Double intertropical convergence zones over the eastern Pacific Ocean: Contrasting impacts of the eastern Pacific- and central Pacific-type El Niños

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1 | INTRODUCTION

During Charles Darwin’s shore excursion at the Galápagos Islands on September 15 to October 30, 1835, he surprisingly found that these equatorial Islands over the eastern Pacific Ocean were barren with scarce precipitation and cool climate. Now we know that the eastern Pacific Ocean features a typical single belt of intertropical convergence zone (ITCZ) north of the equator along with the equatorial cold tongue. The ITCZ can be characterized by intense precipitation (Philander et al., 1996; Zhang, 2001) and deep convection (Xie and Yang, 2014), collocated with the warmest sea surface temperature (SST). It is maintained by the wind–evaporation–SST (WES) (Xie and Philander, 1994) and stratus–SST feedbacks (Philander et al., 1996). Generally, the climate in the eastern Pacific Ocean is dominated by the position and intensity of the ITCZ. The northern ITCZ exists throughout the whole year (Figure 1a). The cross-equatorial southerly winds forced by the north–south asymmetry of ITCZ enhance the Pacific cold tongue (Mitchell and Wallace, 1992), leading to little annual precipitation and cool climate in these equatorial islands. In particular, during boreal spring (March–April), except for a long-standing northern ITCZ, a weak southern ITCZ unusually appears with the suppressed cross-equatorial southerly winds and weakened equatorial cold tongue as well as relatively abundant Galápagos Islands precipitation on annual timescale (Lietzke et al., 2001; Zhang, 2001; Gu et al., 2005) (Figure 1a). This study focuses on the inter-annual variability of such double ITCZs during boreal spring (March–April), an important but overlooked issue.

A double intertropical convergence zone (ITCZ) with poor equatorial rainfall over the eastern Pacific Ocean distinctively occurs in March–April. Here we find that double ITCZs and equatorial precipitation are strongly linked to meridionally symmetric (or asymmetric) sea surface temperature (SST) anomaly patterns during eastern Pacific (EP)-type (or central Pacific [CP]-type) El Niño episodes. EP-type El Niño weakens the north–south asymmetry of the eastern Pacific double ITCZs by moving them equatorward. In contrast, CP-type El Niño strengthens the north–south asymmetry of the double ITCZs by strengthening the northern ITCZ and weakening the southern ITCZ. While EP-type El Niño brings unique flourishing Galápagos Islands owing to warm equatorial SST anomalies with major local and remote climate effects, CP-type El Niño causes drier Galápagos Islands by decreasing equatorial eastern Pacific SST. This study highlights the distinctly different climate effects of EP- and CP-type El Niños in the region.

KEYWORDS
CP-type El Niño, double ITCZs, EP-type El Niño, equatorial rainfall, north–south asymmetry
Two types of El Niño can both remarkably affect the spatial distribution of SST and consequently the features of ITCZ in the tropical Pacific Ocean. Conventional El Niño produces the largest positive SST anomalies (SSTA) in the eastern Pacific Ocean (referred to as EP-type El Niño; e.g., Rasmusson and Carpenter, 1982; Kug et al., 2009), meanwhile a new type of El Niño produces the largest positive SSTA in the central Pacific Ocean (referred to as CP-type El Niño; e.g., Ashok et al., 2007; Kao and Yu, 2009). Due to their differences in El Niño and Southern Oscillation (ENSO) spatial patterns and evolution (e.g., Capotondi et al., 2015; Santosso et al., 2017), EP- and CP-type El Niños will exert different influences on the ITCZs. For EP-type El Niños, double ITCZs are replaced by a broad ITCZ band extending continuously from north of the equator to south of the equator during March–April (e.g., Lietzke et al., 2001; Zhang, 2001; Gu et al., 2005). For CP-type El Niños, previous studies focused on the position change of the eastern Pacific ITCZ during the peak phase of CP-type El Niño (boreal winter) and these results about the position change in the northern ITCZ were even inconsistent due to the coarse resolution or short period of the rainfall data (e.g., Lietzke et al., 2001; Zhang, 2001; Gu et al., 2005): the eastern Pacific ITCZ was shown to shift northward (Kao and Yu, 2009) or slightly southward (Xie and Yang, 2014). However, the strengths of double ITCZs and the equatorial precipitation over the eastern Pacific Ocean impacted by the CP-type El Niño in boreal spring have not been examined and remain unclear.

Here we investigate both the latitude fluctuation and intensity change in double ITCZs, and the equatorial precipitation in response to the two types of El Niño. We will discuss El Niño the different impacts of these two types of El Niño from two aspects: the north–south asymmetry of double ITCZs and the equatorial precipitation. The analyses suggest that while EP El Niño drives the northern and southern ITCZs equatorward with weaker north–south asymmetry, CP El Niño strengthens their north–south asymmetry. Furthermore, this study distinguishes between the different impacts of two types of El Niño on the equatorial rainfall. EP-type El Niño brings unique flourishing Galápagos Islands owing to warm equatorial SSTA with major local and remote climate effects, while CP-type El Niño causes drier Galápagos Islands by decreasing equatorial eastern Pacific SST.

In the rest of this paper, section 2 introduces the data and methods. Section 3 examines the EP- and CP-type El Niños’ different impacts on the double ITCZs and equatorial precipitation. The conclusions are provided in section 4.

2 DATA AND METHODS

We examine monthly mean SST, precipitation and winds at 10 m (referred to as surface winds) with a 0.75 × 0.75° horizontal resolution from the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) dataset (Dee et al., 2011) for 1979–2016. The ERA-Interim dataset is of high resolution and depicts the ITCZs over the eastern Pacific Ocean well (Dee et al., 2011; Zagar et al., 2011). Meanwhile, a new type of El Niño produces the largest positive SSTA in the central Pacific Ocean (referred to as CP-type El Niño; e.g., Ashok et al., 2007; Kao and Yu, 2009). Due to their differences in El Niño and Southern Oscillation (ENSO) spatial patterns and evolution (e.g., Capotondi et al., 2015; Santosso et al., 2017), EP- and CP-type El Niños will exert different influences on the ITCZs. For
the monthly-mean precipitation exceeding 5 mm/day. As shown in Figure 2a, there are two belts of ITCZ in March–April. We define the position of ITCZ as the latitude of maximal zonal-mean precipitation, which was found to be consistent with energy flux equator (EFE) variations (Adam et al., 2016a; 2016b). The intensity of ITCZ is defined as the amplitude of zonal-mean precipitation.

We use the Niño3 index (Kug et al., 2009) and improved El Niño Modoki index (IEMI; Li et al., 2010) to identify the EP- and CP-type El Niño events, respectively. To select the EP-type El Niño events, we first construct two Niño3 indices in January–February and in March–April, respectively. If the Niño3 SST value of a year exceeds 0.95 standard deviation for both indices, this year is defined as the EP-type El Niño decaying year. This definition is valid for both EP- and CP-type El Niños. Accordingly, for March–April months, the composite of EP-type El Niños is based on years 1982/1983, 1986/1987, 1991/1992, 1997/1998 and 2015/2016; and five CP-type El Niño events, including the events of 1990/1991, 1994/1995, 2002/2003, 2004/2005 and 2014/2015. The event of 2009/2010 is a mixed-type El Niño, since it satisfies the standard for both EP- and CP-type El Niños. Accordingly, for March–April months, the composite of CP-type El Niños is based on years 1991, 1995, 2003, 2005 and 2015; the mixed-type El Niño is year 2010.

3 | RESULTS

3.1 | Seasonal evolution

Precipitation over the eastern Pacific has a strong and distinctive annual cycle. In climatology, accompanied by the
warmest SST, an individual ITCZ exists in the Northern Hemisphere (NH) throughout the whole year (Figure 1a). In particular, double ITCZs with the intense precipitation in the Southern Hemisphere (SH) unusually occur during boreal spring (March–April) (e.g., Mitchell and Wallace, 1992; Zhang, 2001; Gu et al., 2005) (Figure 1a).

For EP-type El Niños, the cold tongue is replaced by warm SSTs at the equator and these warm SSTs persist from December of the developing year to May of the decaying year. With the disappearance of the cold tongue in March–April, the northern and southern ITCZs move equatorward and even change to be a single broad equatorial ITCZ belt, increasing the equatorial precipitation and weakening the north–south asymmetry of eastern Pacific climate (Figure 1b).

For CP-type El Niños, at the equator, positive SSTA appear in the central Pacific and are collocated with negative SSTA in the equatorial eastern Pacific during and following its peak phase. CP-type El Niños can intensify the cold tongue. Such colder SSTs further suppress the convergence and weaken the rainfall intensity over the eastern Pacific Ocean south of the equator. Consequently, during March–April of the decaying year of CP-type El Niño, the climatic-existing ITCZ in SH disappears. Only one single ITCZ in NH exists throughout September of the developing year to August of the decaying year of CP-type El Niño (Figure 1c). Previous studies reported that there are five daily states of ITCZ, such as north ITCZ, equator ITCZ, double ITCZs, etc. (Henke et al., 2012; Haffke et al., 2016) and these states covary with SST variations (Adam et al., 2016a; 2016b). In March–April, the double ITCZs occur most frequently (Henke et al., 2012; Haffke et al., 2016) (Figure 1a). Here we suggest that the inter-annual variations of these states are strongly linked to El Niño events: EP-type El Niño favors an equator ITCZ (Figure 1b) and CP-type El Niño favors a north ITCZ (Figure 1c).

### 3.2 Meridional structure and spatial distribution

For climatology in March–April, zonally averaged precipitation maxima emerge on both sides of the equator, separated by a minimum at the equator (Figure 2a). This climatic double ITCZs pattern in March–April is different from the climatology in other seasons (e.g., in September) when a single-ITCZ pattern emerges in the Tropics. For EP-type El Niños, these two precipitation maxima migrate toward the equator and the precipitation at the equator increases remarkably, reducing the north–south asymmetry. In contrast, for CP-type El Niños, the north–south asymmetry of double ITCZs is amplified: the dominating ITCZ located in the NH is further strengthened and the secondary ITCZ located in the SH nearly vanishes. The precipitation on the equator decreases following the CP-type El Niño. In short, the EP-type El Niños modulate the locations of two bands of ITCZs and the CP-type El Niños modulate the strengths of ITCZs, respectively (Figure 2a).

In fact, the ITCZ’s position and intensity are strongly coupled to the underlying SST and winds (Figure 2b,d). In climatology of March–April, a unique double ITCZs pattern emerges: two zonally elongated rainfall belts are located straddling the equator, constrained within the region where SST is warmer than 27 °C (Figure 2b). However, even in March–April, due to the existence of the cold tongue, the equatorial region is still a zone with scarce rainfall (Figure 2b). In this season, the Galápagos Islands usually exhibit a barren landscape because of the scarce rainfall.

During boreal spring of the decaying year of EP-type El Niño, SST warming emerges nearly over the entire tropical eastern Pacific Ocean (Figure 2c). In particular, over the latitudes (3°S–3°N), the SST warming is the strongest, exceeding 1 °C. These strong equatorial SSTA excite strong convergence anomalies. Therefore, driven by the strong SST warming, the two ITCZs both shift toward the equator. Along with the approaching movements of the double ITCZs, the original north–south asymmetry is reduced. Moreover, such equatorward shifts of the ITCZs manifest as great positive rainfall anomalies at the equator. A SST warming of about 1.8 °C corresponds to a precipitation growth of about 5 mm/day. The intense equatorial rainfall has a remarkable ecological effect. The landscape in the Galápagos Islands will turn from a barren one into a vibrant one. If Charles Darwin arrived at the Galápagos Islands in March–April following the EP-type El Niño, he would encounter rainy Galápagos Islands as he expected in the equatorial region.

Differently, during boreal springs of the decaying year of CP-type El Niño, a cooling of SST emerges at and south of the equator and a warming of SST emerges north of the equator (Figure 2d). Such a north-warm and south-cool contrast of SSTA induces enhanced cross-equatorial southerly winds, corresponding to further strengthened convergence in the northern ITCZ and suppressed convergence in the southern ITCZ and the equator. Consequently, precipitation in the northern ITCZ becomes more intense and precipitation in the southern ITCZ is weakened. In other words, CP-type El Niño further reinforces the original north–south asymmetry of double ITCZs. In addition, the latitude of the minimal (or maximal) anomalous precipitation is not perfectly in compliance with the latitude of the minimal (or maximal) anomalous SST. The SST gradients and momentum balance may count as an explanation for this collocation (e.g., Lindzen and Nigam, 1987; Schneider et al., 2014). At the same time, the equatorial rainfall during CP-type El Niños is even less than the climatic equatorial rainfall in March–April. If Charles Darwin arrived at the Galápagos Islands in March–April following the CP-type El Niño, he would also marvel at the lack of rainfall in the equatorial region.
Several theoretical frameworks may account for the relation of the ITCZs with SST and surface wind variations, such as the “energy-flux” framework (e.g., Schneider et al., 2014; Adam et al., 2016a; 2016b), surface momentum balances (e.g., Lindzen and Nigam, 1987), convective quasi equilibrium (e.g., Prive and Plumb, 2007) or classical equatorial wave dynamics (e.g., Gill, 1980). Especially in the energy-flux framework (Adam et al., 2016a; 2016b), the equatorward shift of the ITCZs (or northward shifts of the ITCZs and strengthened northern ITCZ) can be explained by increased atmospheric net energy input, associated with elevated equatorial (or northern) SST for the

**FIGURE 3** Scatter diagrams of (a) EP index (i.e., Niño3 index) versus delta SST for EP (i.e., SST_{AEQ} - 0.5\times[SST_{ASH} + SST_{ANH}]); (b) CP index (i.e., IEMI index) versus delta SST for CP (i.e., SST_{ANH} - SST_{ASH}); (c) delta SST for EP versus change in distance between two ITCZs (i.e., anomalies for |\text{Lat}_{precip\_max\_NH} - \text{Lat}_{precip\_max\_SH}|); (d) delta SST for CP versus delta precipitation for CP (i.e., P_{ANH} - P_{ASH}); (e) delta SST for EP versus equatorial precipitation for EP (i.e., P_{AEQ} - 0.5\times[P_{ASH} + P_{ANH}]); (f) delta SST for CP versus equatorial precipitation for CP (i.e., P_{AEQ} - P_{ANH}). For each subfigure, red solid circles denote the EP-type El Niño decaying years: 1983, 1987, 1992, 1998 and 2016; blue solid circles denote the CP-type El Niño decaying years: 1991, 1995, 2003, 2005 and 2015; green solid circle denotes the mixed-type El Niño decaying year: 2010. All these indices are calculated for the season March–April and are normalized. In all subfigures, the correlations are statistically significant at a 99% confidence level.
3.3 General relationship between SST and double ITCZs

The above mentioned characterizations are not only limited to the typical EP-type/CP-type El Niño years, but valid for all of the years in the data analyzed here. In Figure 3, EP (or CP) is the shorthand for EP-type (or CP-type) El Niño. SSTAEQ (or SSTA↓N, or SSTA↓S) is the averaged SSTA over the EQ (or NH, or SH) region and PAEQ (or PANH, or PASH) is the averaged precipitation anomalies (PA) over the EQ (or NH, or SH) region, where EQ (or NH, or SH) denotes the region within latitudes (1.5°S–1.5°N) (or latitudes (3.75°N–6.75°N), or latitudes (3°S–6°S), all over the eastern Pacific between 140°W and 80°W. Values of 1 SD for EP index, delta SST for EP, distance change and equatorial precipitation for EP are 0.62 °C, 0.52 °C, 1.41° and 2.13 mm/day, respectively. Values of 1 SD for CP index, delta SST for CP and delta precipitation for CP and equatorial precipitation for CP are 1.65 °C, 0.40 °C, 3.21 mm/day and 2.85 mm/day, respectively.

Over the eastern Pacific, when an equatorial SST warming (represented by EP-type El Niño index) occurs, at the same time a SST warming symmetric about the equator in the Tropics and with maximum at the equator (represented by delta SST for EP-type El Niño) occurs (Figure 3a). For CP-type El Niño, the meridional pattern of SSTA is different from that for EP-type El Niño. When a zonally negative–positive–negative SSTA pattern (represented by CP-type El Niño index) emerges over the whole tropical Pacific between 120°E and 80°W, a meridionally north-warm and south-cool SSTA pattern (represented by delta SST for CP-type El Niño) at the same time emerges over the eastern tropical Pacific between 140°W and 80°W (Figure 3b). In other words, EP- and CP-type El Niños induce a meridionally symmetric and asymmetric structure of SST, respectively.

The two different meridional patterns of SST have different impacts on the equatorial precipitation over the eastern Pacific Ocean (Figure 3e,f). In previous studies, it has been long recognized that precipitation increases at the equator and decreases off the equator following the EP-type El Niños. Our results reveal that this regulation of equatorial rainfall by SST is general. Indeed, a meridionally symmetric structure of SST warming (or cooling) can induce an increase (or a decrease) in the equatorial rainfall (Figure 3e). Especially for four EP-type El Niños, equatorial rainfall has a remarkable increase (red circles in Figure 3e). In contrast to EP-type El Niño, a meridionally asymmetric SSTA pattern regulates the equatorial rainfall for the CP-type El Niño (Figure 3f). For four CP-type El Niños, equatorial rainfall does not increase, but it further decreases (blue circles in Figure 3f). These results indicate that EP- and CP-type El Niños, respectively, increase and reduce equatorial Galápagos Islands precipitation (Figure 3e,f), with different climatic and ecological effects. In addition, all the correlations are statistically significant at a 99% confidence level.

4 CONCLUSIONS

During boreal springs, a frequently emerging double ITCZs over the eastern Pacific Ocean is a distinctive seasonal phenomenon (Figure 1). Based on reanalysis during 1979–2016 with high resolution, we identify and quantify the latitude fluctuation and intensity change of these double ITCZs in response to two types of El Niño. Our results clarify the different processes regulating the intensity and position of the eastern Pacific double ITCZs by the different meridional SSTA patterns associated with the two types of El Niño. For EP-type El Niños, a zonally uniform equatorial SST warming corresponds to a meridionally symmetric SST warming (Figures 2b and 3a). Such a meridionally symmetric structure of SST warming leads to an anomalous convergence at the equator (Figure 3b), which reduces the distance between the two ITCZs (Figure 3c), enhances equatorial precipitation (Figure 3e), and reduces the north–south asymmetry of the eastern Pacific climate. For CP-type El Niño, a zonally cool-warm-cool SST pattern over the whole equatorial Pacific actually corresponds to a meridionally north-warm and south-cool SST pattern over the eastern tropical Pacific (Figures 2c and 3b). Such a meridionally asymmetric SSTA pattern induces enhanced cross-equatorial southerly winds (Figure 3c) and causes an enhanced north–south asymmetry.
of eastern Pacific climate with strengthened northern ITCZ and weakened southern ITCZ (Figure 3d) as well as less equatorial precipitation (Figure 3f).

We summarize our conclusion of the climatic impacts of the different regulating processes from two aspects: the north–south asymmetry of double ITCZs and the equatorial precipitation. From the aspect of north–south asymmetry, we find that EP-type El Niño weakens the north–south asymmetry of double ITCZs by driving them equatorward, while CP-type El Niño further amplifies the existing north–south asymmetry of the double ITCZs by strengthening the northern ITCZ and weakening the southern ITCZ. Our analyses identify and quantify the locations of ITCZs impacted by EP-type El Niño and strengths of ITCZs impacted by CP-type El Niño, which were overlooked in previous studies. The inter-annual variability of equatorial eastern Pacific precipitation is large with major climatic and ecological effects over the globe (e.g., Klein et al., 1999; Trenberth et al., 2002; Deser et al., 2010). This study reveals that EP-type El Niño brings unique flourishing Galápagos Islands by increasing the equatorial precipitation, while CP-type El Niño brings us even drier Galápagos Islands by decreasing the equatorial precipitation. Charles Darwin would only encounter the distinctive rainy Galápagos Islands in March–April during the EP-type El Niño, but not during the CP-type El Niño.

All this suggests that EP- and CP-type El Niños may often exert distinctly different climatic and ecological effects in the observations. Recent studies found that the well-known “double ITCZs bias” (Li and Xie, 2014; Li et al., 2015; 2016a; 2016b) could be related to under-represented CP-type El Niños (e.g., Adam et al., 2018) in the Coupled Model Intercomparison Project phase 5 (CMIP5). It is interesting to further study on how the EP- and CP-type El Niños affect the double ITCZs represented in CMIP models. This may provide new insights into the “double ITCZs bias”.

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