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A metric for quantifying El Niño pattern diversity with implications for ENSO–mean state interaction

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Abstract

Recent research on the El Niño–Southern Oscillation (ENSO) phenomenon increasingly reveals the highly complex and diverse nature of ENSO variability. A method of quantifying ENSO spatial pattern uniqueness and diversity is presented, which enables (1) formally distinguishing between unique and "canonical" El Niño events, (2) testing whether historical model simulations aptly capture ENSO diversity by comparing with instrumental observations, (3) projecting future ENSO diversity using future model simulations, (4) understanding the dynamics that give rise to ENSO diversity, and (5) analyzing the associated diversity of ENSO-related atmospheric teleconnection patterns. Here we develop a framework for measuring El Niño spatial SST pattern uniqueness and diversity for a given set of El Niño events using two indices, the El Niño Pattern Uniqueness (EPU) index and El Niño Pattern Diversity (EPD) index, respectively. By applying this framework to instrumental records, we independently confirm a recent regime shift in El Niño pattern diversity with an increase in unique El Niño event sea surface temperature patterns. However, the same regime shift is not observed in historical CMIP5 model simulations; moreover, a comparison between historical and future CMIP5 model scenarios shows no robust change in future ENSO diversity. Finally, we support recent work that asserts a link between the background cooling of the eastern tropical Pacific and changes in ENSO diversity. This robust link between an eastern Pacific cooling mode and ENSO diversity is observed not only in instrumental reconstructions and reanalysis, but also in historical and future CMIP5 model simulations.

1 Introduction

The El Niño–Southern Oscillation (ENSO) is a coupled ocean–atmosphere phenomenon that occurs in the tropical Pacific Ocean. The term El Niño specifically refers to the warm phase of ENSO and is associated with a pattern of warm sea surface temperature anomalies (SSTa) that recurs approximately every 2–7 years along the equator in the Pacific Ocean, while the term Southern Oscillation refers to the associated sea level pressure (SLP) difference between the eastern and western tropical Pacific (Bjerknes et al. 1969; McPhaden 2006). Conversely, El Niño's cold phase companion, La Niña, is a pattern of cool sea surface temperature anomaly. However, debate persists about whether La Niña dynamics warrant defining cold phase conditions as a novel event, or rather an intensified expression of the tropical Pacific mean state (Kug and Ham 2011). The unique character of atmospheric and oceanic dynamics presented specifically by El Niño may account for the large amount of research dedicated to the ENSO warm phase as compared to its sister, La Niña. This study unfortunately contributes to the asymmetry between El Niño and La Niña research by focusing on El Niño spatial pattern diversity.

While there is high consensus on this general qualitative definition of El Niño described above, quantitative definitions of El Niño vary greatly. The term El Niño originally referred to annual warm ocean currents along Peru and

This paper is a contribution to the special collection on ENSO Diversity. The special collection aims at improving understanding of the origin, evolution, and impacts of ENSO events that differ in amplitude and spatial patterns, in both observational and modeling contexts, and in the current as well as future climate scenarios. This special collection is coordinated by Antonietta Capotondi, Eric Guilyardi, Ben Kirtman and Sang-Wook Yeh.

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Ecuador, and only later was associated with large tropical Pacific warming events. Every couple of years, the coastal upwelling of cold nutrient-rich water from the deep ocean would cease, decreasing biological productivity and spelling disaster for local fishing industries. Since this phenomenon usually occurred around Christmas-time, it was termed "El Niño", the Spanish phrase for Christ Child. Given the cultural ad hoc origins of El Niño, there is little guidance as how to technically define El Niño. It is easy to spout that El Niño is a phenomenon of warm SST in the tropical Pacific coupled with weakened trade winds. But exactly how warm must the SST anomaly be in order to be considered an El Niño "event" (Trenberth 1997)? Is there a specific region in which the warming must take place in order to be considered an El Niño (Ashok et al. 2007)? What base period should be used to define SST anomalies practically for both historical and future El Niño events (Wolter and Timlin 1998; Ray and Giese 2012); i.e. how will we contextualize ENSO's natural variability with global warming? While El Niño events typically occur in boreal winter due to atmospheric seasonal locking mechanisms, do El Niño-like patterns that occur in boreal summer count as El Niño events (Tziperman et al. 1994; An and Wang 2001)?

Trenberth (1997) provides a comprehensive and thorough review of the history and evolution of how we have qualitatively and quantitatively defined El Niño since 1950. Though in the 20 years since Trenberth's "The Definition of El Niño" was published, unique events have continued to challenge where, when, and how to draw the lines around El Niño. As a result, there are numerous coexisting indices such as Niño 1 + 2, Niño 3, Niño 3.4, Niño 4, and the Oceanic Niño Index (ONI) that all correspond to different regions in the tropical Pacific (Fig. 1), except for ONI which has the exact same region as Niño 3.4. According to the National Oceanic and Atmospheric Administration (NOAA), an anomaly with respect to the 1971–2000 base period exceeding a threshold between + 0.4–0.5 °C (dependent on the region, see Sect. 2.3) averaged over the given region and over 3 consecutive months (or 5 consecutive months in the case of ONI) is defined as an El Niño event according to that index.

Each index represents a slightly different priority or value in how to define El Niño, as diversity in El Niño SSTa pattern, timing, and strength manifests diverse impacts (Larkin and Harrison 2005; Zhang et al. 2013, 2015). For example, if we value defining El Niño with respect to impact on Peruvian and Ecuadorian fishing industry, Niño region 1 + 2 is the closest to the South American coast and is therefore a good predictor of biological productivity. Conversely, if we value defining El Niño with respect to socio-economic impacts linked to the Indian Monsoons, Niño regions 3, 3.4, and 4 might be better predictors of monsoon rainfall as ENSO dynamics over the tropical Pacific basin interact with monsoon dynamics (Wu et al. 2009). ONI is the operational definition used by NOAA as it is slightly more constrained given that it uses a 5-month, rather than 3-month, running mean. One of the most popular indices currently is Niño 3.4 as it overlaps with both Niño 3 and 4, partially including both the Eastern and Central Pacific.

Atmospheric teleconnections can be defined as changes in large scale atmospheric circulation that remotely affect temperature and rainfall patterns; and teleconnections linked with ENSO events pervasively perturb global temperature and precipitation patterns (Trenberth et al. 1998; Alexander et al. 2002). In addition to climatological impacts, ENSO has been shown to have persistent and at times devastating socio-economic impacts (Trenberth and Guillemot 1996; Barlow et al. 2001; McPhaden 2004; Hong et al. 2006; Kumar et al. 2006; Naylor et al. 2007; Karnauskas et al. 2008; Polhemus 2017). Even relatively weak El Niño events can trigger drought and food shortages particularly in India, Australia, Indo-Pacific islands, and the tropics (Rojas et al. 2014).

While ENSO is a frequently recurring phenomenon, its complex dynamics and high variability create difficulties in making accurate ENSO predictions and forecasts. Furthermore, it has been debated whether ENSO is a cycle or merely a random series of events (Kessler 2002), adding to the unpredictability of ENSO and making it difficult to establish dependable early warning systems (McPhaden 2015). Additionally, multiple kinds of ENSO "flavors" have come to light in the past three decades of ENSO research

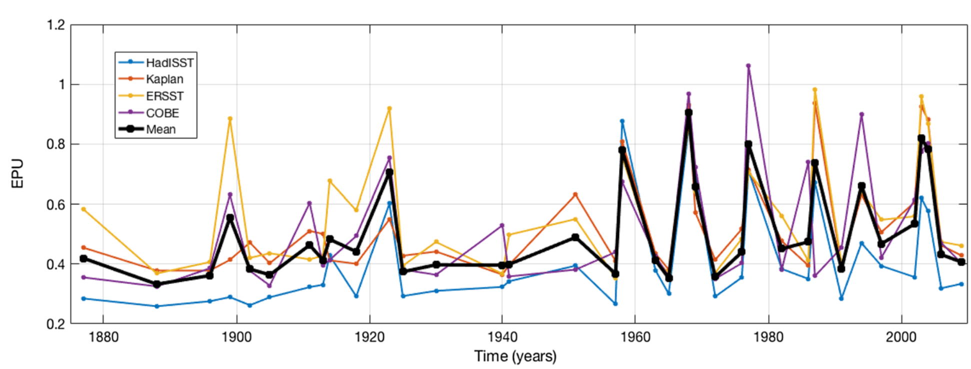

Fig. 1 A timeline of EPU indices for the four instrumental reconstructions: HadISST, Kaplan, ERSSTv4, and COBE2 with the mean between these reconstructions in black. Figure S2 shows this figure with SODA time series for comparison. EPU is defined in Sect. 2.1 of the text

and debate persists about whether there are distinct modes of ENSO variability (Larkin and Harrison 2005; Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009) or whether ENSO-related SST and SLP patterns and consequent teleconnections lie on a continuous spectrum (Trenberth and Stepaniak 2001; Takahashi et al. 2011; Karnauskas 2013; Capotondi et al. 2015; Giese and Ray 2011). This subfield of ENSO research is quickly being termed as "ENSO diversity" (Yu and Giese 2013; Capotondi et al. 2015), i.e. the study of differences in the nonlinear processes governing the genesis, evolution, amplitude and spatial SST pattern.

Most of this ENSO diversity research is focused on warm phase El Niño events, as El Niño events tend to show greater dynamical diversity and stronger, more robust teleconnections (Trenberth et al. 1998; Capotondi et al. 2015). In particular, much research effort has gone into understanding, naming, and contrasting two particular "flavors" of El Niño: central Pacific (CP) and eastern Pacific (EP) El Niño events, following terminology coined by Kao and Yu (2009). ENSO diversity literature frequently refers to EP El Niño events as "canonical" or "conventional", with similar SST and SLP patterns to the composite of a mature El Niño event asserted by Rasmusson and Carpenter (1982). In contrast, another name for CP El Niño is El Niño "Modoki", a Japanese term that means "similar but different".

The useful distinction between these particular flavors of ENSO arise from multiple studies that utilize error orthogonal functions (EOF) analysis to isolate inter-annual SSTa modes and their associated impacts (Dai and Wigley 2000; Ashok et al. 2007; Zhang et al. 2014, 2015). As shown in Larkin and Harrison (2005), the impacts linked with these types are statistically significant. However, the associated impacts connected to these modes are highly variable. In a United Nations Food and Agricultural Organization report, Rojas et al. (2014) shows global agricultural impacts of individual El Niño events using an agricultural stress index; these impacts are direct functions of precipitation and temperature teleconnections linked with ENSO. In this report, a comparison between the EP type 86–87 and 97–98 events that are similar in SSTa pattern show large differences in agricultural impact, particularly in India. Further comparison between weak CP type 02–03 and 04–05 events that have similar SSTa pattern and amplitude also show impact discrepancies, particularly in the United States and Australia. While agricultural systems are clearly subject to much socio-economic variance they are still sensitive to ENSO signals (Cane et al. 1994), and these comparisons illustrate that unique events exist in both CP and EP types. Furthermore, impacts are not always consistent with modal conclusions drawn from EOF analysis.

CP El Niño events are hypothesized as the unique type of El Niño that has increased in frequency over the last three decades (Lee and McPhaden 2010) and will continue to increase in frequency as a result of anthropogenic forcing (Yeh et al. 2009). The question remains however whether CP El Niño events are truly unique, or whether increased observational ability to detect weak warming in the central Pacific, a region that famously has sparse in situ observations prior to the satellite era, has recently revealed this kind of ENSO variability as discussed by Giese and Ray (2011). Moreover, has there been a physical increase in "unique" CP El Niño events? Using the Simple Ocean Data Assimilation model data set and the Center of Heat Index (CHI), a metric that measures the amplitude and longitude of the first moment of heat of an event, Ray and Giese (2012) argue that we have not observed a sufficient number of events to establish a trend, and that weak CP-like events are present at the beginning of the twentieth century using this model indicating that centennial-scale variability may be at play. However, if there is a trend in ENSO diversity as Yeh et al. (2009) and Zhang et al. (2010) argue, then what dynamical processes are driving this increase in diversity, and are these dynamical processes linked to a Pacific climate shift or global warming (Cane et al. 1997; Zhang et al. 2010; Capotondi et al. 2017; Li et al. 2017)? Finally, are "conventional" EP El Niño events similar to each other as canon might imply, or can they exhibit unique features between individual events?

ENSO event intensity (i.e., the amplitude of the maximum SSTa at the peak of the event) has previously been studied as having a large impact on teleconnections (Müller and Roeckner 2008; Stevenson 2012). Existing warning systems take great care to communicate signs that an intense El Niño event may be coming (McPhaden 2015). However, Rojas et al., 2014 points out that there are strong El Niño events (91–92, 97–98) that produce little impact on global food security while some weak to moderate El Niño events (02–03, 04–05, 06–07) have major impacts on the agricultural sector. Thus, understanding ENSO and subsequently ENSO diversity are of paramount importance in increasing predictive forecast skill and therefore preparing affected nations for ENSO-related socio-economic impacts. Moreover, recognizing unique El Niño events may prevent particular El Niño events from being classified by inadequate schemes with overly simplified or nonstationary regional teleconnection patterns associated with them. Because El Niño spatial pattern diversity surely affects atmospheric teleconnections and ENSO-related climate variability, a framework for quantifying uniqueness of an individual event and diversity of a set of events is critically needed and is presented here.

The remainder of the article is organized as follows. Section 2 details the instrumental and model data sets that are included in this study, justifies El Niño event selection methods, describes the framework used for measuring El Niño pattern uniqueness and diversity, and clarifies sea surface temperature anomaly (SSTa) calculation methods. Section 3 explains four primary results: (1) the difference between unique and non-unique El Niño events in all instrumental and model data sets point to a cooling mode mechanism in the eastern tropical Pacific that appears to drive diversity; (2) we compare unique CP-like El Niño events to non-unique EP-like events, but emphasize that there is no evidence for strict bimodal positionality (CP v EP) with respect to El Niño pattern diversity, supporting earlier work by Giese and Ray (2011) which illustrated a normal rather than bi-modal distribution of the longitudinal Center of Heat Index (CHI) in the central-eastern Pacific; (3) on average, historical model simulations aptly capture observed El Niño pattern diversity, but there is much disagreement between simulations; and (4) there is no statistical difference between El Niño pattern diversity in historical vs. future model scenarios. Section 4 discusses the constraints and the strengths of using EPU and EPD methodology and outlines the potential for future work within the spatial diversity framework based on the summarized results presented here.

2 Data and methods

2.1 Instrumental data sets

The focus of this study is constrained to the warm phase of ENSO, El Niño, specifically boreal winter El Niño. While the methods described here can in theory be applied to La Niña spatial SSTa patterns, La Niña events show subtler, smaller differences between spatial patterns (Kug and Ham 2011; Capotondi et al. 2015). Thus, results of this methodology on cold La Niña episodes of ENSO are not robust. Below, we quantitatively describe a spatial pattern diversity framing involving two related indices, El Niño pattern uniqueness (EPU) and El Niño pattern diversity (EPD). This methodology is applied to four instrumental reconstructions HadISST (Rayner 2003), Kaplan (1998), NOAA ERSSTv4 (Huang et al. 2014), and COBE2 (Hirahara 2014), the SODA v2.2.4 reanalysis data set (Carton and Giese 2008), in addition to historical, RCP 4.5, and RCP 8.5 Coupled Model Intercomparison Project Phase 5 (CMIP5) scenarios (Taylor et al. 2012). While instrumental reconstruction data is available for various time periods, we choose the common time period 1870–2016 to make useful comparisons between reconstructions. The SODA data set spans 1871–2010 (a similar but shorter time period than the instrumental reconstructions), while the historical and future model simulations are truncated to span 1860–2005 and 2006–2099 respectively. All fields are interpolated to a common $1^\circ \times 1^\circ$ grid resolution. Results are relatively insensitive to interpolation if the native grid resolution is not significantly coarser than the common interpolated grid (not shown). Furthermore, we discuss an inclusive method of El Niño event selection and compare with other El Niño event selection indices such as Niño3, Niño3.4, and Niño4.

2.2 El Niño pattern uniqueness (EPU) and diversity (EPD)

For a given set of time-varying SST fields, EPU of a single event and EPD for all events in the period of analysis are calculated using the average spatial correlation in tropical Pacific between a single El Niño event and all other El Niño events. EPU represents how unique a certain event is compared to others within the same data set. EPD, the average EPU over the period of analysis, measures the amount of unique (or conforming) events, and thus signifies diversity in a data set. After event selection, EPU of the ith El Niño event in a given set of n events is defined:

$$EPU(i) = 1 - \frac{\sum_{k=1}^{n} corr\left[SSTa_i(lon, lat), SSTa_k(lon, lat)\right]}{n-1} \quad for\ k \neq i$$

In this study, EPU is calculated for SSTa patterns between 160°E–80°W longitude and 5°S–5°N latitude. This region is chosen to be inclusive of the many different "flavors", or patterns, of El Niño as the region zonally covers all other canonical Niño indices. The constraint that $k \neq i$ precludes the redundancy in correlating an El Niño event with itself. Simply, EPU of a single event is one minus the average spatial correlation of that event with all other events for a given time period and specific data set. A high EPU for an individual event indicates SSTa pattern uniqueness, whereas a low EPU indicates a close resemblance to other events in the set. Because spatial correlation ranges from − 1 to 1, EPU and EPD can range from 0 to 2. EPD is the average EPU over the entire set of event. For a given set of n events, EPD is defined:

$$EPD = \frac{\sum_{i=1}^{n} EPU(i)}{n}$$

A high EPD for a given set of events indicates that the set contains many unique spatial SSTa patterns, whereas a low EPD indicates a trend of conformity between events. EPU and EPD are both highly sensitive to the period of analysis and the event selection method. It is useful to make the distinction that EPD is not simply average EPU, as EPU can be averaged over any subset of the period of analysis. In other words, mean EPU of a subset period (not the period of analysis) is not equal to EPD of a period of analysis that matches the subset period. By maintaining this distinction, we are able to analyze diversity within the broader context of the period of analysis.

2.3 SST anomaly calculation

El Niño conditions typically peak in boreal winter, (Kao 2009) and while boreal winter is often defined as December–January–February (DJF), the seasonal peak in El Niño intensities by most ENSO metrics such as Niño 3, Niño 3.4, Niño 4, and the modified Nino Infinity (NI) index (Karnauskas 2013) is better captured by the November–December–January (NDJ) time window (Neelin 2000). Thus, we calculate NDJ SSTa using a sliding 10-year base climatological state that ignores direct effects of low-frequency variability from decadal to long-term trends associated with global warming, similar to the 11-year sliding climatology method used in Giese and Ray (2011). Calculating SSTa using a 10-year sliding mean state is particularly practical for selecting and analyzing El Niño events in future model simulations because, for example, global warming may increase the temperature of the background state; though we are interested in understanding strictly interannual ENSO variability with respect to a base state subject to multiple sources of non-ENSO related low frequency variability. The 10-year sliding mean state is quasi-centered and includes 5 years prior, 4 years following, and the year for which the anomaly is calculated. While results for historical data or model simulations are relatively insensitive to whether the anomaly is calculated based on a sliding or fixed climatology, it is more appropriate to use a sliding climatology for the future simulations due to the significantly trending background state in response to anthropogenic radiative forcing.

2.4 El Niño event selection

El Niño events are selected using a modified Niño Infinity (mNI) index, adapted from Karnauskas (2013). mNI for this study is defined as the area-mean warm anomaly between 3°S–3°N and between 160°E–80°W. Cold anomalies are set to zero and the area average is taken over all grid points. This contrasts with the Karnauskas (2013) method of averaging over only warm grid points, but results for the instrumental data sets are insensitive with respect to this difference. The Karnauskas (2013) Niño Infinity index is calculated for the region 120°E–80°W and 1°S–1°N, which is a thin line along the equator in the tropical Pacific. Also in contrast with the original NI index, mNI excludes the Indonesian warm pool, widens the latitudinal scope along the equator, and is applied to seasonal rather than weekly timescales.

Years for which the normalized mNI index is above 0 for all four instrumental data sets HadISST, Kaplan, ERSSTv4, and COBE2 are chosen as El Niño events (Figure S1). This caveat for El Niño event selection within the instrumental data sets accounts for differences in data reconstruction; the same caveat is not necessary for model data sets that do not struggle with spatial data coverage. The selected El Niño events on which the instrumental reconstructions agree are used to analyze SODA (EPU time series Figure S2a) and create SSTa composites (Fig. 5). EPD and EPU calculated using SODA are sensitive to whether SODA is forced to agree with the instrumental data sets (Figure S2), but the unique and non-unique SST composite maps in Fig. 5 are insensitive to this difference. For indexing purposes, the labeled year corresponds to November of the event, thus the index corresponding to 1986 corresponds to the 1986–1987 event.

The advantages of using this index over other more traditional indices to select El Niño events are an insensitivity to El Niño event positionality as well as an inclusive definition of El Niño that has collective overlap with other Niño indices (Table 1). Because there is no discrimination between warming in the central vs. eastern Pacific, there is no a priori assumption of modality with regards to event selection. Furthermore, as can be verified in Table 1, event selection by the mNI index is comprehensive with respect to the other canonical Niño indices. Event selection using Niño 3, Niño 3.4, and Niño 4 indices is approximated by average NDJ anomaly for their respective regions (see Trenberth 1997) using the SST anomaly calculation method discussed above. NDJ Niño indices that exceed 0.5, 0.4, and 0.4 °C respectively are selected as El Niño events shown in Table 1.

The only El Niño event not captured by mNI is 1953–1954 which is captured by Niño 3.4. Conversely, 2003–2004 and 1968–1969 are considered events using the mNI index, but not by the other metrics. The El Niño event of 2009–2010 is the last selected event because the anomaly calculation method requires lead time to calculate a sea surface temperature anomaly map, thus mNI was not contemporarily available beyond 2013.

3 Results

Within the instrumental reconstructions, there appear to be two clear regimes separated at ~ 1958 with more variable as well as higher overall values of EPU beginning with the 1958–1959 El Niño event (Fig. 1). While the SODA time period is slightly shorter than the reconstructive record, a SODA EPU time series is over-lain on Figure S2 for comparison. Figure S2 shows the SODA EPU time series over-lain onto Fig. 1; both for when SODA is forced to have the same event selection as the reconstructions and for when it is allowed event selection independent of the instrumental reconstructions (as discussed in Sect. 2). When SODA is forced to have the same El Niño events as the instrumental reconstructions, the same regime shift is observed, but when SODA is allowed independent event selection the same regime shift is not observed, consistent with results from Ray and Giese, 2012. An increase in both EPU variance

Table 1 Selected El Niño years by several NDJ Niño metrics compared with the modified Niño Infinity index (mNI)

mNI	Niño 3	Niño 3.4	Niño 4
El Niño years			
1877	1877	1877	1877
1888	1888	1888	1888
1896	1896	1896	1896
1899	1899		
1902	1902	1902	1902
1905	1905	1905	1905
1911	1911		
1913	1913	1913	
1914	1914	1914	1914
1918	1918	1918	
1923		1923	
1925	1925	1925	1925
1930	1930	1930	1930
1940		1940	1940
1941	1941	1941	1941
1951	1951	1951	1951
		1953	
1957	1957	1957	1957
1958		1958	1958
1963	1963	1963	
1965	1965	1965	
1968			
1969	1969	1969	1969
1972	1972	1972	1972
1976	1976	1976	
1977		1977	1977
1982	1982	1982	1982
1986		1986	1986
1987		1987	1987
1991	1991	1991	1991
1994		1994	1994
1997	1997	1997	1997
2002	2002	2002	2002
2003			
2004		2004	2004
2006	2006	2006	2006
2009	2009	2009	2009

Event selection using Niño 3, Niño 3.4, and Niño 4 approximated by NDJ SST averaged within the respective regions (see Trenberth et al. 1997) using the 10-year sliding anomaly calculation method outlined in Sect. 2.2. All instrumental reconstructions are conservatively forced to have the same event selection, mNI for all reconstructions must be above zero to be included as an El Niño event

as well as mean EPU is present after the 58–59 event in all instrumental reconstructions (Fig. 2). Though when these two periods are isolated for analysis, the statistically significant increase in EPD is observed (not shown).

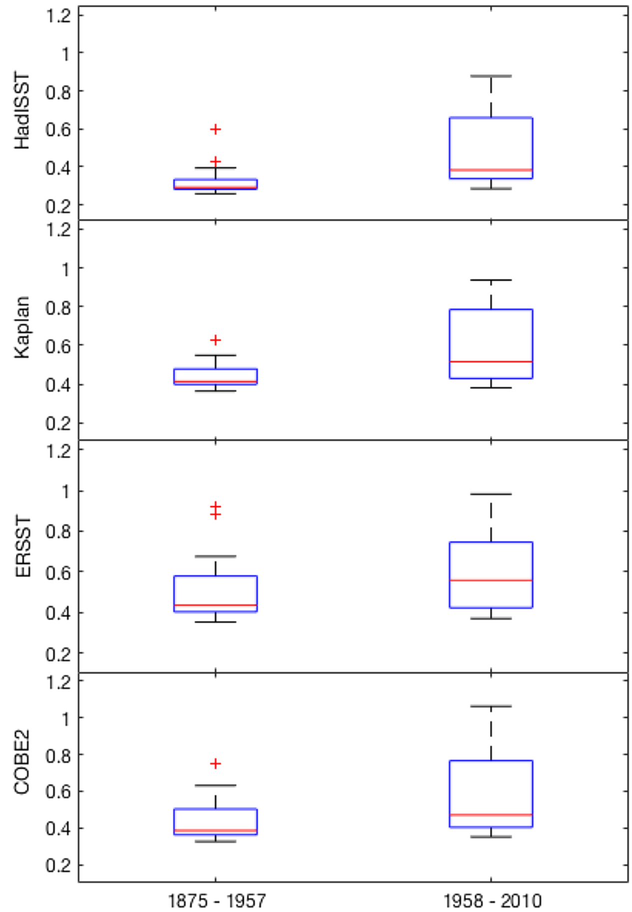

Fig. 2 Boxplots comparing EPU mean and variance between the time periods 1875–1957 and 1958–2010 for all instrumental reconstructions. All reconstructions show a regime shift in 1958 with overall higher EPU and EPU variance. Period of analysis is 1875–2016. The same regime shift is not seen in historical model simulations (not shown)

Figures 3 and 4 respectively show the six most unique and non-unique events from the average instrumental reconstruction EPU time series; these maps constitute the unique and non-unique composites in Fig. 5 (first column). Highly unique events as pictured in Fig. 3 tend to exhibit finer features and CP positionality. Thus, an analysis of El Niño diversity using the EPU and EPD indices independently confirms the assertion that there has been a recent increase in spatially diverse CP-like El Niño events that tend to peak near the international dateline, in agreement with analysis based on empirical orthogonal functions (EOF) (Ashok et al. 2007; Yeh et al. 2009; Lee and McPhaden 2010; Takahashi et al. 2011; Capotondi and Sardeshmukh 2017). Moreover, non-unique events as pictured in Fig. 4 appear spatially homogenous and conform well to the "canonical" picture of the El Niño mature phase laid out by Rasmusson and Carpenter (1982).

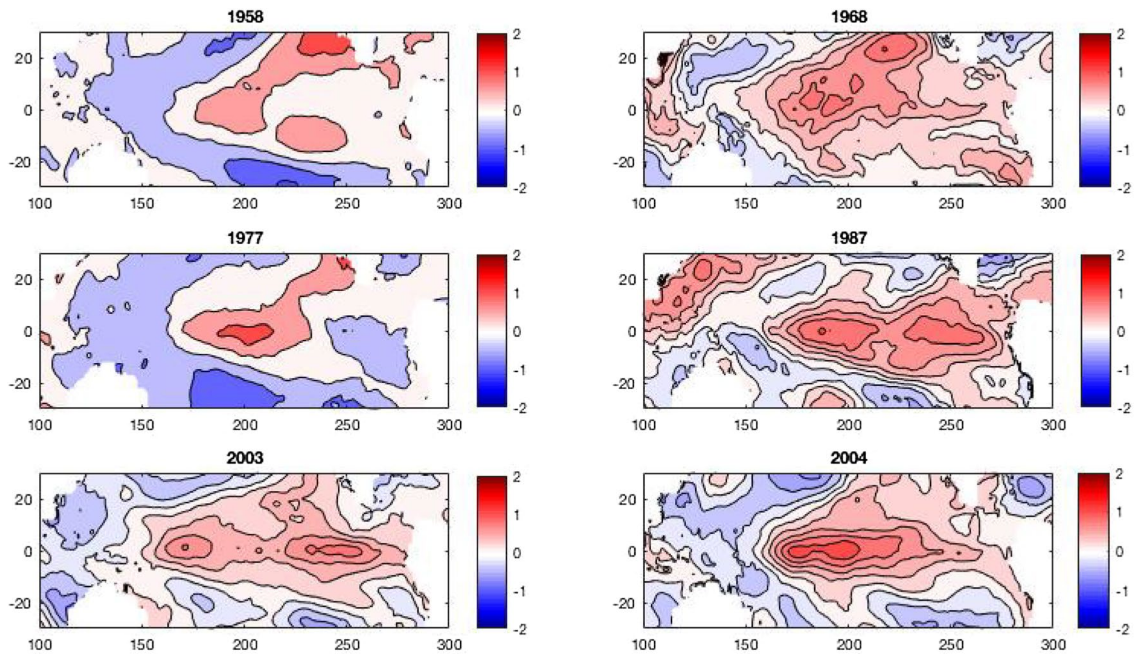

Fig. 3 The six most unique events as determined by mean EPU across instrumental reconstructions (thick black line in Fig. 1). These anomaly maps are averaged between instrumental reconstructions. Period of Analysis is 1875–2016. Four of the six most unique events exhibit fine features and are observed after the onset of the satellite era in the 1960s. All exhibit weak amplitude and positionality in the central Pacific

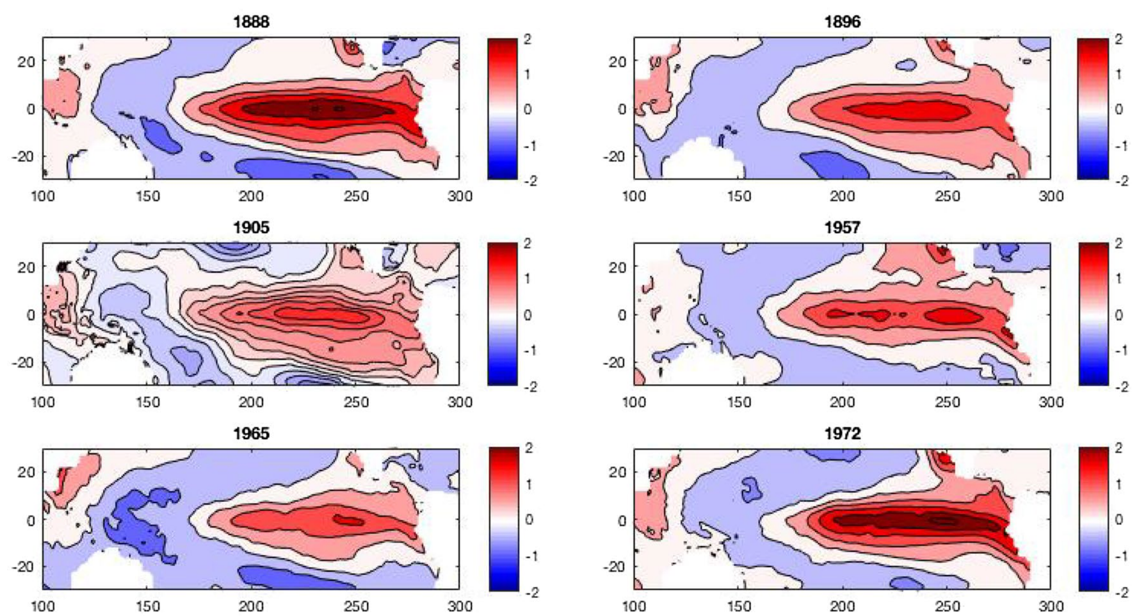

Fig. 4 The six least unique events as determined by mean EPU across instrumental reconstructions (thick black line in Fig. 1). These anomaly maps are averaged between instrumental reconstructions. Period of Analysis is 1875–2016. Four of the six least unique events are observed before the onset of the satellite era in the 1960s and all show strong amplitude and positionality in the eastern Pacific

A potentially troublesome issue with these results is the alignment of increasing EPU with increasing data coverage (Figure S5). Four out of the six most unique El Niño events occur during the satellite era and display fine features that appear to enhance their EPU. Conversely, all of the least unique Niño events in Fig. 4 appear before the development

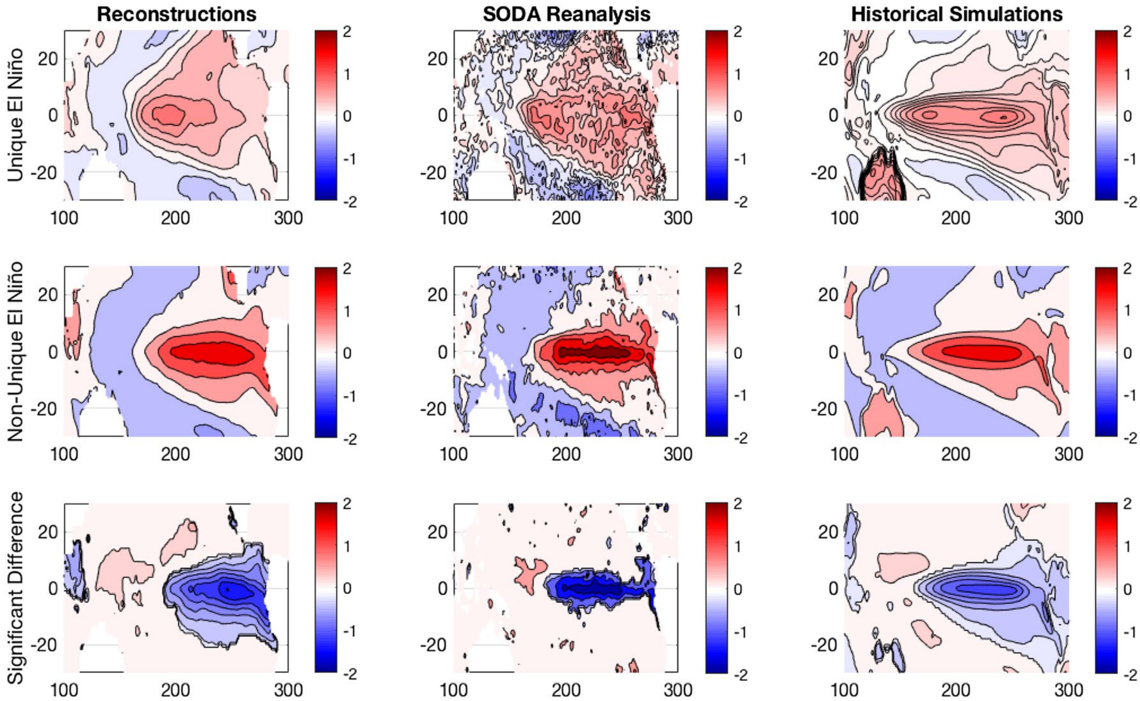

Fig. 5 Composites of the most unique (first row) and the least unique (second row) observed and historical simulated (historical CMIP5 model) El Niño events. The statistically significant difference between them (third row) is the unique composite minus the least unique composite, with significance determined by a 2-tailed student's *t* test, $\alpha = 0.05$. There are six events that constitute each composite for the instrumental reconstructions averaged over the reconstructions (first column), SODA reanalysis (second column); There are six events for each of the 47 historical models (third column) that constitute the unique and non-unique composites

of the Tropical Atmosphere Ocean (TAO) array, and four occur before the beginning of the satellite era in the 1960s and 1970s. Because there is much disagreement between historical CMIP5 models of ENSO diversity over the last century (discussed below) it is not possible to corroborate the shift in EPD and EPU variability using model simulations.

Regarding past conformity between events, instrumental reconstructions often estimate past SST fields by calculating orthogonal spatial patterns of variability using a time period of dense observations and projecting these patterns incorporating historical in situ data, potentially homogenizing between event patterns (Giese and Ray 2011; Ray and Giese 2012). Not only is historical ship track coverage in the central Pacific sparse (Rasmusson and Carpenter 1982), but it is difficult to obtain SST measurements along the equator in the Pacific using buoy-like instruments due to the mean poleward Ekman divergence in the region. Thus, historical detection of warm SST in the central Pacific might be more difficult than the detection of more intense warming in the eastern Pacific along the coast, possibly biasing reconstructive data towards the occurrence of EP events. Moreover, if EP events are considered "conventional", it is plausible that model data sets have been biased with EP events as well. This may account for why the composite of non-unique El Niño events from the instrumental reconstructive, reanalysis, and model data sets conforms to the "conventional" picture of El Niño.

We compare instrumental and model diversity over approximately the last century and a half (Fig. 5); unique and non-unique composites and the statistically significant difference (masked 95% significance) between them are shown for instrumental reconstructions, SODA reanalysis, and CMIP5 historical model simulations. Both instrumental records and model simulations indicate that non-unique El Niño events tend to be much stronger, peaking farther east along the equator while unique El Niño events tend to be weaker and peak in the central Pacific. While there are noticeable differences between the unique and non-unique composites, reconstruction, reanalysis, and historical models agree that the difference between a unique and a non-unique event is a cooling in the far eastern Pacific, a pattern that is remarkably similar to cooling observed by Cane (1997), to the second EOF pattern in Zhang et al. (2010, see Fig. 2), and to the third EOF pattern in Ashok et al. (2007) (see Fig. 3).

This pattern has recently been coined the Pacific tongue cooling mode or the cold tongue mode (CTM) (Zhang et al. 2010; Li et al. 2017), and represents the long-term change in the background state of the tropical Pacific (Ashok et al. 2007; Zhang et al. 2010). Zhang et al. and Li et al. postulate a link between the CTM and global warming, as the principal component of the CTM is well correlated with global average surface temperature (see Zhang et al. 2014 and references therein). Moreover, an analysis of the tropical Pacific heat budget in Li et al. (2015) and an EOF analysis in Li et al. (2017) provide a dynamical explanation for the link between the CTM and global warming by underscoring the importance of cooling by vertical advection of cold anomalous temperature. For example, consider an increased radiative forcing warming the ocean surface (global warming). The surface will warm but subsurface temperatures will initially remain unaffected. The subsurface temperature is then cooler relative to the surface, decreasing the vertical temperature gradient $\frac{\partial T'}{\partial z}$ (vertical axis downward). However, strong mean upwelling in the eastern Pacific cools the east relative to the western Pacific by way of vertical advection, $-w\frac{\partial T'}{\partial z}$, intensifying the CTM pattern under global warming (Li et al. 2017). The link between CTM and ENSO diversity is illustrated in Li et al. (2017) by showing how a positive CTM pattern weakens ocean–atmosphere coupling and Bjerknes feedback intensity, mechanisms that usually aid in forming high amplitude EP events (Bjerknes 1969; Karnauskas 2013). Results obtained using the EPU analysis presented here support this previous work that hypothesizes the importance of the CTM in affecting ENSO diversity. However, the null hypothesis of a causal link between the CTM and increased ENSO diversity should continue to be tested using model simulations.

It has been suggested that an increase in ENSO diversity may be due to global warming (Yeh et al. 2009; Lee and McPhaden 2010; Capotondi and Sardeshmukh 2017). While we observe regime shift in the instrumental reconstructions (Fig. 2) around 1958 that could be linked to global warming, this regime shift is not observed in historical model simulations (Figure S4). Furthermore, there is no statistical difference in EPD distribution between CMIP5 historical, RCP 4.5, and RCP 8.5 model scenarios, and thus no robust projection of a future change in ENSO diversity itself. However, the range of EPD within each model scenario is large indicating model disagreement about ENSO diversity over the last century (Fig. 7). As previously mentioned, disagreement in EPU variance and EPD between historical model simulations is demonstrated in Figure S3 and these vast differences between simulations are seen between future model simulations as well (not shown).

The unifying result between all data sets, both observed and simulated, historical and future, is the difference between unique and non-unique El Niño events. The eastern Pacific CTM is the difference in going from non-unique to unique events over the last century in the instrumental records. This is true not just in the instrumental records and historical model simulations, but also in future model simulations, although there are no regime shifts in simulated data. Furthermore, there is no CTM simulated in historical nor future CMIP5 data; i.e. there is no cooling in the east relative to the western tropical Pacific as there is in some observational data sets (Coats and Karnauskas 2017). This may further explain why there is no robust projection for El Niño pattern diversity in future simulations. Figure 6 is similar to Fig. 5 but features historical and future model scenarios (historical model composites are reproduced in this figure for easy comparison between models). The major difference between Figs. 5 and 6 is in the unique composites, that differs from non-unique composites less in spatial pattern and more in amplitude. The unique composites in future model scenarios are much more similar to the non-unique composites than in instrumental records and do not have clear CP positionality—again with considerable spread (Fig. 7).

While it is difficult to verify the validity of more homogenous diversity in the future, the commonality between composite differences (last row in both Figs. 5, 6) is strong evidence that a cooling mode plausibly drives El Niño diversity. Furthermore, there is still much debate over a causal relationship between global warming and the CTM (Zhang et al. 2010; Li et al. 2017), but if the CTM is driven by anthropogenic forcing this could have broad implications for ENSO diversity (Capotondi and Sardeshmukh 2017; Li et al. 2017).

Caution must be taken with the previous results as Figs. 5 and 6 compare between the extremes—the most unique and the least unique El Niño events. Examining the relationship between the longitude of maximum SSTa and EPU for instrumental reconstruction and model simulations (Fig. 8) reveals that the relationship is perhaps much more non-linear than Fig. 6 might suggest. The maximum anomaly is found using the 5°S–5°N meridional average. In the instrumental reconstructions for example (Fig. 8a), there exist events that peak in the central Pacific with low EPU and events that peak in the eastern Pacific with high EPU. The 2003–2004 event that peaks in the eastern tropical Pacific around 240°E and has a high EPU above 0.8 (top right corner of Fig. 8a) could justifiably be disregarded as not ENSO related. Considering this, many of the most unique El Niño events tend to peak in the central Pacific. Yet, it is not necessarily true that CP events are always unique nor that EP events are never measured as unique relative to CP events. This is also true in the relationship between EPU and longitude of maximum anomaly scatters for historical, RCP 4.5, and RCP 8.5 model scenarios (Fig. 8b–d). In light of these results, "conventional" El Niño events should not necessarily be synonymous with EP El Niño events. Furthermore, while there are two moderately grouped EPU "clusters" in the central and eastern Pacific, Fig. 8 does not support the concept of strict bimodality with respect to "flavors" of El Niño events.

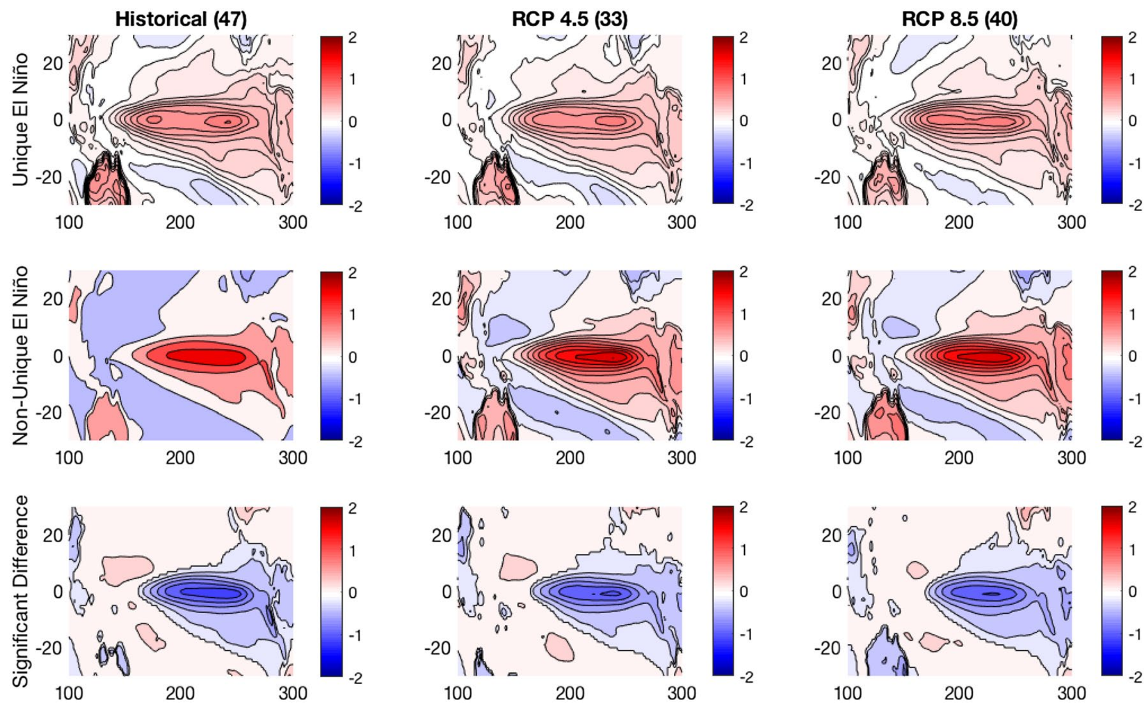

Fig. 6 As in Fig. 5, but for historical and future CMIP5 model scenarios. Composites of the most unique (first row) and the least unique (second row) historical and future simulated El Niño events. The historical composites are reproduced from Fig. 5 for easy comparison between model scenarios. The statistically significant difference between them (third row) is the unique composite minus the least unique composite, with significance determined by a 2-tailed student's t test, $\alpha = 0.05$. There are six events for each of the models with in each model scenario that constitute the composites. The number of models for each scenario is 47 historical (first column), 33 RCP 4.5 (second column), and 40 RCP 8.5 (third column) models. The composite is averaged over the number of models for each scenario

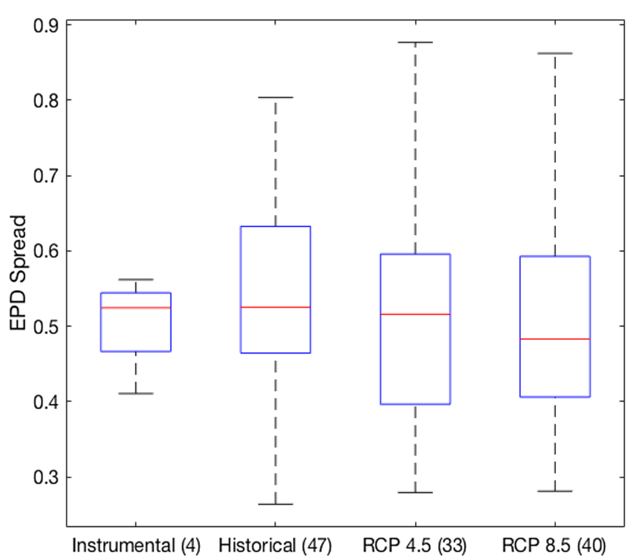

Fig. 7 Boxplots comparing EPD sample statistics within the different data set classifications. There are 4 instrumental reconstructions, 47 historical models, 33 RCP 4.5 models, and 40 RCP 8.5 models

4 Summary and conclusion

EPU time series over the last century for instrumental reconstructions data sets appear to be in rough qualitative agreement, though EPD (overall diversity) varies moderately between the various interpretations of instrumental data. The same qualitative agreement is not seen within historical CMIP5 model simulations, although qualitative agreement was not necessarily expected. However, overall diversity statistics (EPD and EPU variance) vary wildly making it difficult to compare a model EPU time series with the observed EPU time series. This can be seen in Fig. 7, showing EPD distribution between instrumental reconstructions and model scenarios and in Figure S3 that show examples of different historical model EPU time series using three selected models that underestimate, closely resemble, or overestimate observed EPD. Although EPD and EPU variance are seemingly incommensurable between historical model simulations, composites of the six most unique and the six most non-unique El Niño events from each model averaged over all historical models show markedly similar results to composites of the six most unique and the six least unique El Niño events using reconstruction and reanalysis

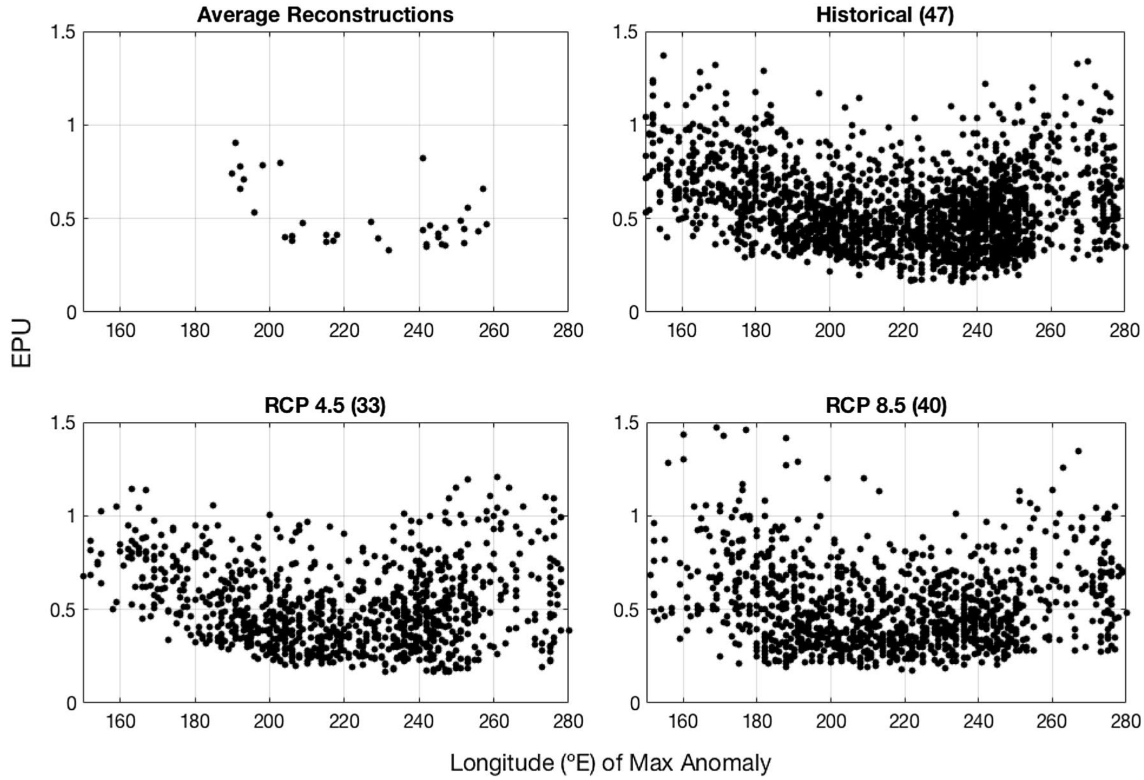

Fig. 8 Scatter plot of EPU vs. longitude of maximum anomaly (meridional average from 5°S–5°N) for **a** instrumental reconstructive average, **b** 47 historical model simulations, **c** 33 RCP 4.5 model simulations, and **d** 40 RCP 8.5 model simulations. All data sets display a non-linear relationship between spatial pattern uniqueness and El Niño event positionality

data (Fig. 5). Hence, while this methodology may not deliver an absolute metric, it is extremely useful as a relative metric that finds the most unique and non-unique El Niño events within a given data set, and comparisons between these SSTs fields are commensurate. Between instrumental reconstructions, reanalysis, and historical model simulations, there is great agreement on what general SST patterns constitutes a unique El Niño, a non-unique El Niño event, and the significant difference between them.

EPU and EPD are novel indices that measure the uniqueness of a single event and diversity of a set of events. The mathematical principles of EPU and EPD are simple, and this analysis can be easily replicated and applied to other sample measurements (like CO_2 flux, SLP, precipitation, etc.) to test for uniqueness. By using this framework, we independently confirm an increase in El Niño spatial pattern diversity beginning in the 1960s and argue a link between this increase in El Niño diversity and the background cooling mode in the eastern tropical Pacific. However, we can neither confirm nor deny whether this rise in diversity is physical or an artifact of poor data coverage prior to 1960. Given the wide spread of EPD in historical CMIP5 model simulations, models cannot yet be used to answer this pressing question within this framework. Furthermore, the lack of a simulated CTM in CMIP5 simulations complicates meaningful comparison between models and instrumental reconstructions. While the timing and physicality of EPU and EPD in instrumental reconstructions is uncertain, it is clear that we can no longer accept the false demarcation between EP El Niño events as exclusively "conventional" or CP El Niño events as exclusively unique. Moreover, strict El Niño bimodality is not supported within the EPU metric.

Further work will attempt to corroborate the regime shift in diversity with historical precipitation and temperature records. Additionally, we will simulate instrumental EPU and EPD using a multivariate regression composed of other climatological parameters such as sea surface height, wind stress, etc. to determine possible dynamical factors giving rise to ENSO diversity. Moreover, it will be important to contextualize EPU and EPD regimes with other decadal oscillations, such as the Pacific Decadal Oscillation and the Indian Ocean Dipole, to understand how such oscillations are diverse themselves and/or modulate ENSO diversity.

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