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ENSO and greenhouse warming

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47 **The El Niño-Southern Oscillation (ENSO) is the dominant climate phenomenon affecting**
48 **extreme weather conditions worldwide. Its response to greenhouse warming has challenged**
49 **scientists for decades, despite model agreement on projected mean state changes. Recent studies**
50 **have provided new insights into the elusive links between ENSO and Pacific climate mean-state**
51 **changes. The projected Walker circulation slow-down is expected to weaken equatorial Pacific**
52 **Ocean currents, boosting the occurrences of eastward propagating warm surface anomalies that**
53 **characterise observed extreme El Niño events. Accelerated equatorial Pacific warming,**
54 **particularly in the east, is expected to induce eastern equatorial Pacific extreme rainfall and**
55 **extreme equatorward swings of the convergence zones, both of which are features of extreme El**
56 **Niño. The frequency of extreme La Niña is also expected to increase in response to more**
57 **extreme El Niños, an accelerated Maritime continent warming and surface-intensified ocean**
58 **warming. ENSO-related catastrophic weather events are thus likely to occur more frequently**
59 **with unabated greenhouse gas emissions. However, model biases and recent observed**
60 **strengthening of the Walker circulation highlight the need for further testing as new models,**
61 **observations and insights become available.**

62 **Introduction.** The impacts of anthropogenic climate change may be felt through changes in modes of
63 natural climatic variability. El Niño-Southern Oscillation (ENSO) is the most important year-to-year
64 fluctuation of the climate system on the planet¹, varying between anomalously cold (La Niña) and
65 warm (El Niño) conditions.
66 Underpinning occurrences of ENSO events is the positive feedback between trade wind intensity and
67 zonal sea surface temperature (SST) contrasts, referred to as the Bjerknes feedback. The trade winds
68 normally pile up warm surface water in the western Pacific while upwelling colder subsurface water
69 in the east along the equator and off the west coast of South America. The resulting east-west surface
70 temperature contrast reinforces an east-west air pressure difference across the basin that in turn drives

71 the Trades. During La Niña, the system strengthens, but during El Niño, the trade winds weaken as
72 atmospheric pressure rises in the western Pacific and falls in the eastern Pacific. The Bjerknes
73 feedback now operates in reverse, with weakened trade winds and SST warming tendencies along the
74 equator reinforcing one another. It is still not clear what sets this quasi-oscillatory behaviour, i.e.,
75 whether ENSO is self sustaining or triggered by stochastic forcing². What is clear is that ocean and
76 atmosphere preconditions are required³, as supported by the fundamental characteristics of the mean
77 tropical climate such as thermal gradients and associated circulations that balance radiative heating⁴.
78 These swings in temperature are accompanied by changes in the structure of the subsurface ocean, the
79 position of atmospheric convection, and associated global teleconnection patterns, severely disrupting
80 global weather patterns^{5,6,7,8,9,10}, affecting ecosystems¹¹ and agriculture¹² worldwide.

81 During the 1982/83 and 1997/98 extreme El Niño events^{6,8}, surface warming anomalies propagated
82 eastward in an uncharacteristic fashion^{13,14}, and massive surface warm anomalies in the eastern
83 equatorial Pacific exceeding 3°C caused an equatorward shift of the Intertropical Convergence Zone
84 (ITCZ). Catastrophic floods occurred in the eastern equatorial region of Ecuador and northern Peru^{6,8}.
85 The South Pacific Convergence Zone (SPCZ), the largest rainband in the Southern Hemisphere,
86 shifted equatorward by up to 1000 km (an event referred to as zonal SPCZ), spurring floods and
87 droughts in south Pacific countries and shifting extreme cyclones to regions normally not affected by
88 such events¹⁰. Other impacts included floods in the southwest US, disappearance of marine life, and
89 decimation of the native bird population in the Galapagos Islands¹⁵. The development of the 1997/98
90 extreme El Niño event was accompanied by an extreme positive Indian Ocean Dipole in boreal
91 autumn, affecting millions of people across Indian Ocean-rim countries. An extreme La Niña ensued
92 in 1998/99, generating droughts in the southwest United States and eastern equatorial Pacific regions,
93 floods in the western Pacific and central American countries, and increased land-falling west Pacific
94 tropical cyclones and Atlantic hurricanes^{7,9,12}.

95 In light of these massive impacts, how ENSO will respond to greenhouse warming is one of the most
96 important issues in climate change science. The issue has challenged scientists for decades but there
97 has been no consensus on how ENSO amplitude and frequency may change^{16,17,18}. Past studies have
98 proceeded without specifically looking into the response of ENSO extremes, and have focused on
99 simple metrics such as temperature variability in the eastern equatorial Pacific and linear dynamics,
100 assuming that the characteristics between El Niño and La Niña are symmetric. Through the Coupled
101 Model Intercomparison Phase 5 (CMIP5) process¹⁹, substantial improvement in modelling ENSO has
102 been made^{18,20,21}. There is recognition that the two opposing extremes are not a mirror
103 opposite^{13,22,23,24,25,26,27}; that is, the impacts of and processes responsible for extreme El Niño and La
104 Niña events are not symmetric^{14,28,29,30,31,32}. Further, the dynamics of extreme ENSO events are

105 different from moderate events^{14,31,32,33}, and therefore the two must be examined separately in terms of
106 their response to greenhouse warming.

107 With this recognition, significant progress has been made in understanding the characteristics of
108 extreme ENSO events in models and observations, as part of the observed diversity of events, such as
109 central Pacific ENSO^{33,34,35} or ENSO Modoki³⁶, their likely future behaviour under greenhouse
110 conditions, and potential changes in their teleconnections. This study provides a review of these
111 advances. We show that the frequency of ENSO extremes is expected to increase, ENSO
112 teleconnections are likely to shift eastward, and these changes can, to a large extent, be interpreted as
113 consequences of mean state changes.

114 **Changes in the mean state.** The dynamics and properties of ENSO are closely linked to the slowly
115 evolving background climate state of the equatorial Pacific Ocean, for example, by rectifying into the
116 mean state^{37,38}, which in turn affect ENSO feedback processes^{1,16}. The tropical Pacific is projected to
117 change under greenhouse warming. The projection (Box 1) includes a weakening of the Walker
118 circulation^{39,40,41}, a faster warming rate in the equatorial than off-equatorial Pacific^{16,39,41}, in the eastern
119 equatorial Pacific⁴¹ and the Maritime continent than in the central Pacific, and over the ocean surface
120 than subsurface^{32,42}. The warming pattern gives rise to an increase in rainfall in the equatorial Pacific,
121 particularly in the eastern part of the basin⁴³.

122 Despite a strong intermodel agreement, there is vigorous debate as to the causes of, and the
123 confidence in, these projected mean state changes. The Walker circulation is expected to weaken
124 because tropical precipitation increases at a slower rate than water vapour, so the tropical atmospheric
125 overturning must slow down with weaker equatorial Trade winds, and would occur even without a
126 change in the west-minus-east SST gradient⁴⁰. Observations show a weakening over the past six
127 decades (1950–2009) but this was accompanied by a weakening in the west-minus-east SST gradient
128 in the Indo-Pacific⁴⁴, suggesting a coupling between oceanic and atmospheric changes. Such coupling
129 would imply that future changes of the Walker circulation need not be static or unidirectional^{18,45} and
130 can be influenced, for instance, by a differential warming between the Pacific and other oceanic
131 basins. For example, a strengthening Walker circulation can be associated with a faster warming in
132 the Indian Ocean^{18,46}, or the Atlantic⁴⁷.

133 Another point of contention is that, in stark contrast to the projection, the Walker circulation has
134 actually strengthened over the past three decades^{48,49,50,51}. The observed strengthening is suggested to
135 play a role in the so-called “global warming hiatus”^{50,52}, but there is debate as to its mechanism. One
136 contributing factor could be the negative phase of Interdecadal Pacific Oscillation (IPO)⁵⁰ as signified
137 by a massive western tropical Pacific sea level rise⁵³. The other could be decadal variations in ENSO
138 properties, for instance, a random string of La Niña events⁵⁴, or a lack of strong eastern Pacific El

139 Niño events⁵⁵ but more frequent central Pacific El Niños⁵⁴ facilitated by the warmer western Pacific
140 mean state⁵⁶. However, the interdecadal fluctuations in ENSO properties and the IPO themselves may
141 be inter-related, given that ENSO rectification can be a mechanism for interdecadal mean state
142 changes^{37,38}.

143 The projected mean state changes are expected to modify ENSO's amplifying and damping
144 feedbacks. The net change in feedbacks has been found to vary considerably across models,
145 contributing to a lack of consensus in the change of ENSO SST variability^{16,17,18}. The increased
146 vertical temperature gradient, due to a surface-intensified ocean warming, would enhance the Ekman
147 pumping feedback that tends to increase variability in the central Pacific³². The weakened easterly
148 Trade winds would lead to an anomalous net poleward transport of warm water¹⁶, causing the depth of
149 the mean equatorial thermocline to shoal. This can enhance the thermocline feedback through an
150 increased sensitivity to wind variability¹⁸, despite being partially offset by a reduction in mean
151 upwelling associated with the weaker mean easterly winds. Surface warming enhances evaporation
152 and cloud cover leading to a reduction in shortwave radiation, thus increasing the efficiency of
153 thermodynamic damping that weakens El Niño growth¹⁶, although uncertainties remain due to models
154 still struggling to represent the observed relationships²¹. This delicate balance between damping and
155 amplifying feedback processes is vastly different across models^{16,17,18,21}. When only models with a
156 better representation of the various linear feedbacks are considered, an inter-model consensus in the
157 temporal evolution of ENSO SST amplitude response is achieved¹⁸, enhancing variability before year
158 2040, when SST warms faster in the eastern Pacific Ocean than over the maritime region, but
159 decreasing variability thereafter, when the latter warms more rapidly.

160 The notion that ENSO properties are affected by the mean state changes appears to be supported by
161 observations and theory^{57,58}. The mid-1970 shift of the IPO from a colder to a warmer tropical eastern
162 Pacific saw a stronger ENSO amplitude⁵⁸, marked by the 1988/1989 and 1998/99 La Niña events,
163 which were characterised by reduced atmospheric convection in the central Pacific, and the 1982/83
164 and 1997/98 extreme El Niño, which featured eastward propagating SST anomalies^{13,14}, a shift of the
165 ITCZ to the eastern equatorial Pacific³¹, and a zonal SPCZ event¹⁰. Since the early 2000s, the colder
166 eastern equatorial Pacific saw reduced ENSO SST variability in the eastern Pacific but increased SST
167 variability in the central Pacific²⁵. The asymmetric features between extreme La Niña and extreme El
168 Niño and the vastly different changes in ENSO SST variability at different longitudes also suggest
169 that an examination of a change in ENSO properties must move away from using only one index at a
170 fixed location, and must take into account spatial asymmetry of ENSO anomalies.

171 **ENSO asymmetry and extremes.** El Niño and La Niña events are not symmetric in spatial
172 pattern^{22,23,24,59} or temporal evolution^{13,60,61}. Extreme El Niño features disproportionately warm
173 maximum SST anomalies in the eastern equatorial Pacific, but the anomaly centre of weak El Niño

174 and extreme La Niña events are situated in the central equatorial Pacific²⁵. The anomaly centre of
175 weak La Niña is located further towards the eastern equatorial Pacific than extreme La Niña^{25,26,31,32}.
176 This spatial asymmetry is characterised by positive SST skewness in the eastern equatorial Pacific,
177 but negative skewness in the central equatorial Pacific⁶². In addition, an extreme La Niña tends to
178 follow an extreme El Niño^{27,32}, but not the other way around. A La Niña can last for more than one
179 year whereas El Niño events tend to terminate abruptly in late boreal winter or spring^{13,60,61}.

180 The asymmetries require at least two ENSO indices to distinguish extreme El Niño from extreme La
181 Niña, or extreme El Niño from weak El Niño^{25,26,31,32}. The two indices may be obtained by Empirical
182 Orthogonal Function (EOF) analysis of SST anomalies, which deconvolves the spatio-temporal SST
183 variability into orthogonal modes, each described by a principal spatial pattern and the corresponding
184 principal component (PC) time series. An event may be described by an appropriately weighted
185 superposition of the two modes. One EOF depicts strong variability in the Niño3.4 or Niño3 region²⁵
186 (Fig. 1a) and the other resembles the central Pacific El Niño pattern^{34,35,36} (Fig. 1b). An extreme El
187 Niño (**red stars**, Fig. 1c, f) is described by the difference between EOF1 and EOF2, or an E-index
188 defined as $(PC1-PC2)/\sqrt{2}$ (Ref. 25), corresponding to extreme positive SST anomalies in the eastern
189 equatorial Pacific (Niño3 region, Fig. 1e). An extreme La Niña (**blue stars**, Fig. 1c) is described by
190 the sum of EOF1 and EOF2, or a large C-index defined as $(PC1+PC2)/\sqrt{2}$ (Fig. 1d) (Ref. 25), giving
191 rise to maximum cooling in the central Pacific (Fig. 1h, i) and can be represented by SST anomalies in
192 the Niño4 region (Fig. 1d).

193 Despite the recognition of inter-event differences⁶³, debates persist as to whether the central Pacific El
194 Niño^{34,35}, whose spatial pattern resembles EOF2, is part of the ENSO asymmetry^{25,26}, or a distinct
195 mode³⁶. Several arguments support the view of the former. Firstly, EOF2 is a “modulator” for
196 describing inter-event differences, and it rarely appears without a substantial projection onto EOF1.
197 Many central Pacific El Niño events (Fig. 1g; **purple** dots in Fig. 1c, defined as when the C-index is
198 greater than one-standard deviation) have a considerable contribution from EOF2, like La Niña events
199 (Fig. 1d) but with an opposite sign. Even weak El Niño events (**yellow** dots Fig. 1c) involve both
200 EOFs (Fig. 1c), and together they represent a “continuum”³³. Indeed, warm and cold events occur
201 over a broad range of longitudes, but their anomaly centres co-mingle³³. Secondly, the anomaly
202 patterns of the central Pacific El Niño and extreme La Niña are somewhat similar, and both can be
203 represented by Niño4 (Fig. 1d). It is extreme El Niño events (**red stars**, Fig. 1c) that are outliers (Fig.
204 1d), exhibiting extraordinary warm anomalies inducing a massive rainfall increase in the eastern
205 equatorial Pacific^{31,64,65}, without which the concept of EOF2 as an independent mode would have little
206 basis²⁵.

207 The fact that the core of ENSO SST anomaly varies longitudinally with event magnitude reflects the
208 asymmetry and diversity of ENSO mechanisms. Nonlinear SST-wind feedback^{27,66} is thought to be a

209 source of ENSO asymmetry: the response of zonal winds to warm SST anomalies is greater than to
210 cold SST anomalies. On shorter time scales, stochastic forcing including westerly wind bursts
211 (WWBs) is more tightly coupled with warm SST anomalies than cold anomalies and the interaction
212 between WWBs and warm SST anomalies constitutes a positive feedback^{67,68}. Their coupling
213 strengthens as the SST anomalies expand eastwards, in association with the eastward extension of the
214 warm pool and reduced equatorial upwelling^{6,8,31}, contributing to larger amplitude of positive SST
215 anomalies in the eastern equatorial Pacific⁶⁸. For extreme El Niño, in addition to the initiation of this
216 coupled process, as well as preconditioning by oceanic heat content³, and enhancement by off-
217 equatorial atmospheric conditions³⁰, all linear positive feedbacks (zonal advection, Ekman pumping,
218 and thermocline feedback) play an important role in the growth of SST anomalies, and these
219 processes strengthen as the anomaly centre moves eastward^{25,69}. The zonal advective feedback
220 process in particular is enhanced by a reversal of the equatorial currents – a feature that characterises
221 extreme El Niño events^{14,70}. At the mature phase, nonlinear vertical advection further contributes to
222 the large positive SST anomalies⁷¹.

223 The large amplitude of warm anomalies attained during an extreme El Niño induce large changes in
224 atmospheric circulation that lead to stronger discharge of the equatorial warm water volume, abruptly
225 terminating the event and preconditioning for a La Niña²⁷. The associated thermocline shoaling in
226 turn facilitates a more efficient Bjerknes feedback through zonal SST gradient between the Maritime
227 region and the central Pacific³². Through nonlinear zonal advection (advection of anomalous zonal
228 temperature gradient by anomalous zonal currents) and Ekman pumping, this leads to strong
229 anomalous cooling in the central Pacific that signifies an extreme La Niña³². This also means that an
230 extreme La Niña tends to develop following a strong El Niño. For central Pacific El Niño events, on
231 the other hand, the thermocline variability and upwelling anomalies are weak due to the deep mean
232 thermocline³³. There, the growth of SST anomalies is largely attributed to zonal advection, though
233 smaller in magnitude than that in the eastern Pacific^{34,72,73}.

234 Recent understanding has led to a description of extreme El Niño and extreme La Niña that is both
235 more dynamic and impact-focused, rather than solely focussing on SST anomalies at fixed locations.
236 An extreme El Niño event features a reversal of the upper equatorial currents to flow eastward,
237 facilitating an eastward propagation of SST anomalies¹⁴, a feature that is not seen during La Niña and
238 weak El Niño events. During extreme El Niño events, the maximum total temperature is situated in
239 the eastern equatorial Pacific. This weakens the meridional and zonal SST gradients, allowing the
240 western Pacific convergence zone and the ITCZ to move to the eastern equatorial Pacific, an essential
241 characteristic of an extreme El Niño event⁶⁴. This massive reorganization of the atmospheric
242 circulation leads to a dramatic rainfall increase in the eastern Pacific^{6,8,31}. The collapse of the mean
243 meridional SST gradients also leads to the SPCZ swinging up to 1000 km toward the equator¹⁰. The

244 use of atmospheric parameters, such as rainfall anomalies in the eastern equatorial Pacific, or
245 outgoing longwave radiation⁶⁵ to define an El Niño^{32,64}, for instance, have direct ties to both local and
246 remote impacts; it has been proven to be of great utility for examining the extreme rainfall response of
247 El Niño to greenhouse warming³¹, as underpinned by the non-linearity of atmospheric response to
248 ENSO SSTs.

249 **Projected changes in extreme ENSO events.** Despite lingering uncertainties, the future mean state
250 changes are robustly produced by climate models. Although most models underestimate ENSO
251 asymmetry⁵⁹, a subset of models can simulate asymmetric and nonlinear behaviour, such as large
252 precipitation increases over the eastern equatorial Pacific, zonal SPCZ, and eastward propagation of
253 warm SST anomalies that characterise the observed extreme El Niño, and strong SST cooling over
254 central Pacific associated with an extreme La Niña. As discussed further below, there is a robust
255 projected increase in the frequency of such events and that this can be explained as consequences of
256 the mean state changes^{10,14,31,32}.

257 However, inter-model consensus continues to be weak in terms of changes in Niño3 SST anomalies.
258 Out of 21 models that are able to produce extreme El Niño and extreme La Niña³², only 12 models
259 produce an increase in ENSO amplitude (Fig. 2a). In association, only 12 models generate an
260 increased frequency of extreme El Niño events defined as Niño3 SST greater than a 1.75-standard
261 deviation (s.d.) value. This is despite a tendency for more occurrences of extreme cold and warm
262 anomalies (Fig. 2c). Using the 9 models that are able to simulate the relative importance of ENSO
263 linear feedbacks¹⁸ does not improve the consensus. The inter-model consensus is slightly better for
264 the Niño4 SST anomalies: 15 out the 21 (71%) models generate an increased amplitude (Fig. 2b), and
265 17 models produce an increased frequency in extreme La Niña, defined as when Niño4 SST is greater
266 than a 1.75-s.d. value in amplitude, and similarly there is a tendency for more extreme cold and warm
267 anomalies (Fig. 2d). The dynamics for the stronger consensus in Niño4 is not fully understood.

268 Given that extreme El Niño is characterized by a shift of the atmospheric convection to the eastern
269 equatorial Pacific, a rainfall-based definition, e.g., as when Niño3 rainfall averaged over DJF exceeds
270 5 mm day⁻¹, provides an alternative avenue for assessing the frequency of such extreme events³¹.
271 Unless stated otherwise, this rainfall-based definition of extreme El Niño is used hereafter.

272 Climate models suggest that the relationship between changes in mean rainfall and ENSO amplitude
273 is complex and maybe time-varying. An increase in the eastern equatorial Pacific mean rainfall from
274 the pre-industrial to the present-day was found to be a good indicator of increased ENSO amplitude
275 over the same period, but for reasons still unknown, such a linkage was found not to hold for changes
276 from the present-day to the later 21st century⁴³. On the other hand, background warming tends to
277 increase the response of rainfall to SST anomalies because rainfall responds nonlinearly to the total

278 temperature^{74,75}. As such, there is a strong inter-model consensus on the increased rainfall response to
279 ENSO SST anomalies, even though there is a far weaker agreement on changes in ENSO SST
280 anomalies⁷⁵. The increased rainfall response to ENSO anomalies is not longitudinally uniform but has
281 a maximum that shifts increasingly eastwards with stronger ENSO SST anomalies, associated with a
282 faster background warming in the eastern than in the central equatorial Pacific^{10,74}.

283 Mean meridional and zonal SST gradients in the equatorial Pacific are barriers to movement of
284 convection centres, and the enhanced warming in the eastern Pacific and equatorial regions weaken
285 these barriers. The weakening mean SST gradients make it easier for a given positive SST anomaly to
286 further weaken or even reverse the meridional (Fig. 3a, b) and zonal SST gradients, leading to
287 increased occurrences of strong convection and high rainfall in the eastern equatorial Pacific^{31,64} (Box
288 1, features A and D), in spite of a convective threshold that is projected to increase with mean SSTs⁷⁶.
289 Consequently, the frequency of extreme El Niño increases by more than double, with a strong inter-
290 model consensus. An analogous situation exists in the Indian Ocean, where anomalous conditions
291 referred to as the positive Indian Ocean Dipole occurs, which features a shift of atmospheric
292 convection to the west Indian Ocean. As a result of the weakening Walker circulation, the west
293 tropical Indian Ocean warms faster than the east. This leads to an increase in the frequency of extreme
294 positive Indian Ocean Dipole events⁷⁷.

295 The projected weakening of westward mean equatorial Pacific upper ocean currents^{40,78} leads to a
296 doubling in El Niño events that feature prominent eastward propagation of SST anomalies¹⁴ (Box 1,
297 feature A). Heat budget analysis shows that advection of temperature by the total current that is
298 eastward contributes to eastward propagation of El Niño temperature anomalies¹⁴. Under global
299 warming, the weakened mean current, associated with the weakened Walker circulation^{40,78}, favours
300 occurrences of an eastward propagation, because it takes a smaller eastward anomaly during an El
301 Niño to reverse the weaker westward mean current, leading to a doubling of eastward propagation
302 events¹⁴. However, unlike observed extreme El Niño events, not all modelled extreme El Niño
303 events, identified using either rainfall-based or SST-based definition, correspond with eastward
304 propagating SST anomalies.

305 The projected faster warming in the equatorial than the off-equatorial Pacific^{39,41,53} is expected to
306 facilitate an increased frequency in zonal SPCZ events¹⁰ (Box 1, feature D). In the central and western
307 equatorial Pacific, the warmest water of the warm pool is situated south of the equator. This positive
308 off-equatorial-minus-equatorial temperature gradient supports the southeastward extension of the
309 SPCZ¹⁰. Because it is the meridional temperature gradient that is important, zonal SPCZ events can
310 occur without an extreme El Niño³¹. The projected warming pattern results in increased occurrences
311 of diminishing meridional SST gradients, leading to an increased frequency of zonal SPCZ events.

312 In fact, the mean state changes concurrently favour an increased frequency of extreme El Niño, zonal
313 SPCZ, and eastward propagating El Niño events, even though the dynamics for the increased
314 frequency in each type of climate extreme are not necessarily to be exactly the same. As such, the
315 frequency of any pairs of the three types of event more than doubles. Importantly, climate events
316 similar to the 1982/83 and 1997/98 events, i.e., with extreme rainfall anomalies in the eastern Pacific
317 accompanied by a zonal SPCZ and eastward propagating SST anomalies, are projected to double (Fig.
318 3a, b).

319 The projected increase in extreme El Niño events more frequently creates a favourable condition for
320 extreme La Niña events to occur, the frequency of which is expected to nearly double. The equatorial
321 Pacific thermocline tends to shoal following an El Niño, facilitating a La Niña to develop³. This also
322 allows more efficient Bjerknes feedback through Ekman pumping and nonlinear zonal advection –
323 processes that are important for extreme La Niña³². Under greenhouse warming, such favourable
324 condition is further facilitated by mean state changes (Box 1, features A and B): the increased vertical
325 temperature gradient is conducive to anomalous Ekman pumping. Faster warming over the Maritime
326 continent than in the central equatorial Pacific leads to more frequent occurrences of strong positive
327 west-minus-east temperature gradients, anomalous easterlies, anomalous oceanic westward flow and
328 upwelling, and therefore strong nonlinear zonal advection and Ekman pumping³². As a result,
329 aggregated over models that are able to produce extreme El Niño and La Niña³², 75% of the increase
330 in extreme La Niña occurs after an extreme El Niño event (defined using rainfall)³². Approximately
331 80% of these extreme El Niño events actually correspond with Niño3 SST anomalies exceeding an
332 extreme threshold (1.75 s.d), so some 60% of the increase occurs following an SST-defined extreme
333 El Niño, analogous to the observed 1997-1998 situation. The rest of the 15% occurs following an
334 SST-defined moderate El Niño, like in 1988-89.

335 The projected increase in the frequency of extreme ENSO events is largely independent from a
336 projected increased frequency of extreme positive Indian Ocean Dipole events⁷⁷, but the sequence of
337 climate extremes similar to what the world experienced during 1997-1999, are projected to increase
338 markedly, from one in 187 years to one in 48 years (Fig. 3c, d); during these two years, an extreme
339 positive Indian Ocean Dipole preceded an extreme El Niño, and was then followed by an extreme La
340 Niña.

341 **ENSO teleconnection under greenhouse warming.** ENSO teleconnections refers to the statistically
342 significant ENSO-coherent fluctuations of a field remote from the central-to-eastern equatorial Pacific.
343 In the tropical Pacific, atmospheric teleconnections are generated through a reorganization of
344 atmospheric convection associated with ENSO SST anomalies that induce a deep baroclinic
345 response⁷⁹. The effect is confined to the near-tropical portions of eastern Australia and western Pacific
346 countries, leading to dry conditions in these regions but wet conditions in the eastern Pacific, during

347 an El Niño. Outside the tropics, the same convective and diabatic atmospheric heating anomalies
348 excite equivalent barotropic Rossby wave trains that propagate into the northern and southern
349 extratropics⁸⁰. Referred to as the Pacific North American pattern⁸¹ and Pacific South American
350 pattern⁸², respectively, these wave trains are the main agents for extratropical teleconnections. They
351 generate changes to midlatitude westerlies thereby affecting rainfall through changes in mean-state
352 baroclinicity, steering of storms by the westerly jet streams, and possible orographic effects⁸³. There is
353 so far no study suggesting that the way in which ENSO teleconnections operate will undergo
354 fundamental changes.

355 The nonlinearity of ENSO teleconnections should continue to operate with progressing greenhouse
356 warming. Stemming from the strong asymmetry in the spatial anomaly pattern between El Niño and
357 La Niña^{25,26,84,85} and between strong and moderate El Niño events^{22,24,25,26,29,66}, ENSO teleconnections
358 are asymmetric with respect to extreme La Niña and extreme El Niño^{31,32}, and with respect to weak
359 and strong events^{22,36,86}. This is underpinned by several features of tropical convection. Firstly,
360 atmospheric convection tends to occur where there are maximum SSTs exceeding the convective
361 threshold (between 26°C and 28°C for the present-day climate)⁷⁶, so that an additional SST
362 perturbation can generate convective available potential energy as to increase the sensitivity of rainfall
363 to SST perturbations. Secondly, during an extreme El Niño event, the atmospheric convection centre
364 is displaced to the eastern equatorial Pacific³¹, in contrast to an extreme La Niña, for which
365 convection, although suppressed in the central Pacific, is enhanced near its climatological position in
366 the western Pacific³². Thus, in terms of the convective anomaly pattern, and therefore far-field
367 teleconnections, the asymmetry between extreme La Niña and extreme El Niño is far greater than that
368 for tropical SST anomalies. A similar asymmetry is seen between a central Pacific El Niño and an
369 extreme eastern Pacific El Niño with the centre of enhanced convection located in the central
370 equatorial Pacific for the central Pacific El Niño, but in the eastern equatorial Pacific for extreme El
371 Niño^{31,36}. These asymmetric features are expected to persist in a warming climate.

372 Under greenhouse warming, the response of the tropical eastern Pacific rainfall anomalies, referenced
373 to the changing mean state, to El Niño SST anomalies is likely to strengthen (Fig. 4), and the centre of
374 maximum response to shift eastward^{31,75,87}. This is because rainfall responds nonlinearly to the
375 absolute SST^{74,75}, increasing faster in the eastern than in the western Pacific. Outside the tropics, the
376 Pacific North American pattern and the Aleutian low are expected to shift eastward, but there are
377 reported variations on how the overall intensity of this teleconnection pattern may change^{87,88,89,90},
378 perhaps in part linked to a lack of consensus on how ENSO SST amplitude will change.

379 Aggregated over models that are able to produce extreme El Niño and La Niña³², a stronger sensitivity
380 of rainfall to positive Niño3 SST anomalies (Niño3 >0.5 s.d.) in the future climate is seen in the
381 eastern equatorial Pacific and some of the extratropical oceans (left column, Fig. 4), such that even if

382 the amplitude of Niño3 SST variability does not change, the teleconnection has a tendency to increase
383 in these regions. The response of rainfall to negative Niño4 SST anomalies ($|\text{Niño4}| > 0.5$ s.d.) shows,
384 by and large, no significant change in either the tropics or the extratropics (right column, Fig. 4),
385 therefore the teleconnection will increase with the increased amplitude of Niño4 SST variability,
386 which enjoys a stronger intermodel agreement. As such, future extreme El Niño and La Niña events
387 will occur more frequently^{31,32}, with at least a similar strength of teleconnection to that of the present-
388 day events. The increased frequency of ENSO extremes is consistent with an increase in ENSO-
389 related hydroclimate variability in the tropical Pacific region, particularly in regions such as southern
390 Asia, with important implications because these regions are already severely stressed by variations in
391 droughts, floods and crop yields⁹¹.

392 **Summary, uncertainties and future research.** The mean climate of the tropical Pacific is expected
393 to change in the coming century as a result of ongoing emissions of greenhouse gases. Potential
394 consequences of these mean state changes include more eastward propagating El Niño events, an
395 increased frequency of extreme El Niño events as defined using extreme rainfall in the eastern
396 equatorial Pacific, a higher frequency of extreme La Niña events, an eastward shift of the ENSO
397 rainfall teleconnection with a likely increased intensity, and more frequent extreme equatorward
398 swings of large-scale convergence zones, such as the SPCZ and the ITCZ. Long records of paleo-
399 ENSO variance suggest that 20th century ENSO activity is significantly stronger than that during
400 previous centuries^{92,93} or millennia⁹⁴. Since such paleo-records typically document changes in both
401 ENSO-related SST and rainfall anomalies, to varying degrees, the recent intensification of ENSO in
402 these reconstructions provides some empirical support for the projections of more extreme ENSO
403 events under greenhouse warming.

404 However, there are known uncertainties that keep the confidence in these projections at the *medium*
405 level, following the IPCC definition. The projected weakening of the Trade winds has been
406 challenged by the observed strengthening over recent decades^{48,49,51}, although low frequency
407 variability can alter long-term trends and the recent strengthening is likely associated with a negative
408 IPO phase linked to the global warming hiatus^{50,52}. The projected increased frequency of extreme El
409 Niño and extreme La Niña events is contingent upon the faster warming in the eastern equatorial
410 Pacific Ocean. This is in turn a balance between an ocean dynamical ‘thermostat’ mechanism that
411 moderates eastern Pacific warming⁹⁵, and various other processes that enhance the warming such as a
412 reduced poleward heat transport away¹⁶, and surface latent heat flux adjustment and the evolution of
413 cloud feedbacks⁴¹. Despite some observational support of the expected enhanced equatorial eastern
414 Pacific warming over the past 60 years, the tropical SST trend over the recent decades has actually
415 featured suppressed warming in the east, contrary to the expected pattern from climate models.

416 The ability of climate models to realistically simulate the present-day mean state climate, ENSO
417 properties, and the associated teleconnection is another source of uncertainties. Firstly, the common
418 “cold tongue”⁹⁶ and the double-ITCZ bias⁹⁷ in the mean state have persisted for decades, and every
419 model suffers from its own intrinsic biases. Although in some cases models with a bias reduction
420 produce an even higher frequency^{31,32}, the extent to which these biases are a source of uncertainty is
421 yet to be tested. Secondly, we still know little about how other important characteristics of ENSO will
422 respond to greenhouse warming, such as interactions between ENSO and the annual cycle,
423 termination and onset of El Niño events, coupling between WWBs and El Niño, and ENSO precursors
424 and amplifying or damping mechanisms. Thirdly, parameterisation of sub-grid physics such as
425 atmospheric convection, cloud formation and their coupling to the resolved dynamics remains
426 inaccurate⁹⁸. Fourthly, the genesis and evolution of ENSO can be affected by processes occurring in
427 the Indian and Atlantic Oceans^{99,100}, but the associated processes are not well understood. An
428 additional uncertainty is whether teleconnection patterns and intensity are correctly represented at
429 regional scales, given that the regional impacts from ENSO extremes might not be resolved by present
430 climate models.

431 Before a significant reduction in these uncertainties is achieved, every effort must be made toward a
432 projection that is consistent with our physical theoretical understanding and with what observations
433 show. To this end, sustained ocean and atmospheric observations and effort to reduce errors are
434 required to help determine the long-term mean state changes and to validate ENSO simulations;
435 efforts to reduce model mean state biases, such as the “cold tongue” bias, must be bolstered; and
436 focused observational and modelling process studies for a fuller understanding of tropical convection
437 and cloud physics toward better parameterization for an improved ENSO simulation, must be
438 strengthened. Although the biases and deficiencies may impede realistic simulation of ENSO
439 extremes of the present-day and future climate, the likelihood of more frequent devastating ENSO
440 extremes has a dynamical basis and should be considered as we prepare to face the consequences of
441 greenhouse warming.

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677 **Additional information**

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689 **Author Contributions**

690 W.C., A.S. G.W., and S.W.Y wrote the initial version of the paper. G.W. performed the model output
691 analysis and generated all Figures. All authors contributed to interpreting results, discussion of the
692 associated dynamics, and improvement of this paper.

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694 The authors declare no competing financial interests. Correspondence and requests for materials
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696

697 **Figure captions**

698 **Figure 1 | Observed ENSO asymmetry. a, b,** First and second principal variability patterns of SST
699 obtained by applying EOF analysis to satellite-era SST anomalies in austral summer (DJF), in the
700 tropical Pacific region of 15°S–15°N, 140°–280°E. The SST anomalies and wind stress vectors are
701 presented as linear regression onto standardized principal component (PC) time series. **c,**
702 Relationship between the two principal component time series. **d,** Relationship between C-index and
703 Niño4 SST index (160°E–150°W, 5°S–5°N, indicated by the blue box in each panel). The C-index is
704 defined as $(PC1+PC2)/\sqrt{2}$. **e,** Relationship between E-index and Niño3 SST index (150°W–90°W,
705 5°S–5°N, indicated by the red box in each panel). The E-index is defined as $(PC1-PC2)/\sqrt{2}$. **f, Blue**
706 **stars** indicate **extreme La Niña** events, i.e., 1988/89 and 1998/99, defined as when both principal
707 components are negative but greater than 1 s.d. in amplitude (as shown in panel c), or quadratically
708 detrended Niño4 is negative but greater than 1.75 s.d. in amplitude (as shown in panel d); **light blue**
709 dots indicate **moderate La Niña** events, i.e., 1983/84, 1999/00, 2007/08 and 2010/11, defined as
710 when the negative Niño4 (unit in s.d) is greater than 1 s.d. but less than 1.75 s.d. in amplitude (as
711 shown in panel d); **green** dots indicate **weak La Niña** events, i.e., 1984/85, 1995/96, 2000/01 and
712 2008/09, defined as when the negative Niño4 is greater than 0.5 s.d. but less than 1 s.d. in amplitude
713 (as shown in panel d); **red stars** indicate **extreme El Niño** events, i.e., 1982/83 and 1997/98, defined
714 as when EOF1 is greater than 1 s.d. and negative EOF2 is greater than 1 s.d. in amplitude (as shown
715 in panel e); **purple** dots indicate **central-Pacific El Niño** events, i.e., 1990/91, 2002/03, 2004/05 and
716 2009/10, defined as when C-index is greater than 1 s.d. (as shown in panel d); **yellow** dots indicate
717 events that are **a mixture of central-Pacific and eastern-Pacific El Niño events**, i.e., 1979/80,
718 1986/87, 1987/88, 1991/92, 1994/95, 2001/02, 2003/04 and 2006/07, defined as when C-index is
719 greater than 0.5 s.d. but less than 1 s.d. (as shown in panel d). **f – i,** anomaly pattern of extreme El
720 Niño, CP El Niño, extreme La Niña, and weak La Niña, respectively.

721 **Figure 2 | Greenhouse warming-induced changes in ENSO properties.** Shown are based on
722 outputs from CMIP5 experiments under historical and RCP8.5 scenarios using 21 models (out of 34
723 in total), focusing on austral summer (DJF). **a, b,** Comparison of Niño3 and Niño4 standard deviation
724 (s.d) in the *Control* period (1900-1999) (x-axis) and *Climate change* period (2000-2099) (y-axis).
725 Numbers in the upper left indicate the number of models that produce an increase in s.d., and in the
726 lower right, number of models that produce a decrease in s.d. **c, d,** Histogram of quadratically
727 detrended Niño3 and Niño4 SST anomalies in s.d. for *Control* period (1900-1999) (**blue**) and
728 *Climate change* period (2000-2099) (**red**). There is a tendency for each index to be more extreme, but
729 the two histograms in each panel are not statistically different ($H=0$) about the 95% confidence
730 interval, using a 2-sided student-*t* test.

731 **Figure 3 | Greenhouse warming-induced changes in climate extremes.** Shown are based on
732 outputs from CMIP5 experiments under historical and RCP8.5 scenarios using 21 models (out of 34
733 in total), focusing on austral summer (DJF). In all panels, extreme El Niño is defined as when Niño3
734 rainfall is greater than 5 mm/day³¹. **a** and **b**, extreme El Niño events concurrent with eastward
735 propagating SST anomalies¹⁴ and zonal SPCZ events¹⁰ (**blue stars**), similar to the 1997/98 extreme
736 El Niño event, for the *Control* period (1900-1999) and *Climate change* period (2000-2099),
737 respectively. The frequency of such events almost doubles. **c** and **d**, Extreme El Niño events preceded
738 by an extreme positive Indian Ocean Dipole, and followed by an extreme La Niña (**red stars**), similar
739 to what happened in 1997-1999, for the *Control* period (1900-1999) and *Climate change* period
740 (2000-2099), respectively.

741 **Figure 4 | Greenhouse warming-induced change in rainfall response to Niño3 and Niño4 SST**
742 **anomalies.** Shown are based on outputs from CMIP5 experiments under historical and RCP8.5
743 scenarios using 21 models (out of 34 in total), focusing on austral summer (DJF). **a, b**, Multi-model
744 average of quadratically detrended rainfall anomalies associated with El Niño, obtained by regressing
745 quadratically detrended rainfall anomalies onto quadratically detrended Niño3 using samples with
746 Niño3 greater than positive 0.5 s.d., in *Control* and *Climate change* periods, respectively. **c**, The
747 difference between **a** and **b** (i.e., **b-a**). Stippling in **c** indicates regions where the difference is
748 statistically significant above the 95% confidence level as determined by a two-sided Student's *t*-test.
749 **d, e** and **f** are the same as **a, b** and **c**, respectively, but for the patterns associated with La Niña, using
750 samples with a Niño4 greater than 0.5 s.d. in amplitude.

751 **Box 1 | Mean state changes and consequences**

752 *(Insert Box Figure)*

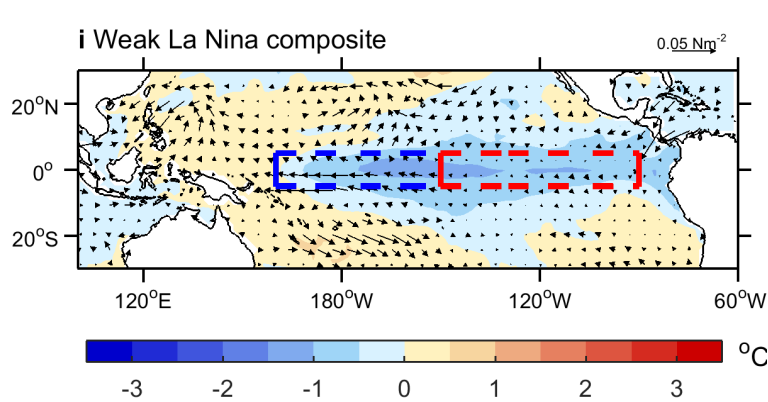
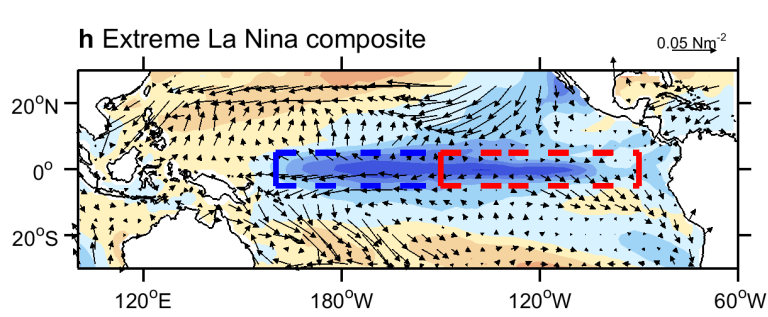
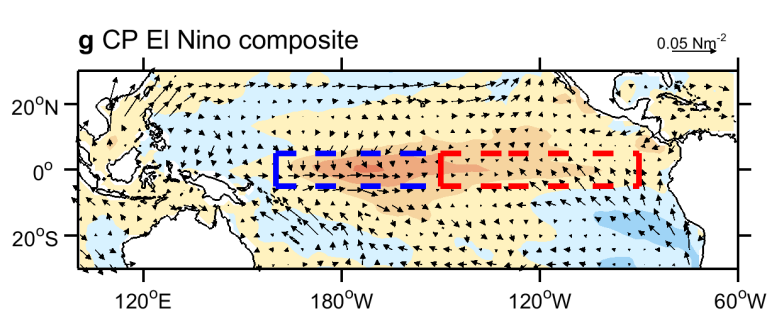
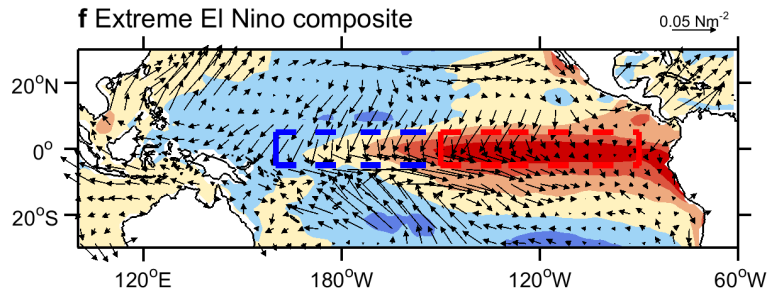
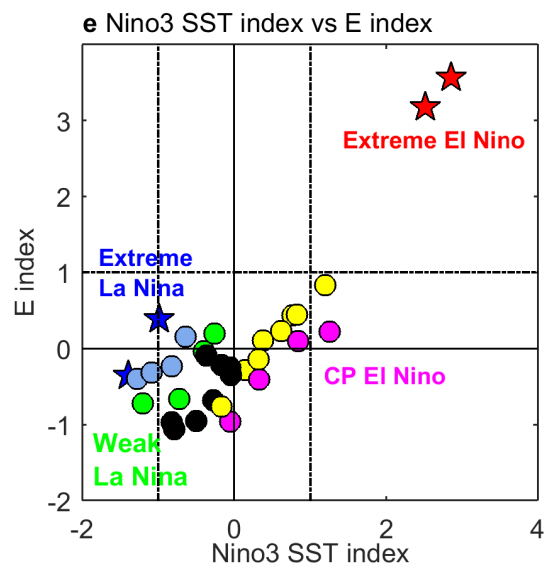
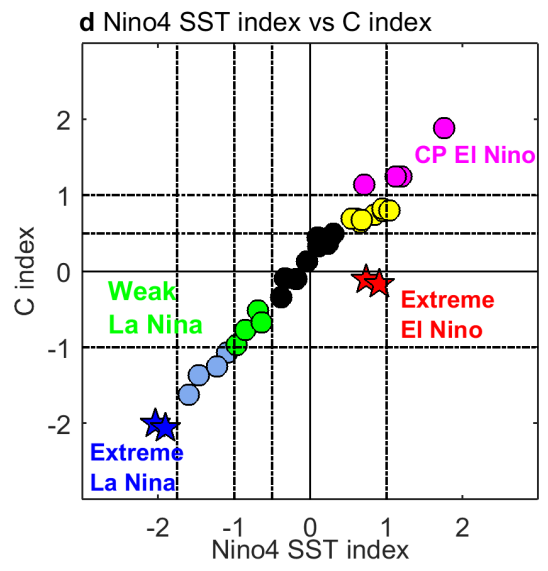
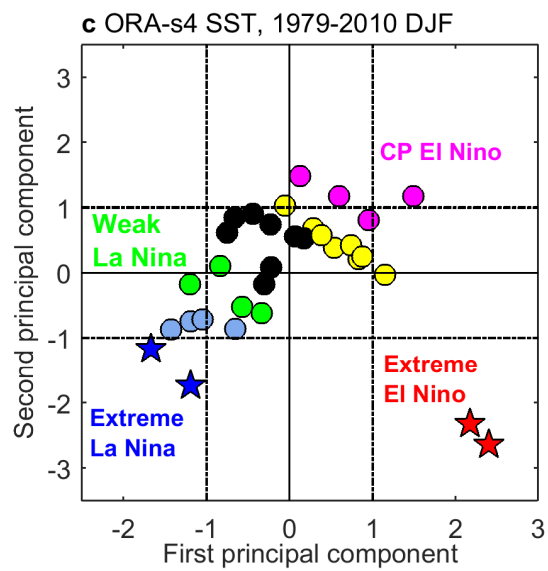
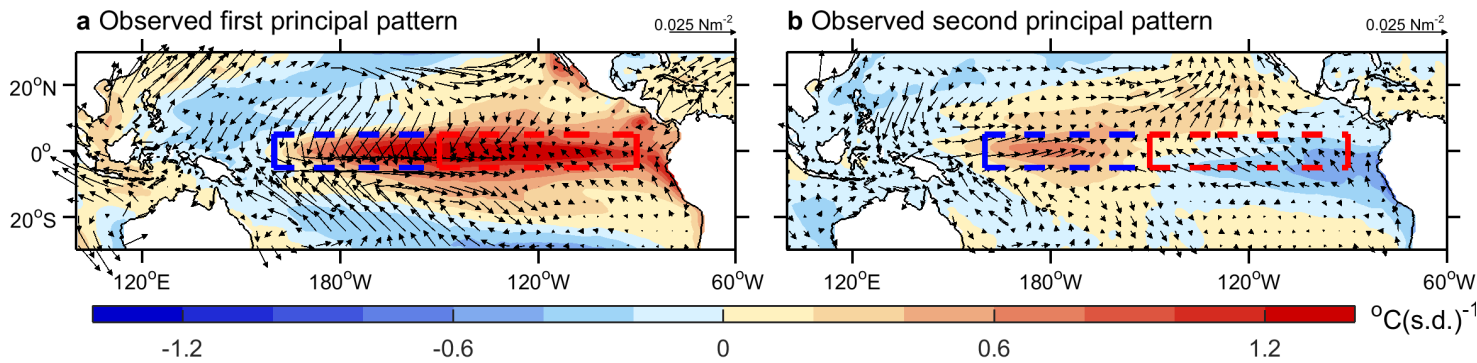
753 **Box Figure | Schematic showing greenhouse-induced future changes at the surface (shown only**
754 **for the north Pacific) and upper ocean along-equator and meridional cross-sections.**
755 **Greenhouse-induced changes** (**red arrows**) to the mean Walker circulation (**dashed black** with
756 shadow) and **mean ocean currents** (**cyan arrows**) are indicated. Major features of changes are
757 indicated by letters **A, B, C**, and **D**.

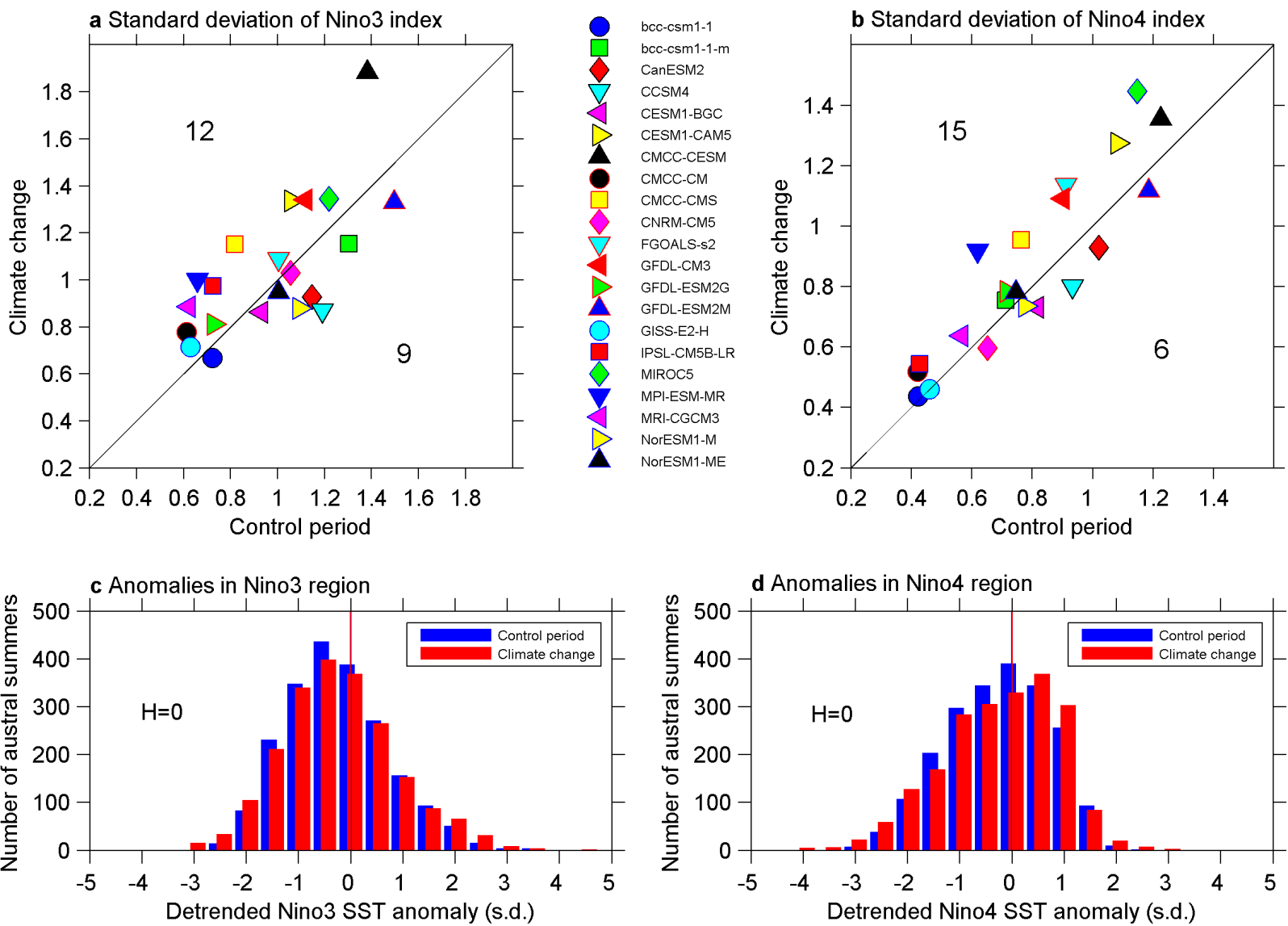
758 **A Features associated with a weakening Walker circulation.** The Trade winds and equatorial
759 currents weaken, the eastern equatorial Pacific warms faster than the surrounding regions, and the
760 thermocline shallows (**present-day: black curve; future: red curve**). The weakening equatorial
761 zonal currents are conducive to an increased frequency of eastward propagating El Niño events. The
762 faster warming in the eastern equatorial Pacific is favourable for an increased frequency of extreme El
763 Niño events by promoting atmospheric convection. The increased occurrences of extreme El Niño are

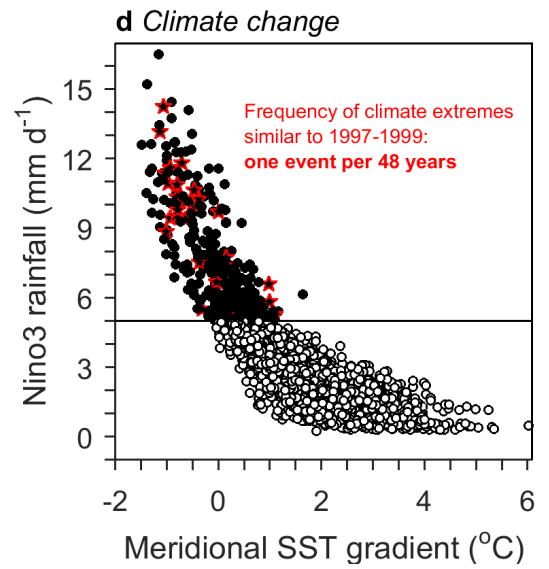
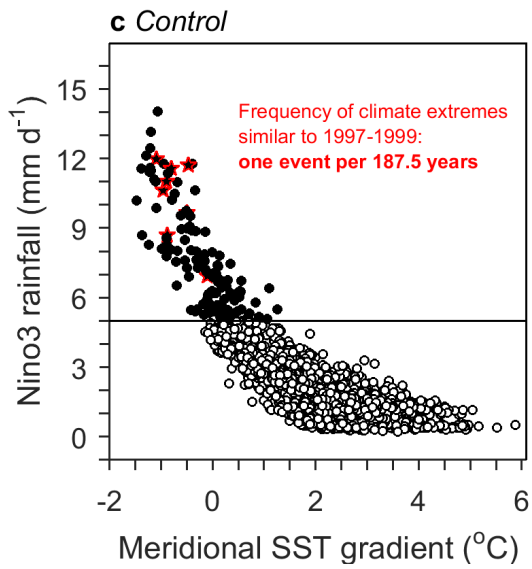
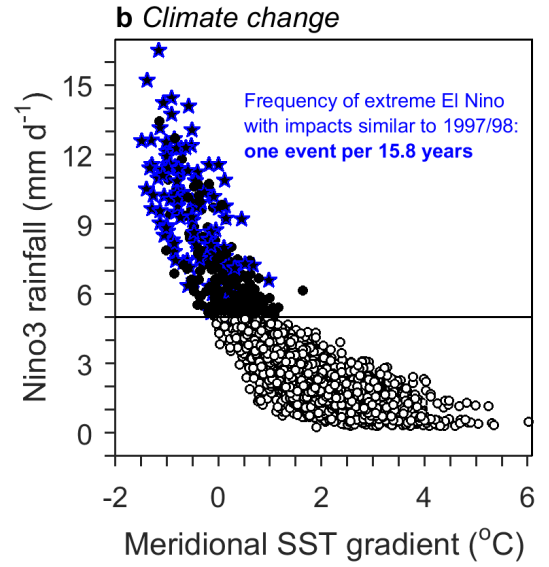
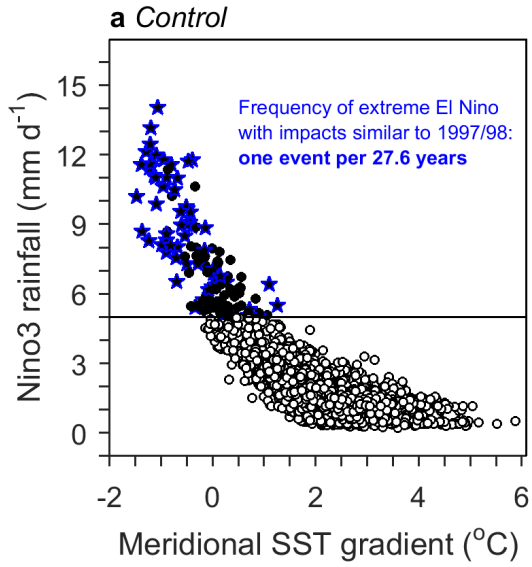
764 in turn conducive to an increased frequency of La Niña due to a discharged thermocline that promotes
765 an influence of the subsurface cool water in the central Pacific.

766 **B Increasing vertical temperature gradients, and C enhanced warming over the maritime**
767 **continent.** These changes are additional factors that facilitate an increased frequency of extreme La
768 Niña events, through nonlinear zonal advection and Ekman pumping.

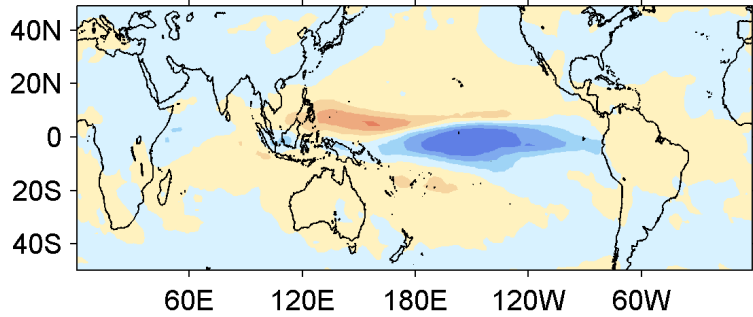
769 **D Accelerated warming in the equatorial rather than in the off-equatorial Pacific.** This change
770 leads to an increased frequency of equatorward shifts of the ITCZ, which characterizes an extreme El
771 Niño, and to an increased frequency of extreme swings of the SPCZ toward the equator. This occurs
772 because atmospheric convection tends to follow maximum sea surface temperatures.



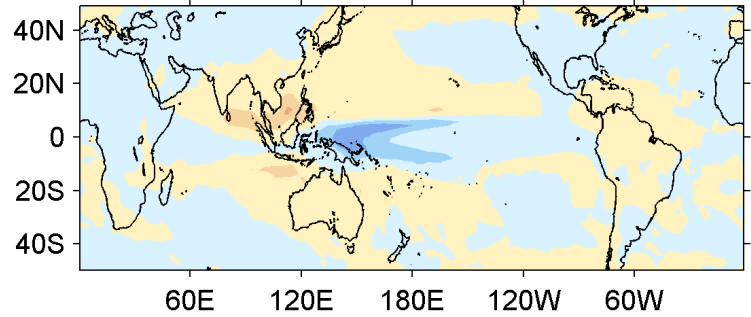




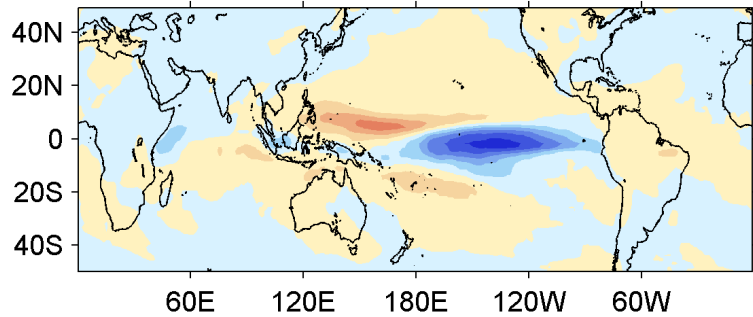
a Control, sensitivity to Nino3 > 0.5 s.d.



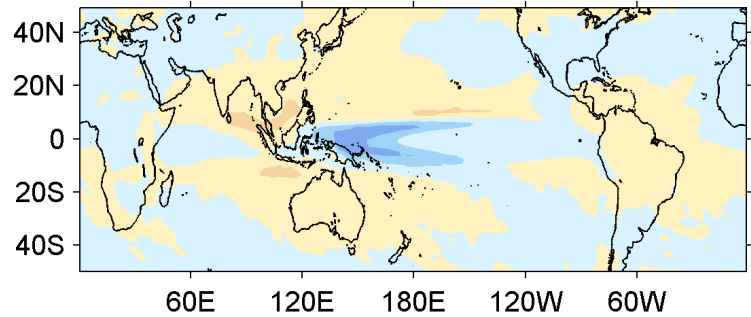
d Control, sensitivity to Nino4 < -0.5 s.d.



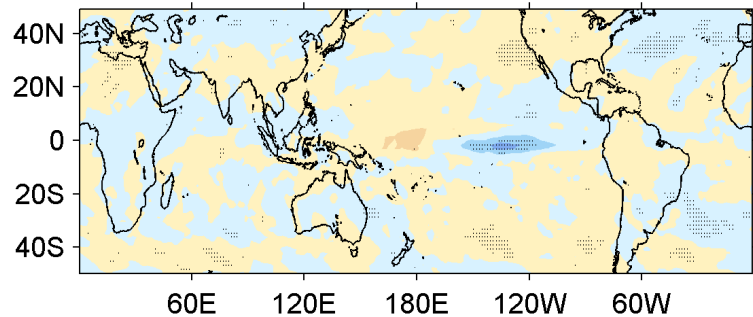
b Climate change, sensitivity to Nino3 > 0.5 s.d.



e Climate change, sensitivity to Nino4 < -0.5 s.d.



c Climate change - Control



f Climate change - Control

