as accurately or slightly better  
281 than NCEP2, as far as the SPCZ climatological features are concerned.

282

### 283 3.2 Interannual variability

284 Figure 5 exhibits a composite of anomalous rainfall and surface winds during the different ENSO  
285 phases. Moderate El Niño and La Nina events generally exhibit opposite patterns. Moderate El Niño years (resp. La  
286 Nina years) are characterized by modest positive (negative) rainfall anomalies in the vicinity of the dateline, while weak  
287 negative (positive) rainfall anomalies prevail in the western equatorial Pacific and south of the climatological SPCZ  
288 position in the southwest Pacific (Fig 5a,c). During these moderate El Niño events (resp. La Nina), the SPCZ  
289 experiences a 3° northward (southward) shift between 150°E and 150°W. This picture is very different during extreme  
290 El Niño events (Fig. 5b): the equatorial rainfall increase is four times larger than during moderate El Niño events and its  
291 pattern is considerably extended and shifted eastward, with a maximum near 165°W. The South Pacific rainfall  
292 decrease is also about twice as large as during moderate events and extends further east to 140°W. Finally, the area  
293 covered by the ITCZ in the western equatorial Pacific also exhibits a large drying that is not present during moderate El  
294 Niño events. These stronger and spatially-extended rainfall anomalies associated with extreme El Niño events translate  
295 into larger SPCZ displacements: the SPCZ eastern portion shifts northward by up to ten degrees, while its western  
296 portion remains close to its climatological position, which produces a more zonally oriented SPCZ from 150°E to  
297 150°W.

298 From year to year, the eastern portion of the SPCZ experiences meridional displacements, with the  
299 largest northward excursions occurring in austral summer 1982 (~+10°), 1992 (~+7°), 1997 (~+10°) and 2015 (~+8°)  
300 (Fig. 6). As discussed in Vincent et al. (2011), these years are indeed characterized by an extreme northward swing of  
301 the SPCZ, which ends up with a more zonally oriented structure. PD\_OBS<sub>ZM</sub> and NCEP2 accurately reproduce these  
302 SPCZ excursions (0.71 correlation between CMAP and both datasets), despite a 20% overestimation of the variability  
303 in NCEP2 (NCEP2 STD=4.99° vs CMAP STD=4.1°). In particular, PD\_OBS<sub>ZM</sub> correctly simulates the SPCZ extreme  
304 northward excursions during the 1982, 1992, 1997 and 2015 El Niño events, with a tendency for both PD\_OBS<sub>ZM</sub> and  
305 NCEP2 to overestimate the northward excursion of the SPCZ during these events (Fig. 6). The variability of the western  
306 portion is also well captured by both NCEP2 and PD\_OBS<sub>ZM</sub>, with a ~0.7 correlation to CMAP (not shown). Overall, in

307 this section, we have demonstrated the capacity of our simulation to reproduce reasonably well the present-day SPCZ  
308 mean state (in particular: much better than in CMIP5 models) as well as its interannual variability.

309

## 310 **4. Results: Response to climate change**

### 311 **4.1 Climatology**

312 In this section, we investigate the climatological SPCZ response to anthropogenic forcing in our 3 sets of  
313 experiments, CMIP<sub>ZM</sub>, OBS<sub>ZM</sub> and COR<sub>ZM</sub> and compare it with that in the CMIP5 MMM. We start with a description of  
314 the changes in CMIP5 MMM, and then compare them with the CMIP<sub>ZM</sub> experiments to assess the impact of our model  
315 setup. We will then compare CMIP<sub>ZM</sub> and OBS<sub>ZM</sub> to evaluate the impact of the historical CMIP5 SST bias. Finally,  
316 OBS<sub>ZM</sub> and COR<sub>ZM</sub> are used to evaluate the effect of the  $\Delta$ SST<sub>GW</sub> bias.

317 The CMIP5 MMM precipitation response to climate change is characterized by a consistent and  
318 significant rainfall increase along the equator, reaching up to 3 mm.day<sup>-1</sup> west of the dateline (Fig. 7a). These  
319 simulations also display a consistent and statistically significant drying of up to 1 mm.day<sup>-1</sup> east of 150°W and south of  
320 10°S. In the southwest Pacific (10°S-30°S; 160°E-160°W) the rainfall change is not statistically significant, with less  
321 than 75% of the models simulating a rainfall increase. Overall, these modest rainfall changes only result in very modest  
322 future changes in the climatological SPCZ location in the CMIP5 CC simulations (solid and dotted black lines in Figure  
323 7a). The projected wind changes depict an intensification of the trade winds in the southeastern part of the domain,  
324 converging towards the equatorial region (Fig. 7a).

325 Let us first explore how our model compares with the CMIP5 MMM. The CC\_CMIP5<sub>ZM</sub> simulation displays a  
326 similar significant precipitation increase in the equatorial region (Fig 7b; ~2.5 mm.day<sup>-1</sup> in CMIP5<sub>ZM</sub> experiment  
327 compared to ~2.2 mm.day<sup>-1</sup> in CMIP5 MMM, on average in the red box Fig. 7d). This significant precipitation increase  
328 is confined to the western/central Pacific or outside the 5°N-5°S band at east of 170°W. CC\_CMIP5<sub>ZM</sub> also yields a  
329 significant drying in the southeast Pacific, extending up to 175°E, and stronger than in the CMIP5 MMM (~1.0  
330 mm.day<sup>-1</sup> in CMIP5<sub>ZM</sub> experiment compared to ~0.4 mm.day<sup>-1</sup> in CMIP5 MMM, on average in the green box Fig. 7d).  
331 These anomalies do not affect the climatological SPCZ position, which remains similar from 150°E to 160°W (solid  
332 and dotted black lines on Figure 7b), but the rainfall decrease east of 170°W leads to a shrinkage of the SPCZ, defined as  
333 the region where precipitation is stronger than 6mm.day<sup>-1</sup>.

334 As expected, correcting the historical CMIP5 SST bias considerably impact the mean simulated rainfall  
335 pattern. CC\_OBS<sub>ZM</sub> (Fig. 7c) displays a significant rainfall increase in the equatorial region between 7°S-10°N, much  
336 stronger than CMIP5<sub>ZM</sub> experiments (~3.5 mm.day<sup>-1</sup> in OBS<sub>ZM</sub> experiment compared to ~2.5 mm.day<sup>-1</sup> in CMIP5<sub>ZM</sub>  
337 experiment, on average in the red box Fig. 6d), reaching a maximum in the western/central Pacific, near 5°N (Fig. 7c).  
338 The CC\_OBS<sub>ZM</sub> simulation also displays a significant rainfall decrease (~0.9 mm.day<sup>-1</sup> on average in the green box Fig.  
339 7d), similar to the CMIP5<sub>ZM</sub> experiment, south of 7°S and north of the SPCZ climatological position extending from the  
340 eastern Pacific to 180°. This response represents a 15% rainfall decrease within the [5°S-15°S; 180°-150°W] region  
341 compared to the present-day climatology. These large-scale and intense anomalies affect the climatological SPCZ  
342 position in its eastern portion (solid and dotted black lines on Figure 7c), with a southward shift of 4° of the maximum  
343 precipitation.

344 Let us finally examine the effect of correcting the  $\Delta$ SST<sub>GW</sub> bias. CC\_COR<sub>ZM</sub> (Fig. 7d) yields a weaker increase

345 of precipitation in the western/central equatorial region compared to  $CC\_OBS_{ZM}$  ( $\sim 3 \text{ mm.day}^{-1}$ , on average in the red  
346 box Fig. 7d). The area of significant increase located north of the equator is confined in the western Pacific in  
347  $CC\_COR_{ZM}$  while it extends throughout the Pacific in  $CC\_OBS_{ZM}$ .  $CC\_COR_{ZM}$  also yields a larger drying south of  $5^\circ S$   
348 and east of  $180^\circ E$  ( $\sim 1.9 \text{ mm.day}^{-1}$  on average in the green box Fig. 6d), which extends farther into the western Pacific  
349 than in  $CC\_OBS_{ZM}$  (Fig. 7d). This represents a  $\sim 20\%$  decrease in rainfall within the  $[15^\circ S-5^\circ S; 160^\circ E-180^\circ E]$  region  
350 compared to present-day climatology. In these two experiments (Fig. 7c,d) these anomalies induce a large southward  
351 shift of the climatological SPCZ position ( $\sim 4^\circ$ ). The trade winds in the south-central part of the domain  $[180^\circ E-150^\circ W;$   
352  $15^\circ S-5^\circ S]$  increase by 40% compared to present-day climatology in  $CC\_COR_{ZM}$ , especially in the southwestern Pacific  
353 where the anomaly of trade winds cross the equator to the north where maximum precipitation anomalies are found.

354 We further use simple surface moisture convergence diagnostics similar to those proposed in Widlansky et al.  
355 (2013) to provide insights on the mechanisms driving the simulated rainfall response to climate change in the CMIP5  
356 models and our experiments (Fig. 8). The anomalous patterns in surface moisture divergence (Figure 8a,b,c,d)  
357 qualitatively match those of the precipitation changes (Fig. 7a,b,c,d) for both the CMIP5 models and our experiments,  
358 indicating that this is an appropriate way to diagnose precipitation changes. Moisture divergence changes are almost  
359 entirely driven by wind divergence changes in our experiments and in the CMIP5 models (Fig. 8e,f,g,h), with moisture  
360 changes playing a smaller role (Fig. 8i,j,k,l). The anomalous moisture convergence in the equatorial region is also  
361 largely driven by dynamical changes, with thermodynamics only damping the dynamical changes (Fig. 8e,f,g,h vs  
362 i,j,k,l). Thermodynamical effects are slightly stronger in  $CMIP5_{ZM}$  (Fig. 8j) than in  $OBS_{ZM}$  (Fig. 8k), and hence damp  
363 the dynamical effect more, leading to larger precipitation changes in  $OBS_{ZM}$  in the equatorial region. In the southeast  
364 Pacific, the increased anomalous moisture divergence that dries the SPCZ eastern edge is also largely driven by  
365 circulation changes (Fig. 8e,f,g,h).

366 Regarding the southwest Pacific and SPCZ region, the moisture divergence anomalies and related precipitation  
367 changes are similar in the OBS and CMIP experiments (Fig. 7b,c and Fig. 8b,c), for which the tendency for dynamical  
368 processes to dry the western portion of the SPCZ is partially compensated by thermodynamical effects (Fig.  
369 8b,c,f,g,j,k). On the other hand, the COR experiment yields a stronger drying of the SPCZ western margin, that can be  
370 related to stronger dynamical processes in COR (Fig. 8h) than in OBS (Fig. 8g). The wind changes responsible for these  
371 moisture convergence modifications can be related to the corrected projected SST pattern in the COR experiment  
372 relative to OBS (Fig. 1d,e). The SST meridional gradient between the equatorial western Pacific ( $160^\circ E-180; 5^\circ S-5^\circ N$ )  
373 and the southwestern Pacific ( $160^\circ E-180; 5^\circ S-15^\circ S$ ), and the SST zonal gradient between the southwestern Pacific  
374 ( $150^\circ E-180; 5^\circ S-15^\circ S$ ) and the south central Pacific ( $180-210^\circ E; 5^\circ S-15^\circ S$ ) are stronger in  $CC\_COR$  ( $0.33^\circ C$  in  
375  $CC\_COR$  vs.  $0.028^\circ C$  in  $CC\_OBS$  and  $0.58^\circ C$  in  $CC\_COR$  vs.  $0.54^\circ C$  in  $CC\_OBS$ , respectively). These different SST  
376 patterns induce southeasterly wind anomalies (blowing from the southeast Pacific dry zone towards the central and  
377 western equatorial Pacific) that are stronger and extend further into the western Pacific in the COR experiment (Fig. 7c  
378 vs 7d).

379 To summarize, 1) our model tends to enhance the precipitation response to anthropogenic forcing compared to  
380 CMIP5 MMM, especially the southeastern Pacific drying, 2) the historical CMIP5 SST biases damp the intensity of the  
381 equatorial rainfall response compared to  $OBS_{ZM}$ , largely through thermodynamical processes, and 3) the projected SST  
382 correction yields a larger drying of the SPCZ western portion, due to southeasterlies that penetrate further west and  
383 north in relation with SST gradient changes.

384

## 385 4.2 Interannual variability

386 A general assessment of the changes in precipitation interannual variability in the present and future  
387 climate is provided in Figure 9. In PD\_OBS<sub>ZM</sub>, large interannual rainfall variations (4 to 8 mm.day<sup>-1</sup>) are found in a  
388 large region extending from 150°E to 150°W and 8°N to 20°S, with a maximum in the SPCZ core region and under the  
389 ITCZ (Fig. 9a). This rainfall variability pattern is considerably affected by anthropogenic forcing (Fig. 9b,c), with a  
390 near doubling of equatorial rainfall variations. In CC\_COR<sub>ZM</sub>, anthropogenic forcing also affects the South Pacific  
391 rainfall variability, with a reduction of rainfall variability south of 5°S. This change in rainfall is likely related to drying  
392 of SPCZ in its western part. Similar results are found in the CMIP5<sub>ZM</sub> experiment (not shown). Finally, the OBS<sub>ZM</sub> also  
393 reveals an enhancement of equatorial inter-annual variability when the historical CMIP5 SST bias is also corrected. In  
394 an idealized framework where the SSTs are climatological, Chung et al., (2014) found that global warming enhances  
395 the nonlinear rainfall response to ENSO SST anomalies, with an increase of precipitation variability, especially along  
396 the equator. Our study confirms these results in a more realistic framework.

397 Enhanced precipitation in the equatorial region however does not appear to be robust for all ENSO  
398 phases (Fig. 10abc). The large equatorial rainfall increase under climate change is indeed clear for El Niño events (Fig.  
399 10ab) but is considerably weaker during La Niña events, being largely confined to the far western Pacific (Fig. 10c).  
400 This is also the case in the OBS<sub>ZM</sub> and CMIP5<sub>ZM</sub> experiments (not shown). To further illustrate that, Figure 10d,e  
401 provides scatterplots of the rainfall difference between future and present climate for each of 36 simulated austral  
402 summers (black dots represent COR<sub>ZM</sub> experiment, cyan dots OBS<sub>ZM</sub> experiment, and brown dots CMIP5<sub>ZM</sub>  
403 experiment) as a function of the ENSO state in the two regions drawn on the upper panels of Figure 10: the equatorial  
404 region (Fig. 10d) and the South Pacific region (Fig. 10e). The amplitude of the equatorial precipitation increase is  
405 considerably larger for an El Niño (up to 2.5 mm/day) than for a La Niña (0mm/day). This illustrates a non-linearity of  
406 the precipitation response to climate change during ENSO phases, as also found in the idealized framework of Chung et  
407 al., (2014). The South Pacific drying in response to climate change has a weaker non-linear dependency to ENSO (-1  
408 mm.day<sup>-1</sup> for La Niña vs. 2.5 mm.day<sup>-1</sup> for El Niño) than the equatorial region.

409 The changes in rainfall interannual variability near the equator are mostly driven by changes in the SPCZ  
410 response to ENSO (Fig. 11). Under present-day conditions, the zonally-oriented SPCZ during extreme El Niño events  
411 remains largely located in the Southern Hemisphere (red thick line; Fig. 11a), with the largest northward excursion of  
412 12° occurring in PD\_OBS<sub>ZM</sub> during the 1997-1998 event. In CC\_COR<sub>ZM</sub>, the SPCZ shifts right onto the equator  
413 between 165°E and 140°W (red dashed line; Fig. 11a), and between 180°E and 140°W in CC\_OBS<sub>ZM</sub> (not shown),  
414 resulting in a northward excursion exceeding 15° during extreme El Niño events (1983, 1992, 1998, 2016) (red dashed  
415 lines, Fig. 11a). During moderate El Niño events, the SPCZ in both CC\_COR<sub>ZM</sub> (Fig. 11b) and CC\_OBS<sub>ZM</sub> (not shown)  
416 experiences a shift of ~3° near the dateline but a far weaker southward excursion in its eastern portion. During la Niña  
417 events, the SPCZ position slightly moves southward by 2° in both present and future climates (Fig. 11c).

418 The SST cold bias in CMIP5 models yields weaker ENSO-related SPCZ present-day movements in  
419 PD\_CMIP5<sub>ZM</sub> (black dashed line versus black thick line; Fig. 11 d,e,f) than in PD\_OBS<sub>ZM</sub> (black dashed line versus  
420 black thick line; Fig. 11 a,b,c). Under climate change, this SPCZ variability increases in CC\_CMIP5<sub>ZM</sub> (STD LatE  
421 PD\_CMIP5<sub>ZM</sub> = 3.04°; STD LatE CC\_CMIP5<sub>ZM</sub> = 4.96°), yielding larger northward SPCZ shifts during the future  
422 conditions than in the current day, for both strong and moderate El Niños. There are thus larger northward

423 displacements of the SPCZ during El Niños in the future than in the present day, especially in our bias-corrected  
424 experiments. But what about the frequency of those zonal events? Cai et al. (2012) demonstrated a near-doubling of  
425 SPCZ zonal events frequency in CMIP models under climate change, and linked this increase to a decreased SST  
426 meridional gradient south of the equator. To assess the robustness of this result in our experiments, we computed  
427 Empirical Orthogonal Functions (EOFs) of precipitation from our regional simulations and identified zonal SPCZ  
428 events from the value of the first two principal components as in Cai et al. (2012) (Figure 12). There are four SPCZ  
429 zonal events (red circle, Fig. 12 a,b) in both of our present-day simulations, corresponding to 1982/1983, 1991/1992,  
430 1997/1998 and 2015/2016 El Nino years. Contrary to what was found by Cai et al. (2012), we find the same number of  
431 SPCZ zonal events in the CC\_COR, CC\_OBS and CC\_CMIP5 climate change experiments, i.e. the doubling of zonal  
432 SPCZ events under future climate conditions is not robust to a change in model physics (CC\_CMIP5), and does not  
433 occur either when additionally correcting the historical CMIP5 SST bias or the  $\Delta SST_{GW}$  bias.

434 To conclude, global warming  $\square$  increases the interannual rainfall variability near the equator and decreases it  
435 under the SPCZ, especially when the SST projections are corrected. The increased equatorial rainfall variability is  
436 mainly related to the non-linear precipitation response to ENSO. Finally, the doubling of SPCZ zonal events discussed  
437 by Cai et al. (2012) is not reproduced in our simulations.

438

## 439 5. Sensitivity tests

440

### 441 **5.1 Sensitivity of the response to the model physics configuration**

442 It is crucial to assess the robustness of our findings with regards to the regional model physics, since it has a  
443 strong impact on how the SPCZ responds to climate change (e.g. Evans et al. 2016). To that end, we ran experiments  
444 with a completely different set of physical parameterizations that also yields a realistic representation of the South  
445 Pacific region climate (BMJ configuration; Jourdain et al., 2011; Jullien et al., 2014).

446 The climatological rainfall pattern (blue circles on Fig. 4) and those induced by ENSO variations (not shown)  
447 are also reasonably well simulated by that model configuration. PD\_OBS<sub>BMJ</sub> yields a realistic rainfall pattern (Fig. 4d)  
448 and latitude of the SPCZ eastern portion (Fig. 4b). However, it displays a 3° southward bias of the SPCZ western  
449 portion (Fig. 4c), resulting in a 25% underestimation of the SPCZ slope (Fig. 4a). In addition, this simulation exhibits a  
450 considerably reduced dry equatorial bias relative to PD\_OBS<sub>ZM</sub> (not shown), but a southward bias of the SPCZ (Fig.  
451 4b,c). Despite the differences in their present-day SPCZ climatology, the ZM and BMJ configurations yield a similar  
452 response to climate change, with a large rainfall increase in the equatorial Pacific in both COR and OBS (Fig 13a,b vs  
453 Fig 7c,d). The COR experiment also produces a large drying of the southwest and south-central Pacific (Fig. 13a vs Fig.  
454 7d). The main difference is a larger ITCZ drying in the BMJ configuration (~20% in BMJ vs ~10% in ZM), and overall  
455 more intense future changes. These anomalous rainfall patterns result in a southward shift (~3°) of the climatological  
456 SPCZ position from present day to future (black thick line vs black dashed line; Fig 13a,b) that is similar to that in the  
457 ZM configuration. In addition, as in ZM, the variability of the SPCZ eastern portion and its northward shift also  
458 increase in the future for our BMJ experiments (not shown; STD LatE PD\_OBS<sub>BMJ</sub> = 5.3°; STD LatE CC\_OBS<sub>BMJ</sub> = 8°;  
459 and STD LatE CC\_COR<sub>BMJ</sub> = 7.8° to be compared to : STD LatE PD\_OBS<sub>ZM</sub> = 4.24°; STD LatE CC\_OBS<sub>ZM</sub> = 6.21°;  
460 and STD LatE CC\_COR<sub>ZM</sub> = 6.18°). Finally, as in BMJ, correcting the CMIP5 mean state cold bias yields a larger

461 precipitation increase in the tropical region and correcting the projected SST change yields a larger drying of the SPCZ  
462 western portion (Fig. 13). Finally, as in ZM, the number of SPCZ zonal events does not increase under climate change  
463 in any of our BMJ simulations.

464 Overall, the main conclusions derived from the ZM configuration remain valid under a very different set of  
465 model parameterisations.

466

## 467 **5.2 Comparison with the CMIP models response**

468 A summary of the mechanisms responsible for the response of precipitation to climate change in the  
469 equatorial and South Pacific regions in CMIP5 models and our regional experiments is finally provided in Figure 14,  
470 which shows scatterplots of the dynamic and thermodynamic components of the moisture transport vs. the total  
471 transport, in key regions.

472 In the equatorial region, dynamical changes (i.e. increased wind convergence) are entirely responsible for  
473 the projected increased rainfall in CMIP5 models (black and gray dots in Fig. 14a,b). The same processes control the  
474 south central Pacific drying (Fig. 14c,d). In the southwest Pacific (Fig. 14e,f), there tends to be a cancellation between  
475 dynamical processes that tend to induce a drying through increased wind divergence and thermodynamical processes  
476 that increase moisture convergence and rainfall in the CMIP5 models. Depending on the respective contributions from  
477 these two processes, CMIP5 models either display increased precipitation in the southwest Pacific, resulting in a large  
478 spread across models and a nearly-zero ensemble mean projected rainfall change.

479 The CMIP<sub>ZM</sub> and CMIP<sub>BMJ</sub> experiments lie at the upper end of the CMIP5 models distribution in both the  
480 western equatorial Pacific (blue symbols in Fig. 14a,b) and the south central Pacific (blue symbols in Fig. 14c,d), the  
481 dynamical component largely explaining the total changes. Correcting historical CMIP5 SST and  $\Delta$ SST<sub>GW</sub> biases  
482 generally lead to an increase of the dynamical response and hence of the rainfall anomaly, this increase being  
483 particularly prominent in the western equatorial Pacific for BMJ. In southwestern Pacific, the drying by dynamical  
484 processes is about  $\sim 20\%$  larger in the experiment using  $\Delta$ SST<sub>COR<sub>GW</sub></sub> (Fig. 14e). On the other hand, the  
485 thermodynamical effects are very similar in all our experiments (Fig. 14f), and have similar amplitudes to those in  
486 CMIP5 models. This yields a larger southwest Pacific drying in the experiments using  $\Delta$ SST<sub>COR<sub>GW</sub></sub>. In other words,  
487 the cold tongue bias induces a bias in projected SST that yield an underestimated change in circulation and associated  
488 moisture divergence, and thus an underestimated southwest Pacific drying.

489

## 490 **6. Summary and discussion**

491

### 492 **6.1 Summary**

493 This study investigates the influence of anthropogenic forcing on the SPCZ mean state and interannual  
494 variability. A present-day simulation (PD\_OBS) with a regional atmospheric model captures the main observed SPCZ  
495 characteristics, with a similar degree of realism to that in the NCEP2 reanalysis. This includes the SPCZ mean state but  
496 also its northward/southward displacements associated with ENSO, including the SPCZ zonal events during extreme El  
497 Niño events. This accurate present-day simulation of the SPCZ justifies the use of our regional model configuration to

498 assess the SPCZ response to climate change. In contrast, a twin simulation with CMIP5 climatological SST (and the  
499 trademark cold tongue bias in CMIP models) yields to a similar SPCZ bias as in the CMIP5 models, with a too zonal  
500 SPCZ.

501 We further performed three simulations to estimate the influence of climate change: CC\_CMIP5, CC\_OBS,  
502 and CC\_COR. In CC\_CMIP5 and CC\_OBS, the boundary conditions from the PD\_CMIP5 and PD\_OBS experiments  
503 are corrected using projected changes from CMIP5. Comparing those two experiments allows for assessing the effect of  
504 the SST bias in CMIP5 models. The CC\_COR simulation is similar to CC\_OBS, but the projected SST change from the  
505 CMIP5 ensemble mean  $\Delta\text{SST}_{\text{GW}}$  is additionally corrected using an “emergent constraint” method, based on Li et al.  
506 (2016). Comparing this last experiment to CC\_OBS allows estimating the effect of the  $\Delta\text{SST}_{\text{GW}}$  bias on the SPCZ  
507 changes.

508 To assess the sensitivity to model physics, we compared our CC\_CMIP5<sub>ZM</sub> simulation to the CMIP5 multi-  
509 model mean. The SPCZ response to climate change is slightly more intense in CC\_CMIP5<sub>ZM</sub> than in CMIP5 MMM,  
510 with a slightly stronger increase of precipitation in the equatorial region ( $\sim 2.2\text{mm}\cdot\text{day}^{-1}$  in CMIP5 MMM and  
511  $2.5\text{mm}\cdot\text{day}^{-1}$  CMIP5<sub>ZM</sub> experiment), and a stronger drying in the southeastern Pacific ( $-1\text{mm}\cdot\text{day}^{-1}$  compared to -  
512  $0.4\text{mm}\cdot\text{day}^{-1}$ ), leading to a shrinkage of the SPCZ. Our model setup hence reproduces qualitatively the rainfall changes  
513 in CMIP5 MMM, but magnifies the amplitude of the precipitation response to anthropogenic forcing.

514 To evaluate the impact of historical CMIP5 SST biases, we compared the CC\_OBS<sub>ZM</sub> simulation to  
515 CC\_CMIP5<sub>ZM</sub>. Correcting the CMIP5 historical SST bias leads to a much stronger equatorial Pacific rainfall increase in  
516 response to climate change ( $\sim 3.5\text{mm}\cdot\text{day}^{-1}$  vs.  $2.5\text{mm}\cdot\text{day}^{-1}$  in the CMIP5<sub>ZM</sub> experiment), mainly due to a weaker  
517 negative feedback of the thermodynamic component of moisture transport in CC\_OBS<sub>ZM</sub>. The drying in the southwest  
518 Pacific is hardly influenced by the CMIP5 SST bias ( $0.9\text{mm}\cdot\text{day}^{-1}$  rainfall decrease in CC\_OBS<sub>ZM</sub> vs.  $1\text{mm}\cdot\text{day}^{-1}$  in  
519 CMIP5<sub>ZM</sub>). These changes are associated with a  $\sim 4^\circ$  southward shift of the mean SPCZ location west of  $170^\circ\text{W}$ .

520 Finally, an original aspect of our study is our evaluation of the impact of plausible biases in the projected SST  
521  $\Delta\text{SST}_{\text{GW}}$ , by comparing CC\_COR<sub>ZM</sub> with CC\_OBS<sub>ZM</sub>. In CC\_COR<sub>ZM</sub> the equatorial rainfall increase is weaker than in  
522 CC\_OBS ( $3\text{mm}\cdot\text{day}^{-1}$  vs.  $3.5\text{mm}\cdot\text{day}^{-1}$ ), while the southeastern Pacific becomes much drier ( $-1.9\text{mm}\cdot\text{day}^{-1}$  vs. -  
523  $0.9\text{mm}\cdot\text{day}^{-1}$ ), and the drying extends further west to  $150^\circ\text{E}$ . Correcting the projected SSTs changes the SST gradients  
524 in the southwestern Pacific, leading to southeasterlies that penetrate further west and north. This induces more moisture  
525 divergence through dynamical processes, and hence a larger drying.

526 All the climate change simulations display enhanced rainfall variability in the equatorial region, but this  
527 change is not the same across ENSO phases. The precipitation increase is strongest during extreme El Niño years,  
528 illustrating the non-linearity of the precipitation response to climate change during ENSO phases, as also found in the  
529 idealized framework of Chung et al., (2014). Finally, our analyses show that the number of SPCZ zonal events under  
530 climate change conditions remains similar to the present-day conditions in all our simulations, in contrast with the result  
531 of Cai et al. (2012) in CMIP3-5 models, questioning the robustness of this result.

532 Last but not least, additional regional simulations using a completely different set of physical  
533 parameterizations give qualitatively similar patterns for the future SPCZ mean change and how these are influenced by  
534 CMIP biases, underlining the robustness of our results.

535

536 **6.2 Discussion**

537 Several studies have already investigated the impact of climate change onto the mean climate within the  
538 SPCZ region, either by directly comparing global climate models (Brown et al. 2012, 2013) or by comparing  
539 atmospheric experiments forced with and without climate change boundary conditions anomalies (Widlansky et al. 2013;  
540 Brown et al. 2015; Evans et al. 2016). A direct analysis of CMIP5 models outputs reveals that the climate change  
541 warming pattern results in a robust precipitation increase in the equatorial Pacific (e.g. Watanabe et al. 2014; Li et al.,  
542 2016), a weak drying of the southeast SPCZ margin in the CMIP5 models but no consistent shift in climatological  
543 SPCZ position (Brown et al. 2012, 2013). Despite stronger rainfall change in our sets of experiments than in CMIP5  
544 MMM, we find that the increased equatorial rainfall and dryer eastern SPCZ are robust features. On the other hand,  
545 CMIP5 MMM, our CC\_OBS<sub>ZM</sub> and CC\_CMIP5<sub>ZM</sub> simulations show an insignificant drying in the western SPCZ part,  
546 while, by contrast, our CC\_COR<sub>ZM</sub> simulation yields a strong significant drying (-20%) in this region.

547 Our results in the OBS experiment are in qualitative agreement with the atmospheric experiments of  
548 Widlansky et al. (2013). Indeed their climate-change bias-corrected simulations pointed toward a significant drying of  
549 the SPCZ and wetter equatorial Pacific conditions during austral summer. In contrast, results from the present-day SST  
550 bias-corrected experiments from Brown et al. (2015) still indicate a future wettening of the southwest Pacific. We  
551 however suggest our results to be more reliable than Brown et al. (2015), due to a more realistic experimental strategy.  
552 Indeed, Brown et al. (2015) used an idealized framework by forcing their atmospheric model with annually averaged  
553 SST, which may have impaired the realism of their projected rainfall response. As acknowledged by these authors, their  
554 objective was indeed not to provide a reliable projection of future rainfall but rather to demonstrate the sensitivity of the  
555 rainfall response to the underlying SST patterns. Evans et al. (2016) also used a present-day SST bias-corrected  
556 strategy, with several regional climate models forced by the same CMIP global warming anomalous pattern. While they  
557 showed that their projected rainfall response was not very sensitive to the choice of the CMIP model used to force their  
558 regional model boundaries, their projections in the southwest Pacific region were more sensitive to the  
559 parameterizations used in their regional model. Despite this sensitivity, they indicated that the majority (7 out of 9) of  
560 their configurations projected a significant drying of the southwest Pacific, in line with Widlansky et al. (2013) and the  
561 present study.

562 In our COR experiment, we have tested the sensitivity of the rainfall response to the characteristics of  
563 the projected SST pattern. Brown et al. (2015) suggested that the amplitude of the rainfall response could be highly  
564 sensitive to the pattern of SST warming. Huang and Ying (2015) and Li et al. (2016) confirmed that the well-known  
565 cold tongue bias in most CMIP models could lead to an underestimation in the east-minus-west gradient of the  
566 projected sea surface warming along the equator. In contrast, Widlansky et al. (2013) argued that the SST warming  
567 pattern was independent of the climatological SST bias by comparing the SST warming pattern from a climate model  
568 run with and without flux adjustment strategy. In line with the previous statistical studies (Huang and Ying, 2015; Li et  
569 al. 2016), we find that biases in the pattern of CMIP5 sea surface warming considerably influence the future changes of  
570 regional precipitations. Future precipitation changes in the western tropical Pacific are indeed driven by two main  
571 processes, which respective contributions are strongly influenced by the underlying background SSTs: a “wet gets  
572 wetter” thermodynamic response and a “warmest gets wetter” dynamical response due to the overall tropical circulation  
573 slowdown (Widlansky et al. 2013).

574 Despite the absence of consensus on how SST variability associated with ENSO may change in the  
575 future (e.g. Cai et al., 2015), CMIP3-5 models project a future increase in the frequency of zonal SPCZ events, which



576 has been attributed to mean changes in meridional SST gradient between the equator and the South Pacific (Cai et al.  
577 2012). In line with recent studies using similar experimental strategy (Chung and Power 2016; Evans et al. 2016), our  
578 results suggest that the frequency of zonal SPCZ events may not increase in the future, in apparent contradiction with  
579 Cai et al. (2012) results. Several reasons could explain this apparent discrepancy. First, while CMIP5 mean present-day  
580 biases have been corrected in all the later studies, the common CMIP model biases in Cai et al. (2012), including the  
581 cold tongue bias, may largely responsible for the unrealistic increase of the zonal SPCZ events frequency in CMIP  
582 simulations. Second, the present and future SST variability is kept constant in our simulations and those of Chung and  
583 Power (2016): it may well be that, in contradiction to what has been initially proposed by Cai et al. (2012), the mean  
584 SST changes may not be the dominant mechanism explaining the zonal SPCZ events frequency increase in their study.  
585 Rather, consistent changes in SST interannual variability in CMIP models may be partly responsible for this increase.  
586 Other hypotheses explaining this discrepancy include as well the diversity of the  $\Delta\text{SST}_{\text{GW}}$  patterns across the CMIP5  
587 models, not taken into account in our multi-model mean of  $\Delta\text{SST}_{\text{GW}}$  CMIP5 pattern or the lack of atmosphere–ocean  
588 feedbacks in these forced atmospheric simulations compared to CMIP models.

589 In any case, this study highlights the importance of a realistic simulation of the tropical Pacific mean state for  
590 improving regional climate projections. Tropical Pacific SST biases, including the prominent cold tongue bias,  
591 influence the projected rainfall response directly but also indirectly by altering the projected SST changes. While a  
592 long-term objective is clearly to reduce long-standing robust SST biases in the tropical Pacific in CMIP models, this  
593 study also advocates for a shorter-term strategy, by using standalone atmospheric experiments where present-day and  
594 future SST projection are bias-corrected. This study also highlights the need to perform this kind of strategy with  
595 different models: while the bias correction approach used in this bias-corrected forced atmospheric study is likely to  
596 improve the reliability of future projection, atmosphere-only present-day simulations still exhibit significant SPCZ  
597 biases (Lintner et al. 2016) that may still impair the reliability of the projected changes, as illustrated by the significant  
598 quantitative differences in the projected rainfall changes in our two model configurations (Fig. 7d vs. Fig. 13a). It is also  
599 possible that the reanalysis products used to build the boundary conditions influence the SPCZ response to  
600 anthropogenic forcing, since the present characteristics of the SPCZ are more or less captured according to the  
601 reanalysis used (eg, Niznik et al. Lintner 2013). Therefore a sensitivity experiment to this parameter will be tested.  
602 Finally, the sensitivity of the projected changes to the statistical correction method used to correct the projected SST  
603 changes should also be tested: results with the simple correction strategy proposed by Li et al. (2016) should be  
604 compared with more complex strategies, such as the one proposed by Huang and Ying (2015) which extracts the  
605 leading bias modes of historical SST CMIP5 simulations and then projecting the tropical Pacific SST changes onto  
606 these historical bias modes.

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