Late-twentieth-century emergence of the El Nino propagation asymmetry and future projections

Author:

Santoso, Agus; McGregor, Shayne; Jin, F; Cai, W; England, Matthew; An, S; McPhaden, M; Guilyardi, E

Late 20th Century Emergence of El Niño Propagation Asymmetry and Future Projections

*Agus Santoso[1,2], Shayne McGregor[1,2], Fei-Fei Jin[3], Wenju Cai[4], Matthew H. England[1,2], Soon-Il An[5], Michael J. McPhaden[6], Eric Guilyardi[7,8]

1. Climate Change Research Centre, University of New South Wales, Sydney, Australia
2. ARC Centre of Excellence for Climate System Science, University of New South Wales, Sydney, Australia
3. Department of Meteorology, University of Hawaii at Manoa, Honolulu, United States
4. CSIRO Marine and Atmospheric Research, Aspendale, Melbourne, Australia
5. Department of Atmospheric Sciences, Yonsei University, Seoul, Korea
6. NOAA/Pacific Marine Environmental Laboratory, Seattle, Washington 98115, USA
7. LOCEAN/IPSL, CNRS, Paris, France
8. NCAS-Climate, University of Reading, UK

*Agus Santoso: a.santoso@unsw.edu.au
Shayne McGregor: shayne.mcgregor@unsw.edu.au
Fei-Fei Jin: jff@hawaii.edu
Wenju Cai: wenju.cai@csiro.au
Matthew H. England: m.england@unsw.edu.au
Soon-Il An: sian@yonsei.ac.kr
Michael J. McPhaden: michael.j.mcphaden@noaa.gov
Eric Guilyardi: eric.guilyardi@locean-ipsl.upmc.fr

The El Niño Southern Oscillation (ENSO) is Earth's most prominent source of interannual climate variability, exerting profound worldwide impacts[1-7]. Despite decades of research, its behavior continues to challenge scientists. During La Niña and modest El Niño, sea surface temperature (SST) anomalies propagate westward along the equatorial Pacific, similar to the seasonal cycle[7]. In stark contrast, SST anomalies propagate eastward during extreme El Niño, prominently in the post-1976 period[7-10], spurring highly unusual weather events worldwide with costly consequences[3-6,11]. The cause of this propagation asymmetry is currently unknown[10]. Here we trace the cause to an asymmetry in the upper ocean circulation in the equatorial Pacific, whereby the westward flowing currents are enhanced during La Niña but reversed during extreme El Niño events. Our results highlight that propagation asymmetry is favored when the westward mean equatorial currents weaken, as projected under global warming[12-14]. By analysing past and future climate simulations, we find that an aggregate of models that exhibit more realistic propagation indeed simulate a doubling in the occurrences of El Niño events that feature prominent eastward propagation characteristics in a warmer world. Our analysis thus suggests that more frequent emergence of propagation asymmetry will be a symptom of a warming planet.

The tropical Pacific is home to intense convection, allowing for strong thermal and dynamical interactions between the upper ocean and the overlying atmosphere[15]. As warm SST anomalies propagate eastward during extreme El Niño events (e.g., 1982/83, 1997/98; Extended Data Fig. 1a) non-linear dynamical heating processes tend to intensify the anomalously warm SST[9], while the western Pacific warm pool (water with temperature greater than $28^{o}C$) extends eastward, moving the eastern edge of the warm pool beyond $160^{o}W$. This induces an eastward shift of equatorial rainfall and an extreme swing of the Southern Hemisphere's largest rainband, the South Pacific Convergence Zone[11], causing

52   extreme hydroclimatic conditions that most severely impact vulnerable island countries in the

53   Pacific[11,16]. Beyond the Pacific, virtually every continent felt the impacts of the drastic shift

54   in weather patterns during the 1982/83 extreme El Niño, and in the U.S. alone crop losses

55   were estimated to be around $10–12 billion[4] (approximately $24-26 billion in 2013 dollars).

56   These profound impacts demand an improved understanding of ENSO propagation dynamics.

57   Many studies have evaluated the relative importance of various ocean-atmosphere feedback

58   processes[17-19], yet the mechanism for the propagation asymmetry remains unresolved. Here

59   we show that an asymmetry in the zonal flow along the equatorial Pacific upper ocean

60   (hereafter referred to as equatorial Pacific current) is the main cause.

61   Utilizing various observational data assimilation systems (see Methods and Supplementary

62   Table 1), we quantify the propagation characteristics of temperature anomalies (T') by

63   compositing the equatorial warming and cooling rates (time derivative of temperature, T_t) of

64   the surface mixed layer for the strongest El Niño events on record (1982/83 and 1997/98, Fig.

65   1a) and all La Niña events (Fig. 1b) since 1976. The composite covers the evolution over a

66   two-year period, before and after the event peak (approximately in January; Jan (1)). The

67   contour of $T_t'=0$ marks the peak of the temperature anomaly (dashed curve, Figs. 1a and b).

68   A linear regression using the samples of zero-value rates is constructed (green line). The

69   slope (β) describes the propagation characteristics: a positive slope indicating temperature

70   anomalies peak earlier in the west, i.e., eastward propagation; a negative slope indicating

71   westward propagation; and the greater the amplitude, the slower the propagation. This

72   analysis shows opposite zonal propagation of SST anomalies between these two types of

73   events; eastward during extreme El Niño ($\beta=0.82$) and westward during La Niña ($\beta=-0.46$).

74   During moderate El Niño the propagation is westward (Extended Data Fig. 1b), similar to La

75   Niña.

76 The direction of propagation has been understood as arising from three main competing

77 positive feedback processes[17,18]. The zonal advective and Ekman pumping feedbacks

78 associated with fluctuations in the Trade Winds involve advection of climatological SST

79 along the equator by anomalous zonal currents (u') and upwelling (w')[20,21], respectively (i.e.,

80 $u'\bar{T}_x$ and $w'\bar{T}_z$; overbar indicates climatological mean, prime indicates anomaly, and subscript

81 indicates gradient along a specified direction). The thermocline feedback involves vertical

82 advection ($\bar{w}T'_z$) associated with eastward propagating internal waves which influence SST in

83 the eastern Pacific through the mean upwelling ($\bar{w}$) of water at the thermocline (a narrow

84 depth range of strong vertical temperature gradients below the mixed layer). These processes

85 can establish propagation of SST anomalies in either direction: eastward if the thermocline

86 feedback dominates, and westward otherwise[17]. Linear theories have highlighted a higher

87 importance of the thermocline feedback in the decades since the mid-1970s[8,22,23]; this would

88 however predict an eastward propagation during La Niña events as well[19], in contrast to

89 observations[10] (Fig. 1b).

90 La Niña anomalies can be viewed as an enhancement of the prevailing climate, with stronger

91 westward flowing surface currents. On the other hand, eastward current anomalies during El

92 Niño associated with anomalously weak Trade Winds[24] (Extended Data Fig. 2), oppose and

93 even exceed in amplitude the background current, leading to a net eastward flow (Fig. 1c).

94 This asymmetry in the total zonal current is apparent in all reanalyses (Extended Data Fig. 3,

95 Supplementary Tables 2 and 3). Our heat budget analysis (see Methods) shows that advection

96 of anomalous temperature by the total current, $(\bar{u} + u')T'_x$, which is strongly westward during

97 La Niña but eastward during extreme El Niño (Fig. 1c; Extended Data Fig. 4), represents one

98 salient asymmetric feature that should be considered.

99   We therefore examine how the mixed-layer heat balance changes when the total current-

100   induced heat flux $((\bar{u} + u')T'_x)$ is removed from the heat-budget equation (see Methods).

101   Evolution of the residual warming and cooling rates shows that without the effect of the total

102   current, an eastward propagation would result for extreme El Niño and La Niña (red dashed

103   line in Figs 2a and b), both with a positive slope of $\beta*$, 0.55 and 0.69, respectively. This

104   reconstructs a linear framework in which the thermocline feedback dominates, leading to an

105   eastward propagation for all events after 1976[19].   Thus it is the westward total flow that plays

106   a key role in determining the westward propagation during La Niña.

107   The role of the total current can be further understood by decomposing it into one component

108   that is due to the long-term mean current $(\bar{u}T'_x)$ and another due to the ENSO-related current

109   anomaly $(u'T'_x)$. We find that the westward long-term mean current favours a westward

110   propagation during both types of events; without it the eastward propagation during extreme

111   El Niño is more prominent and the propagation during La Niña reverses to eastward (red

112   dashed line, Extended Data Figs 1d and e). The current anomaly, on the other hand, has an

113   opposite effect on the two types of events (Supplementary Table 4). Without the effect of the

114   eastward current anomaly, the eastward tendency during extreme El Niño is severely

115   weakened (red dashed line in Fig. 2c). This eastward anomalous current, stronger than the

116   westward mean current, leads to a flow reversal during extreme El Niño (Fig. 1c), making the

117   eastward propagation characteristic more prominent (Fig. 2a). During La Niña on the other

118   hand, the anomalous current reinforces the effect of the westward mean flow for a more

119   pronounced westward propagation (Extended Data Fig. 1e, Figs. 2b, d). During moderate El

120   Niño events, the eastward current anomaly is far weaker than the mean current, and thus the

121   total current remains westward (Fig. 1c, Extended Data Fig. 1c). Thus, for moderate ENSO

122   events, there is no asymmetry, and SST anomalies for both El Niño and La Niña propagate

123   westward (Supplementary Table 4).

124   The non-linear effect is more prominent post-1976 (Supplementary Table 4) when El Niño

125   events are stronger[9,25] with large eastward current anomalies that are occasionally comparable

126   to, or greater than, the mean background current (Fig. 1c). During such events, this effect

127   reinforces eastward propagation induced by the thermocline feedback. During La Niña, the

128   westward current, along with the zonal advective and Ekman pumping feedbacks, weakens

129   the thermocline feedback effect, resulting in a net westward propagation (Fig. 3). This

130   superposition of ENSO-related large current anomalies onto the long-term mean westward

131   current invalidates the assumptions of linearity, making linear theories unable to explain the

132   propagation asymmetry.

133   Thus, interplay between the ENSO-related current anomaly and the climatological current

134   determines the way the equatorial Pacific circulation influences zonal propagation of SST

135   anomalies. This means that a change in ENSO intensity or in the mean current can influence

136   the extent to which the propagation asymmetry can be observed. The post-1976 prominence

137   of the propagation asymmetry is partly because of the extremity of the 1982/83 and 1997/98

138   El Niños. The mean current itself weakened through the 1980-2000 period (dashed curve, Fig.

139   1c), with a consistent weakening of the Trade Winds (Extended Data Fig. 2b). Although this

140   mean current reduction could be interpreted as a rectification of a change in ENSO

141   variability[26,27], a weakened mean current will favour occurrences of an eastward propagation,

142   even if El Niño intensity does not change. Presently there is no agreement among climate

143   models on the magnitude of future ENSO[28,29]. However, the consensus that emerges is a

144   future with weaker equatorial mean westward currents[12-14]. Our study implies that this would

145   increase the likelihood for occurrences of El Niños with prominent eastward propagation

146   characteristics.

147   To this end, we analyze 40 climate models that participated in the Coupled Model

148   Intercomparison Project phases 3 and 5 (CMIP3 and CMIP5), subject to increasing

149   atmospheric CO_2 concentration (see Methods). With the large number of simulated ENSO

150   events, the multi-model aggregate demonstrates robust statistics reaffirming the above

151   conclusion that weaker mean currents and current reversals, which are projected to be of a

152   more typical future condition, are conducive for eastward propagation (see Methods and

153   Extended Data Figs. 5-7). Indeed, we find that a subset of models that are more realistic in

154   terms of flow features and frequency of El Niño events with prominent eastward propagation

155   (19 models; see Methods and Extended Data Figs. 8-10 for model selection), simulate a 100%

156   aggregate increase in the mean occurrence of such events (Fig. 4a), from about 2.7 events in

157   1907-1999 to about 5.4 events in 2006-2098.

158   The role of the current is further highlighted as the increase in eastward propagating events is

159   skewed toward weaker mean currents (Fig. 4b; Extended Data Fig. 10b), and this occurs for

160   El Niño events of all magnitude (Fig. 4c). There is, in particular, a tendency for the increase

161   to be larger in models that project stronger ENSO amplitude (Extended Data Fig. 10c), which

162   is in turn associated with more occurrences of a current reversal (Extended Data Fig. 10d), a

163   feature unique to the 1982/83 and 1997/98 El Niños. Stratifying the statistics (Fig. 4c) in

164   terms of a current reversal or otherwise, 45% of the increase is found to be associated with

165   current reversals, most of which are El Niños stronger than the typical magnitude of past

166   events (Fig. 4d). However, the inter-model consensus for ENSO amplitude projection is

167   weak, despite a reduced mean current in all models (Extended Data Figs. 10b and c). This

168   suggests that a weakened mean current is the determining factor for future increases in

169   eastward propagating events of all magnitudes, including extreme El Niños, either through

170   the thermocline feedback effect or a current reversal, or both.

171   In summary, while different factors have been proposed to explain various non-linear

172   characteristics of ENSO[9,25,30], none have been found to explain the cause for its propagation

173   asymmetry seen in recent decades. Here we have provided observational and modelling

174 evidence that the equatorial Pacific current is an important element for this asymmetry. The

175 superposition of a current anomaly during ENSO onto the long-term mean westward flow

176 enhances the westward currents during La Niña, but reverses the currents during extreme El

177 Niño. The role of the equatorial currents highlighted here casts a fresh perspective on the

178 fundamentals of ENSO behaviour. Given the projected weakening of the background mean

179 flow under global warming, our analysis not only resolves a perplexing scientific issue, but

180 suggests that increased occurrences of ENSO propagation asymmetry will be a manifestation

181 of greenhouse warming with important socioeconomic consequences.

182 **METHODS SUMMARY**

183 The propagation tendency of temperature anomalies during ENSO events is quantified as the

184 slope of the zero-value contour of warming and cooling rates on ENSO time scales that tracks

185 the peak of temperature anomalies as they evolve in time along the equatorial Pacific (Figs.

186 1a, 1b). A positive (negative) slope in the time-longitude space indicates eastward

187 (westward) propagating temperature anomalies: the steeper the slope the slower the zonal

188 propagation and thus the more observable the propagation characteristic. To investigate the

189 factors that can cause temperature anomalies to propagate zonally, we conduct a heat budget

190 analysis of the ocean surface mixed layer. All variables are derived from five ocean

191 reanalysis systems that assimilate high quality observational products going back to 1980 or

192 earlier (Supplementary Table 1). Our surface heat balance explicitly expresses the zonal

193 advection of temperature anomaly by the mean current and is viewed to interact with the non-

194 linear component (i.e., advection by anomalous current). Removing certain heat-flux

195 components from the heat balance would alter the slope of the zero-value contour, and so by

196 comparing the altered slope (β*) with the original (β) its influence on the propagation can be

197 inferred. Because this study concerns asymmetry between El Niño and La Niña, a composite

198 approach is adopted (see Methods for classification of ENSO events). The implication of our

199　results for future climate is assessed through analysis of forty CMIP3 and CMIP5 climate

200　models (see full Methods).

201　**Online Content** Any additional Methods, Extended Data display items, Source Data, and

202　Supplementary Information are available in the online version of the paper; references unique

203　to these sections appear only in the online paper.

204

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286

287 **Figure legends**

288 **Figure 1 | Equatorial Pacific current and zonal propagation of ENSO SST anomalies. a,**

289 Warming and cooling rate (color shades; in unit of °C per month) of the equatorial Pacific

290 surface mixed layer on interannual time scales (an average over 5°S-5°N) composited over

291 extreme El Niño (1982, 1997) lifecycle across all reanalysis products. Red (blue) contours

292 indicate the associated positive (negative) SST anomalies. Statistically significant values at

293 the 95% confidence level are shaded and contoured. **b,** As in **a** but for post-76 La Niña

294 events. The mean of the linear-fit slope (green line) of the phase transition (dashed black

295 line), β (in unit of seconds per meter), across the products is 0.82 in **a** and -0.45 in **b,** both

296 significant above the 95% confidence level ($P<0.05$). **c,** Zonal current velocity averaged

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across the reanalysis products, over 5°S-5°N, 160°E-90°W, and over August to December. Dashed curve highlights interdecadal variation using a 13-year running mean. Gray shading denotes two standard deviation about each mean value, representing monthly spread and variations across reanalyses. Red and blue filled circles indicate occurrences of strong El Niño and La Niña events, respectively, with relative event intensity indicated by different marker sizes. Open circles indicate moderate ENSO events.

Figure 2 | Effect of total and anomalous currents on equatorial Pacific mixed layer heat balance during extreme El Niño and all La Niña events. a, Composite evolution of the interannual-scale mixed layer warming and cooling rates (color shades; in unit of °C per month) during extreme El Niño events (1982, 1997), with advection of temperature anomalies by the total current (arrow) removed. Red dashed and green lines indicate the altered slope β^* and the original β, respectively. **b,** As in **a** but for post-76 La Niña events. Only statistically significant values at the 95% confidence level are shaded in color, contoured, or marked by black arrows (gray arrows otherwise). β^* in **a** and **b** are respectively 0.55 and 0.69, both significant above the 95% confidence level ($P<0.05$). **c,** As in **a** but with the effect of current anomaly removed. **d,** As in **c** but for La Niña. β^* in **c** and **d** are respectively 0.05 and -0.14, both not statistically significant ($P>0.4$).

Figure 3 | Schematic of competing effects on zonal propagation direction during ENSO events. a, Zonal currents in the equatorial Pacific (large gray arrow) have the effect of shifting the initial warm surface anomalies (dashed red patch) eastward during extreme El Niño events, because the current anomaly u' (red arrow) is eastward and exceeds the strength of the westward background current $\bar{u}$ (black arrow). This effect counters westward propagation as induced by the zonal advective and Ekman pumping feedbacks (blue arrow) and enhances eastward propagation induced by the thermocline feedback (pink arrow). **b,**

13

321 During La Niña events, the zonal currents are prominently westward as the current anomaly

322 always enhances the westward flowing mean current. This weakens the thermocline

323 feedback effect and enhances westward propagation as induced by the other two dynamical

324 feedbacks.

325 **Figure 4 | Statistics of El Niño occurrence characterized by prominent eastward**

326 **propagation in CMIP3 and CMIP5 models. a,** Probability density function (PDF) of 19

327 model ensemble mean in the past (1907-1999; blue) and future (2006-2098; red) periods.

328 Each probability distribution is generated from 5000 bootstrap draws using the 19 model

329 samples. The solid curves overlaid are the corresponding PDFs of a fitted normal distribution

330 which are significantly different above the 95% confidence level (P=0.01). Dashed vertical

331 lines indicate the corresponding ensemble average. **b,** Multi-model histogram for the event

332 occurrence as a function of long-term averaged equatorial Pacific current velocity in the past

333 (blue) and future (red) periods, segregated into bins of 0.04 m s^{-1}. **c,** As in **b** but segregated

334 into bin size of 0.25 for the Niño3 index which is detrended and normalized by the standard

335 deviation of the past period. **d,** As in **c** but stratified according to the concurrence with (thick

336 dark bars) and without (thin light bars) current reversals. Dashed vertical line in **d** marks 1.5

337 unit of the normalized value.

338

339 **METHODS**

340 **Heat budget analysis**

341 We consider the heat balance of the surface mixed layer which can be expressed as follows:

342 $T_t = -[(\bar{u} + u')T'_x + u'\bar{T}_x + \bar{w}T'_z + w'(T' + \bar{T})_z + (\bar{v}T')_y + v'(\bar{T} + T')_y] + Res.$ **(1)**

343 The variables *T, u, v*, and *w,* are respectively potential temperature, zonal, meridional, and

344 vertical ocean current velocities. Subscripts denote differential operators (*x, y, z* for zonal,

345   meridional, and vertical directions, respectively, and t for time). Prime and overbar denote

346   anomalous and long-term averaged quantities, respectively. All variables are averaged

347   between 5°S-5°N, over the surface layer depth of 50 m. The rate of change of the mixed

348   layer temperature (T_t) is calculated as monthly increments using a centred-difference

349   approximation. Terms not explicitly expressed in (1), such as eddy effects and damping by

350   net air-sea heat fluxes, are absorbed into *Res*, such that the left and right hand sides of

351   Equation (1) are identical. Equation (1) is slightly different to that adopted in previous

352   studies[8,20,21], as $\bar{u}T'_x$ is expressed explicitly here and is viewed to interact with the non-linear

353   advection term ($u'T'_x$). This combination, uT'_x, where $u = \bar{u} + u'$, is simply interpreted as the

354   zonal advection of temperature anomalies by the total equatorial Pacific zonal current which

355   can be readily observed. The term $\bar{u}T'_x$ tends to be overlooked as it is convolved into the

356   continuity component via volume conservation [i.e., $T'(\bar{u}_x + \bar{v}_y + \bar{w}_z) = 0$] when the heat

357   budget is expressed in flux form [i.e., $(\bar{u}T')_x + (\bar{v}T')_y + (\bar{w}T')_z$].

358

359   **Quantification of propagation characteristic**

360   The contour of T_t=0 marks the peak of T', thus its positive (negative) slope in time-longitude

361   space indicates eastward (westward) propagating T' (Figs. 1a, 1b). The phase transition

362   slope, β, is calculated by fitting a line via least-square method to the contour between 160°E-

363   80°W and May(0)-May(1) to allow some room for temporal movement upon removal of the

364   advection terms. The rationale for the longitudinal extent can be found in the section below

365   under the heading 'Mean currents and ENSO propagation structures across models', and our

366   results are not sensitive to this aspect of the calculation.

367   Removing an important advection component from the right hand side of Equation (1) would

368   alter the spatial and temporal structure of T_t, thus affecting β. For example, a reversal from a

369   negative slope (i.e., westward propagation) to a positive (i.e., eastward) would suggest that

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370   the component removed is crucial in setting the westward propagation. In this way, the role

371   of a certain advection term on the propagation tendency of T' can be determined by

372   comparing the altered slope β^* to the original β. The 95% regression standard error for the

373   slopes is considered in all analysis by setting any slopes to zero if they are not greater than

374   their corresponding error estimates.

375

376   **Datasets and data processing**

377   The reanalysis products utilised are ECMWF ORA-S3[31], ECMWF ORA-S4[32], SODA-2.16[33],

378   SODA-2.2.4[34], and GODAS[35] (Supplementary Table 1). Each reanalysis system assimilates

379   available observations (e.g., hydrographic profile data, moorings, satellites) into an ocean

380   model forced by observed surface wind stress to calculate ocean currents. The reanalysis

381   systems use different ocean models and data assimilation techniques. To focus on processes

382   at ENSO time scales, a Butterworth low-pass filter[36] is applied prior to analysis to remove

383   signals with periods shorter than 18 months. Without filtering, the spatio-temporal structure

384   of the warming and cooling rate T_t is noisy given large high frequency monthly fluctuations.

385   On ENSO time scales, the rate of warming and cooling tracks smoothly the evolution of SST

386   anomalies.

387

388   **ENSO classification and statistical significance test**

389   The classification of ENSO events is based on the Niño3 index derived from the National

390   Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST version-3b[37],

391   averaged over December-February when ENSO events typically peak. ENSO events are

392   defined if the Niño3 amplitude, within each of the pre-76 (1959-1976) and post-76 (1976-

393   2011) periods, is greater than 0.5 units of standard deviation. We classify these as strong if

394   Niño3 exceeds 1 unit of standard deviation, and as moderate or weak otherwise. This yields

395 the following classification of events (developing phase year quoted): *Strong El Niño*: 1965,

396 1969, 1972, 1982, 1991, 1997, 2009; *strong La Niña*: 1970, 1973, 1975, 1988, 1998, 2007,

397 2010; *moderate El Niño*: 1963, 1976, 1987, 1994, 2002, 2006; *moderate La Niña*: 1964,

398 1967, 1984, 1995, 2005. The 95% statistical significance for each composite is evaluated

399 using a bootstrap approach[38] in which samples of size N are randomly drawn repeatedly to

400 obtain 1000 mean values. N is the number of ENSO events within each respective period

401 pooled together for all the reanalysis products. All significance levels are evaluated based on

402 the two-sided *P*-value.

403

404 **Analysis of climate models**

405 The observational analysis results demonstrate that, in the backdrop of the effects by the three

406 ENSO dynamical feedbacks, the equatorial Pacific current is an important element for the

407 zonal phase propagation of ENSO SST anomalies (Fig. 3). The observational-based results

408 are further corroborated through an analysis of 40 CMIP3[39] and CMIP5[40] climate models (see

409 Extended Data 5 for the specific models). The 40 models, each of 186 years in record

410 (inclusive of the past and future simulations), provide a large sample of ENSO events that is

411 about 180 times larger than the observed sample of 25 events. Thus, the models with their

412 differences in the mean state provide a rigorous test bed for the effect of the current which

413 along with the implications for the future are discussed in the following sections.

414 The past and future climate simulations respectively correspond to the 20th century (1907-

415 1999) and future projection scenarios (2006-2098) based on Special Report on Emissions

416 Scenarios (SRES) A1B for CMIP3 and representative concentration pathways (RCP) 4.5 for

417 CMIP5[39,40]. The time spans were necessarily chosen to include as many models as possible

418 that cover the longest record without any missing data.

419

17

Mean currents and ENSO propagation structures across models

Based on the findings of early theoretical studies[17,18] the prevalent direction of the basin-scale ENSO SST anomaly propagation along the equator is an indicator for the dominant dynamical process over a given epoch: net eastward for thermocline feedback and net westward for zonal advective/Ekman feedback. Such definition for the dominant ENSO dynamics has been adopted by previous studies[41,42,43], in which we term hereafter as ENSO 'propagation structure' to be in line with the topic of our study.

The diagnosis for ENSO propagation structure in observations and models has been achieved previously through a lead-lag correlation between the Niño3 index and an east-minus-west SST index which is taken as the difference between the Niño4, representing SST variability in the Central Pacific, and the Niño1+2 for the far eastern Pacific[41,44]. The former is bounded in the west at 160°E and the latter in the east at 80°W, which is the exact longitudinal extent adopted in our study for calculating the phase transition slopes.

Here we diagnose the propagation structure in each past and future period in each model (Extended Data Fig. 5a) by the proportion of westward events (assigned as negative proportion) and eastward events (positive proportion) identified as El Niños and La Niñas with a statistically significant β. For each given period, the proportions of those four types of propagating events (i.e., westward El Niño and La Niña, and eastward El Niño and La Niña; the red/blue bars and lines in Extended Data Fig. 5a) and non-propagating events (non-statistically significant slopes) add up to 1, and so the net propagation structure (gray circles for 1907-1999; black triangles for 2006-2098) can range from -1, if all of the events propagate westward, to +1 if all propagate eastward. For example, the past ENSO events in model number 3 consist of 10% westward El Niños, 17% westward La Niñas, 28% eastward El Niños, 19% eastward La Niñas, and 26% non-propagating El Niños and La Niñas. Summing the proportions of the propagating events and considering the directions: -0.1 + -

18

445   0.17 + 0.28 + 0.19, yields an eastward propagation structure with a relative scale of 0.2 as

446   marked by the gray circle. Although our approach is different to the commonly used

447   correlation-based methods[3,4,5], in that we utilize β, the results using the two methods are

448   largely consistent (figures not shown).

449   We find a significant positive inter-model correlation between ENSO propagation structure

450   and mean equatorial currents (Extended Data Fig. 5b): models with weaker mean currents

451   tend to generate a higher proportion of eastward propagating ENSO events, and the tendency

452   is statistically significant. This suggests that models with weak (strong) mean currents tend

453   to be more (less) favourable for the thermocline feedback resulting in an eastward

454   propagation structure (as explained in Fig. 3). Some of the models that simulate too many

455   eastward propagating La Niña events (Extended Data Fig. 5a; for example, models number 2,

456   3, 10, 17, 24, 25), in contrast to observations (but consistent with linear theories), tend to

457   have a weak mean current. Because the inter-model correlation between the propagation

458   structures and mean zonal wind stresses is basically zero (Extended Data Fig. 5c), such an

459   effect is evidence for the direct influence of the ocean currents (e.g., related to specifications

460   of the ocean model components), rather than, for instance, an effect of ENSO rectification

461   onto the mean climate. These inter-model relationships also hold for the future simulations

462   (see Extended Data Fig. 5 caption). While this result has an important implication for ENSO

463   modelling, this in itself is evidence that the ocean current does have an influence on ENSO

464   zonal phase propagation, that is, a weaker mean current is more favourable for eastward

465   propagation.

466   The model ensemble results in Extended Data Fig. 5b also imply that in a climate state with a

467   weak background current, natural variability alone (within which the system supports

468   naturally varying ENSO propagation structure) would more easily produce eastward

469   propagating events. With even weaker currents projected for the future, consistent with the

19

470   weaker Trade Winds, the thermocline feedback effect for inducing eastward propagation is

471   favoured further (Extended Data Fig. 6). Previous ENSO stability analysis for a number of

472   the CMIP3 models[45] demonstrated that the three main positive feedback processes are

473   projected to increase, and would thus have competing effects on zonal phase propagation.

474   The clear increase in the occurrences of eastward propagation events (Fig. 4a) can be more

475   simply explained in terms of a weakened current as described in our study.

476

477   **Effect of current reversals and models selection**

478   One characteristic of the ENSO system is that the equatorial Pacific current anomaly is

479   correlated with SST anomalies in the east (represented by the Niño3 index) in which the

480   current leads Niño3 by about 3 months (Extended Data Fig. 4b). This highlights the tendency

481   for an eastward (westward) current anomaly in boreal fall (September-December) to precede

482   the peak of El Niño (La Niña) in boreal winter (December-February). A particularly strong

483   eastward anomalous current was observed during the 1982/83 and 1997/98 extreme El Niños

484   that leads to a re-intensified reversal in boreal fall, a feature not seen in other events

485   (Extended Data Fig. 4a). These extreme events are identified by their prominent eastward

486   propagation with phase transition slope β that is stronger than in other events (Extended Data

487   Fig. 4d). Here we demonstrate using an aggregate of models that current reversals have an

488   effect to make eastward propagation characteristic more prominent. Since zonal propagation

489   is the focus of our study, and given the dynamical links of the aforementioned features, we

490   first select the models based on the following criteria:

491   1. The models must be able to simulate at least one prominent eastward propagating El Niño

492   event in either past or future simulation. Such event is defined as that when β is positive,

493   greater than the linear-regression standard error, and is above 0.5 standard deviation unit

494   of all El Niño slopes (i.e., following the observed counterpart; Extended Data Fig. 4d).

495   2. The models must be able to simulate at least one current reversal during boreal fall in

496   either past or future simulation.

497   3. The models must produce a positive correlation between Niño3 and the current during

498   any propagating El Niño events, a relationship also seen in observations (Extended Data

499   Fig. 4c).

500   These criteria result in 24 models that simulate more realistic and distinctive current

501   evolution between strong and moderate El Niño years (Extended Data Fig. 8) as expected

502   from observations (Extended Data Fig. 4a), in contrary to that in the discarded models

503   (Extended Data Fig. 9).

504   The effect of current reversal on zonal phase propagation is clearly exhibited by this

505   aggregate of models, that is, to favour eastward propagation. This is due to the fact that the

506   corresponding β tends to be more positive whenever the events coincide with a current

507   reversal (Extended Data Fig. 7b). In the case where current reversals coincide with westward

508   propagation, the westward slopes are found to be substantially weaker. Such an effect

509   renders a positive correlation between the total current and β (Extended Data Fig. 7a), which

510   is a characteristic also seen in observations (Extended Data Fig. 4d). This positive correlation

511   further highlights the crucial role of the equatorial Pacific current on zonal phase propagation.

512   The effect of the total current on El Niño and La Niña propagation asymmetry is also

513   reproduced (Extended Data Fig. 7c). The asymmetry becomes apparent with strong El Niño

514   events, and more so when these co-occur with current reversals, similar to the observed

515   counterpart (Fig. 2a, b; Supplementary Table 4).

516   An additional criterion is applied, resulting in a further exclusion of 5 models. Each of these

517   excluded models already simulates 11 to 14 El Niño events with prominent eastward

518   propagation slope over the 93 years in the past simulation (Extended Data Fig. 10a). These

21

519   are too frequent relative to the 2 events over the 53 years of observational record, which

520   translates to slightly less than 4 events for the 93 model years. The remaining 19 models

521   simulate from none up to 8 events (i.e., double the expected observed frequency) in the past

522   period. These 19 models also have climatological states that roam the regime of westward

523   propagation structure similar to the observed, as opposed to the 5 excluded models that tend

524   to cluster about the eastward regime with already weak mean currents (Extended Data Fig.

525   5b; models number 8, 17, 24, 25, 29). Given the extreme rarity, and to test whether a change

526   in model climatological state can induce increased occurrence of such events, we retain the

527   19 models for future projections (Fig. 4).

528

529   **Future projection: a parallel with the late 20th Century scenario**

530   With the mean westward currents projected to weaken in the future (Extended Data Fig. 6),

531   thus providing a more conducive condition for increased occurrences of current reversals

532   (Extended Data Fig. 7d), it is expected that there will be more El Niño events exhibiting

533   prominent eastward propagation characteristic in the future.

534   A 100% increase in the mean occurrence of such events is found (Fig. 4a), with 16 out of 19

535   models projecting an increase. Considering only models that simulate less than 8 events

536   increases this to more than 116%, with model consensus consistently above 83%. As

537   expected, retaining those that already simulate frequently occurring events (i.e., saturated

538   with eastward propagation) reduces the amount of increase to 76% when including models

539   that already simulate of up to 11 events, and 46% using all of the 24 models. Nonetheless, in

540   all cases, the models as an aggregate simulate a notable increase in future occurrences of

541   eastward propagating El Niño events that is significant well above the 95% confidence level,

542   with at least 75% of the models projecting an increase.

543   As revealed by the observational analysis, the emergence of an eastward propagation in the

544   post-76 period is in part because the mean westward current is weaker, and in part because

545   the eastward current anomalies associated with the extreme El Niños are sufficiently large to

546   reverse the current. On this regard, the variety of events and mean states provided by the

547   different models point to a slightly different scenario for the future in which the importance

548   of the projected current weakening is highlighted. This is evident as the model consensus is

549   weak in the projection for stronger ENSO amplitude (11 out of 19 models; Extended Data Fig.

550   10c), but all of the models project a weaker mean current (Extended Data Fig. 10b). Despite

551   this, there is still a tendency for stronger increase in the number of eastward propagating

552   events in models that also project a larger increase in ENSO amplitude (Extended Data Fig.

553   10c). This is through the contribution by current reversals (Extended Data Fig. 10d) which

554   tend to occur with stronger El Niño and have an effect in making the eastward propagation

555   characteristic more prominent (Extended Data Fig. 7).

556   It is necessary to note that while weaker mean current facilitates current reversal, such that

557   any modest eastward current anomaly can more easily exceed the background current, the

558   increase in the number of current reversals in the future (Extended Data Fig. 7d) do not

559   always translate to more occurrences in events having a prominent eastward propagation

560   characteristic (Extended Data Fig. 10d). This is expected given the various kinds of event

561   concurrences that the model aggregate provides (Extended Data Fig. 7). In fact, while all of

562   the increase in eastward propagating events is associated with weaker mean currents and El

563   Niño events of all magnitude (Figs. 4b and c), only 45% of this is associated with current

564   reversal events, within which 85% are associated with large magnitude El Niño events (Fig.

565   4d).

566 Thus, given the weak model consensus in projecting an increase in ENSO amplitude, the

567 most robust feature shared between the future projection and the change observed during the

568 late 20th Century is the weaker westward mean current which is projected by all of the models.

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618 **Extended Data Figure legends**

619 **Extended Data Figure 1 | Zonal propagation of SST anomalies and effect of current on**

620 **mixed layer heat balance during ENSO events. a,** SST[37] anomalies along the equatorial

621 Pacific (averaged between 5°S-5°N) over January 1959 to December 2011, with seasonal

622 cycle and linear trend (referenced to the entire 1959-2011) removed. The arrows, whose

623 slopes are calculated from the multi-reanalysis ensemble average, indicate zonal propagation

624 directions. **b,** Composite evolution of interannual-scale heating rate (color shades; in unit of

625 °C per month) of the equatorial Pacific mixed layer during post-76 moderate El Niño events.

626 The phase transition (dashed black line) tracks the evolving peak of temperature anomaly

627 (red and blue contours; red for positive and blue for negative) with a statistically significant

628 linear fit slope (green line; $\beta=-0.97$, $P<0.01$). **c,** As in **b** but with advection due to the total

629 current (arrow) removed, resulting in $\beta^*=-0.29$ (red dashed line) that is statistically

630 significant ($P<0.05$). Only statistically significant values above the 95% confidence level are

631 shaded in color, contoured, or marked by black arrows (gray arrows otherwise). **d,** As in **c**

632 but for extreme El Niño events (1982, 1997) with the effect of mean current (arrows)

633 removed. **e,** As in **d** but for post-76 La Niña events. The β^* values are 1.44 in **d** and 0.61 in

634 **e** which are statistically significant ($P<0.01$).

635

636 **Extended Data Figure 2 | Time evolution of equatorial Pacific zonal current and wind**

637 **stress. a,** The same as Fig. 1c for zonal current velocity averaged across the reanalysis

638 products. The dashed curve highlights interdecadal variation using a 13-year running mean.

639 Gray shading denotes two standard deviation about each mean value, representing monthly

640 spread and variations across reanalyses. **b,** As in **a** but for surface zonal wind stress.

26

641 **Extended Data Figure 3 | Time evolution of the equatorial Pacific zonal current across**

642 **reanalysis products.** Raw time series of zonal current velocity averaged over 5°S-5°N,

643 160°E-90°W, capturing the Niño4 to Niño3 regions, and over the ENSO development phase

644 (August to December). The ensemble average (1980-2006) is marked by the thick horizontal

645 dashed line.

646 **Extended Data Figure 4 | Observed characteristics of equatorial Pacific current**

647 **associated with ENSO. a,** Total current evolution composited over developing phase of

648 ENSO: extreme El Niño (dark red shading/black line), strong El Niño (red shading/dark red

649 line), weak El Niño (pink shading/red line), and La Niña (blue shading/dark blue line). Thick

650 lines indicate the mean composites, and the colored shades are for one standard deviation unit

651 above and below the means representing the spread across the different reanalyses and each

652 classified events. **b,** Lead-lag monthly correlation between the reanalysis ensemble average

653 current and Niño3 with eastward current anomalies leading warm Niño3 anomalies at 3

654 months. **c.** Total current averaged over September to December versus Niño3 (December-

655 February) associated with extreme (dark red circles), strong (red circles), and weak (green

656 circles) El Niño events in each pre and post-76 period, with a correlation coefficient of 0.82,

657 significant at 99% level. Open circles indicate non-statistically significant β. The correlation

658 (r=0.84) remains significant at 99% level even when these points are excluded. **d,** As in **c** but

659 for total current versus β during all ENSO events (blue circles for La Niña). The correlation

660 coefficient between current and statistically significant β for El Niño is r=0.75 which is

661 significant at 99% level. The dashed horizontal line in **d** marks 0.5 standard deviation unit of

662 all the El Niño slopes.

663

664 **Extended Data Figure 5 | ENSO propagation structure in CMIP models. a,** Propagation

665 structure in each CMIP model (gray circles for 1907-1999; black triangles for 2006-2098

666 period) and observations (1959-2011; large open circle). The propagation structure is defined

667 by summing up the proportion of westward events (negative proportion) and eastward events

668 (positive proportion) identified as El Niño (red bar for 1907-1999; red line for 2006-2098)

669 and La Niña (blue bar for 1907-1999; blue line for 2006-2098) with statistically significant β.

670 The different color intensities for the bars and lines contrast the four types of propagating

671 events. The proportions of propagating events and non-propagating events add up to 1, and so

672 the net propagation structure (gray circle or black triangle) can range from a scale of -1, if all

673 events propagate westward, to +1 if all propagate eastward. Eastward (westward)

674 propagation structure is an indication for a more dominant thermocline (zonal advective)

675 feedback mechanism. **b,** Propagation structure versus long-term annually averaged zonal

676 current velocity across all CMIP models (colored markers) in the past simulation, revealing a

677 positive correlation (r=0.40) significant at 95% level (r=0.44 for future). Open circle marks

678 the observed counterpart using data from 1959 to 2011 for a larger event sample. **c,** As in **b**

679 but for mean zonal wind stress, exhibiting no significant correlation (r=0.01; r=0.14 for

680 future). Models marked by dotted horizontal lines in **a,** and squares in **b** and **c,** indicate those

681 selected for future projections (Fig. 4). Models marked with diamonds in **b** and **c** simulate

682 realistic flow features but are saturated with eastward propagating events that they already

683 produce in the past simulation (see Extended Data Fig. 10a).

684

685 **Extended Data Figure 6 | Projected changes of long-term mean zonal wind stress, zonal**

686 **current velocity, and propagation structure across the CMIP3 and CMIP5 models. a,**

687 Future and past difference in long-term mean zonal wind stress and zonal current velocity. **b,**

688 Future and past difference in long-term mean zonal wind stress and ENSO propagation

689 structure (Extended Data Fig. 5). **c,** Future and past difference in long-term mean zonal

690 current velocity and ENSO propagation structure. The correlations between each of the

691   variables are shown in the panels and are statistically significant at the 99% level. Removing

692   the model outlier (miroc3-2-hires) reduces correlations in **a**, **b**, and **c**, to 0.61, 0.47, 0.59,

693   respectively, but are still statistically significant up to the 99% level.

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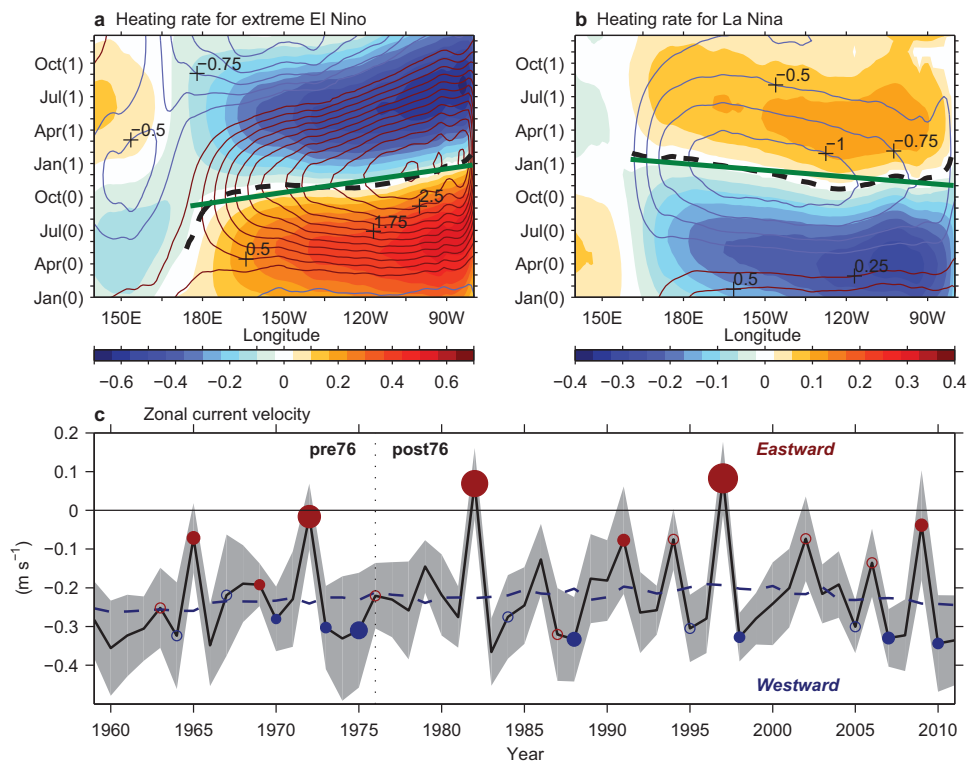695   **Extended Data Figure 7 | Effect of current reversals on zonal phase propagation and**

696   **future projection.** The analysis incorporates the 24 models that simulate realistic flow

697   features (see Methods). **a,** Correlation between total current and phase transition slope during

698   El Niño events in the past simulation (1907-1999). The positive correlation (r=0.46),

699   significant above the 99% level (with 472 data points), confirms the relationship seen in the

700   limited observational record (Extended Data Fig. 4). **b,** Probability density of β for westward

701   (gray) and eastward (red) El Niño events with (darker shading) and without (lighter shading)

702   current reversals. **c,** Probability density of the difference in phase transition slope before and

703   after the effect of total current removed from the heat balance (β-β*), for all La Niña (blue),

704   all El Niño (light red), and El Niño events that co-occur with current reversals (darker red).

705   The probability density for strong El Niño events (greater than 1 standard deviation) is shown

706   by dashed curve. **d,** Probability density of number of current reversals associated with any

707   events in the past (1907-1999; blue) and future (2006-2098; red) periods. Vertical lines in **d**

708   indicate the respective mean values (6.4 and 9.5 for past and future periods, respectively).

709   The statistics in **b**, **c**, and **d** are generated using bootstrap sampling technique with 5000

710   simulations.

711

712   **Extended Data Figure 8 | Monthly evolution of the total current during developing year**

713   **of El Niño events in the selected CMIP3 and CMIP5 models.** Red and gray curves

714   respectively represent El Niño events in both past and future simulations that are classified as

715   above and below 1.5 standard deviation unit of Niño3 (December-February average)
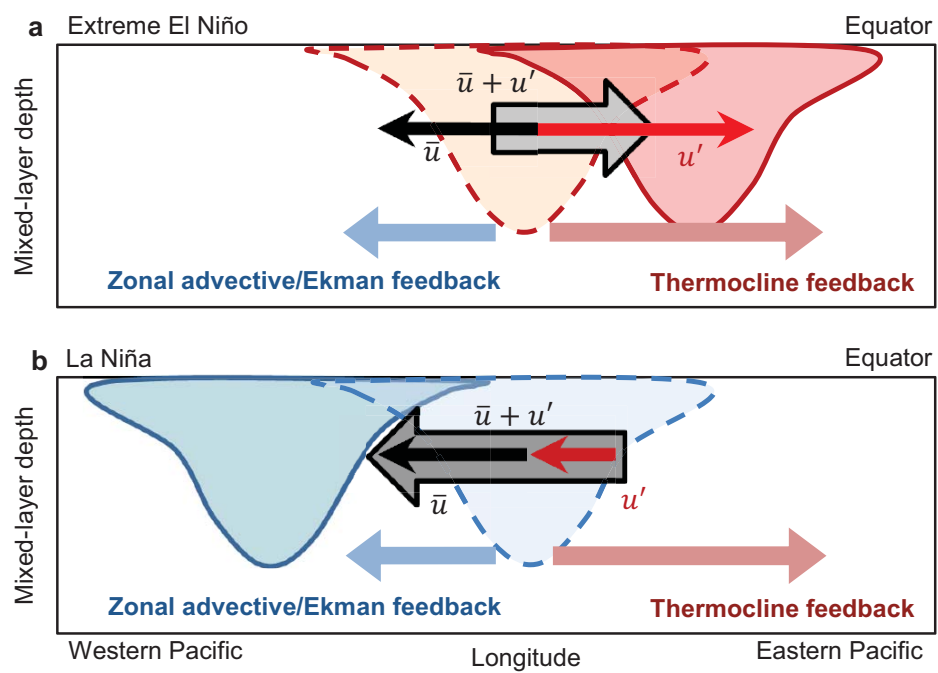
716   normalized by the standard deviation of the past period. Only events with statistically

717   significant transition slopes are considered. The corresponding dashed curves indicate the

718   sample averages.   Each panel displays the correlation coefficient between the equatorial

719   Pacific current (September - December average) and the Niño3 anomalies, following the
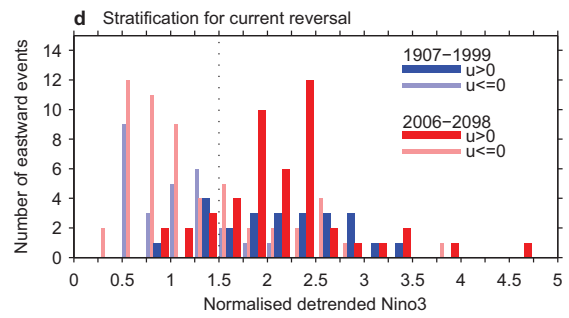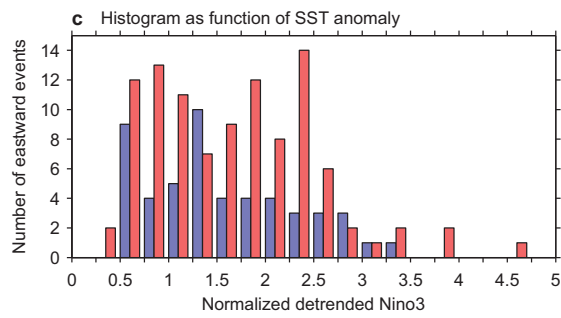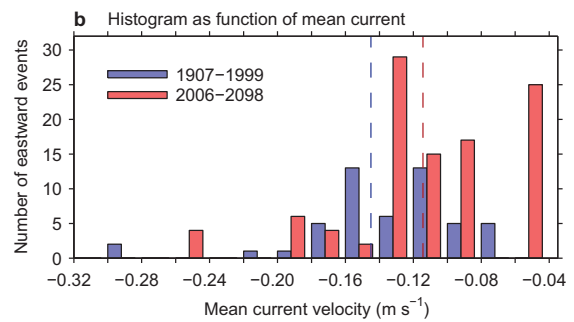
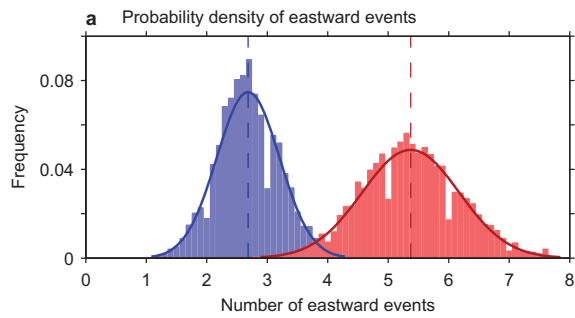720   observed counterpart (Extended Data Fig. 4c).

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722   **Extended Data Figure 9 | As Extended Data Fig. 8, but for the excluded models.**

723   Correlation coefficients displayed in red are not statistically significant.

724

725   **Extended Data Figure 10 | Occurrences of El Niño with prominent eastward**

726   **propagation and future projection as a function of mean current, ENSO amplitude, and**

727   **current reversals in the CMIP3 and CMIP5 models. a,** Number of events for each of the

728   40 models for the past (1907-1999; blue) and future (2006-2098; red) periods (see Methods

729   for event criteria).   The number of events over the 93 model years expected from the

730   observed occurrences is 4 (dotted vertical line). For future projection, we consider models

731   that produce occurrence of none up to 8 events (i.e., doubling; dashed vertical line). Dotted

732   horizontal lines indicate the selected models.   **b,** Future and past difference in event

733   occurrences against that of the long-term mean zonal current velocity. **c,** As in **b** but against

734   the future and past difference in ENSO amplitude as defined by the standard deviation of

735   Niño3 index. **d,** ENSO amplitude difference against the difference in number of eastward

736   propagating events with current reversals.   The correlation coefficients displayed in the
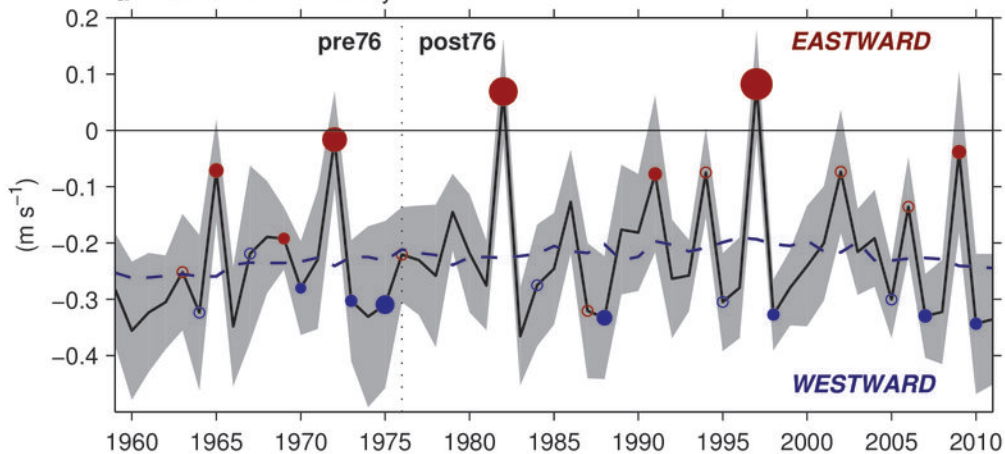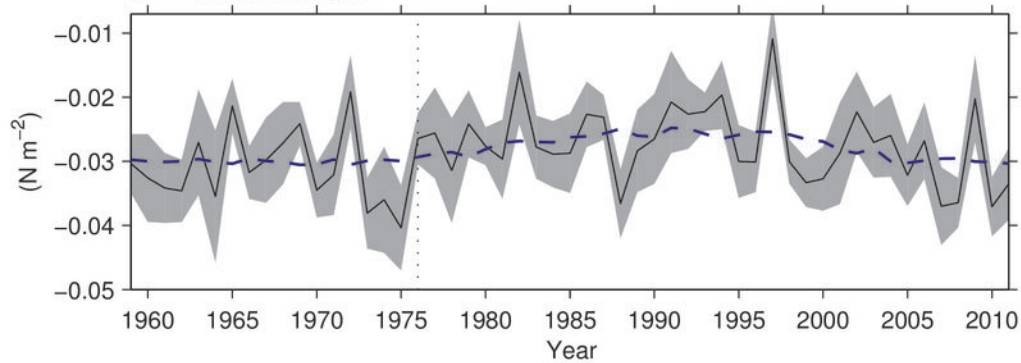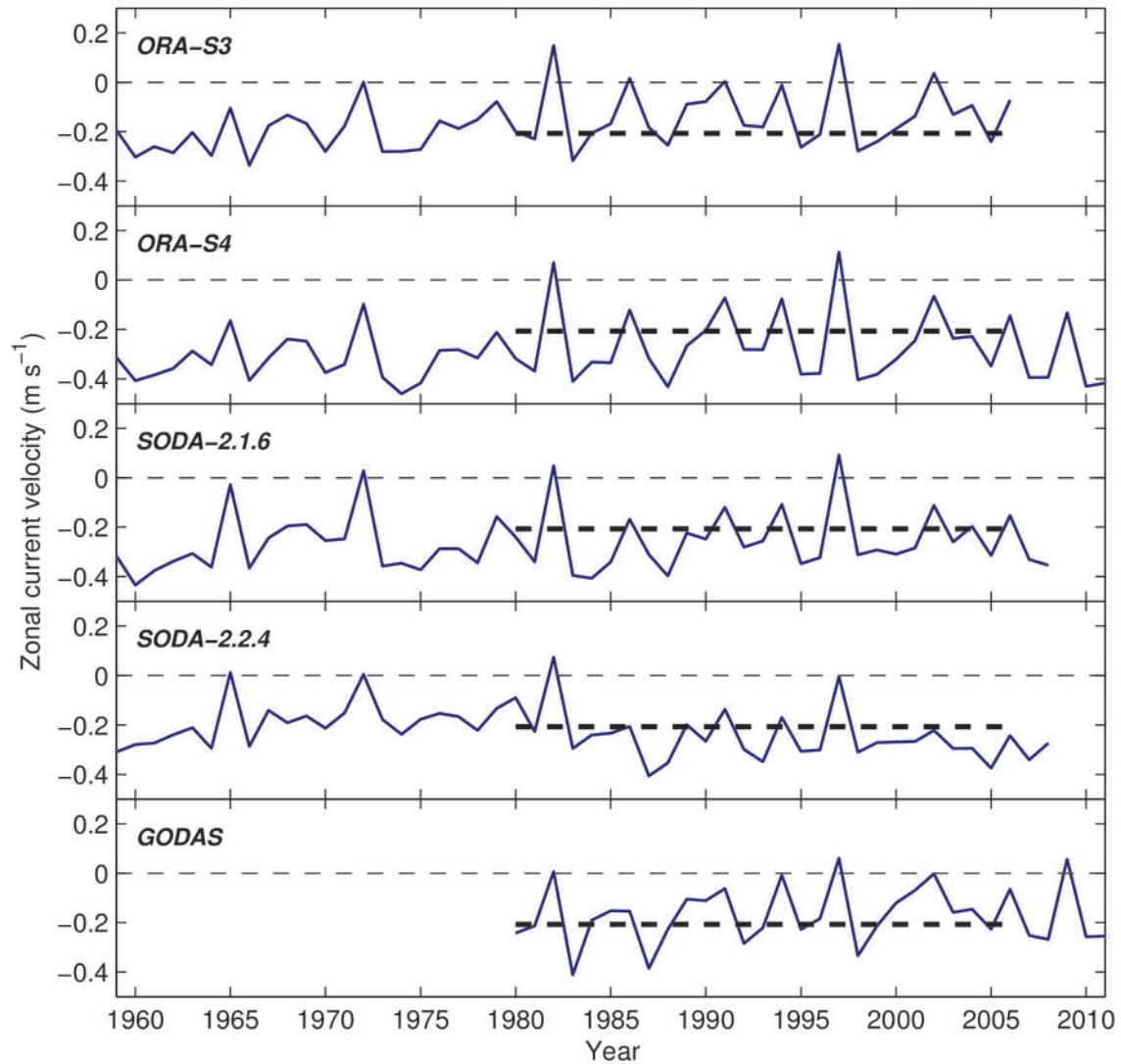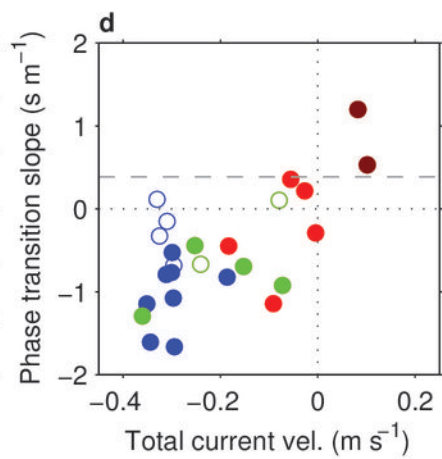
737   panels are significant at 95% level.

738

a Heating rate for extreme El Nino

b Heating rate for La Nina

c Zonal current velocity

a Without total current effect (extreme El Nino)

b Without total current effect (La Nina)

c Without current anomaly effect (extreme El Nino)

d Without current anomaly effect (La Nina)

-0.2 m s^{-1}

a Extreme El Niño   Equator

Mixed-layer depth

$\bar{u} + u'$

$\bar{u}$

u'

Zonal advective/Ekman feedback   Thermocline feedback

b La Niña   Equator

Mixed-layer depth

$\bar{u} + u'$

$\bar{u}$ u'

Zonal advective/Ekman feedback   Thermocline feedback

Western Pacific   Longitude   Eastern Pacific

a Probability density of eastward events

b Histogram as function of mean current

1907−1999
2006−2098

c Histogram as function of SST anomaly

d Stratification for current reversal

1907−1999
u>0
u<=0
2006−2098
u>0
u<=0

a SST anomaly

b Heating rate for weak El Nino

c Without total current effect (weak El Nino)

−0.2 m s⁻¹

−0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4 °C month⁻¹

d Without mean current effect (extreme El Nino)

e Without mean current effect (La Nina)

−4 −3 −2 −1 0 1 2 3 4 °C

−0.6 −0.4 −0.2 0 0.2 0.4 0.6

−0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4

a Zonal current velocity

b Zonal wind stress

a

ENSO propagation structure

Westward ← → Eastward

Obs (open circle)

b
Mean current ($\times10^{-1}$ m s^{-1})
r=0.40

c
Mean wind stress ($\times10^{-2}$ N m^{-2})
r=0.01

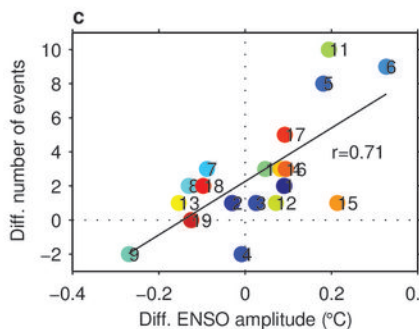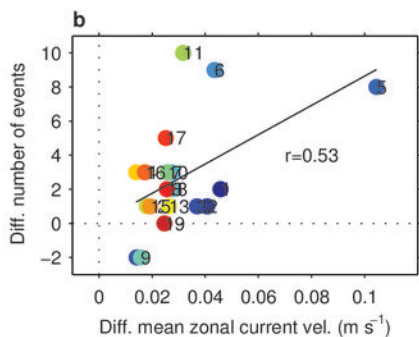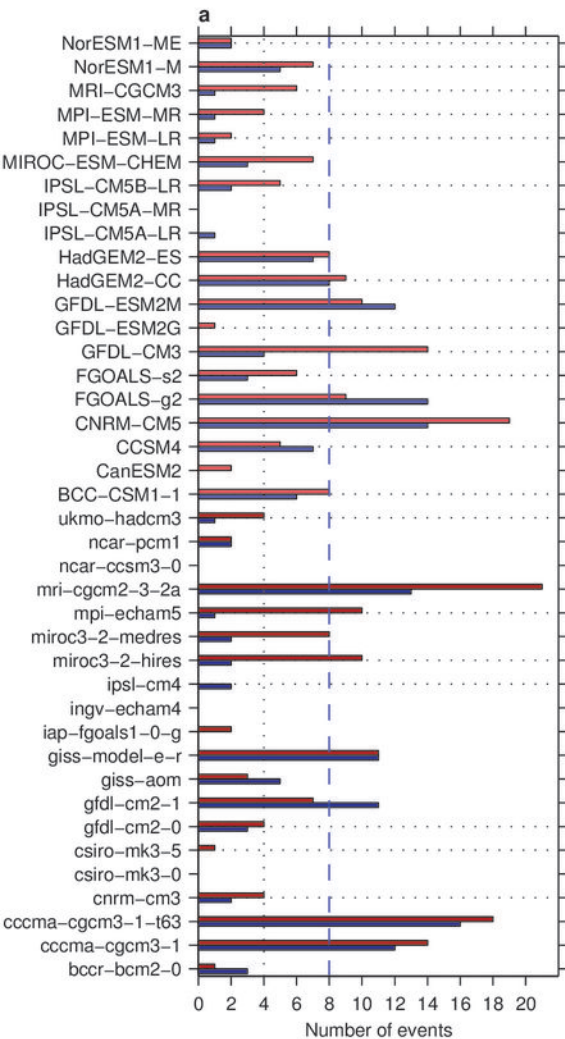ENSO propagation structure
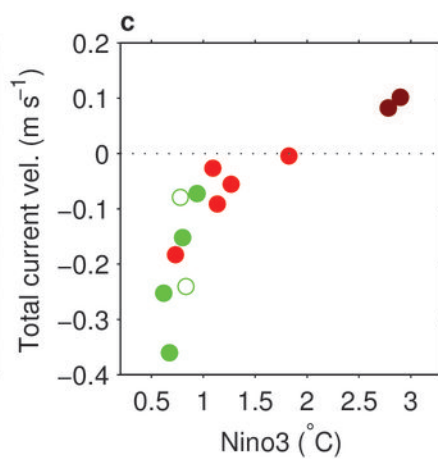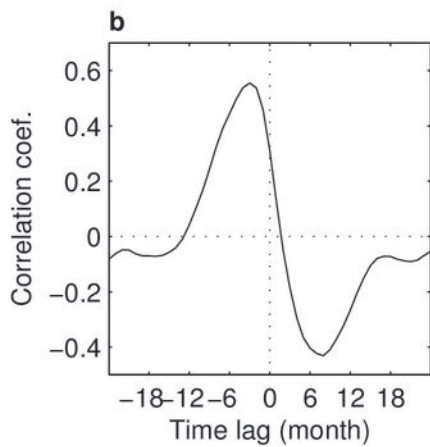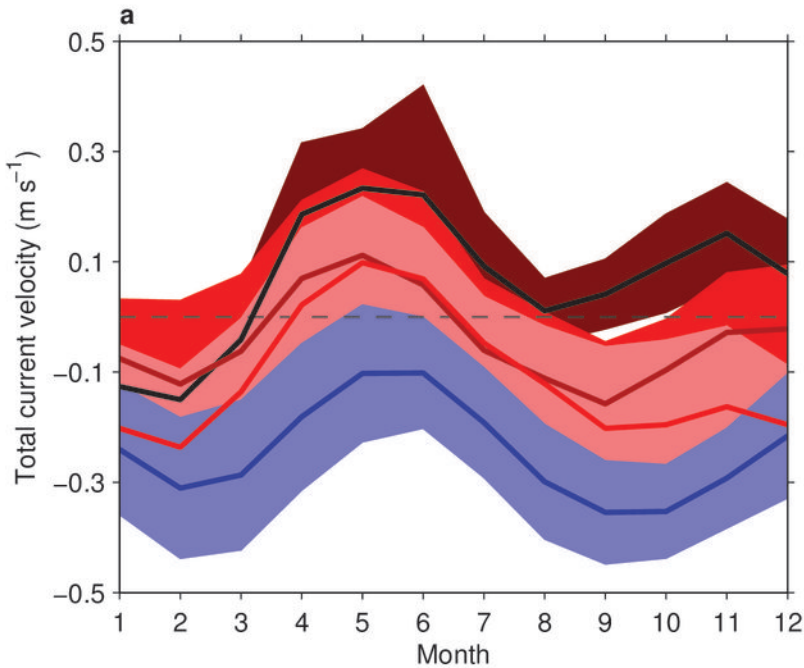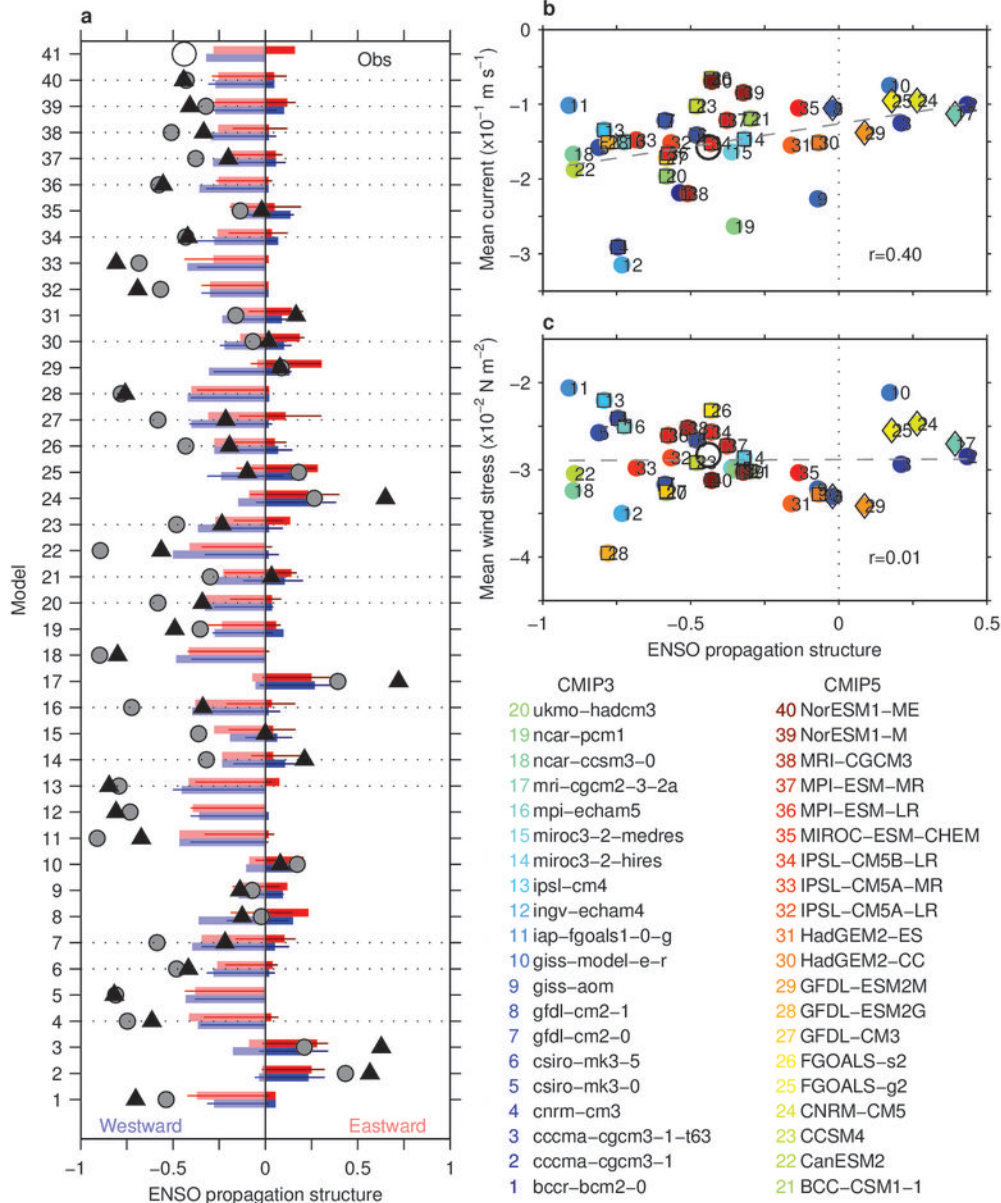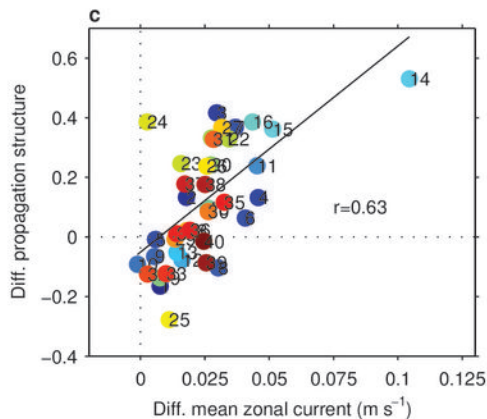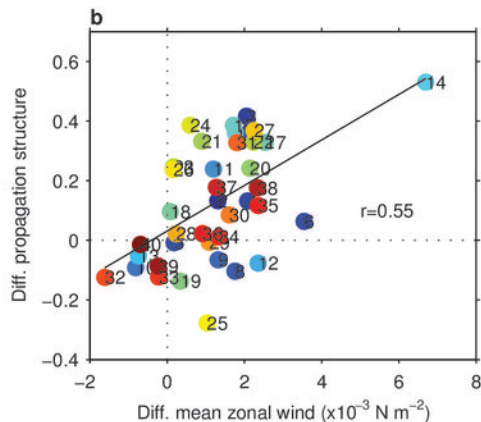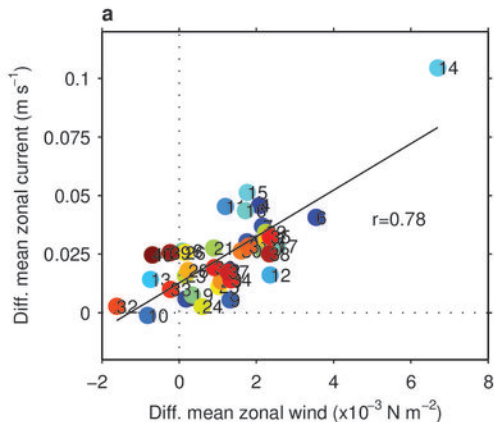
CMIP3	CMIP5
20 ukmo-hadcm3	40 NorESM1-ME
19 ncar-pcm1	39 NorESM1-M
18 ncar-ccsm3-0	38 MRI-CGCM3
17 mri-cgcm2-3-2a	37 MPI-ESM-MR
16 mpi-echam5	36 MPI-ESM-LR
15 miroc3-2-medres	35 MIROC-ESM-CHEM
14 miroc3-2-hires	34 IPSL-CM5B-LR
13 ipsl-cm4	33 IPSL-CM5A-MR
12 ingv-echam4	32 IPSL-CM5A-LR
11 iap-fgoals1-0-g	31 HadGEM2-ES
10 giss-model-e-r	30 HadGEM2-CC
9 giss-aom	29 GFDL-ESM2M
8 gfdl-cm2-1	28 GFDL-ESM2G
7 gfdl-cm2-0	27 GFDL-CM3
6 csiro-mk3-5	26 FGOALS-s2
5 csiro-mk3-0	25 FGOALS-g2
4 cnrm-cm3	24 CNRM-CM5
3 cccma-cgcm3-1-t63	23 CCSM4
2 cccma-cgcm3-1	22 CanESM2
1 bccr-bcm2-0	21 BCC-CSM1-1

a

b

c

20 ukmo–hadcm3
19 ncar–pcm1
18 ncar–ccsm3–0
17 mri–cgcm2–3–2a
16 mpi–echam5
15 miroc3–2–medres
14 miroc3–2–hires
13 ipsl–cm4
12 ingv–echam4
11 iap–fgoals1–0–g
10 giss–model–e–r
9 giss–aom
8 gfdl–cm2–1
7 gfdl–cm2–0
6 csiro–mk3–5
5 csiro–mk3–0
4 cnrm–cm3
3 cccma–cgcm3–1–t63
2 cccma–cgcm3–1
1 bccr–bcm2–0

40 NorESM1–ME
39 NorESM1–M
38 MRI–CGCM3
37 MPI–ESM–MR
36 MPI–ESM–LR
35 MIROC–ESM–CHEM
34 IPSL–CM5B–LR
33 IPSL–CM5A–MR
32 IPSL–CM5A–LR
31 HadGEM2–ES
30 HadGEM2–CC
29 GFDL–ESM2M
28 GFDL–ESM2G
27 GFDL–CM3
26 FGOALS–s2
25 FGOALS–g2
24 CNRM–CM5
23 CCSM4
22 CanESM2
21 BCC–CSM1–1

a Total current versus transition slope

b Transition slopes with and without current reversal

c Effect of total current on ENSO propagation

d PDF of number of current reversals

Panel a: Slope (s m^{-1}) vs Zonal current velocity (m s^{-1}), r=0.46

Panel b: Frequency vs Slope (s m^{-1}); No reversal, With reversal, With reversal, No reversal

Panel c: Frequency vs Slope difference (s m^{-1}); La Nina, El Nino, Strong El Nino, El Nino with reversal

Panel d: Frequency vs Number of current reversals; 1907–1999, 2006–2098