

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

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1	Late 20 th Century Emergence of El Niño Propagation Asymmetry and Future
2	Projections
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The El Niño Southern Oscillation (ENSO) is Earth's most prominent source of 27 interannual climate variability, exerting profound worldwide impacts¹⁻⁷. Despite 28 29 decades of research, its behavior continues to challenge scientists. During La Niña and 30 modest El Niño, sea surface temperature (SST) anomalies propagate westward along the equatorial Pacific, similar to the seasonal cycle⁷. In stark contrast, SST anomalies 31 propagate eastward during extreme El Niño, prominently in the post-1976 period⁷⁻¹⁰, 32 spurring highly unusual weather events worldwide with costly consequences^{3-6,11}. The 33 cause of this propagation asymmetry is currently unknown¹⁰. Here we trace the cause 34 to an asymmetry in the upper ocean circulation in the equatorial Pacific, whereby the 35 36 westward flowing currents are enhanced during La Niña but reversed during extreme 37 El Niño events. Our results highlight that propagation asymmetry is favored when the westward mean equatorial currents weaken, as projected under global warming¹²⁻¹⁴. By 38 39 analysing past and future climate simulations, we find that an aggregate of models that 40 exhibit more realistic propagation indeed simulate a doubling in the occurrences of El 41 Niño events that feature prominent eastward propagation characteristics in a warmer world. Our analysis thus suggests that more frequent emergence of propagation 42 asymmetry will be a symptom of a warming planet. 43

44 The tropical Pacific is home to intense convection, allowing for strong thermal and dynamical interactions between the upper ocean and the overlying atmosphere¹⁵. As warm SST 45 46 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 47 anomalously warm SST⁹, while the western Pacific warm pool (water with temperature 48 greater than 28°C) extends eastward, moving the eastern edge of the warm pool beyond 49 160°W. This induces an eastward shift of equatorial rainfall and an extreme swing of the 50 Southern Hemisphere's largest rainband, the South Pacific Convergence Zone¹¹, causing 51

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 billion⁴ (approximately \$24-26 billion in 2013 dollars).

These profound impacts demand an improved understanding of ENSO propagation dynamics. Many studies have evaluated the relative importance of various ocean-atmosphere feedback processes¹⁷⁻¹⁹, yet the mechanism for the propagation asymmetry remains unresolved. Here we show that an asymmetry in the zonal flow along the equatorial Pacific upper ocean (hereafter referred to as equatorial Pacific current) is the main cause.

Utilizing various observational data assimilation systems (see Methods and Supplementary 61 Table 1), we quantify the propagation characteristics of temperature anomalies (T') by 62 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 contour of $T_t'=0$ marks the peak of the temperature anomaly (dashed curve, Figs. 1a and b). 67 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 analysis shows opposite zonal propagation of SST anomalies between these two types of 72 events; eastward during extreme El Niño (β =0.82) and westward during La Niña (β =-0.46). 73 74 During moderate El Niño the propagation is westward (Extended Data Fig. 1b), similar to La 75 Niña.

The direction of propagation has been understood as arising from three main competing 76 positive feedback processes^{17,18}. The zonal advective and Ekman pumping feedbacks 77 associated with fluctuations in the Trade Winds involve advection of climatological SST 78 along the equator by anomalous zonal currents (u') and upwelling $(w')^{20,21}$, respectively (i.e., 79 $u'\bar{T}_x$ and $w'\bar{T}_z$; overbar indicates climatological mean, prime indicates anomaly, and subscript 80 indicates gradient along a specified direction). The thermocline feedback involves vertical 81 advection $(\overline{w}T_z)$ associated with eastward propagating internal waves which influence SST in 82 83 the eastern Pacific through the mean upwelling (\overline{w}) of water at the thermocline (a narrow depth range of strong vertical temperature gradients below the mixed layer). These processes 84 85 can establish propagation of SST anomalies in either direction: eastward if the thermocline feedback dominates, and westward otherwise¹⁷. Linear theories have highlighted a higher 86 importance of the thermocline feedback in the decades since the mid-1970s^{8,22,23}; this would 87 however predict an eastward propagation during La Niña events as well¹⁹, in contrast to 88 observations¹⁰ (Fig. 1b). 89

90 La Niña anomalies can be viewed as an enhancement of the prevailing climate, with stronger westward flowing surface currents. On the other hand, eastward current anomalies during El 91 Niño associated with anomalously weak Trade Winds²⁴ (Extended Data Fig. 2), oppose and 92 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 of anomalous temperature by the total current, $(\bar{u} + u')T'_x$, which is strongly westward during 96 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 line in Figs 2a and b), both with a positive slope of β^* , 0.55 and 0.69, respectively. This 103 104 reconstructs a linear framework in which the thermocline feedback dominates, leading to an eastward propagation for all events after 1976¹⁹. Thus it is the westward total flow that plays 105 a key role in determining the westward propagation during La Niña. 106

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 anomaly $(u'T'_x)$. We find that the westward long-term mean current favours a westward 109 110 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).

The non-linear effect is more prominent post-1976 (Supplementary Table 4) when El Niño 124 events are stronger^{9,25} with large eastward current anomalies that are occasionally comparable 125 126 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 variability^{26,27}, a weakened mean current will favour occurrences of an eastward propagation, 141 142 even if El Niño intensity does not change. Presently there is no agreement among climate models on the magnitude of future ENSO^{28,29}. However, the consensus that emerges is a 143 future with weaker equatorial mean westward currents¹²⁻¹⁴. Our study implies that this would 144 145 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

atmospheric CO₂ concentration (see Methods). With the large number of simulated ENSO 149 150 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 1907-1999 to about 5.4 events in 2006-2098. 157

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 feature unique to the 1982/83 and 1997/98 El Niños. Stratifying the statistics (Fig. 4c) in 163 164 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 results for future climate is assessed through analysis of forty CMIP3 and CMIP5 climatemodels (see full Methods).

Online Content Any additional Methods, Extended Data display items, Source Data, and
 Supplementary Information are available in the online version of the paper; references unique
 to these sections appear only in the online paper.

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designed and conducted the analysis. W.C. and A.S. wrote the initial draft of the paper. All
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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 significant above the 95% confidence level (P < 0.05). c, Zonal current velocity averaged 296

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.

303 Figure 2 | Effect of total and anomalous currents on equatorial Pacific mixed layer heat 304 balance during extreme El Niño and all La Niña events. a, Composite evolution of the 305 interannual-scale mixed layer warming and cooling rates (color shades; in unit of °C per 306 month) during extreme El Niño events (1982, 1997), with advection of temperature 307 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. 308 Only statistically significant values at the 95% confidence level are shaded in color, 309 310 contoured, or marked by black arrows (gray arrows otherwise). β^* in **a** and **b** are respectively 311 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 312 respectively 0.05 and -0.14, both not statistically significant (P>0.4). 313

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, During La Niña events, the zonal currents are prominently westward as the current anomaly always enhances the westward flowing mean current. This weakens the thermocline feedback effect and enhances westward propagation as induced by the other two dynamical 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 model ensemble mean in the past (1907-1999; blue) and future (2006-2098; red) periods. 327 328 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 (blue) and future (red) periods, segregated into bins of 0.04 m s⁻¹. c, As in b but segregated 333 into bin size of 0.25 for the Niño3 index which is detrended and normalized by the standard 334 335 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 unit of the normalized value. 337

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
$$T_t = -\left| (\bar{u} + u')T'_x + u'\bar{T}_x + \bar{w}T'_z + w'(T' + \bar{T})_z + (\bar{v}T')_y + v'(\bar{T} + T')_y \right| + Res. (1)$$

The variables *T*, *u*, *v*, and *w*, are respectively potential temperature, zonal, meridional, and 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 between 5°S-5°N, over the surface layer depth of 50 m. The rate of change of the mixed 347 layer temperature (T_t) is calculated as monthly increments using a centred-difference 348 349 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 Equation (1) are identical. Equation (1) is slightly different to that adopted in previous 351 studies^{8,20,21}, as $\bar{u}T'_{x}$ is expressed explicitly here and is viewed to interact with the non-linear 352 advection term $(u'T'_x)$. This combination, uT'_x , where $u = \bar{u} + u'$, is simply interpreted as the 353 354 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 continuity component via volume conservation [i.e., $T'(\bar{u}_x + \bar{v}_y + \bar{w}_z) = 0$] when the heat 356 budget is expressed in flux form [i.e., $(\bar{u}T')_x + (\bar{v}T')_y + (\bar{w}T')_z$]. 357

358

359 Quantification of propagation characteristic

The contour of $T_t=0$ marks the peak of T', thus its positive (negative) slope in time-longitude space indicates eastward (westward) propagating T' (Figs. 1a, 1b). The phase transition slope, β , is calculated by fitting a line via least-square method to the contour between 160°E-80°W and May(0)-May(1) to allow some room for temporal movement upon removal of the advection terms. The rationale for the longitudinal extent can be found in the section below under the heading 'Mean currents and ENSO propagation structures across models', and our results are not sensitive to this aspect of the calculation.

Removing an important advection component from the right hand side of Equation (1) would alter the spatial and temporal structure of T_t , thus affecting β . For example, a reversal from a negative slope (i.e., westward propagation) to a positive (i.e., eastward) would suggest that the component removed is crucial in setting the westward propagation. In this way, the role of a certain advection term on the propagation tendency of T' can be determined by comparing the altered slope β^* to the original β . The 95% regression standard error for the slopes is considered in all analysis by setting any slopes to zero if they are not greater than their corresponding error estimates.

375

376 Datasets and data processing

The reanalysis products utilised are ECMWF ORA-S3³¹, ECMWF ORA-S4³², SODA-2.16³³, 377 SODA-2.2.4³⁴, and GODAS³⁵ (Supplementary Table 1). Each reanalysis system assimilates 378 379 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 at ENSO time scales, a Butterworth low-pass filter³⁶ is applied prior to analysis to remove 382 383 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

ENSO classification and statistical significance test

The classification of ENSO events is based on the Niño3 index derived from the National Oceanic and Atmospheric Administration (NOAA) extended reconstructed SST version-3b³⁷, averaged over December-February when ENSO events typically peak. ENSO events are defined if the Niño3 amplitude, within each of the pre-76 (1959-1976) and post-76 (1976-2011) periods, is greater than 0.5 units of standard deviation. We classify these as strong if 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, 2010; moderate El Niño: 1963, 1976, 1987, 1994, 2002, 2006; moderate La Niña: 1964, 397 398 1967, 1984, 1995, 2005. The 95% statistical significance for each composite is evaluated using a bootstrap approach³⁸ in which samples of size N are randomly drawn repeatedly to 399 400 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 are further corroborated through an analysis of 40 CMIP3³⁹ and CMIP5⁴⁰ climate models (see 408 Extended Data 5 for the specific models). The 40 models, each of 186 years in record 409 (inclusive of the past and future simulations), provide a large sample of ENSO events that is 410 411 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.

The past and future climate simulations respectively correspond to the 20th century (1907-1999) and future projection scenarios (2006-2098) based on Special Report on Emissions Scenarios (SRES) A1B for CMIP3 and representative concentration pathways (RCP) 4.5 for CMIP5^{39,40}. The time spans were necessarily chosen to include as many models as possible that cover the longest record without any missing data.

420 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.

433 Here we diagnose the propagation structure in each past and future period in each model 434 (Extended Data Fig. 5a) by the proportion of westward events (assigned as negative 435 proportion) and eastward events (positive proportion) identified as El Niños and La Niñas 436 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; 437 438 the red/blue bars and lines in Extended Data Fig. 5a) and non-propagating events (non-439 statistically significant slopes) add up to 1, and so the net propagation structure (gray circles 440 for 1907-1999; black triangles for 2006-2098) can range from -1, if all of the events 441 propagate westward, to +1 if all propagate eastward. For example, the past ENSO events in 442 model number 3 consist of 10% westward El Niños, 17% westward La Niñas, 28% eastward 443 El Niños, 19% eastward La Niñas, and 26% non-propagating El Niños and La Niñas. 444 Summing the proportions of the propagating events and considering the directions: -0.1 + -

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.

The model ensemble results in Extended Data Fig. 5b also imply that in a climate state with a weak background current, natural variability alone (within which the system supports naturally varying ENSO propagation structure) would more easily produce eastward propagating events. With even weaker currents projected for the future, consistent with the 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 models⁴⁵ 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 (Extended Data Fig. 4a). These extreme events are identified by their prominent eastward 485 486 propagation with phase transition slope β that is stronger than in other events (Extended Data Fig. 4d). Here we demonstrate using an aggregate of models that current reversals have an 487 488 effect to make eastward propagation characteristic more prominent. Since zonal propagation is the focus of our study, and given the dynamical links of the aforementioned features, we 489 490 first select the models based on the following criteria:

The models must be able to simulate at least one prominent eastward propagating El Niño
 event in either past or future simulation. Such event is defined as that when β is positive,
 greater than the linear-regression standard error, and is above 0.5 standard deviation unit
 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 in496 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).

These criteria result in 24 models that simulate more realistic and distinctive current evolution between strong and moderate El Niño years (Extended Data Fig. 8) as expected from observations (Extended Data Fig. 4a), in contrary to that in the discarded models (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.

The effect of the total current on El Niño and La Niña propagation asymmetry is also reproduced (Extended Data Fig. 7c). The asymmetry becomes apparent with strong El Niño events, and more so when these co-occur with current reversals, similar to the observed counterpart (Fig. 2a, b; Supplementary Table 4).

An additional criterion is applied, resulting in a further exclusion of 5 models. Each of these excluded models already simulates 11 to 14 El Niño events with prominent eastward propagation slope over the 93 years in the past simulation (Extended Data Fig. 10a). These

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 simulate from none up to 8 events (i.e., double the expected observed frequency) in the past 521 522 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

With the mean westward currents projected to weaken in the future (Extended Data Fig. 6), thus providing a more conducive condition for increased occurrences of current reversals (Extended Data Fig. 7d), it is expected that there will be more El Niño events exhibiting 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 20 th Century is the weaker westward mean current which is projected by all of the models.
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618 Extended Data Figure legends

Extended Data Figure 1 | Zonal propagation of SST anomalies and effect of current on 619 mixed laver heat balance during ENSO events. a, SST³⁷ anomalies along the equatorial 620 621 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 linear fit slope (green line; $\beta = -0.97$, P < 0.01). c, As in b but with advection due to the total 628 current (arrow) removed, resulting in $\beta^{*}=-0.29$ (red dashed line) that is statistically 629 630 significant (P < 0.05). Only statistically significant values above the 95% confidence level are shaded in color, contoured, or marked by black arrows (gray arrows otherwise). **d**, As in **c** 631 but for extreme El Niño events (1982, 1997) with the effect of mean current (arrows) 632 633 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

Extended Data Figure 2 | Time evolution of equatorial Pacific zonal current and wind stress. a, The same as Fig. 1c for zonal current velocity averaged across the reanalysis products. The 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. b, As in a but for surface zonal wind stress.

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 horizontal645 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, significant at 99% level. Open circles indicate non-statistically significant β . The correlation 657 658 (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

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

Extended Data Figure 6 | Projected changes of long-term mean zonal wind stress, zonal current velocity, and propagation structure across the CMIP3 and CMIP5 models. a, Future and past difference in long-term mean zonal wind stress and zonal current velocity. b, Future and past difference in long-term mean zonal wind stress and ENSO propagation structure (Extended Data Fig. 5). c, Future and past difference in long-term mean zonal 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.

694

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), significant above the 99% level (with 472 data points), confirms the relationship seen in the 699 700 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)

normalized by the standard deviation of the past period. Only events with statistically
significant transition slopes are considered. The corresponding dashed curves indicate the
sample averages. Each panel displays the correlation coefficient between the equatorial
Pacific current (September - December average) and the Niño3 anomalies, following the
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.

























gfdl-cm2-1 0.90





CNRM-CM5



GFDL-ESM2G



MPI-ESM-LR



NorESM1-ME



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