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Interannual ENSO diversity, transitions, and projected changes in observations and climate models

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Abstract

Diverse characteristics of El Niño Southern Oscillation (ENSO) events challenge the traditional view of tropical coupled ocean-atmosphere systems. The probability of a transition from one type of event to another is influenced by multiple factors of which many are projected to change. Here we assess the likelihood of ENSO transitions in observations and climate models, including a distinction between events that peak in the Eastern Pacific (EP) and Central Pacific (CP). We find that the initial ENSO state influences the likelihood of certain transitions and that some transitions are not physically possible or stochastically likely. For example, transitions to CP events are more likely than EP events except from a neutral state. We also find that El Niños tend to occur as singular events compared to La Niñas. While consecutive El Niño and La Niña events of EP type are possible, opposing EP events do not occur in succession. We identify several transitions likely driven by internal dynamical processes including neutral conditions to El Niño, CP El Niño to another El Niño, EP El Niño to CP La Niña, CP La Niña to CP El Niño and La Niña, and EP La Niña to neutral and CP El Niño. Projections of future transitions show an increased probability of transitions to CP El Niño events while transitions to EP La Niña events become less frequent under a high-emissions scenario. Accordingly, transitions to these events become more and less likely, respectively. We also find changes in the likelihood of specific transitions in a warming world: consecutive CP El Niño events become more likely while EP El Niño events become less likely to transition into CP La Niña events. These changes are expected to occur as early as 2050 with some changes to be accelerated by the end of the 21st century.

1. Introduction

The El Niño—Southern Oscillation (ENSO), as the dominant source of interannual global climate variability [1], displays a diverse range of event properties and spatial patterns that consequently influence its life cycle and transition. Typical ENSO dynamics describe the ocean and atmosphere conditions in the tropical Pacific as an oscillation starting with an El Niño (EN) warming phase in austral winter, peaking in austral summer and generally reversing to La Niña (LN) in the following winter [2–5]. The warming and cooling patterns during EN and LN events generate climatic perturbations that induce different atmospheric teleconnections and impacts [6–8]. In some regions, the impacts of successive EN and LN events oppose to one another [9, 10]. For example, while some water resources deplete during EN, they could replenish during LN [11], depending on the events' location and intensity [12, 13]. When similar events occur in sequence, their impacts may be amplified compared to single or episodic events [14].

Although the development of each ENSO phase involves common ocean-atmosphere feedback processes related to the recharge and discharge of heat [2], each ENSO cycle varies. Conceptual ENSO models elucidate the average evolution of events and their oscillatory dynamics but fail to explain temporal and spatial deviations from the mean [15]. Differences in the location of sea surface temperature anomalies (SSTA) are thought to be one unaccounted factor within the oscillation framework that may be important for the event life cycle. The diversity of ENSO events occurring in the eastern Pacific (EP events) versus those occurring in the central Pacific (CP events) can lead to differences in properties such as the depth of the thermocline, anomalous zonal currents and advective feedbacks [16]. While the recharge mechanism describes both EP and CP ENSO events' life cycles [17], differences in their year-to-year variability, including protracted and unusual sequences, are not well understood.

Early studies on protracted or multi-year ENSO events have suggested an association between an increased EN episode duration and global warming [18]. A prolonged episode of EN events in the early 1990 s appeared quite unusual considering the instrumental period [19]. With the recognition of spatial diversity of ENSO [20], these protracted warming events may reflect multiple EN events of different spatial character [21], rather than a single protracted EN event.

The El Niño period 2014–2016 is an example of such a protracted EN event of unusual character. Despite a strong EP El Niño (EPEN) event being widely predicted, El Niño conditions failed to materialise in the Eastern Pacific [22] but developed in the central Pacific similar to a CP El Niño (CPEN) event [23], or a 'mixed' type El Niño event in 2014 [24, 25]. Surface conditions including an unusual easterly wind burst [26, 27], a lack of westerly wind events [28, 29], and the role of off-equatorial surface temperatures [30] have been implicated in this event. Other studies hypothesised that a mean state shift in low-frequency variations in the Pacific was a major contributor to these unusual conditions [31, 32] and the persistent warmth in the Pacific Ocean coincided with a period of apparent slowing of global warming [33, 34]. This recent episode of El Niño-like conditions raised many questions about the underlying predictability of El Niño events, underlying low-frequency variability, and our knowledge of the ENSO system and diversity within it [35].

Transitions between different types of El Niño such as in 2014–2016 are rarely observed and predictions might become more challenging [22] due to recent changes of ENSO. Observations indicate an increasing number of CPEN events during the most recent decades of the instrumental period [36–40]. However, most studies investigating future changes of ENSO using coupled general circulation models (CGCMs) show a lack of model agreement [16, 41–45]. An increasing complexity of ENSO has drawn attention to future changes of El Niño and ENSO events in general. A future increase of ENSO variability [46] could increase the amplitude of El Niño events and consequently increase the likelihood of multi-year La Niña events [47]. The wide range of varying characteristics and the limited number of observed events hampers generalisations of ENSO properties and the ability to sufficiently constrain multiyear variability in climate models [48]. Given these challenges, only a few studies have quantified the observed transitions of El Niño and La Niña [49] and diverse ENSO events in climate models in the past and future [50]. The degree of model agreement in such metrics therefore remains unknown.

Here we investigate the transition between different types of ENSO events considering the diversity of ENSO by differentiating between EP and CP events. We quantify the probabilities of ENSO transitions in instrumental records and in Coupled Model Intercomparison Project (CMIP) models using conditional probabilities. We attempt to answer the question of whether the occurrence of unusual transitions like in 2014–2016 is expected to change with greenhouse warming. We compare the historical and projected simulations during the 20th and 21st century using long instrumental records as a baseline to assess potential future changes.

2. Data and methods

2.1. ENSO states in observations and CMIP models

We identify the different ENSO states by performing Empirical Orthogonal Function (EOF) analysis on observed and modelled seasonal averaged Tropical Pacific SSTs (15° S-15° N,140° E-80° W) similar to [44]. We extract the first and second EOF to identify the different types of ENSO events at a seasonal timescale averaged for austral winter (June to August; JJA), spring (September to November; SON), summer (December to February; DJF) and autumn (March to May; MAM) (figure 1(a)). El Niño (EN)

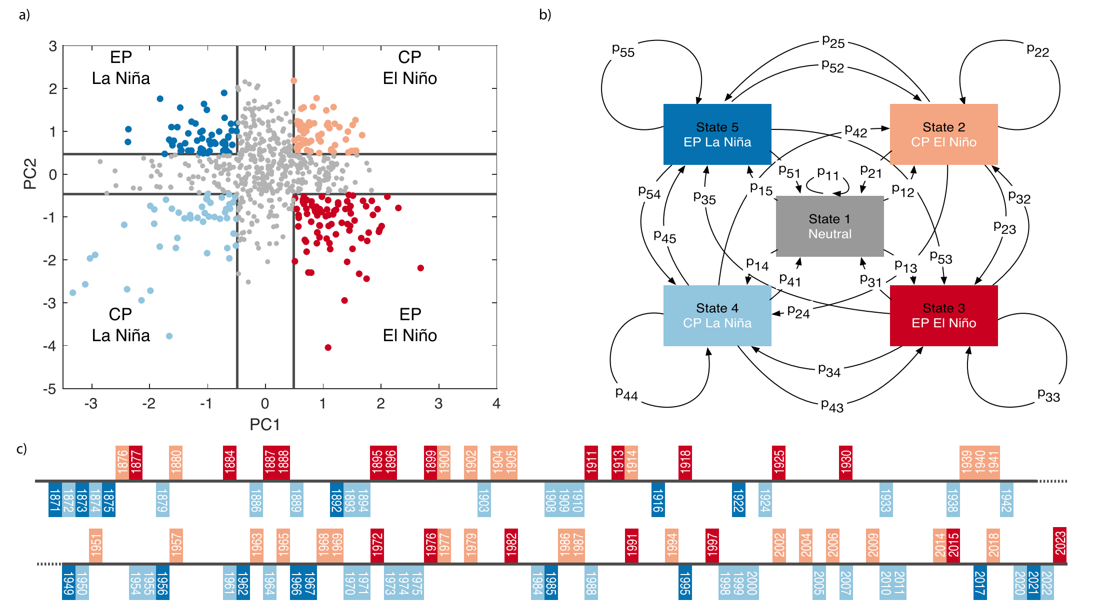

Figure 1. (a) Classification of five ENSO states using the first (PC1) and second (PC2) principal component of detrended SSTA. PC1 distinguishes neutral conditions within 0.5 standard deviation from EN and LN events, whereas positive or negative PC2 (exceeding the ±0.5 standard deviation) defines EP or CP ENSO events. (b) Schematic of the five-state, first-order Markov chain between the different states: neutral, EP and CP El Niño and EP and CP La Niña events (boxes) related by transition probabilities indicated by arrows. (c) Time line of ENSO events during the long instrumental period (HadISST) indicate EP El Niño (dark red), CP El Niño (light red), EP La Niña (dark blue) and CP La Niña (ligth blue) events.

and La Niña (LN) events are defined by exceeding the ±0.5 standard deviation of the first principal component (PC1) for at least two consecutive seasons, including the peak season DJF. If PC1 indicates EN or LN conditions, the second principal component (PC2) is used to classify events into eastern Pacific (EP) or central Pacific (CP) types by exceeding ±0.5 standard deviation of PC2 [44, 51, 52]. Prior to EOF analysis, the seasonal climatology based on the full length of the SST record is removed and the SST record is quadratically detrended.

We use three long instrumental datasets to quantify the observed transitions: the SST dataset from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISSTv.1) [53] spanning the years 1871–2023, the Extended Reconstructed Sea Surface Temperature (ERSSTv.5) spanning 1854–2023 [54], and the Centennial *in situ* Observation-Based Estimates (COBE) spanning 1850–2023 [55]. The thermocline depth in the tropical Pacific is approximated by the depth of the 20 ° C isotherm (D20) from 1960 to 2020 (Predictive Ocean Atmosphere Model for Australia Ensemble Ocean Data Assimilation System (PEODAS); [56]) and heat content of the equatorial Pacific by the integrated warm water volume (WWV) above the 20 ° C isotherm (D20) isotherm from 1980 to 2024 (Tropical Ocean Atmosphere Project (TAO); [57]). ENSO indices are calculated for the for the Niño3 (5° N-5° S,150°–90° W) and Niño4 (5° N-5° S, 160° E-150° W) and Niño3.4 region (5° N-5° S,170°–120° W).

We quantify the transition probabilities of ENSO using Markov chains (see supplement). A finite state-space Markov chain represents the time correlation of discrete variables also called state space [58]. A schematic of the five-state, first-order Markov chain shows the three different states of ENSO in figure 1(b). There are 25 transition probabilities (p_{ij}) that control a possible change in state for the sequential time step. The transition probabilities are conditional probabilities for a specific state at time $t+1$ given the following states at time t.

We also examine the ENSO transitions for both historical and future simulations from 66 models included in CMIP Phase 5 (CMIP5; [59]) and Phase 6 (CMIP6; [60]). For the 20th century, monthly outputs were used over the 100 year period from 1900–1999 from the historical experiments with prescribed historical forcing. For the 21st century, CMIP5 and CMIP6 models were forced under historical forcing up to 2005 and 2014, respectively. Thereafter, to the year 2100, we make use of the simulations forced by the high emissions representative concentration pathway (RCP) 8.5 scenario (for CMIP5) and the approximately equivalent Shared Socioeconomic Pathway (SSP) 5–8.5 (for CMIP6) [60, 61].

A total of 66 models (31 CMIP5 and 35 CMIP6 models) are evaluated for their ability to simulate ENSO variability. We concentrate here on SST features that are important for ENSO diversity. This includes the correct seasonality, location of variability and the absence of a dominant secondary variability peak, following [45] (supplementary table 2). We distinguish between all models ('All' model subset) and realistic ENSO models ('ENSO' models) that agree with observations on the seasonality, location of variability and absence of secondary peak criteria. We further consider a third subset of models ('ENSO and transition' models) that pass the model evaluation and have a good representation of the observed transitions measured by a positive correlation coefficient between the simulated and observed transition probabilities.

3. Results

3.1. Observed ENSO event cycle

Typical ENSO dynamics [2] follow an initial warming phase during austral autumn, peak in summer, and then transition into La Niña in the following winter. Strong El Niño events such as 1982/83 (figure 2(a)) and 1997/98 (figure 2(c)) show this evolution with positive preceding the event. During these strong El Niño years, atmospheric and oceanic indices like Niño3.4 and SOI show strong anomalies that exemplify a typical seasonal ENSO evolution. Immediately after these strong EPEN events, SSTs decline due to the discharge of equatorial heat, transitioning into colder La Niña conditions.

While warm conditions during the EPEN events of 1982/83 and 1997/98 lasted about one year, the La Niña events that followed persisted for several years. These La Niña events often occur in the Central Pacific rather than the Eastern Pacific (figures 2(a) and (c)). Successive multi-year La Niña episodes can be of similar type (figure 2(c) following the 1997/98 event) or alternate between Central (CPLN) and Eastern Pacific (EPLN) La Niña (figure 2(a) following the 1982/83 event).

Despite similar spatio-temporal patterns of the two strong EPEN events, we show that El Niño events can also differ substantially. Figure 2 shows warming events that are not immediately followed by cooler than normal (i.e. La Niña) conditions despite negative Warm Water Volume anomalies (WWVA). For example, from 1990 to 1995 the tropical Pacific remained warmer than usual without a transition into neutral or La Niña conditions (figure 2(b)). Throughout this period, the Niño3.4 region indicates mostly warmer than usual conditions but negative WWVA. The warming events during this protracted El Niño episode [62] show strong SST warming in the central Pacific. CPEN events can also be succeeded by La Niña or neutral conditions, as was observed in 2004/2005 (figure 2(d)).

As mentioned earlier, an unusual SST evolution was observed in 2014-2016 (figure 2(d)). The atmospheric and oceanic indices indicated warmer than usual conditions and positive WWVA during 2014 in the central Pacific, which intensified in 2015. The SST evolution shows the extraordinary character of this event. Neutral conditions prevailed across the Pacific with warmer conditions developing in the far eastern Pacific. This warming in the eastern Pacific abruptly stopped and continued in the central Pacific, only to then reoccur in 2015 and develop into a strong EPEN event.

Another example of an unusual ENSO event episode is the CPEN event in 2018/19. The CPEN event resulted in a lingering warming event observed in 2019, which then triggered three consecutive La Niña events of varying character (CPLN, EPLN & CPLN) but positive WWVA (figure 2(d)). These positive WWVA persisted during the three La Niña events unlike the negative WWVA during the 1998–2001 La Niña period (figure 2(c)). These events did not only present a huge challenge to seasonal prediction efforts but also questioned our understanding of the ENSO oscillation by highlighting the diversity of ENSO transitions.

3.2. Observed ENSO transitions

We first assess the observed year-to-year transitions of different ENSO events using long seasonal instrumental SST records. The majority of ENSO events agrees with previous identified events (e.g. [16, 20, 44, 52, 63]). Figure 3(a) shows the transition probabilities grouped by the initial state for three different century-long instrumental datasets (HadISST, ERSST and COBE). We identify nine of the 25 transitions as statically different from random chance using a Monte Carlo approach. The transitions from neutral to CPEN (p_{12}) and EPEN (p_{14}), CPEN to both El Niño events (p_{22} & p_{23}), EPEN to CPLN (p_{34}), CPLN to CPEN and CPLN (p_{42} & p_{44}) and EPLN to neutral and CPEN events (p_{51} & p_{52}) are likely driven by internal dynamical processes. Given these significant internally driven ENSO transitions, one could expect more predictability in these cases (supplementary table S1).

The conditional probability p_{11} to remain in neutral conditions is among the highest of the self-transitions and the most likely transition from a neutral state. The development of an ENSO event of any type following a neutral year is overall evenly distributed, even though the interquartile range indicates a slightly higher chance of CPEN and LN events to occur compared to EP type events.

From a recharge oscillation framework, it appears surprising that La Niña events (p_{14} & p_{15}) can arise from neutral conditions without a preceding El Niño event. It is conceivable that the preceding neutral conditions have slightly elevated SSTs but did not reach the El Niño threshold. On the other hand, ENSO asymmetry between El Niño and La Niña events in terms of event intensity would make it harder to for a preceding El Niño event not to be detected as El Niño events are stronger on average than La Niña events. A delayed discharge [64, 65] could potentially explain

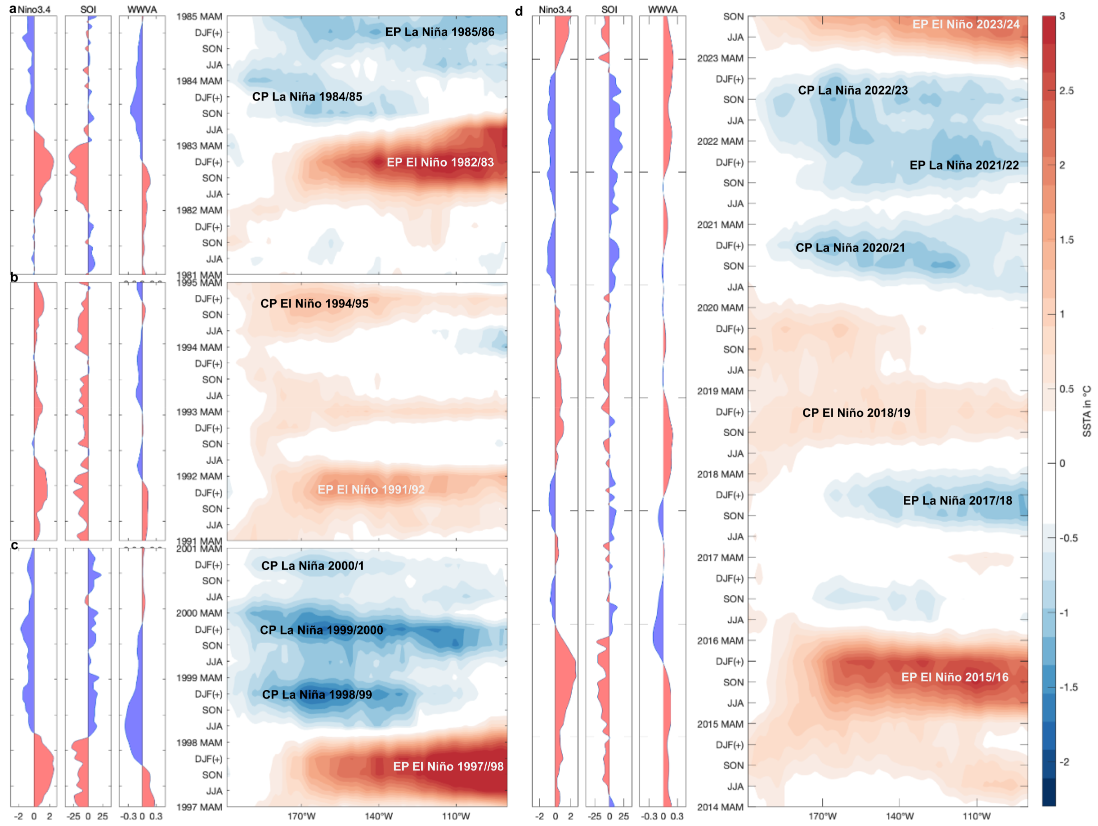

Figure 2. Temporal evolution of different ENSO episodes given by the Niño3.4 index, the Southern Oscillation Index (SOI), Warm Water Volume anomalies (WWVA) and time-longitude evolution of SSTA average (HadISST) over 5° N–5° S from left to right (a)–(d). Different El Niño events are shown from their initialisation (year-1) up to 4 years (a)–(c) following the event.

the occurrence of La Niña events without a preceding El Niño event [66]. Nevertheless, most La Niña events do not arise from neutral conditions but from preceding ENSO conditions (e.g. p_{24} & p_{54}) which is shown by higher transition probabilities.

The transitions following El Niño events are similar for CP and EPEN events. The most likely transition after an El Niño event is a return to neutral conditions (p_{21} & p_{31}) followed by a CPLN (p_{24} & p_{34}) event and CPEN (p_{22} & p_{32}) as the second most likely transition. This is most pronounced for EPEN events (p_{31}) which show the highest likelihood among all transition based on the HadISST and COBESST observational datasets. The El Niño or La Niña conditions following either EP or CP El Niño events are most likely of central Pacific character (p_{24} & p_{34}). The least likely transition out of EPEN events is the development of an EPLN (p_{35}). All observational datasets agree that this transition has not occurred. This aligns well with observations of LN events peaking further west compared to El Niño events [67].

Transitions arising from a La Niña event show some disagreement among the observational datasets, in particular for CPLN (p_{41}) returning to neutral conditions and EPLN to develop into a CPEN (p_{52}). Different interpolation methods used to produce these gridded SST datasets and time periods could potentially explain these differences. Nevertheless, all observational datasets agree that a consecutive CPLN event (p_{44} & p_{54}) is more likely transition following a CP and EPLN event.

The least common transition from EPLN events is to an EPEN (p_{53}). The complete discharge of ocean heat during an EPLN hinders the possibility of a developing El Niño conditions in the Eastern Pacific. Interestingly, the discharge of heat during EPLN conditions appears to still enable enough heat retention in the Central Pacific (p_{52}) to allow a CPEN to follow. It appears to be also far more likely to have consecutive La Niña events of EP character (p_{55}) than an EPEN event. Again this is consistent with the observed tendency of La Niña events to last two or more years [47, 68]. Compared to self-transitions of EPEN events (p_{33}), the transition probability of consecutive EP and CPLN events is twice as high.

Overall, the observed transitions (figure 3(b)) indicate that El Niño conditions are more likely to manifest as isolated or singular events compared to La Niña events. In more than half of the EPEN cases, the tropical Pacific transitions into a neutral state in the subsequent year. In contrast, the most likely transition from a CPLN is a second, consecutive CPLN

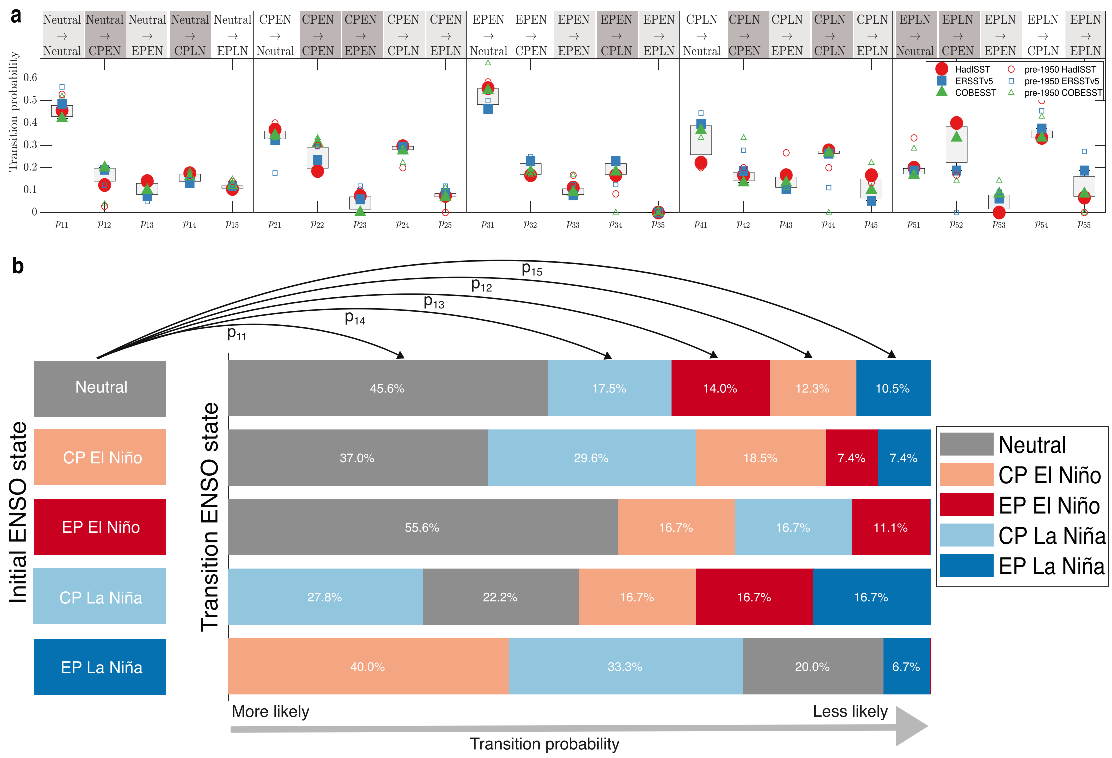

Figure 3. Observed transition probabilities for long instrumental datasets. (a) Boxplot of transition probabilities indicates the interquartile range of the three instrumental datasets HadISST, ERSSTv.5 and COBESST based on the entire instrumental period and early instrumental period (pre-1950). Transitions highlighted in light/dark gray exceed the 25th/5th and 75th/95th percentiles of Monte Carlo testing (n = 1000) conducted on the HadISST dataset, indicating significant internally driven ENSO transitions. Observed transition probabilities (b) for each inital state (left) to its next state in the following year ($t+1$) transition ENSO state based on HadISST. Transitions are sorted from more likely (left) to less likely (right).

event. Similarly, EPLN are more likely to transition to CPEN or La Niña events, but in only 20% of the cases EPLN remain a singular event.

The observed transitions also show that transitions to CP type events are more likely than EP type events. Regardless of the initial ENSO state, all transition prefer transitions to CP El Niño and La Niña events over EP type events except for transitions from a neutral state. From a neutral state, the development of an EPEN events (14%) is more likely than a CP El Niño event (12.3%). In contrast, after EPEN and EPLN events there is only a 11% chance of an EPEN type event, and 6.7% chance of an EPLN event, respectively. It becomes clear that the initial ENSO states influence the likelihood of certain transitions while also revealing transitions that are not possible. However, it is important to acknowledge that some of the observed transition probabilities are interpreted as a stochastic process, and thus, they may not necessarily indicate direct physical causality.

3.3. Composites of ENSO transitions

Next we assess the zonal SST structure and seasonal evolution of the different ENSO transitions. Figure 4 shows the time-longitude SST and thermocline depth (D20) composites for the different transitions. Any ENSO event, including El Niño and La Niña events, that arise from neutral conditions appear to be related to somewhat warmer SSTAs along the western equator (figure 4 first row). The year preceding an EPEN event shows positive SSTA in the western Pacific which can push the edge of the warm pool eastwards. With the subsequent eastward shift of convection, the development of an El Niño event in the following year can be promoted [69]. Similar to EPEN, CPEN events also show positive SSTA in the Warm Pool area but also slightly cooler anomalies in the eastern Pacific with weaker thermocline anomalies compared to EPEN events. While for both El Niño events these cooler SSTAs occur mainly during austral summer, the cooler SST conditions that precede EPLN events occur earlier. For EPLN events, negative SSTAs are visible along the equator during SON while CPLN events show slightly warmer SSTAs in the central Pacific during SON before the event. Interestingly, in the year preceding both types of La Niña events from neutral conditions weak but zonally extensive lower thermocline anomalies can already be observed.

EPEN events (figure 4 second row) with a shallow D20 in the eastern Pacific are found to transition to neutral or either type of El Niño but not to EPLN events. EPEN events that directly transition to neutral conditions in the following year show a fast warming

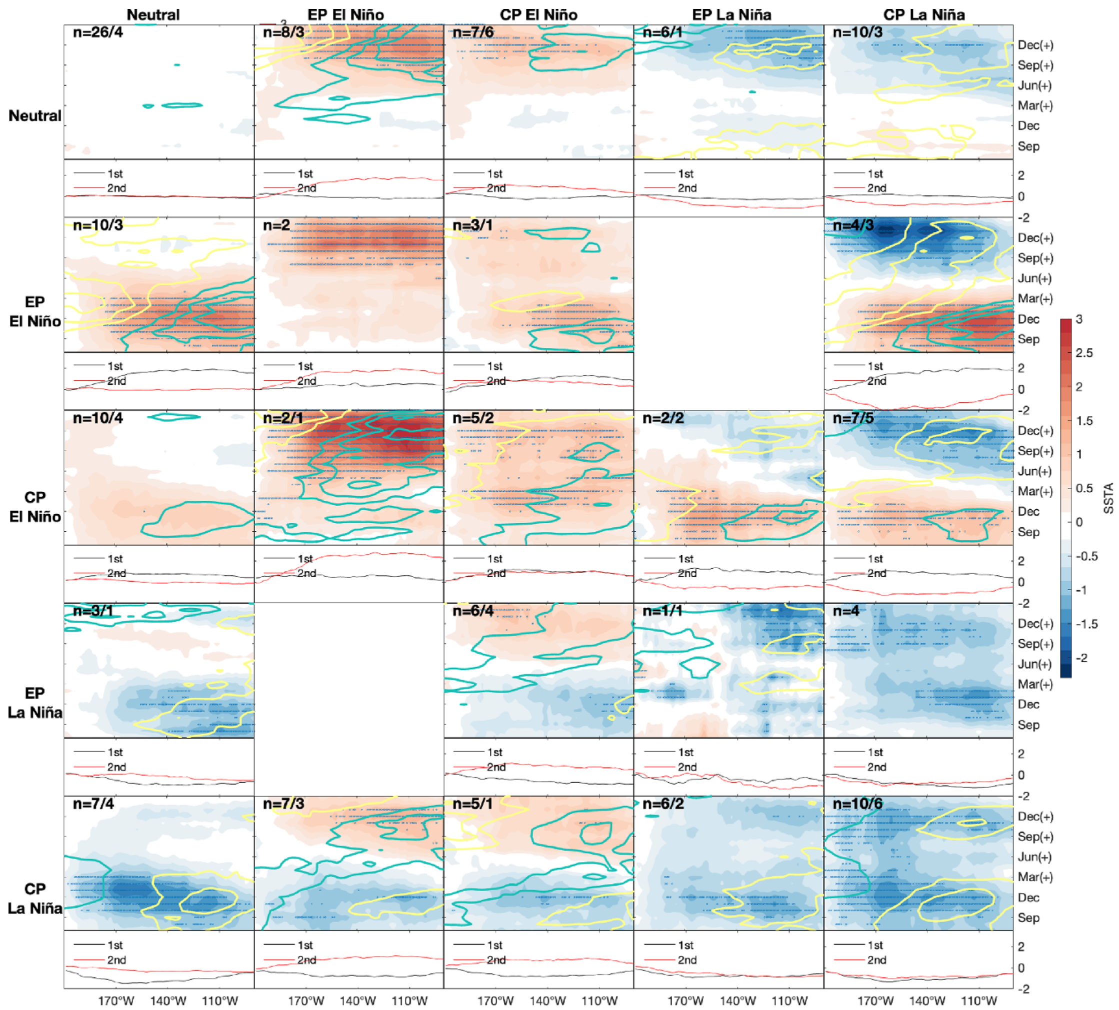

Figure 4. Zonal composite plot of SSTA (shading) along the equatorial Pacific (5° N–5° (S) based on the HadISST dataset and the thermocline depth (D20) as contours. Contour interval is 10 m with yellow contours representing negative D20 anomalies (lower thermocline), and green contours representing positive D20 anomalies (higher thermocline). The transition are shown from the event on the left (rows) to the following event at the top (columns) as time-longitude composites during the instrumental period. The number of years that are composited are indicated in the upper left corner for SSTs and D20. Stippling indicates significance exceeding the 25th and 75th percentile of randomly sampling. Zonal composite mean of the first (grey) and second (red) year are shown as line-plots below.

in the eastern Pacific but positive SSTA in the Warm Pool area persisting into the following year. By contrast, EPEN events that are transitioning to CPLN events show immediately neutral or cooler SSTAs at the beginning of austral summer. Interestingly, consecutive El Niño events are much weaker compared to EPEN events that transition to CPLN conditions. It appears that a critical heat content threshold needs to be reached to enable the initialisation of La Niña events and deepen the thermocline further.

For CPEN events the strength of the event is unrelated to the following year's transition (figure 4 third row). All CPEN events reach similar maximum SSTA but can transition to neutral, El Niño or La Niña conditions in the following year. The only apparent difference of consecutive CPEN events is that the first event might peak slightly later (MAM) compared to all other transitions where CP events peak in DJF.

The patterns that distinguish transitions out of La Niña events are less clear (figure 4 fourth & fifth row). Just as EPEN do not transition into EPLN, the reverse, that is, the transition from EPLN to EPEN, is also not observed. Most of the EPLN will transition to either CPEN or CPLN conditions. Only one instance of a consecutive EPLN event has occurred. EPLN that transition to neutral conditions are strongly defined by cooler anomalies early on compared to the other transitions. The zonal structure and intensity of CPLN events is relatively similar for all transitions (figure 4 fifth row). The most common transition, consecutive CPLN events, prominently shows the strongest negative SSTA in the central Pacific and strongest D20 anomalies in the eastern Pacific. However, it remains unclear whether a CPLN will evolve into another CPLN or transition to neutral conditions based solely SSTs and D20 anomalies. The initial CPLN exhibits striking similarities between

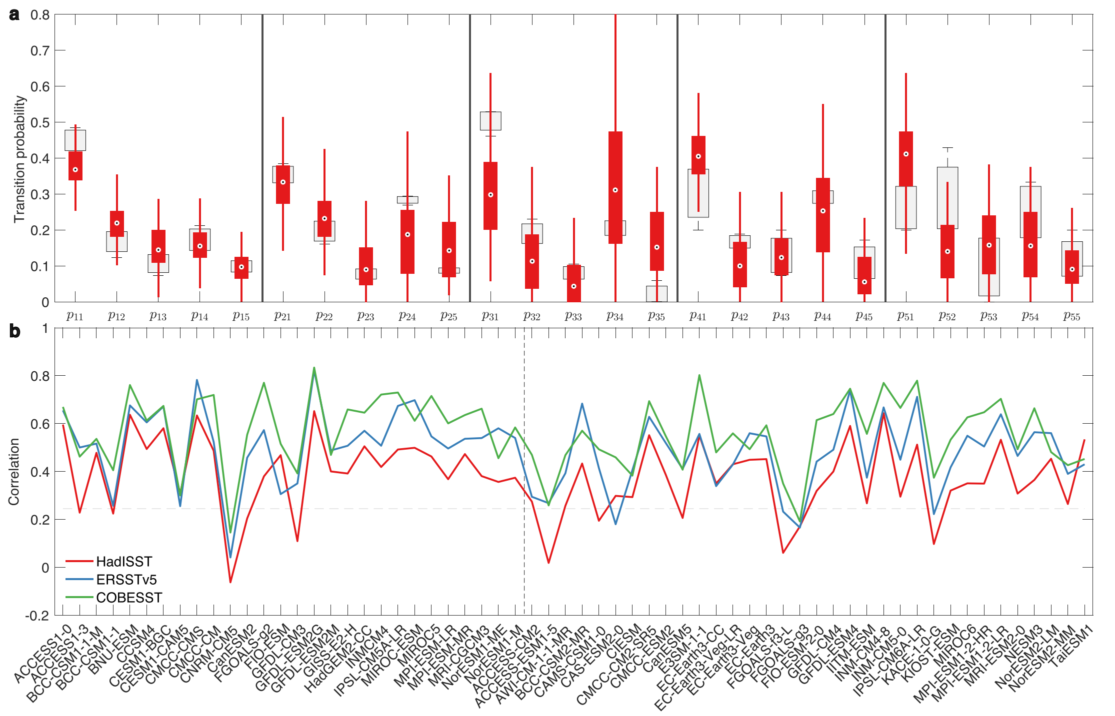

Figure 5. (a) Comparison of observed (grey boxplot similar to figure 2) and modeled (red boxplot) transition probabilities derived from the CMIP5 and CMIP6 models. (b) Individual model representation of all transition probabilities by the correlation coefficient with the observed transition probabilities for the three different SST datasets. Horizontal line indicates the 90% confidence level of significant correlations exceeding $r = 0.26$.

neutral and successive CPLN events, that could suggest that atmospheric forcings may play a crucial role in determining the next transition [47].

3.4. ENSO transitions in CMIP models

Comparing observed ENSO event transitions to CMIP models (supplementary figure S7), we show an overall good agreement in transition probabilities (figure 5(a)). Model ensemble spread aligns closely with observed interquartile range, with substantial overlap for most transitions. EP and CPEN frequencies, as well as La Niña events from neutral conditions (p_{12}-p_{15}), are well represented in most models. However, self-transition (p_{11}), EPEN to neutral (p_{31}), and CPEN to CPLN (p_{24}) transitions are slightly underestimated, while La Niña events followed by neutral conditions are overestimated (p_{41} & p_{51}). Notably, models frequently simulate La Niña events returning to neutral, contrary to observations. Significant disparities between observed and modelled ENSO transitions exist for EPEN followed by EPLN events (p_{35}). All instrumental datasets agree that the EPEN to EPLN transition has not occurred and may be physically implausible [50]. The interpretation of this transition in models should be handled with caution.

Details of the individual models' performance in the representation of ENSO transitions are shown in figure 5(b). The correlation of simulated and mean observed transition probabilities ($n = 25$) gives an estimate of how well each model represents ENSO transitions. Again, most of the models show good agreement with the observed ENSO transitions, as evidenced by the positive correlation coefficients. The best overall representation of ENSO transitions is achieved by GFDL-ESM2G, INM-CM4-8 and BNU-ESM. Models like the CNRM-CM5, ACCESS-ESM1-5 and FGOALS-f3-L have the least skill in simulating the observed transitions, based on the lowest correlations. Model biases like the representation of ENSO seasonality and asymmetry are likely linked to the transition performance in models (supplementary figure S.8–10). For further analysis of future changes in transitions we therefore exclude models with non-significant correlations and use a subset of models with a good representation of the transitions, defined by significant correlations with observations that are positively evaluated.

3.5. Projected changes in ENSO transitions in CMIP models

External forcing such as anthropogenic warming could potentially introduce mean state or dynamical changes that alter characteristics of ENSO behaviour including ENSO transition probabilities. For example, increasing SSTs in the tropical Pacific, involving less ocean heat uptake, could alter the probability of initiation of an ENSO event, which could

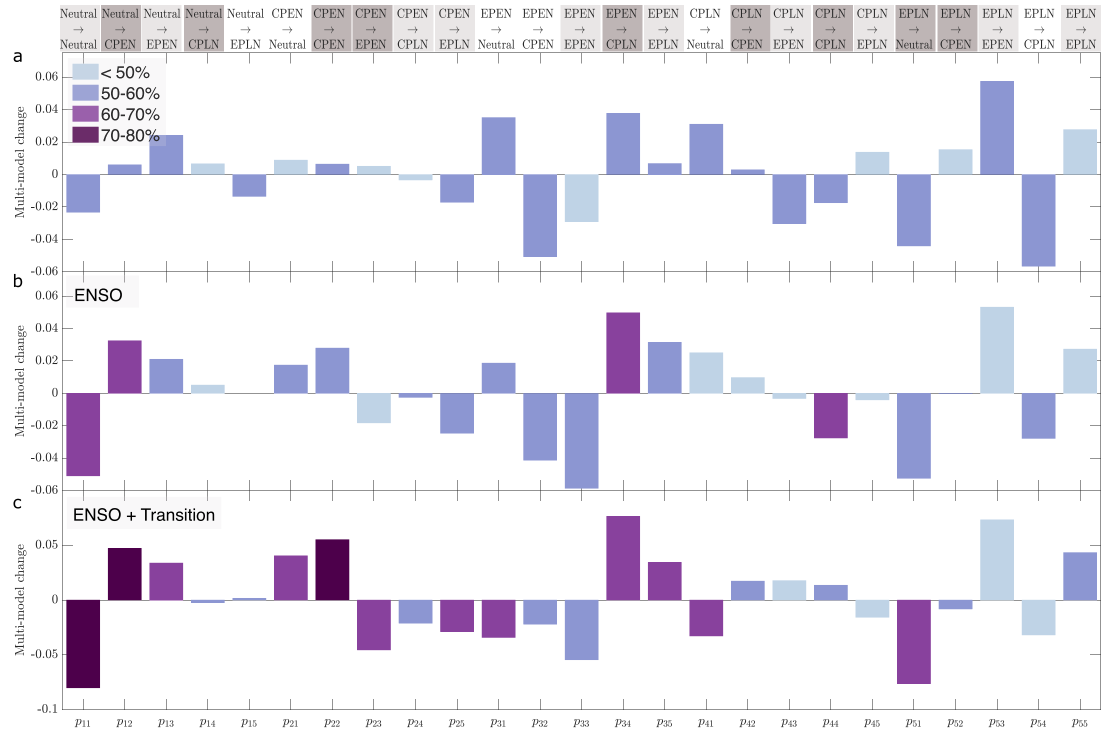

Figure 6. Future changes of transitions probabilities in CMIP models as the difference of the 20th century (1900–1999) and the 21st century (2000–2099) shown by the average multi-model change (bars) and model agreement on sign is indicated by bar colour. (a) Multi-model ensemble of all available CMIP5 and CMIP6 model simulations ($n = 62$). (b) Subset of CMIP5 and CMIP6 model simulations passing the model evaluation (ENSO subset $n = 42$). (c) Multi-model ensemble of CMIP5 and CMIP6 model simulations passing the model evaluation and have positive correlation with the observed transition probabilities (ENSO and transition subset $n = 32$). Transitions highlighted in light/dark gray exceed the 25th/5th and 75th/95th percentiles of Monte Carlo testing indicating significant internally driven ENSO transitions according to figure 3.

reinforce or hinder further event development or transitions.

Here we assess possible future changes of ENSO transitions by comparing CMIP model simulation derived transition probabilities of the 20th century (1900–1999) with the high emission scenario in the 21st century (2000–2099). The transition probabilities differ between the individual models. We therefore calculate the relative changes of transition probabilities for each model and compare them between 20th and 21st centuries.

The multi-model ensemble mean change between the 20th and 21st century simulations shows substantial changes in transitions that appear consistent among different subsets of models (figures 6(a)–(c)). First, we consider all available CMIP5 and CMIP6 model simulations ($n = 66$) to get a general overview (figure 6(a)). More confidence is then added by considering only models that pass the model evaluation (ENSO $n = 42$) (figure 6(b)). We also examine the subset of those models that represent observed ENSO and transitions reasonably well (ENSO and Transition models $n = 32$) (figure 6(c)).

Overall frequency changes indicated by ENSO events arising from neutral conditions (p_{11}-p_{15}) show substantial shift towards more El Niño events of EP and CP character (figure 6(a)). Independent of the subset, the majority of models indicate an increasing number of EP and CPEN events (p_{12} & p_{13}) and fewer consecutive neutral (p_{11}) conditions. The increasing number of CPEN events will then more likely transition to neutral (p_{21}) or another CP El Niño event (p_{22}) and less likely to La Niña events (p_{24}&p_{25}). An increasing number of EPEN events (p_{13}) comes with an increasing tendency of transition to both La Niña types (p_{34} & p_{35}) and neutral conditions (p_{31}) but declining tendency for consecutive El Niño events (p_{32} & p_{33}).

There is less model agreement among the subsets on other transition changes such as transitions arising from CPLN (p_{41}-p_{45}) conditions. Depending on the subset, the ensemble average change is relatively small and models disagree on the sign of changes. Among these transitions there is some evidence of an increase of CPLN to CPEN (p_{42}) but other transitions show opposite signs of change. The smallest but most confident subset of models, which simulate transitions well (figure 6(c)) suggests with 65% of model agreement a decrease of CPLN to neutral conditions (p_{41}) but shows no overall agreement on the what CPLN events are more likely to transition into (p_{42}-p_{45}). Despite most La Niña events being of CP type, models face greater difficulty in constraining transition changes for CPLN compared to EP types.

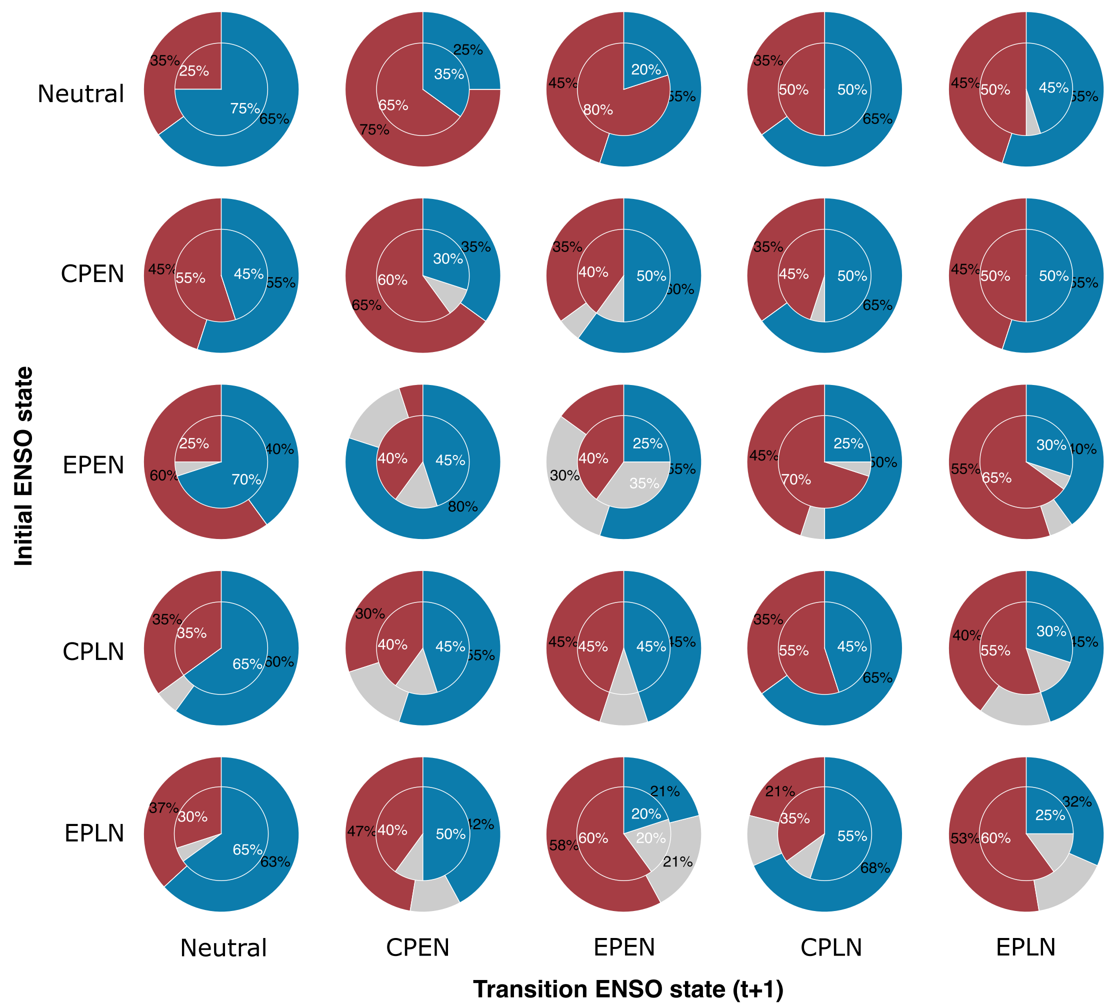

Figure 7. Changes of transitions probabilities in CMIP models (ENSO and transition subset $n = 32$) depicted as percentages, with red indicating an increase and blue indicating a decrease for each transition. The inner pie chart illustrates the difference between the 20th century (1900–1999) and the first half of the 21st century (2000–2050), while the outer pie chart represents the difference between the first half of the 21st century (2000–2050) and the second half of the 21st century (2050–2100). Rows correspond to the initial state (year = (t), and columns represent the first transition (year = t+1).

The majority of the models and subsets show a decrease of transitions from EPLN events to neutral conditions (p_{51}) and an increase of transitions to EPEN events (p_{53}). Interestingly, consecutive EPLN events (p_{55}) show an increase, while all subsets show declines in the transitions from EPLN to CPLN events (p_{54}).

The smallest yet most confident subset of models (ENSO + Transition models) that accurately represent ENSO and transitions (figure 6(c)) shows a consistent response: a significant decrease in neutral conditions, an increase in CPEN events, and more consecutive CPEN events, with over 70% of models agreeing on these changes. Increased frequency of transitions from neutral to EPEN (p_{13}), CPEN to neutral (p_{21}), and EPEN to CPLN (p_{34}) are projected with strong agreement. Additionally, a decrease in transitions from CPEN to EPEN (p_{23}) and other transitions (p_{23}, p_{25}, p_{31}, p_{35}, p_{41}, p_{51}) is suggested by more than 60% of these models. Given the overlap of future changes suggested by most models with observed transitions differing from stochastic processes, we argue that ENSO transition changes between the 20th and 21st centuries are driven by external forcing factors.

3.6. Timing of projected changes in ENSO transitions in CMIP models

The majority of CMIP models depict clear projected changes in ENSO transitions. Since models may not respond simultaneously and changes might be delayed or opposing [70], we next consider different timings of changes by comparing the first with the second half of the 21st century.

Previously identified transition changes, such as the decrease in neutral years, increase in CP and EPEN events, and decrease in EPEN and CPLN events transitioning to neutral conditions, occur predominantly in the first half of the 21st century (figure 7). The increase in EPEN events and La Niña events transitioning to either another EPEN or an EPLN event is also most pronounced in the first half of the century, according to up to 70% of models. The strongest change in model agreement during this period is the increase in EPEN events from neutral conditions, indicated by 80% of models. This increase does not amplify further in the second half of the century.

Some transition changes are amplified from the first to the second half of the 21st century. This includes the increase in CPEN events arising from neutral conditions, from 65% to 75%, and consecutive CPEN events, from 60% to 65% of models agreeing on the change. Decreases are also amplified. The strongest amplification is for EPEN events transitioning to CPEN events, with 45% of models indicating a decrease in the first half and 80% agreeing on the decrease in the second half. Other amplified changes include the decrease in CPLN transitions to another CPLN or CPEN, CPEN events transitioning to EPEN and La Niña events, and EPLN events transitioning to CPLNs.

There is also evidence of non-continuous or opposing transition changes from the first to the second half of the 21st century. For example, 70% of models indicate fewer EPEN events transitioning to neutral conditions in the first half, while 60% show an increase in this transition in the second half. Similarly, most models suggest an increase in consecutive CPLN events in the first half, but no further amplification and a decrease in this transition in the second half.

Overall, differences in projected changes between the first and second half of the 21st century provide insights into the timing of transition changes. However, opposing changes should be viewed cautiously due to the large degree of internal variability and the low probability of some transitions.

4. Discussion

Motivated by recent observed ENSO transitions, we have used long instrumental records and climate models simulations to investigate ENSO diversity, transitions and future changes. El Niño events, occurring every 2–7 years, align with transition probabilities from neutral conditions. Similarly, we show evidence that the asymmetry in the duration between El Niño and La Niña events [67, 71] applies to EP and CP type of events. Compared to La Niña, both types of El Niño are found more likely to occur as singular events. The most common transition post-El Niño is a return to neutral or CP type events. The 2014–2016 ENSO episode, with a CPEN followed by an EPEN, is notably rare, having occurred only once before in the observational record. The EPEN to EPLN transition is the least likely and may be physically implausible, as it has not been observed.

The recent sequence of La Niña events from 2020 to an El Niño in 2023 represents a distinctive sequence of anomalous transitions. Starting from a slightly warmer SST background in the central Pacific, a CPLN emerged in 2020 and transitioned to an EPLN event. This transition is the least likely after a CPLN event. In 2021/2022, the EPLN transitioned back to a CPLN, a more common shift, followed by the 2023/24 EPEN. We find the development of an EPEN after a La Niña is not possible after an EPLN but is one of the most likely transitions after a CPLN. Our year-to-year analysis underscores the lower likelihood of these recent transitions but indicates the importance of further assessments of multi-year transitions beyond one year.

The comparison of model simulations with observed transitions identifies several, well-performing models [72] that realistically represent ENSO transitions. ENSO seasonality and asymmetry are found to have an impact on the transition performance of models. Under a high emission scenario, we find an increase in CPEN events confirmed by the majority of models and those with realistic ENSO simulations. Previous research lacks consensus on future CPEN event frequency. While observations and paleoclimate evidence [40, 73] suggest an increase in CPEN events in recent decades [36–40], most future projections show model disagreement [16, 41–45]. An increase in CPEN events raises the likelihood of transitioning to another CPEN. However, a decrease in neutral events reduces transitions to La Niña, while EPEN to CPLN transitions are expected to increase in a warming world. This aligns with findings by [50], indicating fewer neutral conditions and more CPEN and CPLN events in the future. Different transition timings reveal certain changes may accelerate, dampen, or change sign. The rise in CPEN and consecutive CPEN events is evident throughout the 21st century, while the decline in EPEN to CPEN and consecutive La Niña events occurs later. Further work is needed to clarify less certain changes, such as consecutive EPEN events, which are not well constrained by models.

There is considerable spread among the instrumental dataset-derived transition probabilities. The small number of observed events but also the quality of long instrumental records and their spatial construction, especially in the early part of the records, limits the interpretation of observed transitions. Despite small differences in individual probabilities across different periods, the overall pattern of frequent and infrequent transitions remained consistent. Discrepancies with other studies may stem from different time periods, event definitions, or decadal variability. For example, the study [74] found CPEN events are less likely followed by La Niña events compared to EPEN events, while our results are more nuanced. We find EPLN events rarely follow CPEN events, but CPLN events do. Longer instrumental records and model experiments are needed to assess such disagreement by increasing the number of events to provide more robust statistics.

This study examined sea surface and subsurface conditions in the tropical Pacific, though data availability limits these insights. Key processes for understanding ENSO diversity also include equatorial wind anomalies [29], zonal advection [36], shifts in convection centers [75], and ocean heat content [76]. Additionally, subtropical Pacific [14] and trans-basin processes are crucial for understanding different transitions. Future work could include atmospheric circulation and oceanic processes and variables to reduce uncertainties, explore dynamical mechanisms for transitions, the role of model biases [72] and low-frequency variability in more detail [77]. Climate models that accurately simulate decadal variability could reduce uncertainties in future projections.

Most studies aim to identify, predict, and distinguish the factors responsible for ENSO event initialisation [78] while our study suggests paying careful attention to the mechanism of ENSO terminations and transitions. We highlight the importance of distinguishing different ENSO types, as their diversity plays a crucial role. Further assessment of the physical mechanisms behind projected transition changes is vital, especially considering that some observed transition probabilities should be viewed within a stochastic framework. Investigating why certain transitions are more likely than others could be extended to large ensembles as they potentially reduce uncertainties by minimising model differences and facilitate studying transitions beyond one year. As climate change intensifies, the frequency and nature of El Niño and La Niña events and their transitions are expected to change. Understanding these transitions and their response to warming is essential to improve and adapt seasonal prediction systems to spatially diverse ENSO events.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling groups (listed in supplementary table 2 of this paper) for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals with data available at https://esgf.llnl.gov/. SOI data is provided by the Australian Bureau of Meteorology. COBE-SST2 and NOAA ERSST V5 data data provided by the NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at 02.01.2024. Ocean heat content is provided by TAO Project Office, NOAA/PMEL www.pmel.noaa.gov/tao/wwv/data/ and the Predictive Ocean Atmosphere Model for Australia Ensemble Ocean Data Assimilation System (PEODAS) D20 thermocline depth at http://opendap.bom.gov.au:8080/thredds/catalogs/bmrc-poama-catalog.html.

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