

1 **Model under-representation of decadal Pacific trade wind trends and its link to tropical Atlantic bias**

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3 Jules B. Kajtar\*<sup>1,2,3</sup> (orcid.org/0000-0003-0114-6610), Agus Santoso<sup>1,2</sup> (orcid.org/0000-0001-7749-8124),

4 Shayne McGregor<sup>1,4</sup> (orcid.org/0000-0003-3222-7042), Matthew H. England<sup>1,2</sup> (orcid.org/0000-0001-9696-

5 2930), and Zak Baillie<sup>1,2</sup>

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7 <sup>1</sup> Australian Research Council's Centre of Excellence for Climate System Science, Australia

8 <sup>2</sup> Climate Change Research Centre, University of New South Wales, NSW, Australia

9 <sup>3</sup> College of Engineering, Mathematics, and Physical Sciences, University of Exeter, Exeter, UK

10 <sup>4</sup> School of Earth, Atmosphere and Environment, Monash University, Victoria, Australia

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12 \* Corresponding author: Jules B. Kajtar; j.kajtar@exeter.ac.uk. Now at College of Engineering,

13 Mathematics, and Physical Sciences, University of Exeter, Exeter, UK

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15 Keywords: Pacific trade winds, decadal variability, Walker Circulation, CMIP5

16

17 **Acknowledgements**

18 This study was supported by the Australian Research Council. We acknowledge the World Climate Research

19 Programme's Working Group on Coupled Modelling, which is responsible for the Coupled Model

20 Intercomparison Project (CMIP), and we thank the climate modelling groups for producing and making their

21 model output available. We also acknowledge the observational reconstructions provided by the Hadley

22 Centre (HadISST), NOAA/OAR/ESRL PSD (20<sup>th</sup> Century Reanalysis, ERSST and NCEP/NCAR

23 Reanalysis), and ECMWF (ERA-20C).

24 **Abstract**

25 The strengthening of the Pacific trade winds in recent decades has been unmatched in the observational  
26 record stretching back to the early twentieth century. This wind strengthening has been connected with  
27 numerous climate-related phenomena, including accelerated sea-level rise in the western Pacific, alterations  
28 to Indo-Pacific ocean currents, increased ocean heat uptake, and a slow-down in the rate of global-mean  
29 surface warming. Here we show that models in the Coupled Model Intercomparison Project phase 5  
30 (CMIP5) underestimate the observed range of decadal trends in the Pacific trade winds, despite capturing the  
31 range in decadal sea surface temperature (SST) variability. Analysis of observational data suggests that  
32 tropical Atlantic SST contributes considerably to the Pacific trade wind trends, whereas the Atlantic  
33 feedback in coupled models is muted. Atmosphere-only simulations forced by observed SST are capable of  
34 recovering the time-variation and the magnitude of the trade wind trends. Hence, we explore whether it is the  
35 biases in the mean or in the anomalous SST patterns that are responsible for the under-representation in fully  
36 coupled models. Over interannual time-scales, we find that model biases in the patterns of Atlantic SST  
37 anomalies are the strongest source of error in the precipitation and atmospheric circulation response. In  
38 contrast, on decadal time-scales, the magnitude of the model biases in Atlantic mean SST are directly linked  
39 with the trade wind variability response.

## 40 **1. Introduction**

41 The Pacific trade wind strengthening in recent decades has been unprecedented in the observational record  
42 stretching back to the late 19<sup>th</sup> century (L'Heureux et al. 2013). The acceleration has been proposed as the  
43 mechanism behind the early 21<sup>st</sup> century global surface warming slowdown (England et al. 2014). In this  
44 mechanism, heat uptake is increased through the acceleration of the wind-driven ocean overturning  
45 circulation, and the subducted heat is accumulated in the western Pacific (England et al. 2014) before being  
46 transported to the Indian Ocean via the Indonesian Throughflow (Lee et al. 2015). These upper ocean  
47 circulation changes have altered the pattern of sea surface temperature trends over the Pacific Ocean. Given  
48 the profound climatic impacts associated with a redistribution of heat in the upper ocean, understanding the  
49 drivers of Pacific trade wind variability is essential for interannual and decadal climate predictions and  
50 monitoring.

51

52 The Pacific trade winds are the surface level expression of the Pacific Walker Circulation cell (e.g. Gill  
53 1980). This cell encompasses an ascending branch over the Maritime Continent, prevailing westerly winds in  
54 the upper troposphere, a descending branch over the eastern Pacific, and the trade winds that extend across  
55 the surface of the equatorial Pacific Ocean. Possible reasons for the unprecedented trade wind acceleration  
56 during the early 21<sup>st</sup> century – beyond that due to the negative phase of the Interdecadal Pacific Oscillation  
57 (IPO; England et al. 2014) – include contributions from aerosol forcing (Takahashi and Watanabe 2016), and  
58 sea surface warming trends over the Indian Ocean (Luo et al. 2012; Mochizuki et al. 2016), or Atlantic  
59 (Kucharski et al. 2011; McGregor et al. 2014; Chikamoto et al. 2016; Kucharski et al. 2016a; Kucharski et al.  
60 2016b; Li et al. 2016; Ruprich-Robert et al. 2016), or both (Zhang and Karnauskas 2017). Using atmospheric  
61 model experiments forced with SST trends, McGregor et al. (2014) and Li et al. (2016) argued that the  
62 Atlantic warming is more important than the Indian Ocean warming, although tropical interactions across the  
63 three ocean basins can be quite different across different time-scales (Kajtar et al. 2016; Kucharski et al.  
64 2016b). Specifically, El Niño tends to heat the Indian and Atlantic basins on interannual time-scales (Lau  
65 and Nath 1994), whereas Indian and Atlantic SST trends tend to influence the Pacific on multi-decadal time-  
66 scales (e.g. Li et al. 2016). Coupled models may be deficient in this regard, with eastern Pacific SST  
67 apparently overly constraining the global mean climate (Douville et al. 2015). However, the model mismatch  
68 on decadal variability does not appear to have implications for future projections (England et al. 2015).

69

70 The recent trade wind acceleration is in apparent contrast to the projected weakening of the Walker  
71 Circulation under greenhouse warming (Vecchi et al. 2006; Vecchi and Soden 2007). Power and Kociuba  
72 (2011) showed that models and observations tend to be in agreement regarding the weakening trend of the  
73 Walker Circulation over the 20<sup>th</sup> Century, and external forcing has been estimated to account for about half  
74 of the change. Yet recent studies (e.g. England et al. 2014; Kociuba and Power 2015) show that historical  
75 and pre-industrial model simulations participating in the Coupled Model Intercomparison Project, phase 5  
76 (CMIP5) appear unable to reproduce anywhere near the magnitude of the recent observed trends. The  
77 reasons behind this shortcoming in models remains unclear. Motivated by the importance of the Pacific trade  
78 winds on global climate, our study aims to explore the contribution of Atlantic Ocean SST variations on  
79 Pacific trade wind trends in climate models. We find that biases in the patterns of Atlantic SST anomalies, as  
80 well as the mean Atlantic SST distribution, likely inhibit the tropical Atlantic connection to the central  
81 Pacific on decadal time-scales in CMIP5 models. An understanding of the nature of these biases will thus  
82 ultimately help to explain the underestimation of the Pacific trade wind variability in models, and lead to  
83 improved multi-year forecasting skill (Chikamoto et al. 2015).

84

85 The rest of this paper is divided as follows. After outlining the data and methods in Section 2, the decadal  
86 wind stress and SST trends in observations and models, and the relationships between them, are analysed in  
87 Section 3. We then explore the notable differences in the Atlantic feedback in models as compared to  
88 observations (Section 4), before delving into an analysis of the source of the atmospheric response bias in  
89 models (Section 5).

90

## 91 **2. Data and methods**

92 In this study, we focus on the drivers of Pacific trade winds trends over the 20<sup>th</sup> and early 21<sup>st</sup> century, in  
93 observations and the historical CMIP5 simulations. Since most historical simulations end at year 2005, we  
94 extend them with the RCP8.5 scenario simulations to cover a common time-span of 1900 to 2014 amongst  
95 all models and reanalysis products. The choice of RCP extension does not make a significant difference for  
96 this early period of the 21<sup>st</sup> century (e.g. England et al., 2015). Using only the “r1i1p1” experiments, models  
97 that do not span from the year 1900, or do not have an appropriate RCP8.5 extension, are not included. The

98 three variables analysed herein were sea surface temperature (CMIP5 variable name: tos), wind stress (tauu),  
99 and rainfall (pr). Later we also analyse the Atmospheric Model Intercomparison Project (AMIP) r1i1p1  
100 simulations, which were run with observed SST forcing, but this experiment is available for fewer models,  
101 and only over the period 1979 to 2008.

102 The observed data was gathered from the HadISST (Rayner et al. 2003), NOAA-20CR v2c (Compo et al.  
103 2011) and ERA-20C (Poli et al. 2016) reanalysis products. The HadISST sea surface temperature is analysed  
104 together with the NOAA-20CR wind stress and precipitation, whereas the ERA-20C product has all three  
105 variables available. Again, we choose a common period of 1900 to 2014, with the exception of ERA-20C,  
106 which ends at 2010. The NOAA-20CR/HadISST and ERA-20C reanalysis products provide the  
107 observational basis for our model comparison throughout, but for validation purposes, we initially compare  
108 sea surface temperature trends to ERSST v4 (Huang et al., 2014) and wind stress trends to NCEP/NCAR  
109 Reanalysis 1 (Kalnay et al. 1996).

110

111 Most of the following analysis is of running 10-year trends, but where we use annual data, the 11-year  
112 running mean is first removed from the time-series to nullify lower frequency variability. All quoted values  
113 of correlation are the Pearson's correlation coefficient.

114

### 115 **3. Decadal wind stress and SST trends in observations and models**

116 Observed zonal wind stress variability across the equatorial Pacific tends to be greater in the west, peaking  
117 near the dateline, as shown by the standard deviation of the annual data and 10-year trends in the reanalysis  
118 products (Fig. 1a, b). The CMIP5 models exhibit a large distribution, and while most models do simulate the  
119 stronger variability in the west, the ensemble mean peak in variability is too far to the east, and the overall  
120 magnitude of variability, particularly over decadal time-scales, is underestimated. This model deficiency is  
121 further highlighted in the range of the 10-year trends in  $\tau_{PAC}$ , an index of zonal wind stress averaged over  
122  $160^{\circ}E - 150^{\circ}W$  and  $8^{\circ}S - 8^{\circ}N$  (Fig. 1c). Although some models simulate the observed extreme positive  
123 trends (i.e. trade wind decelerations), none capture the range, nor the extreme negative trends observed in  
124 recent decades (i.e. the recent trade wind acceleration). Note however that the two reanalysis products are not  
125 completely consistent with each other, with the NOAA-20CR trends showing larger range than those  
126 calculated using ERA-20C. This difference is primarily due to a strong negative trend in NOAA-20CR in the

127 early 20<sup>th</sup> Century (Fig. S1), but these early observations tend to be less reliable. To check the consistency  
128 among observations, we introduce the NCEP/NCAR reanalysis wind stress. There is reasonable agreement in  
129 the 10-year trends of the Pacific wind stress index (Fig. S1a), and the running correlations between them tend  
130 to improve with time (Fig. S1c). The NCEP/NCAR reanalysis is not used in the remainder of this study due  
131 to its shorter time coverage (it starts in 1948).

132

133 McGregor et al. (2014) showed that the Atlantic-Pacific SST see-saw is a strong driver of the Pacific trade  
134 winds. More specifically, they revealed a strong correlation between the “trans-basin variability (TBV)  
135 index” and western Pacific wind stress. The TBV is defined as the difference between the area-averaged  
136 Atlantic SST (ATL; 70°W–20°E) minus Pacific SST (PAC; 120°E–90°W). It will be shown later that  
137 tropical SST between 20°S–20°N contributes most strongly to the central Pacific wind stress trends, hence  
138 the choice here to restrict the TBV index to this meridional range (in contrast to McGregor et al. 2014, who  
139 use the domain 30°S–60°N). The two observational products show stronger agreement in the TBV trends  
140 compared with the  $\tau_{\text{PAC}}$  trends (Fig. 2a), most likely because the TBV is an area-average over a much larger  
141 region. But to provide further validation, we introduce the ERSST product. There is agreement between all  
142 three sets (Fig. S1b). Again, the running correlations tend to improve over time (Fig. S1d), although the  
143 world-war I and II periods are marked by sharp declines, most likely due to sparser observations. The  
144 HadISST climatology is used in favour of ERSST from this point on, primarily because it is of higher  
145 resolution. Overall, the CMIP5 models appear to capture the observed variability of the TBV index, as well  
146 as the Pacific and Atlantic components separately (Fig. 2). The multi-model range in 10-year trends of the  
147 TBV index compares well with the observed, although individual models exhibit different levels of  
148 variability (Fig. 2a). Somewhat surprisingly, the 5% to 95% range in the multi-model distribution of 10-year  
149 trends in PAC spans a larger range than the observed (cf. black and grey bars, Fig. 2b), however the number  
150 of sampled decades is of course much larger in the multi-model set compared to the individual observed  
151 realisations.

152

153 The trans-basin SST gradient correlates strongly with western Pacific wind stress at the annual time-scale in  
154 observations (McGregor et al. 2014). For our TBV narrowed to the tropics, the correlation with the wind  
155 stress is stronger for decadal trends than with annual data (namely, -0.84 compared with -0.76 for NOAA-

156 20CR, and -0.75 compared with -0.58 for ERA-20C). Despite the deficiency in simulating the observed  $\tau_{\text{PAC}}$   
157 variability (Fig. 1), the models nevertheless capture the decadal TBV- $\tau_{\text{PAC}}$  correlation reasonably well (Fig.  
158 S2), although the multi-model ensemble correlation is slightly underestimated. In terms of the sensitivity of  
159 the wind stress trends to the TBV, almost all the models also underestimate compared to the observed  
160 relationships (Fig. 3a). This indicates that the smaller range of Pacific wind trends in the models could be  
161 due to a weaker coupling between the winds and the SST gradient across the Pacific-Atlantic basins. Further  
162 examination of the individual TBV components reveals that the models perform well in capturing the  
163 observed correlation between the wind and the PAC SST index (Fig. S2). Although the models are again  
164 consistent in the sign of the regression, the apparent degree of coupling is also underestimated (Fig. 3b). In  
165 stark contrast, the relationship between Pacific zonal wind stress and the ATL index shows a large disparity  
166 between models and observations (Fig. S2, 3c), with inconsistent sign in the correlations across models.  
167 Twelve models exhibit statistically significant positive correlations, (i.e. warm Atlantic SST trends  
168 correspond with westerly Pacific wind stress trends), and the rest of the models show statistically  
169 insignificant correlations. In contrast, the NOAA-20CR  $\tau_{\text{PAC}}$  correlation with HadISST ATL is negative and  
170 statistically significant. The ERA-20C negative correlation is not statistically significant over the entire 20th  
171 century period, but the agreement with NOAA-20CR improves over more recent decades. For example, over  
172 the period 1970 to 2014, the regression between 10-year trends in  $\tau_{\text{PAC}}$  and ATL is  $-0.034 \text{ N m}^{-2} \text{ K}^{-1}$  ( $p < 0.01$ )  
173 for NOAA-20CR and  $-0.030 \text{ N m}^{-2} \text{ K}^{-1}$  ( $p < 0.01$ ) for ERA-20C.

174

175 Since the Indian Ocean is known to influence the Pacific on decadal time-scales (Luo et al. 2012; Li et al.  
176 2016; Mochizuki et al. 2016; Zhang and Karnauskas 2017), it is instructive to explore the relationship  
177 between Indian Ocean SST (IND; averaged over  $20^{\circ}\text{S}$ – $20^{\circ}\text{N}$  and  $40^{\circ}\text{E}$ – $120^{\circ}\text{E}$ ) and the Pacific wind stress  
178 index. As with the TBV and PAC indices, but aside from a small number of exceptions, the models are  
179 overall consistent with observations with regard to the relationship between  $\tau_{\text{PAC}}$  and IND (Fig. S3).

180

181 It is clear that overall the Pacific component of the TBV is more strongly connected with decadal Pacific  
182 wind stress trends than the Atlantic, or indeed with the Indian Ocean. For example, in the NOAA-20CR  
183 product, the Pacific wind stress response is  $0.35 \text{ N m}^{-2} \text{ K}^{-1}$  to PAC (Fig. 3b) compared with  $-0.17 \text{ N m}^{-2} \text{ K}^{-1}$  to  
184 ATL (Fig. 3c). But the unprecedented 1992 to 2011 equatorial Pacific wind stress trend was not consistent

185 with a Pacific-only SST driving mechanism (England et al. 2014). The Atlantic SST trend seems to have  
186 been crucial for the unprecedented trade wind trends (McGregor et al. 2014; Chikamoto et al. 2016), and in  
187 fact the Atlantic may be the most consistent remote driver of tropical SST variability (Li et al. 2016;  
188 Kucharski et al. 2016b). The differences across the models and with observations seen in Fig. 3c motivate  
189 further examination on the implications of the inconsistent Atlantic feedback on the Pacific wind-stress  
190 trends via the TBV. The Indian Ocean is not explored further, since, as noted earlier, the models largely  
191 behave consistently with observations in that connection.

192

#### 193 **4. Contribution of tropical Atlantic SST bias**

194 Over interannual time-scales, the Atlantic component tends to dominate the TBV index (McGregor et al.  
195 2014), and this relationship persists for the re-defined TBV domain used in this study. On decadal time-  
196 scales, the Atlantic component continues to play a strong role, although its contribution to the TBV is  
197 slightly weaker than the Pacific component (in observations; Fig. 4a). The models, on the other hand, tend to  
198 show a weaker TBV contribution from the Atlantic (see MMM, Fig. 4a). The correlations across models  
199 suggest that where the Atlantic SST trends contribute more strongly to the TBV, the correlation between the  
200 ATL index and  $\tau_{\text{PAC}}$  trends tend to be more negative (Fig. 4b). In other words, where there is a stronger  
201 Atlantic contribution to trans-basin SST variability in models, warm Atlantic SST trends are more strongly  
202 connected with enhanced Pacific trade wind trends, as seen in observations. Similarly, the inter-model  
203 analysis shows that stronger correlations between PAC and TBV trends tend to occur with stronger  
204 correlation between PAC SST and  $\tau_{\text{PAC}}$  trends (Fig. 4c). It is important to again emphasise that among  
205 models, the ATL and  $\tau_{\text{PAC}}$  correlation is less consistent with observations than the PAC and  $\tau_{\text{PAC}}$  correlation.  
206 This strong inter-model disagreement, but statistically significant relationship (Fig. 4b), motivates the  
207 analysis of Pacific wind trend responses specifically to Atlantic SST trends in models.

208

209 The regressions of running 10-year  $\tau_{\text{PAC}}$  trends with SST reveal an Interdecadal Pacific Oscillation (IPO)  
210 signature that is similar in the multi-model mean (Fig. 5a) and the two reanalysis products (Fig. 5c, e).  
211 Models perform reasonably well in simulating the IPO (Henley et al. 2017), and so this robust connection to  
212 the Pacific trade wind trends is not surprising. Differences between the modelled and observed regression  
213 patterns are nevertheless apparent. For instance, the  $\tau_{\text{PAC}}$  trends in observations are more sensitive than in



214 models to SST trends over the Pacific and Indian Oceans, including the Maritime Continent. But despite the  
215 differences in magnitude in these regions, the multi-model regressions are at least of the same sign as the  
216 observations. This is in stark contrast to the Atlantic, where the regression pattern is entirely different in the  
217 models and observations. Namely, there is a statistically significant positive signal in the southern tropical  
218 Atlantic in the multi-model mean, while the observations display a statistically significant negative signal. It  
219 is known that the CMIP5 models exhibit strong biases in the southern tropical Atlantic, and the biases  
220 originate from a range of possible sources (e.g., Toniazzo and Woolnough 2014). The observations reveal an  
221 Atlantic meridional dipole signature, and although the positive signal emerges in the northern tropical  
222 Atlantic in the model mean, it is confined closer to the equator. The Atlantic dipole pattern in observations,  
223 however, does not give a complete picture, since this regression analysis treats each spatial point  
224 independently of its neighbours. We have performed a multiple linear regression analysis to re-construct the  
225  $\tau_{\text{PAC}}$  trends from SST trends alone, which incorporates the area-average SST trends of the Pacific, and the  
226 South and North Atlantic Ocean regions, as three separate terms. In that reconstructed expression, the  
227 coefficients for the North and South Atlantic terms carry the same sign. In other words, when considering the  
228 Atlantic SST influence on the Pacific trade wind trends, our choice of using the ATL region is appropriate,  
229 and does not need to be split further into northern and southern components to capture opposite signs, as  
230 might have been inferred from Fig. 5c, e.

231

232 Considering the different  $\tau_{\text{PAC}}$  trend responses to Atlantic SST trends among models and observations (Fig.  
233 3c), we now examine the atmospheric response, specifically rainfall, to Atlantic SST trends. Interestingly,  
234 there is stronger agreement between the models and observations for the  $\tau_{\text{PAC}}$  trends regressed with  
235 precipitation trends across the tropical Atlantic (Fig. 5b, d, e). In particular, the negative signals denote  
236 decreasing Atlantic precipitation trends in association with westerly  $\tau_{\text{PAC}}$  trends. This precipitation linkage  
237 reflects Atlantic convection changes and their associated impact on the Pacific Walker circulation  
238 (McGregor et al. 2014). Surprisingly, the decreased precipitation over the tropical Atlantic (Fig. 5b) does not  
239 appear to be consistent with local warming trends in the models (Fig. 5a). This is unlike the observations in  
240 which reduced precipitation (Fig. 5d, f) can be seen as a physically consistent response to local sea surface  
241 cooling (Fig. 5c, e; more clearly seen in the southern tropical Atlantic). Finally, it is interesting to note that

242 the familiar double-intertropical convergence zone (ITCZ) is apparent in the multi-model mean even on this  
243 decadal time-scale (Fig. 5b; Lin 2007).

244

245 The Atlantic Ocean model discrepancy can be explored further by examining the responses to Atlantic SST  
246 trends, as done by regressing the ATL index onto grid-point SST and rainfall (Fig. 6). This analysis shows  
247 that, unlike in the observations (Fig. 6d, f), the precipitation response over the tropical Atlantic in the multi-  
248 model mean is very weak, with little stippling (Fig. 6b), despite similarities in the SST patterns (cf. Fig. 6a  
249 and Fig. 6c, e; albeit weaker in the multi-model mean). This indicates that either the Atlantic precipitation  
250 response is too weak in each of the models, or that large inter-model diversity tends to cancel out positive  
251 and negative responses in the multi-model mean. Either way, the modelled precipitation response in the  
252 tropical Atlantic appears to respond more consistently to the tropical Pacific warming (which induces  
253 subsidence and therefore drying on the Atlantic side), rather than local SST trends (cf. Fig. 5b and Fig. 6b).  
254 In this way, the models seem to simulate overly strong remote forcing of the Atlantic by Pacific SST, and too  
255 little forcing of the Pacific by Atlantic SST. It will be shown later that the Atlantic precipitation response to  
256 local SST is even weaker on the annual time-scale. In terms of the Pacific response, the models show  
257 increasing central Pacific precipitation (Fig. 6b), which is consistent with the Pacific warming (Fig. 6a). The  
258 observed analyses (Fig. 6d, f) on the other hand show decreasing central Pacific precipitation, consistent with  
259 either Pacific cooling or Atlantic warming, both of which are known to induce atmospheric subsidence over  
260 the Central Pacific (McGregor et al. 2014; Chikamoto et al. 2016; Li et al. 2016). Since precipitation is a  
261 proxy for convection, these results indicate that the models are deficient in simulating convective processes  
262 over the tropical Atlantic. If convection is muted, then so too will be the influence of the Atlantic on the  
263 descending branch of the Pacific Walker Circulation cell, thus leading to weaker Atlantic influence on the  
264 surface level expression of the Walker Circulation, namely the Pacific trade winds. Hence our findings  
265 indicate that the Atlantic-Pacific connection in the models is not consistent with observations. It is likely due  
266 to biases in the Atlantic region that appear to limit the response of the atmospheric circulation and  
267 convection to the underlying SST anomalies.

268

269 **5. Possible causes of atmospheric response bias**

270 To further elucidate the nature of the biases in the coupled models, we first consider whether similar issues  
271 also exist in atmospheric-only simulations. Here we examine the Atmospheric Model Intercomparison  
272 Project (AMIP) simulations from the CMIP5 model set. The AMIP experiments are simulated with observed  
273 global SST fields, but they are only available for much shorter period (1979 to 2008), and with fewer  
274 models. With prescribed observed SST fields, variability in Pacific wind stress is greatly enhanced, at both  
275 the annual (Fig. 7a) and decadal (Fig. 7b) time-scales. Where previously in the historical coupled simulations  
276 the variability was weaker-than-observed across all models (Fig. 1), here in the AMIP simulations it is  
277 greater in many models. Although different biases now become apparent, particularly the overly strong  
278 variability signal over the Pacific warm pool. The time-series of 10-year  $\tau_{\text{PAC}}$  trends shows that the variations  
279 in models are synchronized with observations, despite the differences in magnitudes (Fig. 7c). Thus, the  
280 strong biases that are apparent in the coupled simulations are muted in the atmosphere-only simulations  
281 forced by observed SST, and hence the multi-model ensemble range in 10-year  $\tau_{\text{PAC}}$  trends is greatly  
282 improved (Fig. 7d; Ma and Zhou 2016). The regression fields of  $\tau_{\text{PAC}}$  trends with SST and precipitation are in  
283 significantly greater agreement with observations in the AMIP runs (Fig. 8) compared to the fully coupled  
284 historical runs (Fig. 5). Likewise, the AMIP precipitation trend over the Atlantic is in good agreement with  
285 observations (cf. Fig. S4 with Fig. 6b, d, f). Finally, there are some differences in the fields over the two  
286 time-periods analysed in the observations, most notably over the Indian and North Atlantic Oceans (cf. Fig.  
287 5c–f and Fig. 8c–f), but these differences may be related to multi-decadal variability (Kucharski et al.  
288 2016a).

289

290 In order to understand why the coupled models do not appear to generate the correct decadal precipitation  
291 response to Atlantic SST (Fig. 6b, d, f), we regress the annual ATL index with precipitation (Fig. 9) and  
292 compare this response to anomalous SST patterns (Fig. S5). For this analysis, the 11-year running mean is  
293 removed from the annual time-series, for all indices and at each spatial point in the field variables. In the  
294 observations, it is apparent that the precipitation anomalies are bounded by the 27.5° C isotherm of the  
295 climatological SST, and the same isotherm of the anomalous plus climatological SST field (Fig. 9b, c),  
296 consistent with theory (e.g., Graham and Barnett 1987; Zhang 1993; Sud et al. 1999; Johnson and Xie 2010).  
297 Note that the anomalous plus climatological SST field is computed by regressing annual ATL SST index  
298 with the SST field (Fig. S5), and then adding that to the climatological mean SST field. The precipitation

299 anomalies situated near the equator are the most important for remote teleconnections with deep atmospheric  
300 circulation, since the response to off-equatorial atmospheric heating is somewhat different (Gill 1980).  
301 Atmospheric heating over the tropical Atlantic has been shown to drive Kelvin-wave-induced wind  
302 anomalies that extend across the Indian and Central Pacific Oceans (Li et al. 2016). Despite the multi-model  
303 mean displaying very little signal (Fig. 9a), the individual models exhibit a vast array of differences to the  
304 observed behaviour. The region between the climatological and anomalous 27.5° C isotherms are situated in  
305 different regions, and in many cases, they do not align with their precipitation anomalies. This picture is in  
306 stark contrast to the AMIP simulations where the precipitation response is similar to observations (Fig. S6),  
307 which is consistent with the fact that the AMIP models are forced by observed SST. This coupled-model  
308 inconsistency underscores the likely role of anomalous SST gradients and a lack of surface wind  
309 convergence in the atmospheric response (e.g., Graham and Barnett 1987), which may not be simulated  
310 properly by the freely-evolving climate models. This implication is supported by our analysis which shows a  
311 strong tendency for models that simulate more realistic spatial structure of Atlantic SST anomalies (Fig. S5)  
312 to simulate more realistic precipitation anomalies (Fig. 9, 10c).

313

314 The background SST climatology also has the potential to play an important role in the precipitation  
315 response to anomalous SSTs, as it sets the location of the climatological 27.5° C isotherm and the  
316 background gradients (and surface wind divergence) that SST anomalies are imposed over. The pattern of  
317 mean SST shows that the models tend to be too warm off the coast of West Africa, and too cool off the  
318 Brazilian Coast up to the Caribbean Sea (Fig. S7). Hence the patterns of mean precipitation are also shifted.  
319 To first order, the observed tropical Atlantic SST climatology is characterised by warm waters to the north,  
320 and cooler water to the south (the mean tropical SST north of the equator in the ATL region is close to 2°C  
321 warmer than south of the equator; Fig. 10a). Thus, we have made the choice to analyse the model  
322 representation of the meridional SST gradient. We find that all but one model exhibits a weaker-than-  
323 observed meridional climatological SST gradient, and some are reversed. Overall, the models are too cool in  
324 the north and too warm in the south (Fig. S7), likely associated with the more southward position of the  
325 Intertropical Convergence Zone (ITCZ) compared to observations (Richter et al. 2014). Richter et al. (2014)  
326 linked the southward ITCZ bias to weaker-than-observed equatorial easterly winds, leading to warm bias in  
327 the equatorial eastern Atlantic. Note that our focus on meridional gradient SST is a different perspective to

328 the equatorial SST focus presented by Ritcher et al. (2014), whose analysis is confined to the region 2°S to  
329 2°N; although their finding that models are generally too cool in the west and too warm in the east is not  
330 inconsistent with ours. We find that models with a more realistic climatological SST gradient tend to also  
331 simulate a more realistic range of 10-year trends in  $\tau_{\text{PAC}}$  (Fig. 10b). Similarly, more realistic climatological  
332 precipitation field over the Atlantic leads to improved range of 10-year  $\tau_{\text{PAC}}$  trends (inter-model correlation  
333  $r=0.34$ ,  $p<0.05$ ; figure not shown). Hence, the representation of the tropical Atlantic climatology appears to  
334 be important for the simulation of the decadal Pacific wind stress trends, through better representation of  
335 atmospheric convection which is key for the atmospheric bridge mechanism. As noted earlier, where the  
336 models simulate more realistic spatial structure of Atlantic SST anomalies, then they also tend to simulate a  
337 more realistic pattern of precipitation anomalies (Fig. 10c). Precipitation is a proxy for convection in the  
338 tropics, and hence improved precipitation response over the Atlantic might also indicate improved feedback  
339 into the Pacific Walker Circulation cell.

340

## 341 6. Conclusion

342 Variability of decadal trends in Pacific wind stress is under-represented in CMIP5 coupled models, despite  
343 the fact that the magnitude of decadal SST variability is reasonably well simulated. Furthermore, the  
344 relationship between the Atlantic-Pacific trans-basin SST gradient and the Pacific wind stress in models  
345 agrees with observations. However, our study suggests that model biases over the tropical Atlantic are  
346 largely to blame for the under-representation of Pacific wind stress trends. The correlation between decadal  
347 Atlantic SST trends and the Pacific wind stress trends are the opposite to observations in most models.  
348 Although the tropical Pacific SST is the dominant driver of the trade winds, the Atlantic state plays a role in  
349 driving the wind trends to extreme values. Hence, our results suggest that the breakdown of the Atlantic-  
350 Pacific connection in models leads to the under-representation of these extremes.

351

352 We examined both the climatological SST and anomalous SST biases over the tropical Atlantic. At the  
353 outset, we found that in the AMIP experiments, the Pacific wind stress variations are reasonably well  
354 recovered. Therefore, given the particular observed configuration of the climatological and anomalous SST  
355 fields, the atmosphere models are able to simulate the range of the wind stress trends. McGregor et al. (2014)  
356 find that, in the AMIP multi-model trend over 1992 to 2011, the zonal wind at 850hPa is in stronger

357 agreement with observations than at the surface, attributing the difference to a deficiency in the downward  
358 mixing of momentum. Exploration of the winds at various atmospheric levels in the historical CMIP5  
359 simulations may uncover further interesting features. However, our inter-model analysis indicates that the  
360 Pacific trade wind trend variability is improved where the Atlantic SST climatology bias is reduced in the  
361 coupled models. Furthermore, we found that the Atlantic precipitation response is improved where the  
362 pattern of Atlantic SST anomalies is more like observations. Since precipitation is a proxy for convection,  
363 we infer that the coupled models are deficient at generating the convective processes that would otherwise  
364 drive the descending branch of the Walker Circulation over the tropical Atlantic. Without this feedback into  
365 the Walker Circulation, there is an absence of a connection to the Pacific trade winds, which are the surface  
366 level expression of the Pacific Walker Circulation cell.

367

368 A confounding factor in this inter-model study is that models present biases in different ways and locations.  
369 For example, the north, south, and equatorial Atlantic regions are known to have differing influences on  
370 decadal Pacific dynamics (Chikamoto et al. 2016). Hence, although a particular model may perform well in  
371 one region, it might be masked by stronger biases in another region. We will examine this issue in a future  
372 study by running model experiments with a range of SST configurations, but in particular, with the biased  
373 CMIP5 multi-model mean Atlantic SST climatology, in a partially coupled climate model. These  
374 experiments will allow us to more deeply understand how the Atlantic SST climatology is connected to the  
375 range of the Pacific trade wind trends.

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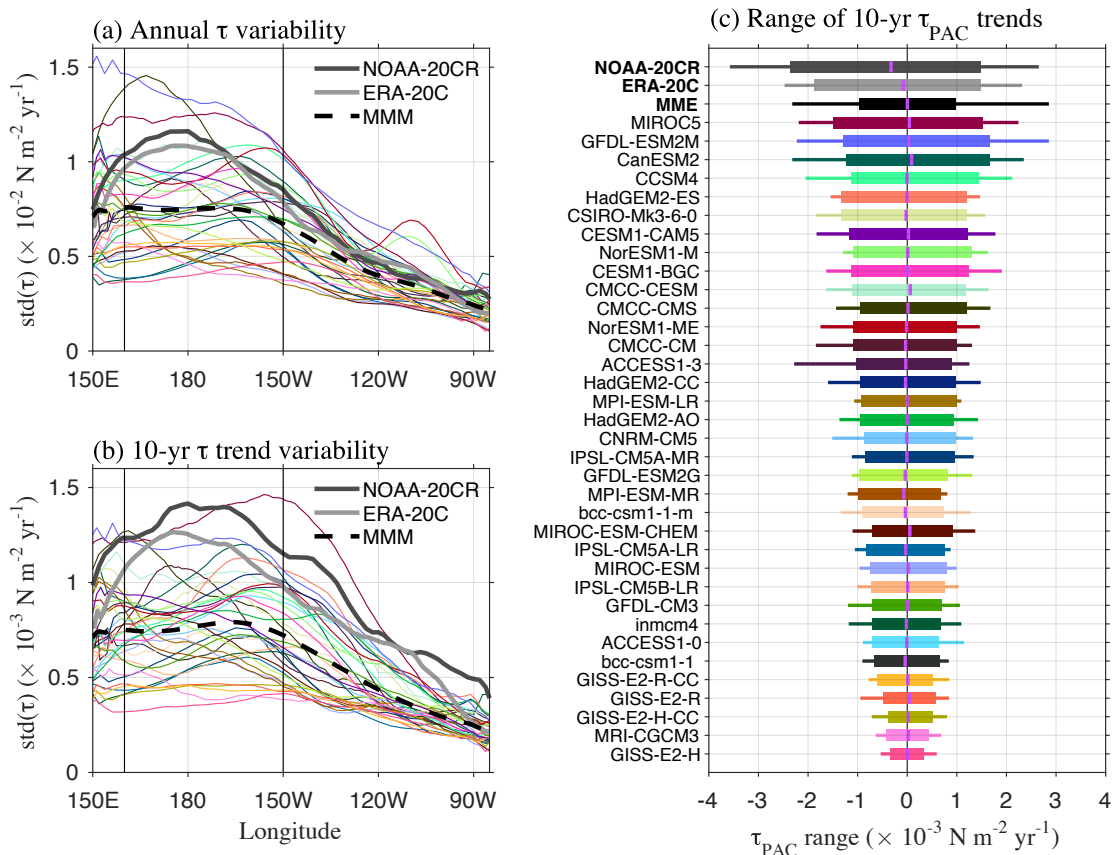
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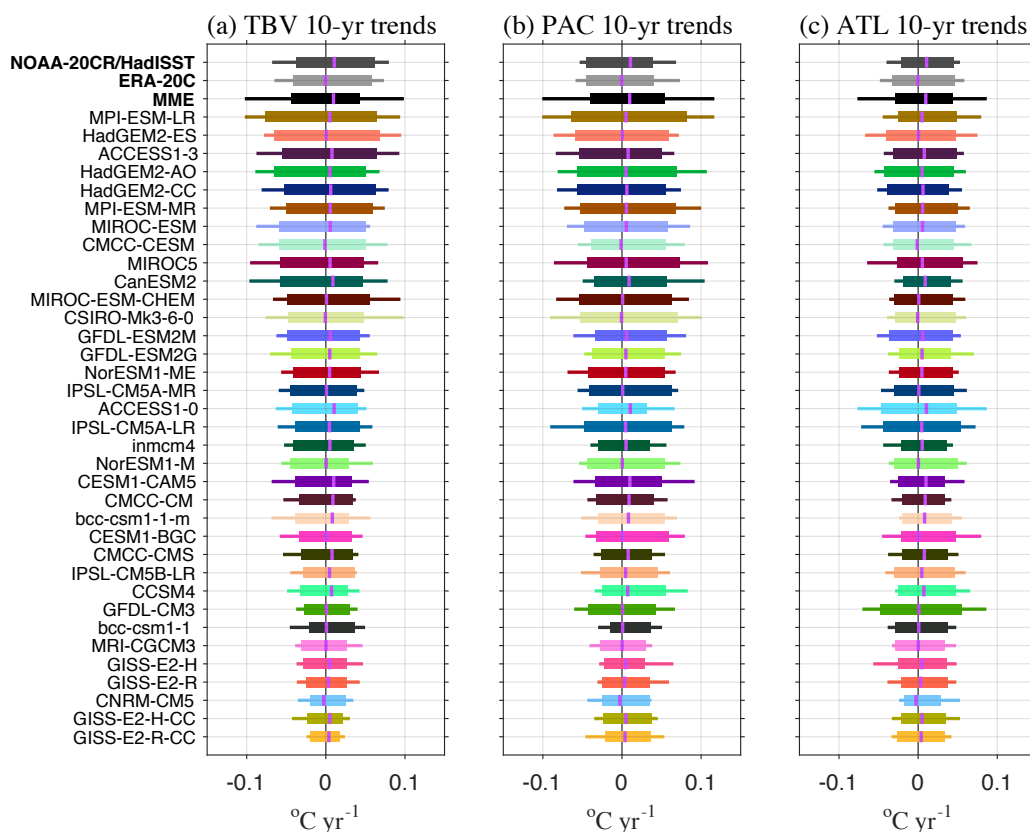
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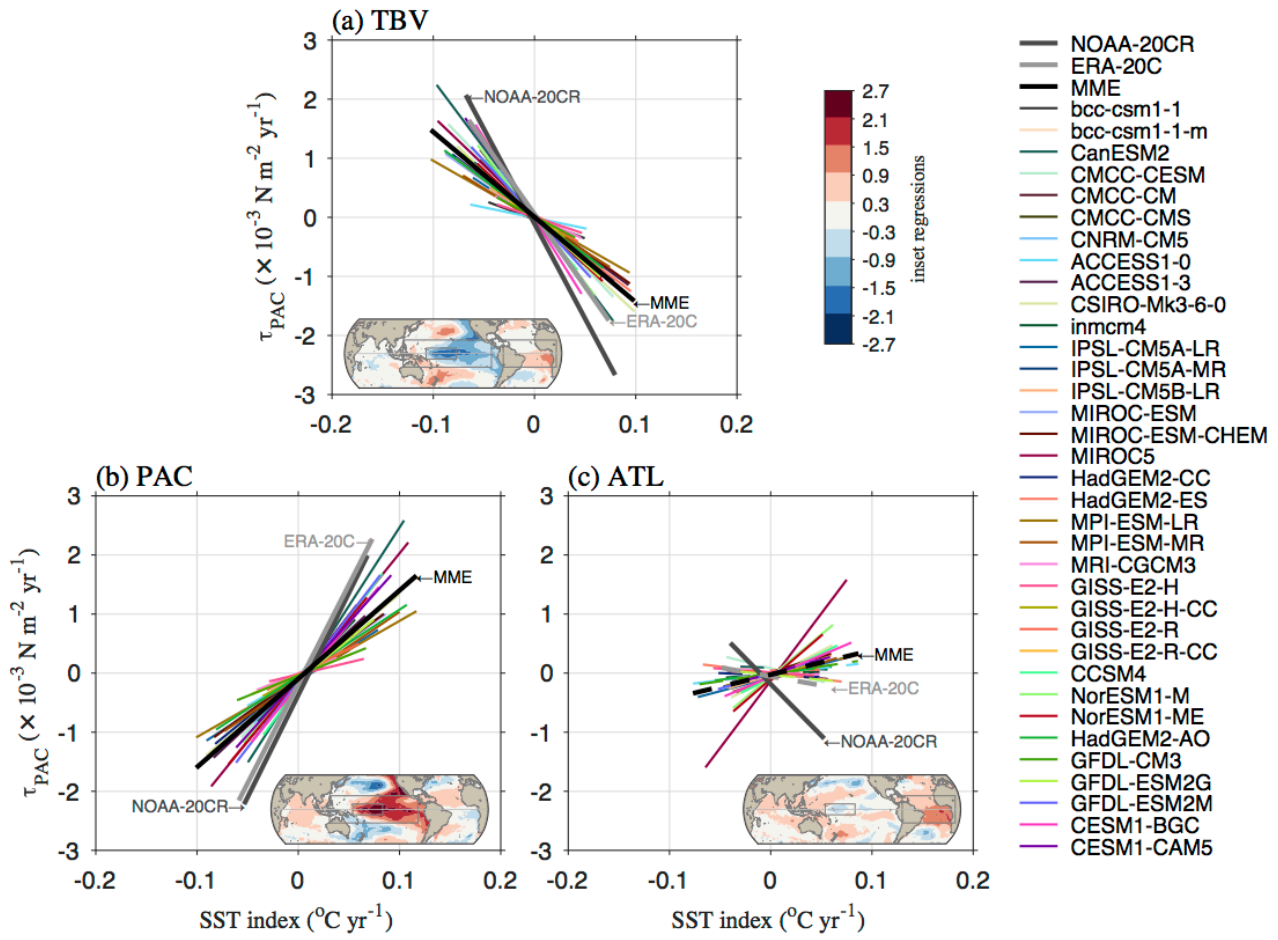
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17 **Fig. 1** Variability of Pacific zonal wind stress, in CMIP5 models and observations. **a**, Equatorial mean  
 18 of the standard deviation of annual zonal wind stress ( $\tau$ ) averaged over  $8^{\circ}\text{S}$  to  $8^{\circ}\text{N}$ , shown only for the  
 19 Pacific sector. **b**, As in **a**, but for the standard deviation of running 10-year zonal wind stress trends. **c**, The  
 20 range of 10-year trends in the  $\tau_{\text{PAC}}$  index (zonal wind stress averaged over  $160^{\circ}\text{E}$  –  $150^{\circ}\text{W}$  and  $8^{\circ}\text{S}$  –  $8^{\circ}\text{N}$ ,  
 21 as indicated by the vertical lines in **a** and **b**). MMM (in **a** and **b**) denotes the multi-model mean. MME (in  
 22 **c**) denotes the range of the multi-model ensemble. The widths of the bars (in **c**) denote the 5% to 95%  
 23 intervals, and the whiskers denote the full range. Vertical purple dashes denote the mean trend. The  
 24 individual models are ordered by the width of the 90% intervals.



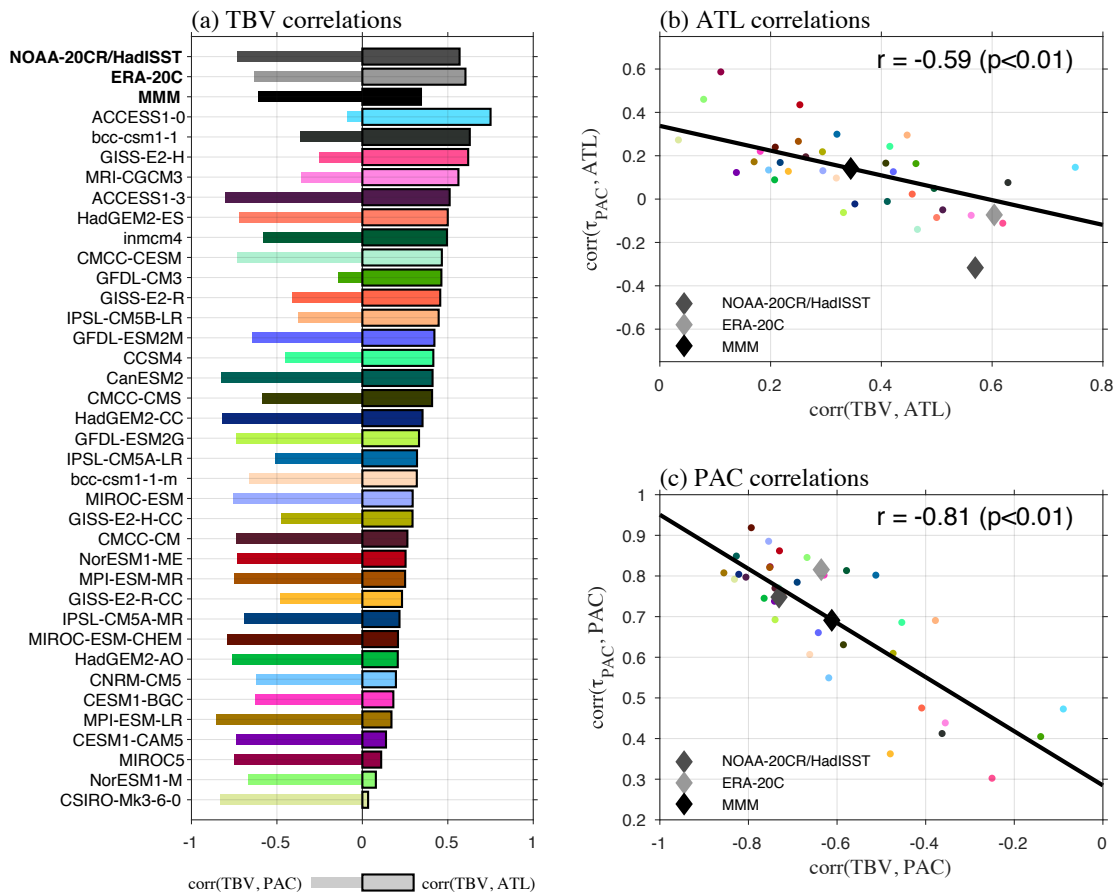
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26 **Fig. 2** Range in 10-year trends of SST indices, in CMIP5 models and observations. **a**, Trans-basin  
 27 variability index (tropical Atlantic minus the tropical Pacific SST index). **b**, Tropical Pacific index (SST  
 28 averaged over 120°E – 90°W and 20°S – 20°N). **c**, Tropical Atlantic index (SST averaged over 70°W –  
 29 20°E and 20°S – 20°N). MME denotes the ranges of the multi-model ensemble. The widths of the bars  
 30 denote the 5% to 95% intervals, and the whiskers denote the full range. Vertical purple dashes denote the  
 31 mean trend. The individual models are ordered by the range of TBV.



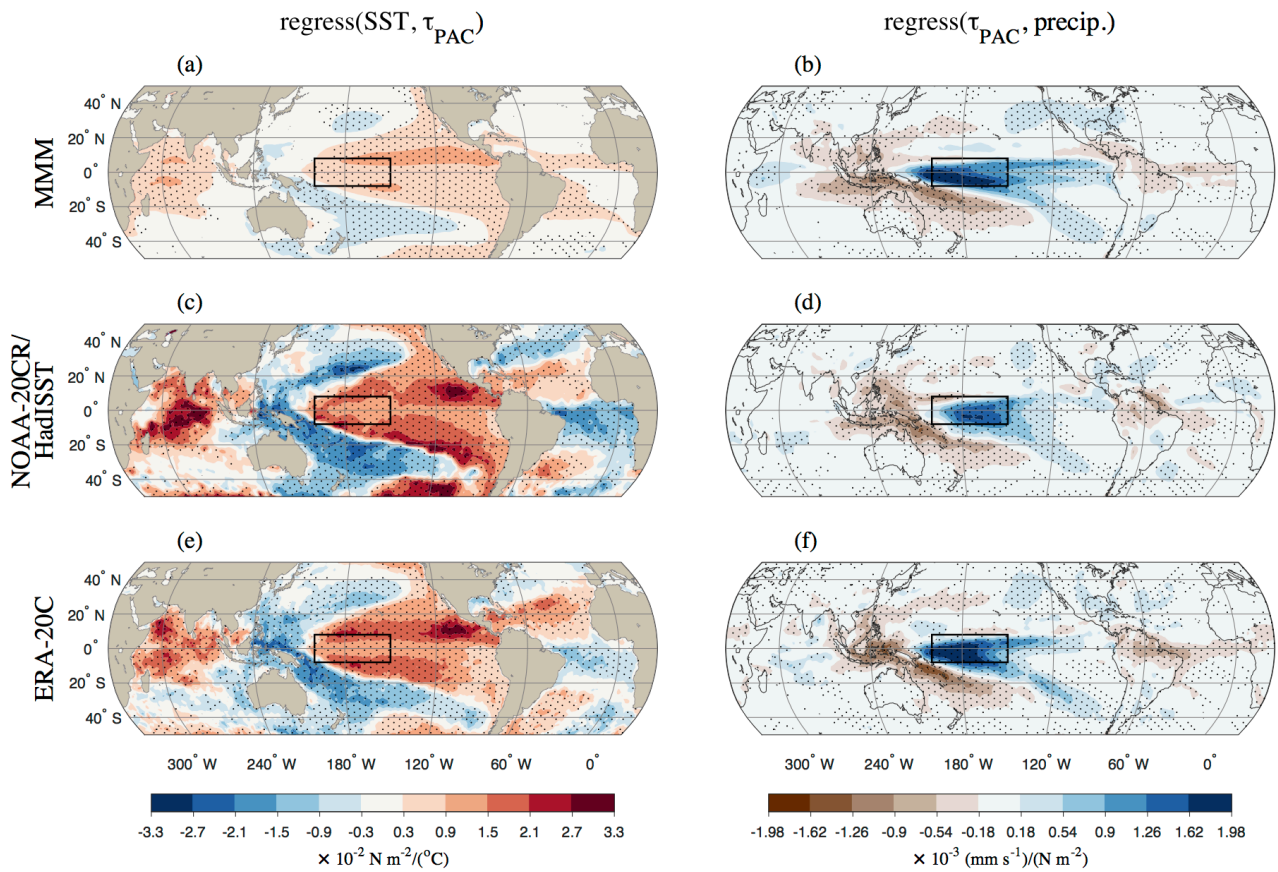
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33 **Fig. 3** Regression lines of 10-year trends in the Pacific wind stress index ( $\tau_{PAC}$ ) against various SST  
 34 **indices (TBV, PAC, and ATL), in CMIP5 models and observations. a,** Trans-basin variability  
 35 **(TBV). b,** Tropical Pacific index (PAC). **c,** Tropical Atlantic index (ATL). The lines are terminated at the  
 36 minimum and maximum values of the respective SST index trends. Solid lines indicate a statistically  
 37 significant regression at the 95% level, and broken lines indicate otherwise. The inset in each panel is the  
 38 running 10-year trends of the corresponding SST indices regressed with the SST field trends in HadISST.  
 39 The grey rectangles in the insets denote the area of the SST and  $\tau_{PAC}$  indices.



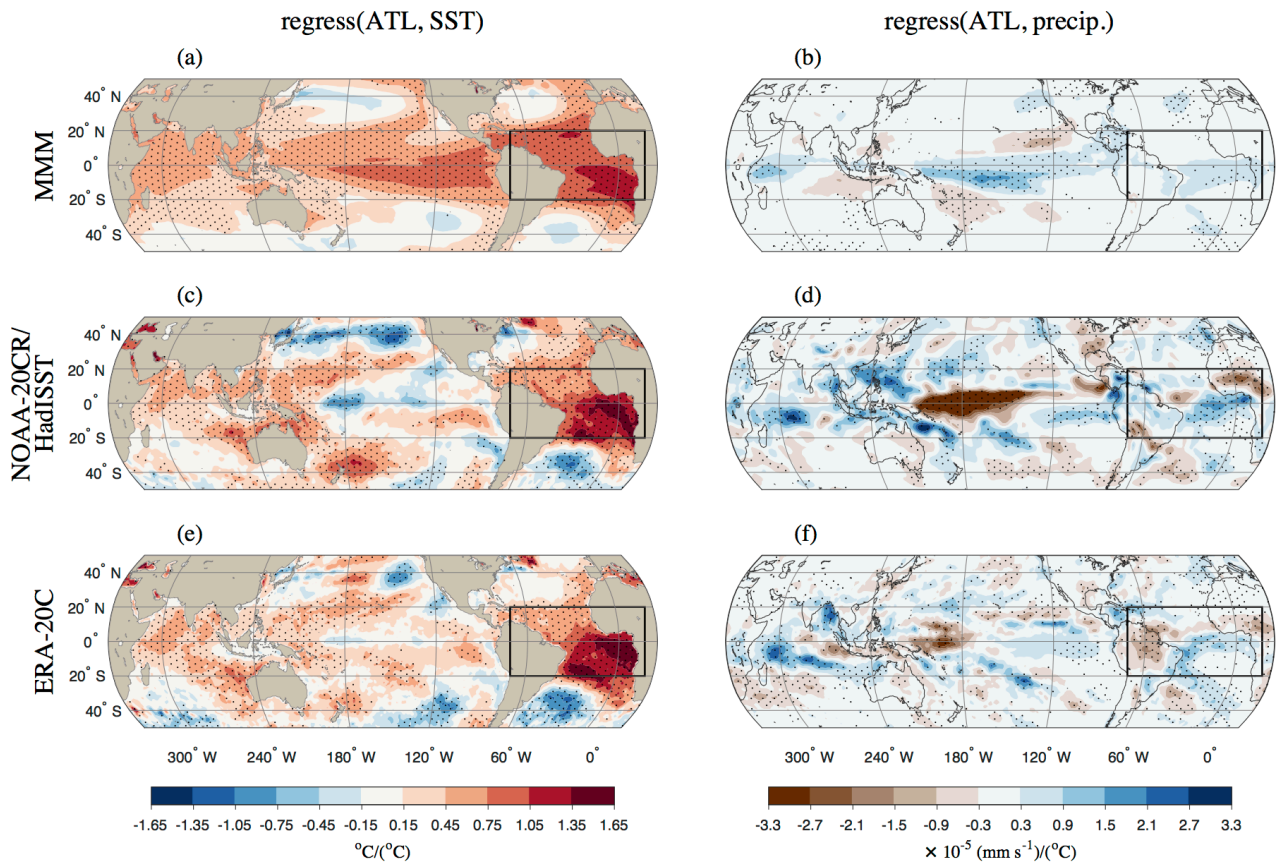
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41 **Fig. 4 Correlations between 10-year trends of Pacific wind stress and SST indices, in CMIP5 models**  
 42 **and observations. a**, Trans-basin variability index correlations with the tropical Atlantic and tropical  
 43 Pacific SST indices. **b**, Relationship across models and observations between the TBV-ATL and the  $\tau_{PAC}$ -  
 44 ATL (Fig. S2) correlation coefficients. **c**, Relationship across models and observations between the TBV-  
 45 PAC and the  $\tau_{PAC}$ -PAC (Fig. S2) correlation coefficients. In **b** and **c**, the inter-model correlation and  
 46 corresponding p-values are quoted in the top right of the panel.



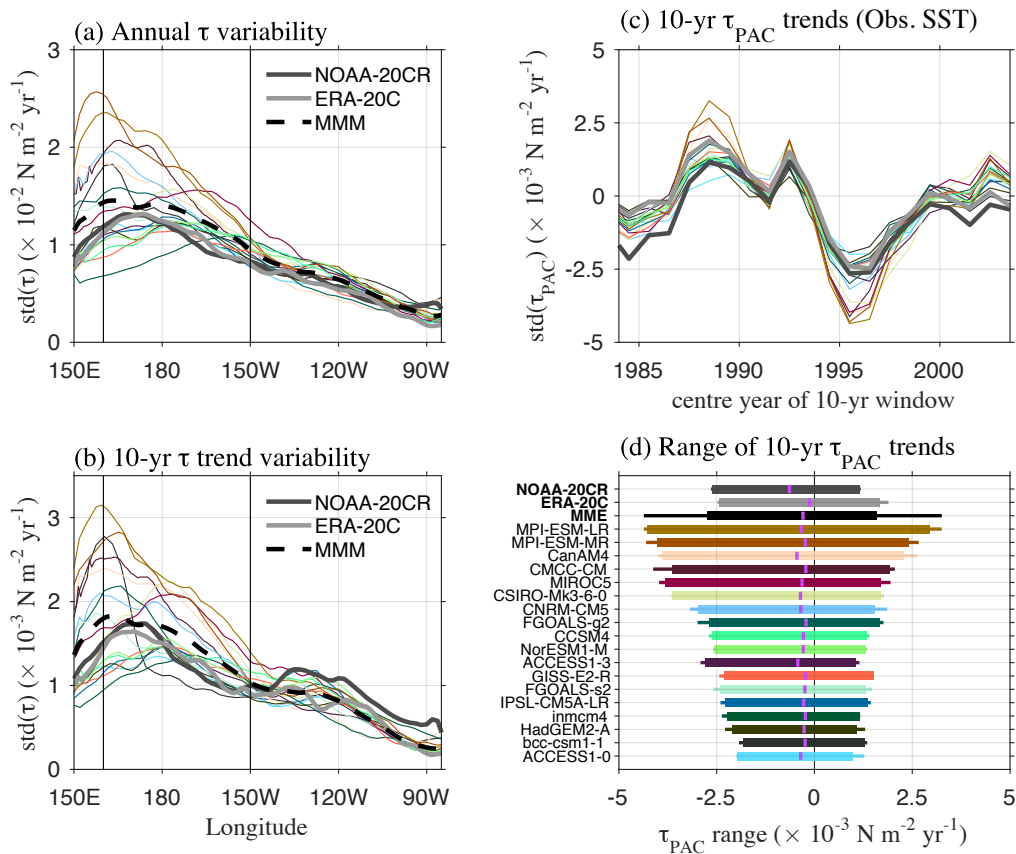
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48 **Fig. 5 Running 10-year trends of the Pacific wind stress regressed with SST and precipitation trends,**  
 49 **in CMIP5 models and observations. a**, Multi-model mean regression of running 10-year  $\tau_{PAC}$  trends with  
 50 SST field trends. **b**, Multi-model mean regression of running 10-year  $\tau_{PAC}$  trends with precipitation field  
 51 trends. Note that the regression in **a** is performed such that the plot represents the  $\tau_{PAC}$  response per unit  
 52 temperature at each grid-point (and thus consistent with Fig. 3), whereas the regression in **b** shows the  
 53 precipitation response per unit  $\tau_{PAC}$ . **c,d**, As in **a** and **b**, but for NOAA 20CR wind stress and precipitation,  
 54 and HadISST sea surface temperature. **e,f**, As in **a** and **b**, but for ERA 20C. For the multi-model means in **a**  
 55 and **b**, the stippling denotes regions where at least 75% of the models agree on the sign on the regression.  
 56 For the reanalysis products in **c–f**, the stippling denotes statistically significant regression coefficients at  
 57 95% confidence level.



58

59 **Fig. 6 Running 10-year trends of the Atlantic SST index (ATL) regressed with SST and precipitation**  
 60 **trends, in CMIP5 models and observations. a**, Multi-model mean regression of running 10-year ATL  
 61 trends with SST field trends. **b**, Multi-model mean regression of running 10-year ATL trends with  
 62 precipitation field trends. **c,d**, As in **a** and **b**, but for NOAA 20CR precipitation, and HadISST sea surface  
 63 temperature. **e,f**, As in **a** and **b**, but for ERA 20C. Stippling denotes the same as in Fig. 5.



64

65 **Fig. 7 Variability of Pacific zonal wind stress, in AMIP models and observations.** Only the period

66 1979-2008 is considered, corresponding to the span of the AMIP experiments. **a**, Equatorial mean of the

67 standard deviation of annual zonal wind stress ( $\tau$ ) averaged over  $8^{\circ}\text{S}$  to  $8^{\circ}\text{N}$ , shown only for the Pacific

68 sector. **b**, As in **a**, but for the standard deviation of running 10-year zonal zonal wind stress trends. **c**, Time-

69 series of running 10-year trends in the  $\tau_{\text{PAC}}$  index. **d**, The range of 10-year trends in the  $\tau_{\text{PAC}}$  index. MMM

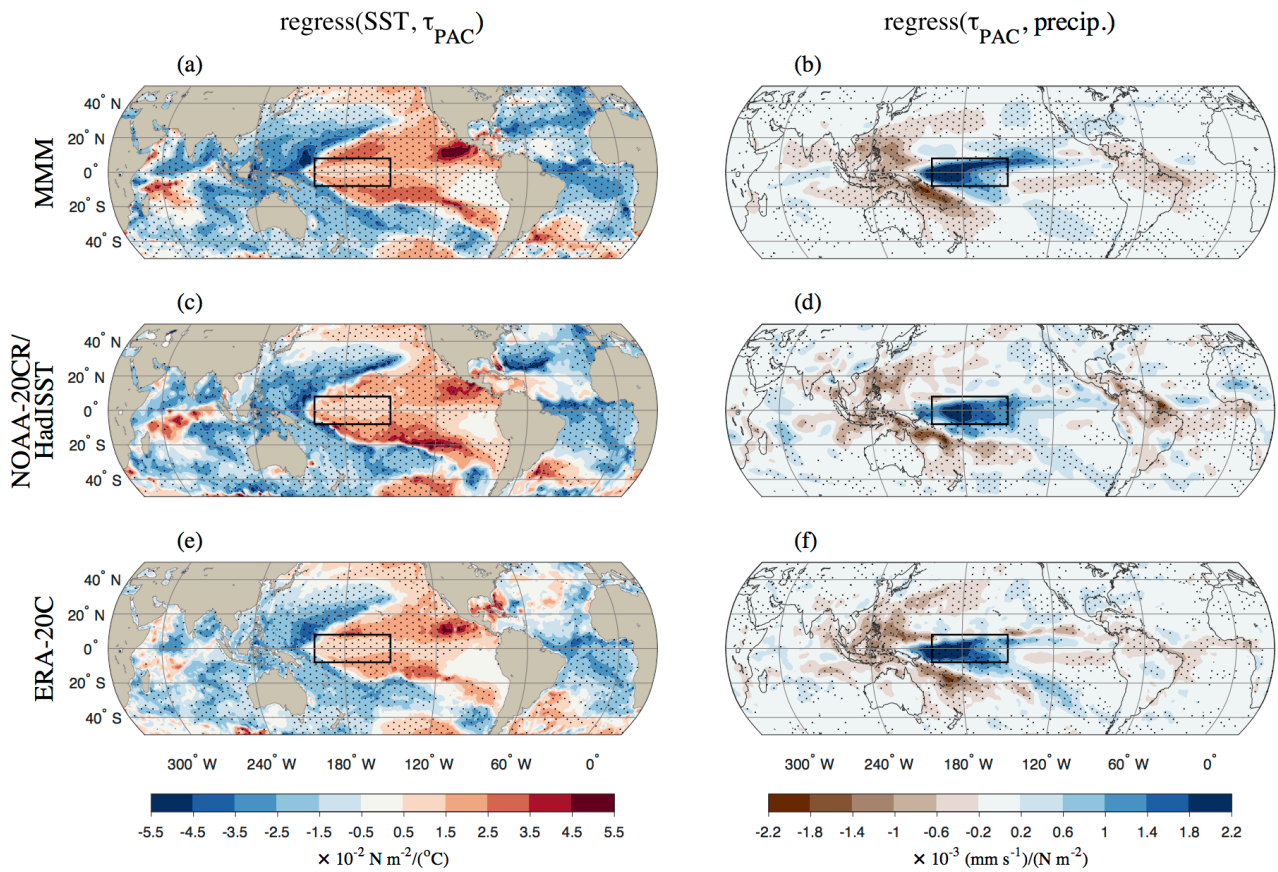
70 (in **a** and **b**) denotes the multi-model mean. MME (in **d**) denotes the range of the multi-model ensemble.

71 The widths of the bars (in **d**) denote the 5% to 95% intervals, and the whiskers denote the full range.

72 Vertical purple dashes denote the mean trend. The individual models are ordered by the width of the 90%

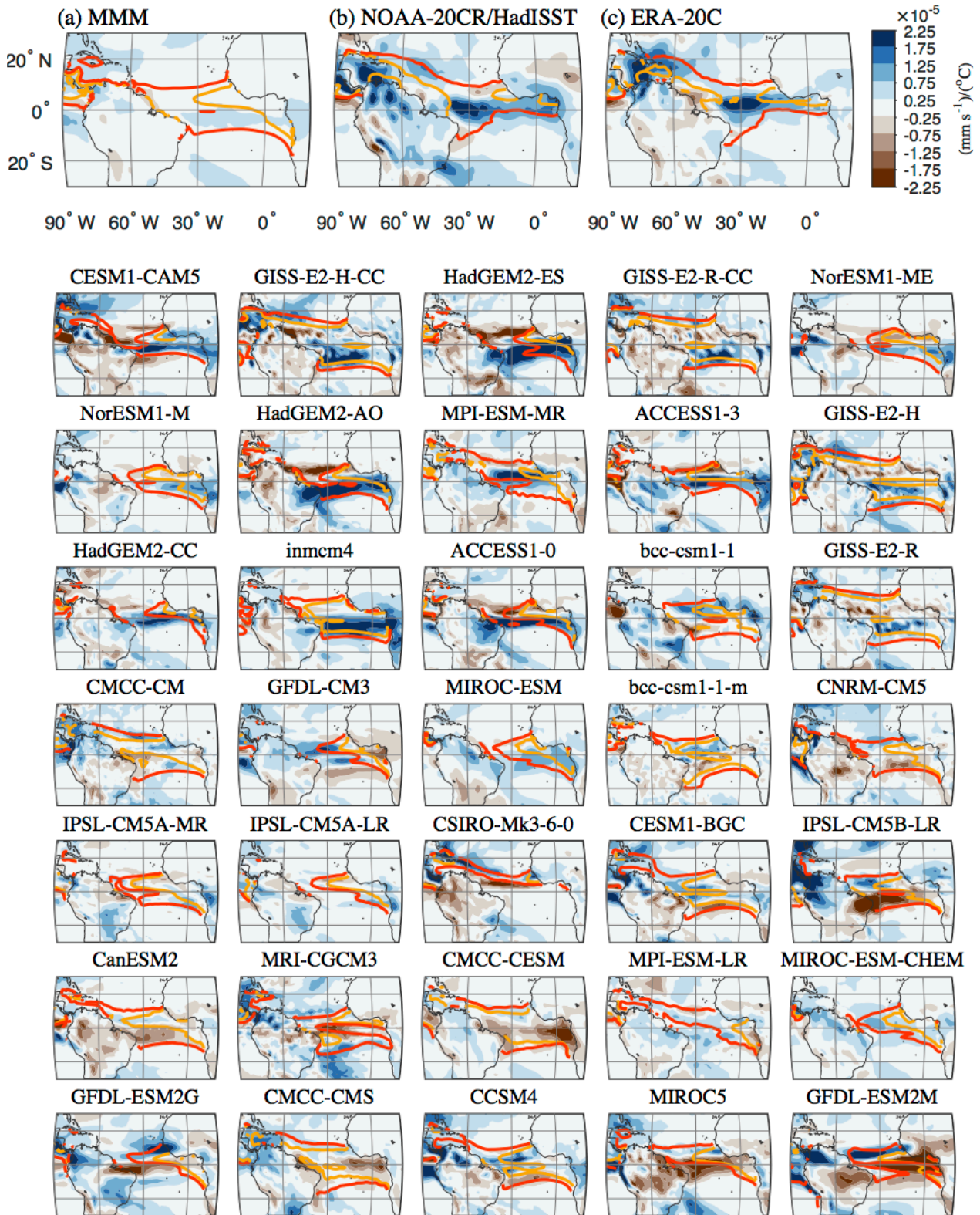
73 intervals.





74

75 **Fig. 8 Running 10-year trends of the Pacific wind stress regressed with SST and precipitation fields,**  
 76 **in AMIP models and observations.** Only the period 1979-2008 is considered, corresponding to the span  
 77 of the AMIP experiments. **a**, Multi-model mean regression of running 10-year  $\tau_{PAC}$  trends with observed  
 78 SST field trends. **b**, Multi-model mean regression of running 10-year  $\tau_{PAC}$  trends with precipitation field  
 79 trends. Note that the regressions are computed in the same way as for Fig. 5. **c,d**, As in **a** and **b**, but for  
 80 NOAA 20CR wind stress and precipitation, and HadISST sea surface temperature. **e,f**, As in **a** and **b**, but  
 81 for ERA 20C. Stippling denotes the same as in Fig. 5.



82

83 **Fig. 9 Annual ATL SST index regressed with precipitation, in CMIP5 models and observations. a,**

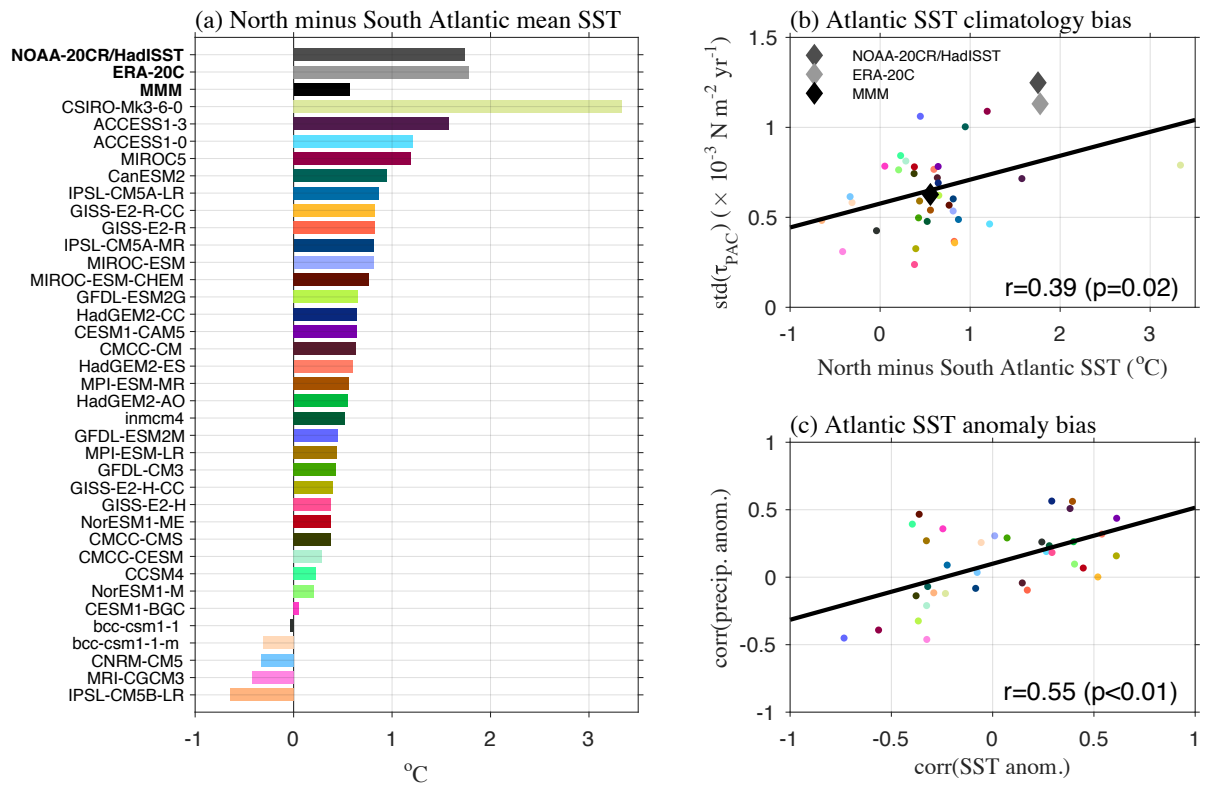
84 Multi-model mean of the regression of annual ATL SST indices with precipitation fields. **b,** Annual

85 HadISST ATL index regressed with NOAA 20CR precipitation field. **c,** Annual ATL index regressed with

86 precipitation field in ERA 20C. The remaining panels are the same as **a–c,** but for each individual CMIP5

87 model. The models are ordered by strongest correlation with the mean of the two observed fields of ATL

88 index regression with SST (Fig. S5b, c). The yellow contours denote the 27.5° C isotherm of the  
89 climatological SST. The orange contours denote the 27.5° C isotherm of the anomalous SST field plus the  
90 climatological SST. The anomalous SST field is computed by regressing annual ATL index with SST (Fig.  
91 S5).



92

93 **Fig. 10 Atlantic SST biases, and their influence on Pacific wind stress trends and Atlantic**  
 94 **precipitation. a**, Climatological mean North Atlantic SST (averaged over 70°W – 20°E and 20°S – 0°)  
 95 minus mean South Atlantic SST (averaged over 70°W – 20°E and 0° – 20°N). **b**, Inter-model relationship  
 96 between north minus south Atlantic SST, and the standard deviation of  $\tau_{PAC}$  10-yr trends. **c**, Inter-model  
 97 relationship between the model versus observation correlation of Atlantic SST anomalies and the model  
 98 versus observation correlation of Atlantic precipitation anomalies. The Atlantic anomalous SST field is  
 99 computed by regressing the ATL index with SST (Fig. S5), and the Atlantic anomalous precipitation field  
 100 by regressing the ATL index with precipitation (Fig. 9). The correlation coefficients and corresponding p-  
 101 values are quoted in the bottom right corners of **b** and **c**.

# **Model under-representation of decadal Pacific trade wind trends and its link to tropical Atlantic bias**

**Jules B. Kajtar<sup>\*1,2,3</sup>, Agus Santoso<sup>1,2</sup>, Shayne McGregor<sup>1,4</sup>, Matthew H. England<sup>1,2</sup>, and Zak Baillie<sup>1,2</sup>**

<sup>1</sup> Australian Research Council's Centre of Excellence for Climate System Science, Sydney, Australia

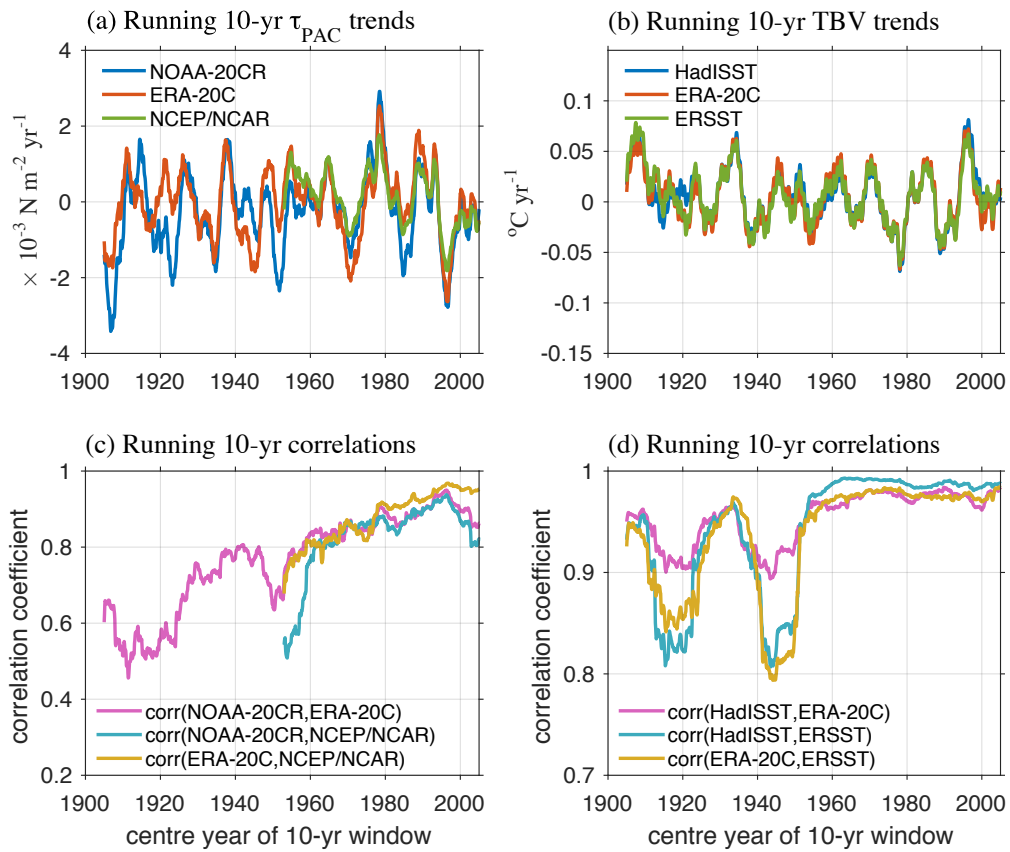
<sup>2</sup> Climate Change Research Centre, University of New South Wales, Sydney, NSW, Australia

<sup>3</sup> Present Address: College of Engineering, Mathematics, and Physical Sciences, University of Exeter, Exeter, UK

<sup>4</sup> School of Earth, Atmosphere and Environment, Monash University, Melbourne, VIC, Australia

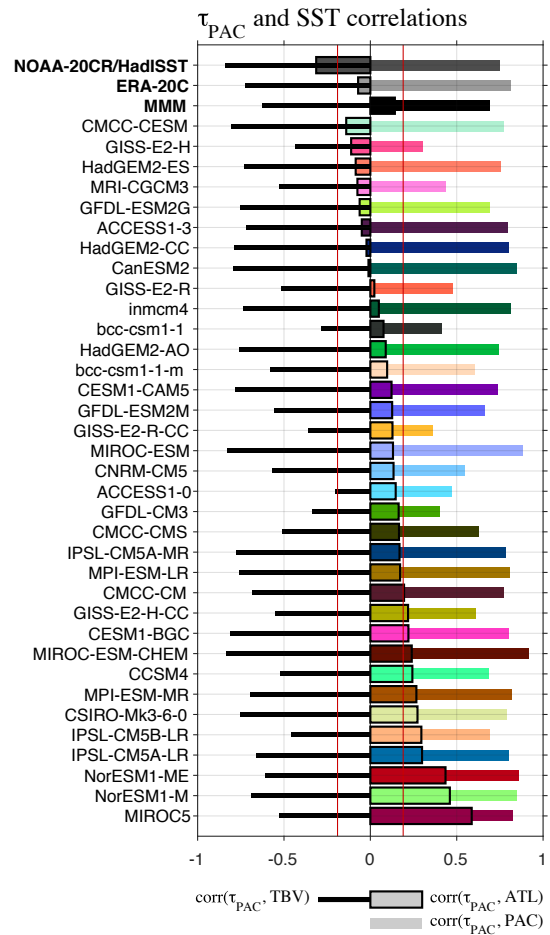
\* Corresponding author: [j.kajtar@exeter.ac.uk](mailto:j.kajtar@exeter.ac.uk).

**Supplementary Material**

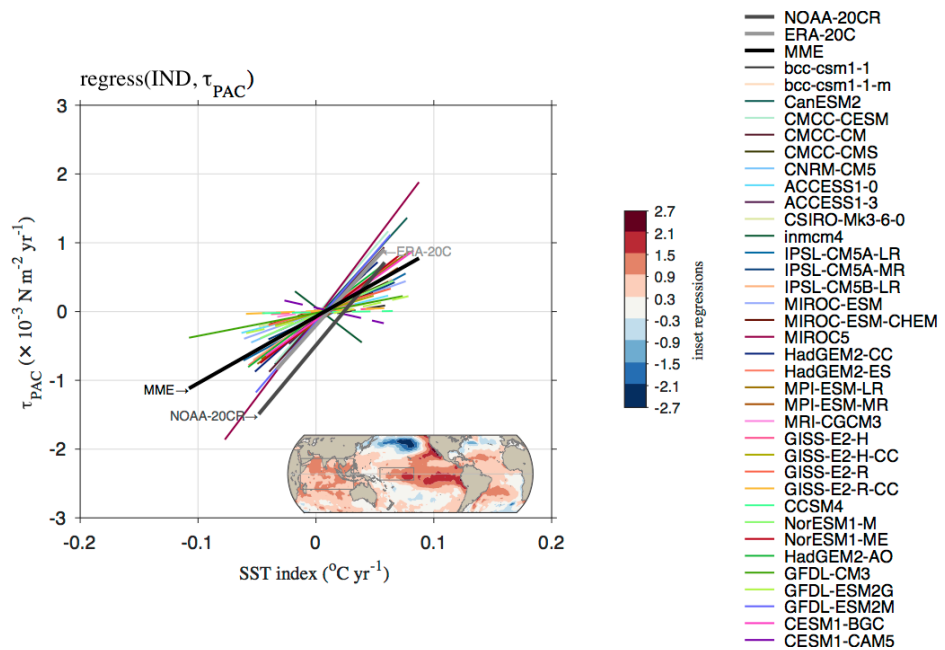


**Fig. S1** Running 10-year trends of the Pacific wind stress ( $\tau_{PAC}$ ) and trans-basin variability (TBV) indices, in a range of reanalysis products. **a** Running trends of Pacific wind stress index ( $\tau_{PAC}$ ). **b** Running trends of trans-basin variability SST index. **c** Running correlations in 10-year windows between  $\tau_{PAC}$  from different products. **d** Running correlations in 10-year windows between TBV from different products.

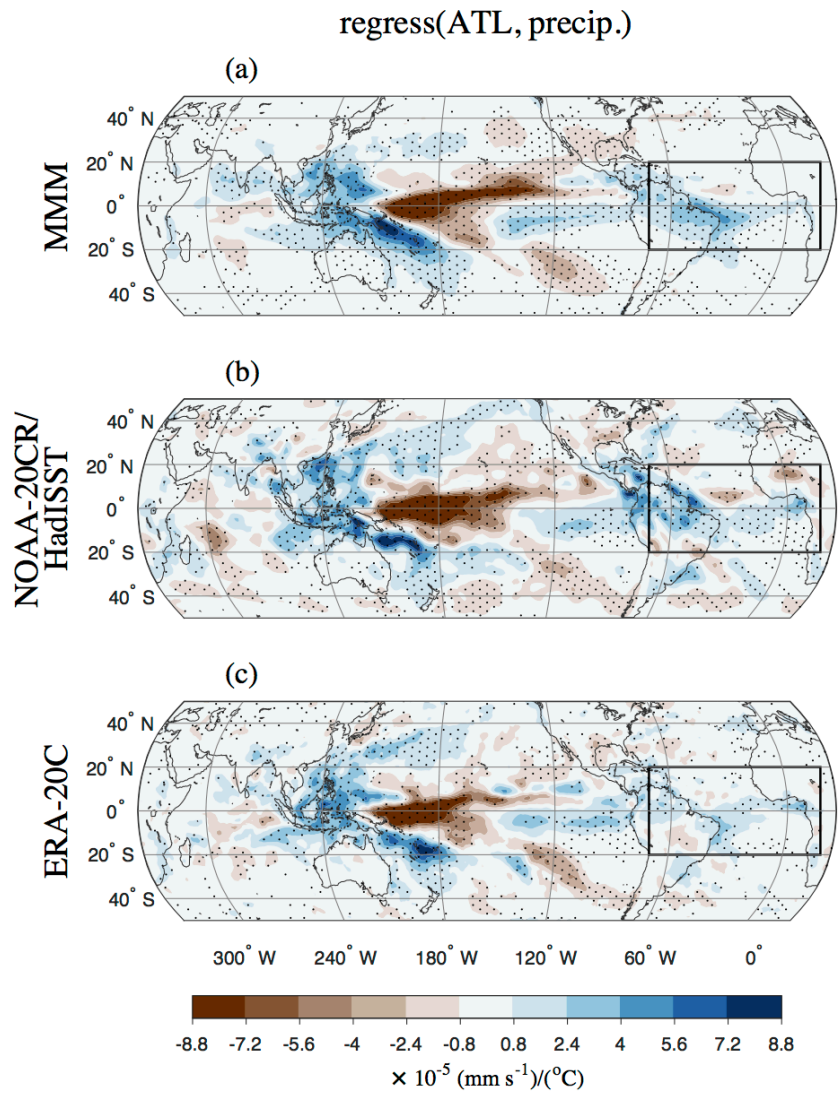
**Fig. S2** Correlations between 10-year running trends in the Pacific wind stress index and SST indices, in CMIP5 models and observations. The SST indices are: the trans-basin variability index (TBV), the tropical Pacific index (PAC), and the tropical Atlantic index (ATL). The *red vertical lines* indicate the level beyond which the correlations are statistically significant at the 95% level. MMM denotes the multi-model mean correlations.



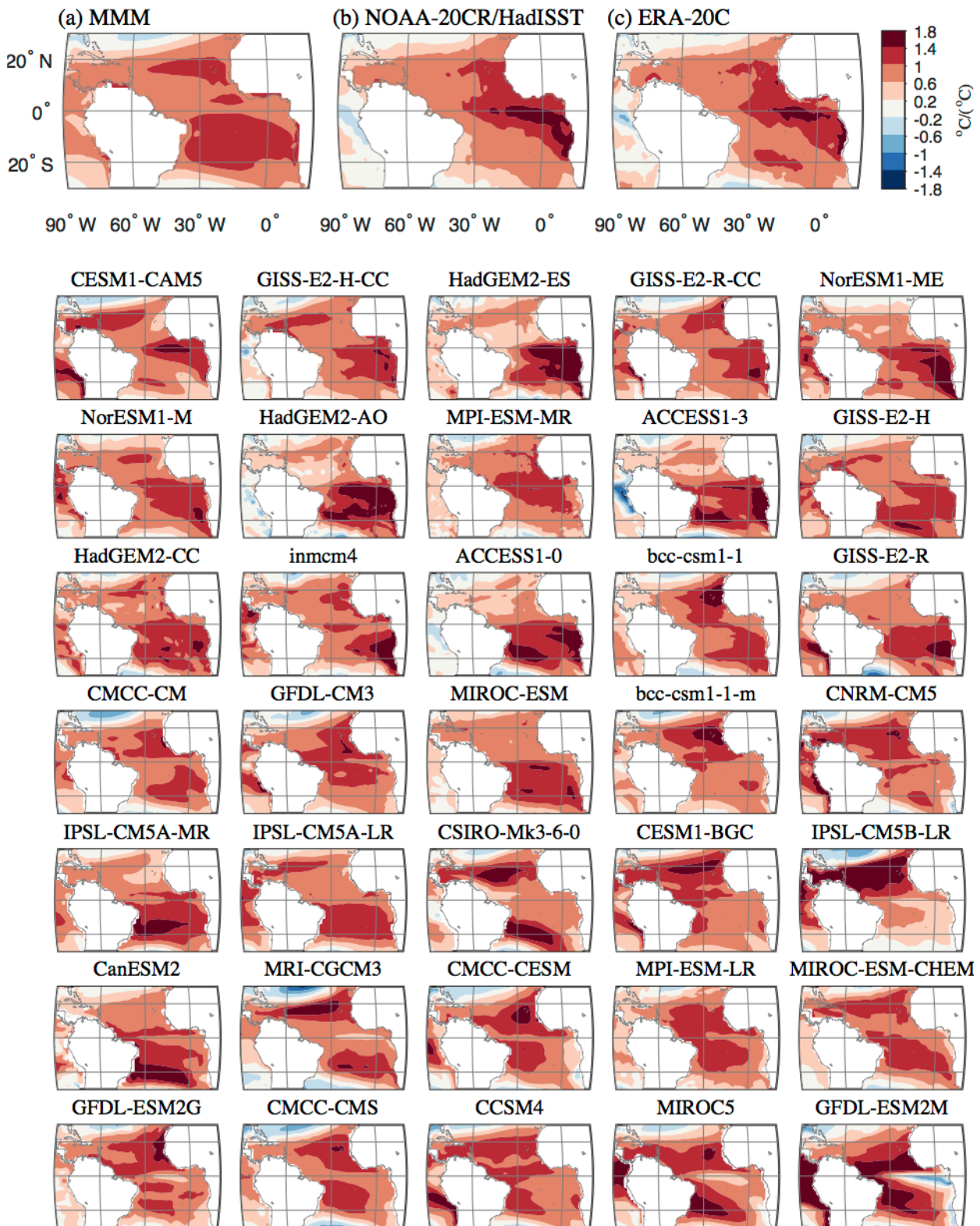
**Fig. S3** Regression lines of 10-year trends in the Pacific wind stress index ( $\tau_{PAC}$ ) against the Indian Ocean SST index (IND), in CMIP5 models and observations. The *lines* are terminated at the minimum and maximum values of the IND index trends. *Solid lines* indicate a statistically significant regression at the 95% level, and *broken lines* indicate otherwise. The inset is the running 10-year IND trends regressed with the SST field trends in HadISST. The *grey rectangles* in the inset denote the area of the IND and  $\tau_{PAC}$  indices.



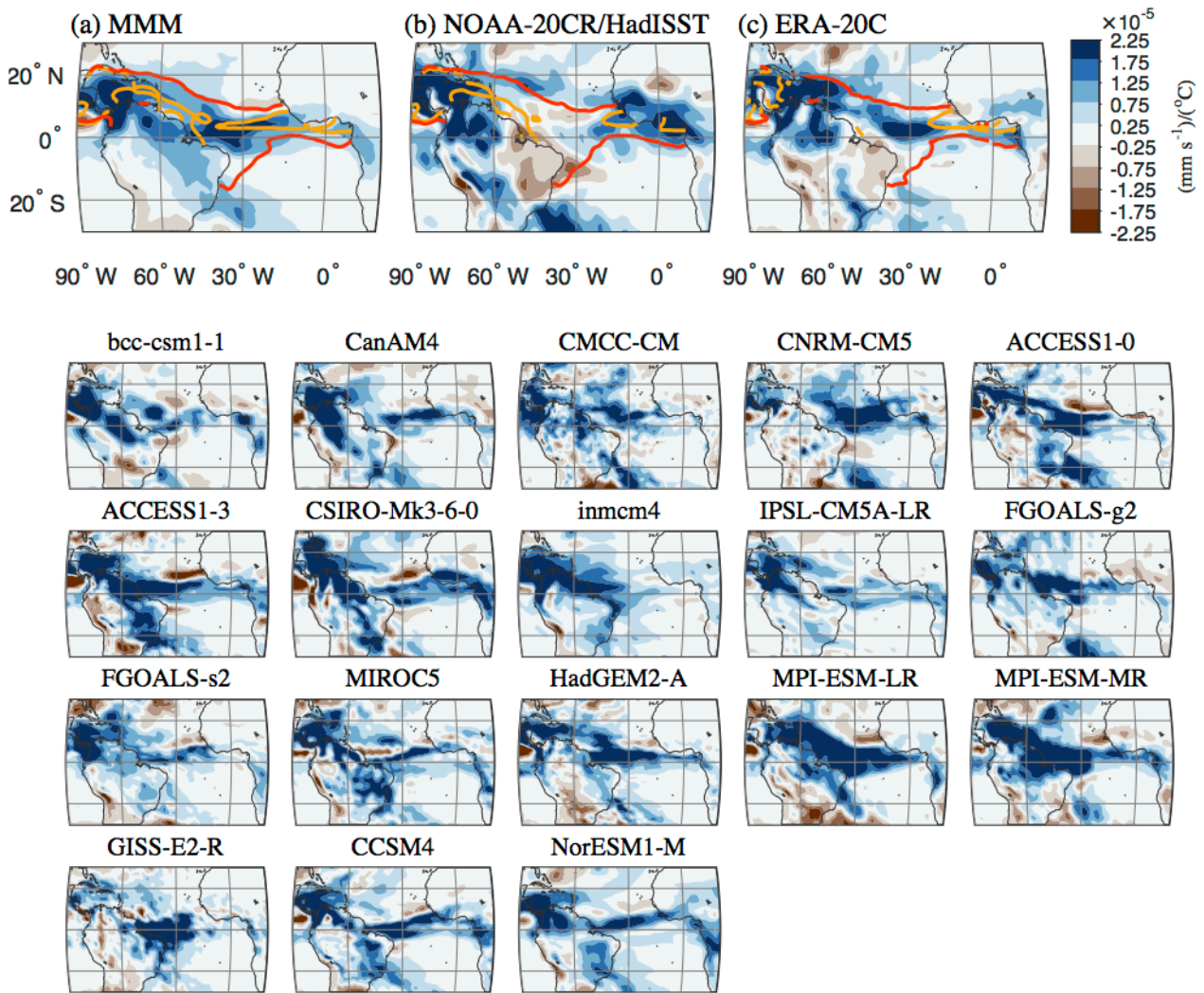
**Fig. S4** Running 10-year trends of the ATL SST index regressed with precipitation trends, in AMIP models and observations. Only the period 1979-2008 is considered, corresponding to the span of the AMIP experiments. **a** Multi-model mean regression of running 10-year ATL trends with precipitation field trends. **b** As in **a**, but for NOAA-20CR precipitation and HadISST ATL index. **c** As in **a**, but for ERA-20C. *Stippling* denotes the same as in Fig. 5.







**Fig. S5** Annual ATL SST index regressed with SST fields, in CMIP5 models and observations. **a** Multi-model mean of the regression of annual ATL SST indices with SST fields. **b** HadISST regression. **c** ERA-20C regression. The remaining panels are the same as **a–c**, but for each individual CMIP5 model. The models are ordered by strongest correlation with the mean of the two observed SST regression fields (**b** and **c**).



**Fig. S6** Annual ATL SST index regressed with precipitation, in AMIP models and observations. Only the period 1979-2008 is considered, corresponding to the span of the AMIP experiments. **a** Multi-model mean regression of annual ATL SST indices with precipitation fields. **b** Annual HadISST ATL index regressed with NOAA-20CR precipitation field. **c** Annual ATL index regressed with precipitation field in ERA-20C. The remaining panels are the same as **a–c**, but for each individual AMIP model. The *yellow contours* in **a–c** denote the  $27.8^{\circ}\text{C}$  isotherm of the climatological SST. The *orange contours* in **a–c** denote the  $27.8^{\circ}\text{C}$  isotherm of the anomalous SST field plus the climatological SST (as in Fig. 8). The isotherm contours have been omitted from the individual model panels, since they are identical to those in **a**. Note that we have selected the  $27.8^{\circ}\text{C}$  isotherms here (as opposed to  $27.5^{\circ}\text{C}$  like Fig. 9) since the climatological mean SST is generally warmer for this recent period than over the entire twentieth century. Precipitation in the tropical region occurs over a threshold that is assumed to be a function of the mean tropical temperature (Johnson & Xie, 2010).

**Fig. S7** Atlantic climatological mean SST and precipitation fields, in CMIP5 models and observations. **a** Multi-model mean SST and precipitation fields. **b** NOAA-20CR precipitation and HadISST mean fields. **c** ERA-20C mean fields. The *colour shading* denotes SST and the *overlaid contours* denote the mean precipitation (mm/day).

Climatological mean SST and precip.

