Stronger Increase in the Frequency of Extreme Convective than Extreme Warm El Niño Events under Greenhouse Warming

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ABSTRACT

Since 1979, three extreme El Niño events occurred, in 1982/83, 1997/98, and 2015/16, with pronounced impacts that disrupted global weather patterns, agriculture, fisheries, and ecosystems. Although all three episodes are referred to as strong equatorial eastern Pacific (EP) El Niño events, the 2015/16 event is considered a mixed regime of both EP and central Pacific (CP) El Niño. During such extreme events, sea surface temperature (SST) anomalies peak over the EP region, hereafter referred to as an extreme warm El Niño (ExtWarmEN) event. Simultaneously, the intertropical convergence zone (ITCZ) moves southward to the usually dry and cold Niño-3 region, resulting in dramatic rainfall increases to more than 5 mm day^{-1} averaged over boreal winter, referred to as an extreme convective El Niño (ExtConEN) event. However, in climate models from phase 5 of the Coupled Model Intercomparison Project (CMIP5) that are able to simulate both types of events, ExtConEN events are found not to always coincide with ExtWarmEN events and the disassociation becomes more distinct under greenhouse warming when the increased frequency of ExtConEN events is notably larger than that of ExtWarmEN events. The disassociation highlights the role of eastward migration of western Pacific convection and equatorward shift of the South Pacific convergence zone associated with the faster warming over the EP region as a result of greenhouse warming.

1. Introduction

Earth's interannual climate variability is prominently modulated by El Niño–Southern Oscillation (ENSO), alternating between a warm El Niño phase and a cold La Niña phase (e.g., McPhaden et al. 2006). During a typical El Niño event, the eastern equatorial Pacific Ocean, which is normally dry and cold, warms as a result of a deepening thermocline in the east. By weakening the west–east tilt in thermocline along the equatorial Pacific Ocean, it reduces the sea surface temperature contrast between the western and eastern Pacific Ocean. The associated change in sea level pressure gradient slows down the prevalent easterlies and weakens the Walker circulation. As a result, atmospheric convergence and the associated ascendant air motion move eastward (Cane 2005; McPhaden et al. 2006;

McPhaden and Zhang 2009). Such changes in oceanic and atmospheric circulation can generate impactful weather events around the globe (Aronson et al. 2000; Bell et al. 1999; Glynn and de Weerd 1991; McPhaden et al. 2006; Merlen 1984; Philander 1983; Santoso et al. 2017, 2019; Vincent et al. 2011; Vos et al. 1999).

During extreme events, such as those of 1982/83, 1997/98, and 2015/16, the reorganization of air–sea circulations is more intense (Cai et al. 2014, 2015, 2017, 2018). It includes migration of the convergence zone from the west to the east (Philander 1990; Power and Smith 2007; Santoso et al. 2013), shifts of the ITCZ southward to the equator (Power et al. 2013; Cai et al. 2014, 2015, 2017), and swings of the South Pacific convergence zone (SPCZ) to a more zonal alignment and closer to the equator (Vincent et al. 2011; Cai et al. 2012). Therefore, it can induce more severe disruption of global weather patterns, for example, catastrophic floods over Ecuador and Peru (Philander 1983;

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Vos et al. 1999), and spur natural disasters, for example, a wide range of coral bleaching in the Pacific and beyond (Glynn and de Weerd 1991; Aronson et al. 2000).

As global warming induced by human activities has been significantly changing the climate mean state, it causes widespread concern among the public about the rising risks associated with extreme El Niño events under climate change (Cai et al. 2014, 2015, 2017, 2018). Given that observations are short, coupled climate model simulations offer an effective way to evaluate global warming influences on climate by eliminating internal variabilities through a multimodel ensemble approach (Cai et al. 2017; Wang et al. 2017). The multimodel mean projects a faster warming over eastern tropical Pacific Ocean characterized by an eastward shift of the Walker circulation (e.g., Bayr et al. 2014). Although the current versions of the models have many common biases in the simulated mean state compared to observations, such as the cold tongue bias (Wittenberg et al. 2006; Ham and Kug 2012; Bellenger et al. 2014; Bayr et al. 2018; Timmermann et al. 2018), double ITCZ over the tropical Pacific Ocean (e.g., Hwang and Frierson 2013; Li and Xie 2014), and zonal SPCZ bias (e.g., Niznik and Lintner 2015), there is no compelling evidence thus far indicating that these common biases have a systematic impact on projected occurrences of extreme El Niño events.

To evaluate projected influences of global warming on ENSO properties, the conventional approach (e.g., Collins et al. 2010; Taschetto et al. 2014) was to utilize SST anomalies at fixed-point locations such as the commonly used Niño-3 region (5°S – 5°N , 150° – 90°W). No intermodel consensus was found in changes of variability of the ENSO SST indices under a high- CO_2 emission scenario by using all available models participating in CMIP3 and CMIP5 (Collins et al. 2010; Taschetto et al. 2014). This approach therefore leads to no consensus on projections of changes in strong El Niño frequency. As the Niño-3 region is the prevalent center for eastern Pacific (EP) El Niño events in observations (Kug et al. 2009; Kao and Yu 2009; Takahashi et al. 2011; Dommenges et al. 2013; Takahashi and Dewitte 2016; Capotondi et al. 2015; Santoso et al. 2017), the cause behind failure in reaching a consensus on future changes by using Niño-3 SST has been debated (Watanabe et al. 2012).

Unlike SST variability, the response of rainfall to SST anomalies is projected to increase as a result of global warming-induced mean-state change (Watanabe et al. 2012; Chung et al. 2014; Power et al. 2013). By recognizing the nonlinear relationship between rainfall and a north-equator-minus-equator meridional temperature gradient over the eastern equatorial Pacific Ocean, Cai et al. (2014) defined an extreme El Niño event as when Niño-3 rainfall is greater than 5 mm day^{-1} averaged over

the December–February (DJF) season. This alternative definition captures all the three recent extreme events that are characterized by a southward shift of the ITCZ to the equator. Due to the faster warming over the eastern equatorial Pacific Ocean under climate change (Xie et al. 2010; Tokinaga et al. 2012), Cai et al. (2014) found that the ITCZ is projected to shift southward more frequently. Therefore, more extreme El Niño events are expected.

Despite the strong consensus in changes of Niño-3 rainfall variability under greenhouse warming, the lack of consensus in terms of El Niño SST variability continued to unsettle climatologists and modelers (e.g., Santoso et al. 2019). Until recently, Cai et al. (2018) highlight that different models simulate different centers for the EP El Niño regime that are not necessarily located at the center of the Niño-3 region. Following the method proposed by Dommenges et al. (2013) and Takahashi and Dewitte (2016), Cai et al. (2018) used an E index (see section 2b) to represent SST variability over the EP region, finding that SST variability is projected to increase at each model's unique EP center, particularly in models with better simulation of ENSO nonlinearity. As such, strong EP El Niño events defined by SST variability (see section 2b) are projected to increase with a high intermodel consensus. In the more realistic subset of models, the EP El Niño center tends to be confined in the Niño-3 region, thus a relatively high intermodel consensus is also obtained using the Niño-3 index (Cai et al. 2018).

The consensus in projected changes of rainfall and SST variability under greenhouse warming leads to a situation where it is necessary to reconcile the two different definitions of extreme El Niño events (see sections 2b and 2c). For convenience, we hereafter refer to the definition of extreme El Niño using rainfall as an *extreme convective El Niño (ExtConEN) event*, with the other definition using SST as an *extreme warm El Niño (ExtWarmEN) event*. Here we aim to examine and clarify the link between ExtConEN and ExtWarmEN and how global warming may influence this relationship. Section 2 describes data and methods used. Section 3 examines observed extreme El Niño characteristics using the two extreme definitions. Section 4 compares the simulated extreme El Niño events using the two definitions. Section 5 focuses on the increase in independent ExtConEN events and investigates the mechanisms. A summary is given in section 6.

2. Data and methods

a. Observations

To illustrate observed characteristics associated with ExtWarmEN and ExtConEN, we use monthly SST from

Hadley Centre Sea Ice and Sea Surface Temperature dataset, version 1.1 (HadISST v1.1; [Rayner et al. 2003](#)); atmospheric surface temperature and surface wind stress from the National Center for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) Global Reanalysis 1 ([Kistler et al. 2001](#)) and rainfall from the version 2 of the Global Precipitation Climatology Project (GPCP; [Adler et al. 2003](#)) monthly precipitation analysis. Here we focus on period after 1979 (to 2016) when the satellite era begins.

b. Definition of extreme warm El Niño event

Based on the method of [Dommenges et al. \(2013\)](#), [Takahashi and Dewitte \(2016\)](#), and [Cai et al. \(2018\)](#), we define ExtWarmEN via empirical orthogonal function (EOF) analysis of monthly SST anomalies over an equatorial domain (15°S – 15°N , 140°E – 80°W). For observation, the monthly SST anomalies are referenced to the long-term mean and quadratically detrended; for CMIP5 models, monthly anomalies are referenced to the climatology of the first 100 years and then quadratically detrended. Central Pacific (CP) ENSO and EP ENSO regimes are then identified using the first two principal components (PC) time series such that their temporal variability can be described by a C index $[(\text{PC1} + \text{PC2})/\sqrt{2}]$ and E index $[(\text{PC1} - \text{PC2})/\sqrt{2}]$, respectively. PC1 and PC2 are both normalized. In this study, we use 17 models selected from the CMIP5 database ([Taylor et al. 2012](#)), based on their ability to simulate a reasonable degree of nonlinearity between PC1 and PC2 compared with observations ([Cai et al. 2018](#)). We define an ExtWarmEN as when the E index averaged over the DJF season is greater than 1.5 standard deviations (s.d.) ([Cai et al. 2018](#)). We have tested that using different threshold values (e.g., 1.25, 1.75) does not affect our results.

c. Definition of extreme convective El Niño event and model selection

ExtConEN event is defined as when Niño-3 rainfall averaged over the DJF season exceeds a threshold of 5 mm day^{-1} ([Cai et al. 2014](#)). There are two model selection criteria. One is that a model must be able to generate at least one extreme convective El Niño event, and the other is that the simulated rainfall skewness over Niño-3 region must be greater than one as observed. This restriction removes most of the dry models with serious cold tongue bias (figures not shown). Almost all events that exceed 5 mm day^{-1} in Niño-3 rainfall also correspond with a negative vertical velocity averaged over heights above 500 hPa in the CMIP5 models ([Cai et al. 2017](#)), indicating the occurrence of deep convection in the eastern equatorial Pacific Ocean. It has also

been shown that the projected increase in ExtConEN is due to not only the increase in the mean climatological rainfall but also the increased probability of deep convection as a result of mean-state change ([Cai et al. 2017](#)). Among the 17 selected models, only two could not generate ExtConEN ([Cai et al. 2014](#)). Therefore, 15 out of the 17 were utilized based on their ability to generate both ExtWarmEN and ExtConEN. Those models are BCC_CSM1.1(m), CCSM4, CESM1(BGC), CESM1(CAM5), CMCC-CESM, CMCC-CM, CMCC-CMS, CNRM-CM5, FGOALS-s2, GFDL CM3, GFDL-ESM2M, GISS-E2-H, IPSL-CM5B-LR, MIROC5, and MRI-CGCM3. Where multiple realizations may apply for one model, we only use the first to ensure that all models are equally represented. We use monthly SST, rainfall, and zonal surface wind stress from 1900 to 2099, under historical forcing and a high- CO_2 emission scenario (representative concentration pathway 8.5). We compare the occurrences of ExtWarmEN and ExtConEN between two different periods, 1900–99 as control/historical period, and 2000–99 as climate change period. In [section 4](#) we further classify the events to facilitate our analysis.

d. Diagnosis of nonlinear Bjerknes feedback

During El Niño development, a westerly wind anomaly over the western to central tropical Pacific Ocean drives a downwelling Kelvin wave that deepens the thermocline over the eastern tropical Pacific Ocean, leading to a surface warming. This surface warming then decreases the east–west temperature contrast, in turn strengthening the westerly wind anomalies, and this positive feedback process, termed the Bjerknes feedback ([Bjerknes 1969](#)), ensues taking El Niño to its peak. The converse occurs during La Niña, but the positive feedback is stronger during El Niño due to nonlinear dynamical processes in the equatorial Pacific (e.g., [An and Jin 2004](#); [Santoso et al. 2017](#)). The associated process is referred to as the nonlinear Bjerknes feedback.

To diagnose the nonlinear Bjerknes feedback controlling the response of atmospheric circulation to SST anomalies associated with E index, we follow the method proposed by [Cai et al. \(2018\)](#). For each model, we identify the location of maximum zonal wind stress anomalies corresponding to the E index using monthly data by linearly regressing the zonal wind stress to E index. This is because the westerly wind anomaly center is located to the west of the corresponding SST anomaly center, as SST warm anomalies are a response of wind-induced eastward-propagating equatorial downwelling Kelvin waves. We calculate the monthly wind anomalies at the wind center [see extended data in Table 1 in [Cai et al. \(2018\)](#)] and plot them against the E index. We then bin the E index and wind index based on E-index values

at intervals of 0.25 s.d. and obtain the median values for both indices within each bin. The nonlinear Bjerknes feedback can be represented by a ratio of the regression slope for the wind response to E index when E index is positive over the slope for that when E index is negative. A greater ratio indicates that the nonlinear feedback is stronger, as the wind response to warm SST anomalies is more intense than for cold SST anomalies in the eastern Pacific. We use monthly data due to westerly winds playing a more critical role in seasons before DJF during an El Niño year.

e. Bootstrap test

To examine whether the increase in the total occurrence of extreme El Niño events is statistically significant, we used a bootstrap method. All numbers presented indicating the total occurrences of extreme El Niño events (Figs. 2 and 7) are counted using 1500 samples (100 years from 1900 to 1999 for 15 models, or 100 years from 2000 to 2099 for 15 models). For example, to test whether the increase in the occurrence of concurrent-extreme events is significant (red dots in Fig. 2), the 1500 samples in control climate were resampled randomly to construct 10 000 realizations of 1500-yr records. In the random resampling process, any concurrent-extreme event is allowed to be selected again. The standard deviation of the number of concurrent-extreme events in the interrealization control climate is 7.9 events per 1500 years. The same applies to the occurrences in climate change, generating a standard deviation of 10 events per 1500 years. As the increase in the total occurrence of concurrent-extreme events ($109 - 65$) exceeds the sum of the two standard deviations ($7.9 + 10$), the increase in the frequency of concurrent-extreme events is at least statistically significant at 95% confidence level. Besides, the number of degrees of freedom for the calculation of the statistical significance of the correlations is simply the number of events, assuming each DJF value is independent from each other.

f. Three gradients controlling shift in different convergence zone

Given that the convection zone over the western Pacific Ocean and the SPCZ both contribute to the occurrence of deep convection over the EP Ocean during El Niño events, we investigate their role. To represent the zonal movement of the western Pacific convection zone, we construct a zonal surface temperature (ST) gradient between the Maritime Continent (5°S – 5°N , 100° – 125°E ; dashed black box in Fig. 9a) and the eastern tropical Pacific Ocean (5°S – 5°N , 150° – 90°W ; black box in Fig. 9a). The zonal ST gradient is not sensitive to regions used to construct the temperature contrast between west and east (Fig. 10). There is a strong nonlinear relationship between

this gradient with rainfall changes over the east. When the gradient weakens, rainfall increases nonlinearly, featuring a positive skewness (Figs. 10d,h,l,p). However, the changes in the zonal gradient do not influence total rainfall over western box (Figs. 10c,g,k,o), potentially indicating the role of local processes.

For the western meridional temperature gradient, this has been put forth by Cai et al. (2012) to capture the meridional shift in SPCZ. It is defined as the average SST over the off-equatorial region (10° – 5°S , 155°E – 120°W ; dashed blue box in Fig. 9a) minus the average over the equatorial region (5°S – 0° , 155°E – 120°W ; blue box in Fig. 9a). The western Pacific meridional SST gradient can well capture the zonal shift in SPCZ (Cai et al. 2012). They applied EOF analysis on tropical Pacific rainfall region, resulting in two leading modes (see their Figs. 1a and 1b). The leading pattern features anomalies along the climatological rainband position. The second pattern is characterized by opposing rainfall anomalies in the equatorial western and central Pacific, such that when it is imposed onto the first mode, it depicts a zonal swing of the SPCZ toward the equator (see their Fig. 1). During zonal SPCZ events, there is a negative relationship between meridional gradient and the second principal component (see their supplementary Fig. 8), indicating that, when the meridional gradient weakens, the SPCZ turns to be more zonally aligned and closer to the equator.

The meridional shift in ITCZ can be well represented by the SST gradient (Cai et al. 2014) between a region north of the equator (5° – 10°N , 150° – 90°W ; dashed green box in Fig. 9a) and a region along the equator (2.5°S – 2.5°N , 150° – 90°W ; green box in Fig. 9a). There is a strong nonlinear relationship between this gradient with Niño-3 total rainfall. When the gradient weakens, Niño-3 rainfall increases nonlinearly, featuring a positive skewness.

3. Observed extreme El Niño characteristics

To highlight rainfall distributions corresponding to the two regimes of EP and CP ENSO [see extended data Figs. 1a–d in Cai et al. (2018) for the SST patterns], we regress rainfall anomalies onto PC1 and PC2 of the tropical Pacific SSTs (see section 2b). The positive EOF1 phase exhibits a convective center in the central to eastern Pacific (Fig. 1a). A positive EOF2 phase resembles a dipole mode with a warm-and-wet anomaly center to the west and a cold-and-dry anomaly center to the east (Fig. 1b). The nonlinear relationship between the first two principal components exhibits an upside-down V-shape curve in DJF season (see Fig. 1a in Cai et al. 2018). The V-shape curve is composed of two parts: one part with a positive slope contributed by most events; the other one

FIG. 1. Observed ENSO characteristics. (a),(b) Anomalous rainfall patterns obtained by regressing rainfall anomalies onto first and second principal components of SST in the tropical Pacific region (15°S–15°N, 140°E–80°W) over satellite-era (post-1979), respectively. The monthly SST variability patterns (contours) and associated wind stress patterns (vectors) are also indicated in each panel. (c),(d) As in (a) and (b), but regressing onto the E index and C index, respectively, (see section 2b) for DJF seasons in which ENSO events typically mature. The regressions used here are bilinear. (e) Relationship between rainfall averaged in Niño-3 region and E index focusing on DJF seasons. Red dots indicate ExtConEN events, i.e., 1982/83, 1997/98, and 2015/16, defined by a Niño-3 rainfall greater than 5 mm day⁻¹. (f) Relationship between meridional SST gradient (SST averaged over 5°–10°N, 150°–90°W minus equatorial region of 2.5°S–2.5°N, 150°–90°W; dashed green box minus green box in Figs. 9a and 9b) and E index focusing on DJF seasons. Red dots indicate ExtWarmEN events, i.e., 1982/83, 1997/98, and 2015/16, defined by an E index greater than 1.5 s.d. Correlation coefficients between two indices and associated p value are indicated in (e) and (f).

with a negative slope but consisting of many fewer samples. The amplitude of both PC1 and PC2 for events that form the second part with a negative slope is much larger than the positive slope part. This reflects nonlinearity of the ENSO system (Dommenges et al. 2013; Takahashi and Dewitte 2016; Cai et al. 2018), which can be represented by the quadratic fitting of PC1 to PC2 [$PC2(t) = \alpha[PC1(t)]^2$]: the greater the α in amplitude, the stronger the nonlinearity.

A combination of the two principal patterns leads to two different ENSO regimes, that is, CP and EP ENSO

(Kug et al. 2009; Kao and Yu 2009; Takahashi et al. 2011; Dommenges et al. 2013; Takahashi and Dewitte 2016; Capotondi et al. 2015). The corresponding time series for the two regimes can be represented by the C index and E index (see section 2b). We then regress DJF rainfall anomalies onto the DJF C index and E index to highlight mature ENSO features. As shown by Figs. 1c and 1d, the EP and CP patterns highlight a deep convection center over the EP and CP regions, respectively (see also Santos et al. 2019, their Fig. 2). By defining a strong EP El Niño event (ExtWarmEN) as when the E index is

FIG. 2. A comparison between simulated Niño-3 rainfall and E index. (a) Relationship between rainfall averaged in Niño-3 region and E index focusing on DJF seasons over 1900–99 using 15 selected models. Red dots indicate concurrent-extreme events. Purple dots indicate ExtConEN-only events. Green dots indicate ExtWarmEN-only events. (b) As in (a) but for 2000–99. Number of occurrences for three different-colored groups are indicated within each panel (confidence intervals are based on a bootstrap test; see section 2e).

greater than 1.5 s.d. (see section 2b), we can capture 1982/83, 1997/98, and 2015/16 (Fig. 1e). The three events are also regarded as ExtConEN (see section 2c). We therefore compare variability of Niño-3 rainfall and E index (Fig. 1e), which are highly correlated to each other. When E index is greater, rainfall over Niño-3 region becomes more intense. The event of 2015/16 sits near the threshold for both ExtWarmEN and ExtConEN. As the meridional temperature gradient between a region north of the equator (5° – 10° N, 150° – 90° W) and a region along the equator (2.5° S– 2.5° N, 150° – 90° W) controls the occurrence of ExtConEN (Cai et al. 2014), the gradient also correlates with the E index (Fig. 1f). When the E index is greater, the equator warms faster than the off-equatorial region. This equatorial warming leads to a weakened meridional gradient over the EP Ocean.

Definitions of both ExtWarmEN and ExtConEN are in accord with each other in the observations, capturing all the three extreme El Niño events (Fig. 1), indicating that an ExtWarmEN corresponds to an ExtConEN. However, this inference is based on a short observational record. The correspondence might not always hold if more samples were available in the past, or in the future. We examine the consistency of this link using the CMIP5 models.

4. Projection of extreme convective and warm El Niño events

Using the selected 15 models (see sections 2b and 2c), we construct a scatterplot between Niño-3 rainfall and

the E index, during the historical (1900–99) and climate change (2000–99) periods. As shown in Fig. 2, models simulate a strong relationship as observed (Fig. 1e). However, there are discrepancies between ExtWarmEN and ExtConEN, for example, there are many ExtConEN events that are not concurrent with ExtWarmEN (purple dots), and a few ExtWarmEN events that are not concurrent with ExtConEN (green dots). To facilitate our analysis, we divide the ExtConEN and ExtWarmEN events into three different groups: *concurrent-extreme events* for which the E index and Niño-3 rainfall are greater than 1.5 s.d. and 5 mm day^{-1} , respectively; *ExtWarmEN-only events* for which the E index is greater than 1.5 s.d. but Niño-3 rainfall is lower than 5 mm day^{-1} ; and *ExtConEN-only events* for which the Niño-3 rainfall is greater than 5 mm day^{-1} but the E index is lower than 1.5 s.d. There are very few ExtWarmEN-only events (17 out of 1500 years in historical and 13 out of 1500 years in climate change period), indicating the rarity of ExtWarmEN events that do not induce deep convection over the EP region (Fig. 2). This corroborates the lack of such events in the relatively short 40 years of observations (Fig. 1e). Observations also lack ExtConEN-only events that are relatively infrequent in the historical period of the multimodel ensemble, although such events become substantially more frequent under climate change (see section 5).

Comparing Fig. 2a with Fig. 2b, there is a notable increase in both concurrent-extreme events and ExtConEN-only events from historical to future period. The differences

in the increase of both concurrent-extreme events and ExtConEN-only events are worth highlighting. First, the increase in ExtConEN-only events is much more than that in the concurrent-extreme events. The concurrent-extreme events are projected to increase from 65 events to 109 events (68% increase) and the ExtConEN-only events are projected to increase from 27 to 130 (381% increase). Second, the ExtConEN-only events are approximately one-third of the concurrent-extreme events during the historical period, whereas it increases to more than the total occurrence of the concurrent-extreme events under climate change. Moreover, the increase in concurrent-extreme and ExtConEN-only events are simulated by most selected models, that is, not as a result of dominance by outlier models, and statistically significant.

a. Concurrent extreme events

The mechanism for the increase in concurrent-extreme events involves establishment of deep convection over the eastern Pacific region (Cai et al. 2014), and enhanced air–sea coupling as a result of an intensified upper-ocean stratification along the equator (Cai et al. 2018). Under greenhouse warming, the majority of models, and thus the average across multimodels, project faster warming of the eastern equatorial Pacific Ocean than the surrounding areas (e.g., Xie et al. 2010; Power et al. 2013; Cai et al. 2014). Note that the reliability of this multimodel projection has been undermined by persisting model biases. Debates on this issue had been intensified due to the recent global warming hiatus, which featured a long-term cooling over the tropical Pacific with a strengthened Walker circulation (e.g., England et al. 2014). However, attributing observed trends to external forcing is a challenge due to internal variability (at least on a decadal time scale; e.g., Bordbar et al. 2019), as well as uncertainty in long-term observational data, which can exhibit differing trends (Chung et al. 2019 and references therein). Reducing the cold tongue bias in models has been suggested to either enhance (e.g., Li et al. 2016; Ying et al. 2019) or contradict (e.g., Seager et al. 2019) the “El Niño-like” warming projection. There could also be other biases in the ocean interior (e.g., Kohyama et al. 2017), in other ocean basins (e.g., Cai et al. 2019), and so forth that may concurrently affect the projection. For the purpose of this present study, we rely on the ensemble of models selected based on their fidelity in simulating ENSO nonlinearity and convective extreme El Niño, which overall exhibit much reduced cold tongue bias compared to the discarded models (figure not shown). The projected faster warming of the eastern equatorial Pacific Ocean than the surrounding areas weakens the barrier that keeps the ITCZ north of the equator. Therefore, the

ITCZ tends to more easily move southward such that more occurrences of deep convection occur over Niño-3 region in the future. By changing the mean ocean surface state, greenhouse warming enhances stratification of the upper equatorial Pacific Ocean (Cai et al. 2018; Yeh et al. 2009; DiNezio et al. 2009; Capotondi et al. 2012). This strengthens the wind–ocean coupling, which is conducive for noise perturbations such as westerly wind bursts (e.g., Capotondi et al. 2018) to generate and enhance warm anomalies over the EP Pacific. As a result, more strong EP El Niño events (i.e., ExtWarmEN) occur.

As a result of increased temperature anomalies over the EP Ocean, the meridional temperature gradient between the north of the equator and the equator decreases. The weakened gradient facilitates the ITCZ to move southward to the eastern tropical Pacific Ocean, increasing convection over the Niño-3 region inducing a concurrent-extreme event. The increase in concurrent-extreme events indicates that the selected CGCMs can generate a reasonable response of atmospheric circulation to SST changes.

b. ExtWarmEN-only events

Although ExtWarmEN-only events are uncommon, they are simulated by most of the selected models. Comparing Figs. 2a and 2b, there are no appreciable impacts from climate change on the occurrence of ExtWarmEN-only events, with a slight projected decrease from 17 (around 1.13 events per century) to 13 (around 0.87 events per century). This decrease is not statistically significant.

We construct composites for SST and rainfall anomalies using all those events across all models (Figs. 3a,b). The center for SST anomalies during ExtWarmEN-only events are over the eastern tropical Pacific Ocean, similar to that for concurrent-extreme events (Fig. 4b). An apparent difference is that SST anomalies during ExtWarmEN-only events have smaller amplitude (Figs. 2 and 3c). In addition, the location for its convection center is notably further to the west compared to that for both ExtConEN-only events and concurrent-extreme events (Figs. 3b,d and 4d,e).

5. The increase in ExtConEN-only events

The ExtConEN-only events are projected to increase from 27, that is, 1.8 events per 100 years, under historical period to 130, that is, 8.7 events per 100 years, under climate change (Fig. 2). Although ExtConEN-only event is infrequent over the historical period, the increase in the ExtConEN-only events under climate change contributes approximately to two-thirds of the total increase in the occurrences of ExtConEN events (a sum of occurrence of

FIG. 3. Composites of SST and rainfall anomalies during ExtWarmEN-only events. (a) Multimodel ensemble mean of SST anomalies during ExtWarmEN-only events (green dots in Fig. 2) from 1900 to 2099 focusing on DJF seasons. The black box indicates Niño-3 region. The purple contours indicate 1.5°C. (b) As in (a), but for rainfall anomalies. The green contours indicate 5 mm day⁻¹ total rainfall. (c) The difference in SST between (a) and multimodel ensemble mean of SST anomalies for concurrent-extreme events (red dots in Fig. 2). (d) The difference in rainfall between (b) and multimodel ensemble mean of rainfall anomalies for ExtConEN-only events (purple dots in Fig. 2). Stippling in (c) and (d) indicates regions where the difference is statistically significant above the 95% confidence level as determined by a two-sided Student's *t* test.

ExtConEN-only events and concurrent-extreme events). To reveal its mechanism, we construct SST and rainfall composites during ExtConEN-only events and compare with that during concurrent-extreme events.

SST anomalies during ExtConEN-only events are located to the west of SST anomalies for the concurrent-extreme events and with a weaker magnitude (Figs. 4a,b);

and the difference in SST anomalies between concurrent-extreme and ExtConEN-only events resembles an EP El Niño pattern (Fig. 4c). The same applies to rainfall anomalies for ExtConEN-only events, which correspond to much weaker anomalies with a center confined to the west compared to that of concurrent-extreme events (Figs. 4d–f). This is consistent with Fig. 2, which indicates

FIG. 4. A comparison between ExtConEN-only events and concurrent-extreme events. (a) Multimodel ensemble mean of SST anomalies during ExtConEN-only events (purple dots in Fig. 2) from 1900 to 2099 focusing on DJF seasons. The black box indicates the Niño-3 region. The purple contours indicate 1.5°C. (b) As in (a), but for concurrent-extreme events (red dots in Fig. 2). The green contours indicate 5 mm day⁻¹ total rainfall. (c) The difference in SST between (b) and (a). (d)–(f) As in (a)–(c), but for rainfall anomalies. Stippling in (c) and (f) indicates regions where the difference is statistically significant above the 95% confidence level as determined by a two-sided Student's *t* test.

FIG. 5. Longitudes of maximum SST anomalies in the two different groups of extreme El Niño events. (a) Histograms for center of maximum SST anomalies for ExtConEN-only events (blue) and concurrent-extreme events (red). Calculations are based on SST anomalies averaged over 5°S – 5°N using 15 selected CMIP5 CGCMs, from 1900 to 2099 focusing on DJF seasons. (b) Histograms for center of maximum SST anomalies during ExtConEN-only events for control period (blue) and climate change periods (red). (c) As in (b), but during concurrent-extreme events. The p value indicating whether two elements are statistically different according to a two-sided Student's t test is indicated within each panel.

that both the E index and Niño-3 rainfall during ExtConEN-only events are weaker than the concurrent-extreme events. Although the deep convection center for ExtConEN-only events is located over the CP region, the contours of 5 mm day^{-1} using total rainfall extend to the EP region and cover more than half of the Niño-3 region. This is in sharp contrast to ExtWarmEN-only events (Figs. 4d and 3b), where the 5 mm day^{-1} contour of total rainfall does not extend to the east.

a. ExtConEN-only events and CP El Niño

Many ExtConEN-only events have a center of maximum SST anomalies located over the CP Ocean compared with concurrent-extreme events, in which the maximum SST anomalies are over EP region (Fig. 5a). Nonetheless, anomalous warming still occurs in the EP region (Fig. 4a) that can be sufficient to shift atmospheric convection toward the eastern equatorial Pacific (e.g., Borlace et al. 2014). The location of maximum SST anomalies for either group of extreme El Niño events, does not differ much between the historical and the future period (Figs. 5b,c). Thus, it is reasonable to compare the distributions of SST and rainfall anomalies over 1900–2099, without the need to separate into two periods. It also indicates that extreme events occur more frequently but with little change in their anomaly pattern. As ExtConEN-only events are mostly located over the CP Ocean, it is likely that the occurrence of

an ExtConEN-only event may be partially due to the occurrence of a CP El Niño event. To test this possibility, we examine the relationships between Niño-3 rainfall and the E index and between Niño-3 rainfall and the C index (Fig. 6).

The Niño-3 rainfall is significantly correlated with both the E index and the C index during concurrent-extreme events (Figs. 6a,b). That is because the correlation between E index and C index during concurrent-extreme events is high with a correlation coefficient of -0.73 (figure not shown). During ExtConEN-only events, the correlation between the E index and C index collapses ($R = 0.12$). However, the Niño-3 rainfall still correlates significantly with the E index but not with the C index. Thus, occurrences of deep convection during ExtConEN-only events is not due to occurrences of CP El Niño events, even though the center for SST anomalies is mostly in the CP region. The associated mechanism is further discussed below.

b. Key role of meridional gradient in deep convection over Niño-3 region

As described by Cai et al. (2014), the increase in the occurrence of ExtConEN events is due to the faster warming over the eastern tropical Pacific Ocean than the surrounding areas. The positive meridional SST gradient between north of the equator and the equator collapses during ExtConEN and pushes the ITCZ

FIG. 6. Simulated relationship between Niño-3 rainfall and (a) the E index and (b) the C index. (a) Scatterplot between Niño-3 rainfall (mm day^{-1}) and E index (s.d.), using outputs from 1900 to 2099 DJF seasons. The purple dots indicate ExtConEN-only events; the red dots indicate concurrent-extreme events. Correlation coefficients, slope, and the p value are also indicated for each group of extreme El Niño events. (b) As in (a), but for the relationship between Niño-3 rainfall (mm per day) and the C index (s.d.).

equatorward toward the Niño-3 region. However, the meridional gradient for the 2015/16 extreme El Niño event is still positive (Fig. 1f). This indicates that the ITCZ is not the only source of deep convection over the Niño-3 region during the 2015/16 event.

To investigate whether CGCMs can simulate events similar to the 2015/16 El Niño, we construct scatterplots similar to Fig. 1f, using outputs from the 15 selected CMIP5 models in the control and climate change periods. Figures 7a and 7b show that CGCMs are able to simulate both extreme convective El Niño events and extreme warm El Niño events but with a positive meridional SST gradient, that is, similar characteristics to the 2015/16 El Niño. First, concurrent-extreme events with a positive gradient are few and the occurrence of such events do not change under greenhouse warming (18). This indicates that events similar to the 2015/16 extreme El Niño event (a concurrent-extreme event that corresponds to a positive gradient) may be rare (Zhong et al. 2017) and such events are not projected to change under greenhouse warming. Second, the increase in the occurrence of concurrent-extreme events is caused by the increased occurrences of events with a negative meridional gradient (from 47 to 91). Moreover, all the ExtWarmEN-only events, which are themselves relatively rare events (Fig. 2), correspond to a positive meridional gradient, highlighting the key role of the negative meridional gradient in bringing deep convection to the Niño-3 region.

By categorizing ExtConEN-only events using the meridional SST gradient, approximately half of the events

correspond to a negative gradient and half correspond to a positive gradient; the increase in ExtConEN-only events with a positive gradient (from 13 to 75) is more than the increase in ExtConEN-only events with a negative gradient (from 14 to 55), and it contributes to approximately 60% of the total increase in ExtConEN-only events (from 27 to 130). The increase in the ExtConEN-only events with a negative gradient is caused by the faster warming over the eastern tropical Pacific Ocean that is conducive to the southward shift of the ITCZ (Cai et al. 2014). This raises the question as to what causes the increase in ExtConEN-only events that are associated with a positive meridional temperature gradient (discussed below).

c. Rainfall sources from the SPCZ and the western Pacific during ExtConEN-only events

As discussed in section 5a, the occurrence of deep convection during ExtConEN-only events has a relationship with the E index but not with the C index, even though the center for SST anomalies is mostly in the CP region. We also know that the nonlinear Bjerknes feedback of atmospheric circulation to the E index generates a greater response for warm anomalies than for cold anomalies (Cai et al. 2018). This enhances the response of westerly winds to warm SST anomalies and therefore weakens the mean temperature contrast between the western and eastern Pacific, promoting further growth of warm anomalies over the eastern tropical Pacific Ocean. Because both ExtConEN-only events and

FIG. 7. Simulated relationship between eastern Pacific meridional SST gradient and the E index. (a) Scatterplot between meridional SST gradient ($^{\circ}\text{C}$; see Fig. 1f for definition) and the E index (s.d.), using outputs from 1900 to 1999 DJF seasons. The purple dots indicate ExtConEN-only events: purple dots with a black circle indicate ExtConEN-only events with a negative meridional gradient; purple dots without black circle indicate ExtConEN-only events with a positive meridional gradient. The red dots indicate concurrent-extreme events: red dots with a black circle indicate concurrent-extreme events with a negative meridional gradient; red dots without a black circle indicate concurrent-extreme events with a positive meridional gradient. Green dots indicate ExtWarmEN-only events. As all ExtWarmEN-only events correspond with positive meridional gradient, there are no green dots with black circles. Occurrences for different groups are indicated (confidence intervals are based on a bootstrap test; see section 2e). (b) As in (a), but for climate change period, i.e., 2000–99.

concurrent-extreme events are related to SST anomalies at the EP regime center, we investigate whether there is a difference in the nonlinear Bjerknes feedback (see section 2d) to the E index between the two different groups of extreme El Niño events.

As shown in Fig. 8a, the response of zonal wind stress anomalies to the E index during concurrent-extreme events is nonlinear, that is, with a stronger response for warm anomalies than that for cold anomalies. The ratio of slope for the positive E-index samples and slope for the negative

FIG. 8. Nonlinear Bjerknes feedback represented by asymmetric responses of wind anomalies to positive and negative E index. (a) Response of monthly zonal wind stress anomalies (N m^{-2}) to the E index (s.d.) during concurrent-extreme events using 15 selected CGCMs from 1900 to 2099 (see section 2d for detail). Red line indicates the regression slope from wind anomalies to positive E-indices (red dots); blue line indicates the regression slope from wind anomalies to negative E-indices (blue dots). Values for each slope with associated 95% confidence intervals based on a Student's t test, as well as the ratio between red line and blue line, are also shown. (b) As in (a), but using monthly data during ExtConEN-only events.

FIG. 9. (a) Climatological mean surface temperature distributions using NCEP–NCAR Reanalysis 1 (Kistler et al. 2001) during 1979–2015. (b) As in (a), but for the multimodel ensemble (MME) mean of the selected models during 1900–99. (c) Observed relationship between zonal ST gradient and western meridional SST gradient. Zonal ST gradient is the temperature difference between Maritime Continent [5°S – 5°N , 100° – 125°E , dashed black box in (a)] and eastern tropical Pacific Ocean [5°S – 5°N , 150° – 90°W , black box in (a)]. Western meridional SST gradient [10° – 5°S , 155°E – 120°W minus 5°S – 0° , 155°E – 120°W ; dashed blue box minus blue box in (a)] is the same as in Cai et al. (2012), which controls the equatorial shift of SPCZ. Red dots indicate the three observed extreme El Niño events, 1982/83, 1997/98, and 2015/16. (d),(e). As in (c), but for the relationships between eastern meridional SST gradient [5° – 10°N , 150° – 90°W minus 2.5°S – 2.5°N , 150° – 90°W ; dashed green box minus green box in (a)] and western meridional SST gradient and zonal ST gradient, respectively. (f)–(h) As in (c)–(e), but using selected 15 models from 1900 to 2099. Red dots indicate concurrent-extreme events; purple dots indicate ExtConEN-only events; green dots indicate ExtWarmEN-only events. The correlation coefficients and associated p values are indicated in each panel.

E-index samples, which represents the nonlinearity, is 3, highlighting a greater response of the atmospheric circulation to warm anomalies in EP region during concurrent-extreme events. However, the slope ratio collapses during ExtConEN-only events (ratio = 1.1, Fig. 8b). This indicates that the nonlinearity of atmospheric response to SST changes that underlines the dynamics of EP El Niño is considerably weaker during ExtConEN-only events.

From section 5b, around half of the ExtConEN-only events occur with a positive meridional SST gradient. In other words, deep convection during those events is not likely to be contributed by a southward shift of the ITCZ. Given that the convection zone over the western Pacific Ocean and the SPCZ both contribute to the occurrence of deep convection over the EP Ocean during El Niño events, we investigate their role. To represent the zonal

FIG. 10. Sensitivity test of zonal surface temperature gradient. (a) The multimodel ensemble mean of climatological surface temperature in the historical period. The zonal gradient is defined as the temperature average over the western box (dashed black; 5°S–5°N, 100°–125°E) minus that over eastern box (solid black; 5°S–5°N, 150°–90°W). (b) Relationship between the zonal gradient as indicated in (a) and the eastern meridional SST gradient, with the correlation coefficient indicated. (c),(d) As in (b), but with the total rainfall over western box and eastern box, respectively. The remaining rows are as in (a)–(d), but for different zonal gradients defined by the dashed black box minus solid black box regions: (e)–(h) 5°S–5°N, 100°–150°E minus 5°S–5°N, 150°–90°W; (i)–(l) 5°S–5°N, 120°–150°E minus 5°S–5°N, 170°–90°W; and (m)–(p) 5°S–5°N, 120°E–180° minus 5°S–5°N, 180°–90°W. Red dots indicate concurrent-extreme events, purple dots indicate ExtConEN-only events, and green dots indicate ExtWarmEN-only events.

movement of the western Pacific convection zone, we construct a zonal ST gradient between the Maritime Continent (5°S–5°N, 100°–125°E; dashed black box in Fig. 9a) and the eastern tropical Pacific Ocean (5°S–5°N, 150°–90°W; black box in Fig. 9a). To represent meridional movement of the SPCZ, we construct the western Pacific meridional SST gradient as in Cai et al. (2012). It is

defined as the average SST over the off-equatorial region (10°–5°S, 155°E–120°W; dashed blue box in Fig. 9a) minus the average over the equatorial region (5°S–0°, 155°E–120°W; blue box in Fig. 9a). Climatologically, the western Pacific Ocean, south equatorial, and northeastern equatorial regions are warmer than the eastern Pacific Ocean, central tropical Pacific Ocean, and tropical eastern

equatorial regions, respectively. This indicates the location of the three convergence zones, as indicated by Figs. 9a and 9b. Please note that it is not sensitive to the regions chosen to construct the three gradients (see section 2f; Fig. 10). During observed extreme El Niño events (Cai et al. 2014) and under greenhouse warming (Cai et al. 2014, 2015), the eastern tropical Pacific Ocean warms more than surrounding areas; not only does the ITCZ tend to move southward, but the western convergence zone also easily moves eastward and SPCZ swings equatorward. When the zonal ST gradient and the western and eastern Pacific meridional SST gradients all weaken, deep convection over the western Pacific moves eastward, the SPCZ moves northward to the equator, and the ITCZ moves southward to the equator.

It turns out that the three observed gradients are highly correlated with each other, as indicated in Figs. 9c–e. The models can simulate a similar relationship as observed (Figs. 9f–h). Both the zonal ST gradient and the western Pacific meridional SST gradient are weakened during ExtConEN and ExtWarmEN events. Thus, movement of the western Pacific convection zone, the SPCZ, and the ITCZ all play a role in the occurrences of deep convection over the EP Ocean during ExtConEN-only events. In the case when the eastern meridional SST gradients are positive (i.e., when southward migration of ITCZ is less favored), the former two factors would play a greater role in establishing deep convection in the EP Ocean.

6. Summary

Extreme El Niño events can be identified using rainfall averaged over the Niño-3 region (referred to in this study as “extreme convective events”), or SST anomalies over the EP region (extreme warm events). In the relatively short observations, extreme warm El Niño events have always been concurrent with extreme convective El Niño events. The 15 selected CGCMs show that such concurrent-extreme events are projected to increase in frequency under greenhouse warming, consistent with the findings of Cai et al. (2014) and Cai et al. (2018). In the large model sample, however, extreme convective and warm events are able to occur independently (i.e., ExtConEN-only, ExtWarmEN-only) in both control and climate change periods.

The ExtWarmEN-only events are rare and not influenced by greenhouse warming. In these rare occurrences, the rainfall anomaly center is well confined to the west of the SST anomaly center. On the other hand, the increase in ExtConEN-only events is prominent, contributing to more than 50% of the total increase in extreme convective El Niño events. We show that this is not only due to the southward shift of the ITCZ, but also due to the eastward

shift of the western Pacific deep convection zone and the northward shift of the SPCZ, all playing a greater role under greenhouse warming because of the mean-state change. While the SST anomalies during ExtConEN-only events are mostly over the central Pacific Ocean, they are still part of the EP ENSO regime rather than the CP ENSO regime, except that the usually strong nonlinear atmospheric response is not fully developed. The associated large rainfall in the EP region is also contributed by movement of the western Pacific convergence zone and the SPCZ.

Our results indicate that most ExtWarmEN events can lead to deep convection over eastern tropical Pacific Ocean, highlighting the influential impacts of strong EP El Niño events. However, the occurrence of deep convection over eastern tropical Pacific Ocean increases more than the occurrence of strong SST anomaly in EP regime, underscoring increased sensitivity of atmospheric circulation to mean-state change induced by greenhouse warming. Although ExtConEN and ExtWarmEN are not entirely in accord with each other, we have shown that ExtConEN events are to a large extent linked to EP SST anomalies. Thus, the two definitions of extreme El Niño are linked and they capture different characteristics of extreme El Niño from two different perspectives, that is, atmospheric circulation and SST anomalies.

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