The linkage between two ENSO types/modes and the interdecadal changes of ENSO around the year 2000

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ABSTRACT
This study focuses on the interdecadal changes in ENSO properties emerging around the year 2000. Compared to 1980–1999, after 2000, the ENSO amplitude weakened, the occurrence of the central Pacific (CP) El Niño increased, and the eastern Pacific (EP) El Niño became suppressed. Meanwhile, the dominant period of ENSO shortened from quasi-quadrennial (QQ) to quasi-biennial (QB). The authors show that these changes in ENSO properties are evidently consistent with the change in the stability of the ENSO mode through connecting the two ENSO types with the two coupled ENSO modes, i.e. the QQ and QB modes. It is suggested that the relative activity or stability of the two ENSO modes changed after the year 2000. The intensity of both the QQ and QB mode weakened. The QQ mode, which is linked to EP ENSO and was significantly strong during 1980–1999, became much weaker after 2000 in terms of the EP type almost disappearing. Compared with the weakness of the QQ mode, the QB mode, as manifested by the CP type, remained active and became dominant in the tropical Pacific after 2000. Analysis shows that the changes in mean states in the tropical Pacific were likely responsible for the interdecadal ENSO changes around the year 2000.

1. Introduction
ENSO is the leading mode of interannual variability in the tropical Pacific and has a significant effect on global weather and climate. In the tropical Pacific, decadal and interdecadal changes are also important and may modulate the features of ENSO (Fedorov and Philander 2000; McPhaden, Lee, and McClurg 2011; Sun and Yu 2009; Yeh and Kirtman 2004). In the late 1970s, the properties of ENSO, including its amplitude, spatial pattern, and periodicity, experienced an interdecadal change (An and Wang 2000; Rasmusson and Carpenter 1982; Wallace et al. 1998). It has been suggested that this decadal variation, or ENSO regime change, was connected with changes in the different types of ENSO (Ren et al. 2013).

A large number of studies suggest the existence of another type of ENSO – one that differs from the canonical type in many aspects. Here, we use the name ‘Eastern-Pacific (EP) ENSO’ to refer to the canonical type and ‘Central-Pacific (CP) ENSO’ to refer to the other type (Kao and Yu 2009; Yeh et al. 2009; Zheng et al. 2014). Connected with the two ENSO types, there are two important coupled modes of ENSO in the tropical Pacific: the quasi-quadrennial (QQ) mode and quasi-biennial (QB) mode (Bejarano and Jin 2008). Furthermore, the two independent ENSO types/modes, which actively coexist in the tropical Pacific, changed in the late 1970s; EP ENSO, which corresponds to the QQ mode, enhanced, and CP ENSO, which corresponds to the QB mode, occurred more frequently (Ren et al. 2013).

Compared to pre-2000, the ability to predict ENSO declined significantly after 2000 (Barnston, Tippett, and L’Heureux 2012), and the warm water volume was...
not a dependable precursor for ENSO (Horii, Ueki, and Hanawa 2012; McPhaden 2012). Meanwhile, a grand La Niña-like background state, which is characterized by a strengthened Walker circulation and a steepened equatorial thermocline tilt (Hu et al. 2013), was observed in the tropical Pacific after 2000 and may be leading to more CP ENSO events (Xiang, Wang, and Li 2013). Coincident with these changes, ENSO shifted into a higher-frequency and weaker-intensity regime. The air–sea coupling in the tropical Pacific weakened at ENSO time scales (Hu, Kumar, and Huang 2016; Zheng et al. 2015). This study focuses on the linkage between the two ENSO types/modes and the interdecadal changes of ENSO around the year 2000. We contrast the changes in ENSO properties between pre- and post-2000 and examine the possible roles of the two ENSO types/modes in forming the observed ENSO interdecadal changes around 2000.

2. Data

In this study, the SST data employed are from ERSST.v4 (Huang et al. 2015), which is available at a monthly resolution on a 2° × 2° grid. The research region is the equatorial Pacific (5°S–5°N, 120°E–80°W). The ocean temperature data are from GODAS on a 1/3° latitude × 1° longitude horizontal grid (Behringer and Xue 2004). The wind data are from NCEP Reanalysis-2 (Kanamitsu et al. 2002). The study period is January 1980 to December 2015. To ensure clear comparisons, we separate the period into two parts: 1980–1999 and 2000–2015.

We also compute the traditional Niño indices, including Niño3 (5°S–5°N, 150°–90°W), Niño4 (5°S–5°N, 160°E–150°W), and Niño3.4 (5°S–5°N, 170°–120°W), based on the ERSST.v4 data. Furthermore, we utilize the warm-pool Niño index (WPI) and cold-tongue Niño index (CTI), which were proposed by Ren and Jin (2011), to describe temporal evolutions and extract the characteristic patterns for both ENSO types. The climatology in this study is 1980–2015.

3. Results

The characteristics of ENSO changed notably after the year 2000, in that El Niño occurred more frequently and was weaker (Figure 1). Five El Niño events have happened in the tropical Pacific after 2000: 2002/2003, 2004/2005, 2006/2007, 2009/2010, and 2015/2016. Three of them (2002/2003, 2004/2005, 2009/2010) were CP El Niños. The 2006/2007 El Niño was more like an EP–CP mixed type event. The 2015/2016 super El Niño event, which has its positive SST anomaly center in the Niño3.4 region, is different from the previous two super El Niño events (1982/1983 and 1997/1998). This means that no typical

EP El Niño event has occurred since 2000, and CP El Niños have occurred more frequently. Moreover, compared to the El Niños that happened during 1980–1999, including several strong EP El Niño events, the strength of events became notably weaker after 2000, particularly in the first decade of the twenty-first century. We also check the autocorrelations of the three Niño indices (Figure 2), which can visibly reflect the dominant periods of the corresponding regions. The curves reach their minima at a
lag of 18–24 months before 2000, but only 12–20 months after 2000. The dominant ENSO period shortened greatly after 2000, and the Niño3 index curves change the most robustly. Meanwhile, the significance of ENSO’s periodicity decreased markedly.

The life cycle of ENSO’s structure also changed after 2000, which is connected with the different changes of the two ENSO types/modes. Figure 3 shows some considerable differences between 1980–1999 and 2000–2015. The lead–lag regressions of SST anomalies onto the Niño3.4 index demonstrate a westward shift of the positive center by about 20° in Figure 3(b) compared with that in Figure 3(a). By regressing the SST anomalies onto the CTI and WPI, we find that the positive centers are almost static from Figure 3(c) and (e) to Figure 3(d) and (f). Another feature is that the SST anomalies propagated eastward in the equatorial Pacific before 2000, and then became static or weakly propagating after 2000. Ren et al. (2013) concluded that the propagation of EP ENSO was eastward after the late 1970s, while CP ENSO made no net contribution or a minor contribution to the eastward propagation. The results indicate that the spatial structures of both ENSO types have not clearly changed after 2000, but the dominant mode in the equatorial Pacific has changed from the QQ mode to the QB mode, based on the fact that more CP El Niño events have occurred since 2000.

Next, we use wavelet analysis to analyze the periodicity of ENSO, as shown in Figure 4. The wavelet power spectra of the three Niño indices are quite different before and after 2000. We can see that two significant periods of around 30 and 60 months, respectively, existed during 1980–1999, meaning both the QB and QQ mode were significant at that time, though the appearance of ENSO was characterized mainly by the EP type. After 2000, the periodicity of ENSO has overall become apparently weaker. The intensity of the QQ mode has weakened remarkably in the whole of the tropical Pacific. The intensity of the QB mode has strengthened in the central tropical Pacific, while it has weakened in the eastern tropical Pacific. Furthermore, the QB mode has become the only significant mode in the tropical Pacific. Moreover, the wavelet power spectra of the CTI and WPI, as representative of the two ENSO types, have changed notably. The lower-frequency part of the CTI, which was 40–60 months, has disappeared since 2000, and the WPI has a significant period of around 30 months. The change in the dominant period of the two indices is highly consistent with the change in the significance of the QQ and QB modes. Before 2000, the dominant lower-frequency period of the ENSO cycle was notable, and mainly reflected by the mode of EP ENSO. After 2000, the QB mode became dominant, with the absence of EP ENSO events and the growing occurrence of CP ENSO events. ENSO experienced a significant interdecadal change around 2000, closely linked with the change in the relative activity or stability of the two important ENSO modes in the tropical Pacific.

Next, we further discuss the possible mechanism underlying the observed interdecadal ENSO change. According to the above analysis, the intensities of both the QQ and QB mode weakened after 2000, especially the QQ mode, which corresponds to EP ENSO and nearly disappeared in the eastern tropical Pacific after 2000. Bejarano and Jin (2008) discussed the relationship between basic states and the growth rates of both modes in a modified version of the Zebiak–Cane model, in which two control parameters, denoted as \(a_H\) and \(a_W\), are used to alter the reference thickness of the upper-layer ocean \(H_0 = a_H H_c\) and the mean wind stress \(\overline{\tau}_X = a_W(\overline{\tau}_X^{c}, \overline{\tau}_Y^{c})\). Here \(\overline{\tau}_X^{c}, \overline{\tau}_Y^{c}\) denotes the observed climatological mean wind stress, and \(H_c = 150\) m is the standard value for the reference upper-layer thickness. Referring to their definitions and estimates of the two parameters, we consider the real basic state during 1980–1999 as the reference state (see the position at \(a_H = 140/150\) and \(a_W = 1\), Figure 3(a) and (b) in Bejarano and Jin 2008), where both the QQ and QB mode were almost equally active with similar growth rates. After 2000, with time, the observed basic states change in different ways over the eastern and central-western tropical Pacific, respectively, as shown in Figure 5. In the eastern Pacific, the thermocline depth, as approximately represented by the parameter \(a_W\), has not obviously reduced, but the zonal trade winds have weakened notably. Such changes in the eastern tropical Pacific basic state may correspond to a reduced \(a_H\) and weaken the QQ mode directly, which is centered in the eastern tropical Pacific. In contrast, in the western and central tropical Pacific, the thermocline depth has increased greatly (reduced \(a_H\)) and the zonal trade winds have also strengthened (increased \(a_W\)), as seen in Figure 5. In this case, these changes of the two parameters induced by the basic state changes may cancel out each other’s effects on the two modes. However, this will be dependent on the relative magnitudes of the changes in their actual values, i.e. whether the QB mode can be weakened over the regions after 2000 in terms of the logic in Bejarano and Jin (Figure 3(b) in 2008).

4. Summary

This study analyzes the interdecadal changes of ENSO properties emerging around the year 2000. Results show that, after 2000, ENSO events occurred more frequently but became much weaker; the main directions of SST anomaly propagation turned from eastward to almost static; and the significance of ENSO’s periodicity decreased greatly. It is demonstrated that such significant changes in ENSO’s amplitude, frequency and spatial pattern are essentially
Figure 3. Lead–lag regressions of the meridional mean (5°N–5°S) equatorial Pacific SST anomalies upon the (a, b) Niño3.4 index, (c, d) CTI (cold-tongue Niño index), and (e, f) WPI (warm-pool Niño index) before (left-hand panels) and after (right-hand panels) 2000. Note: The periods are 1980–1999 and 2000–2015. Units: °C.
significant periods at ENSO timescales were around 30 and 60 months, reflecting the fact that both the QQ and QB mode were significantly active at that time, though the observed appearance of ENSO was mainly characterized by EP ENSO. In contrast, after 2000, the EP type almost disappeared and the CP type became relatively weaker but occurred more frequently. Meanwhile, the dominant period of ENSO was around 30 months, but the approximately 60-months period became insignificant. Furthermore, these changes could be associated with the dramatic weakening of the QQ mode, while the intensity of the QB mode also weakened in the eastern tropical Pacific but remained significant over the western-central tropical Pacific. However, the spatial structures of both ENSO types did not clearly change, as determined by directly comparing the two periods of 1980–1999 and 2000–2015.

Our results reveal the possible roles of the two ENSO types/modes in forming the observed ENSO interdecadal changes. The essence of the interdecadal changes of ENSO is that the relative activity or stability of the two ENSO modes has changed since 2000. The intensity of both the QQ and QB mode has weakened after 2000, but the QB mode has remained active, as manifested by the CP type becoming dominant in the tropical Pacific after 2000. Meanwhile, the QQ mode has become much weaker and lost dominance in terms of the EP type almost disappearing. The observed changes of ENSO properties were under such changes of the stability of ENSO.

The causes of the interdecadal ENSO changes around 2000 are also preliminarily discussed in this study. It is suggested, since 2000, the mean surface trade winds connected with the different changes in the two ENSO types, which correspond to two coupled ENSO modes – the QQ mode and QB mode. During 1980–1999, the

Figure 4. Wavelet analysis of the Niño4 index, Niño3.4 index, Niño3 index, WPI (warm-pool Niño index), and CTI (cold-tongue Niño index) for the different periods.
Note: The 95% confidence level is represented by red dashed lines. The periods are 1980–1999 and 2000–2015.

Figure 5. Mean (contours) and difference (shading) of (a) zonal surface wind stress and (b) the meridional mean (2°N–2°S) ocean temperature along the equatorial Pacific.
Notes: The mean is the average of January 2000 to December 2015. The difference is between January 2000 to December 2015 and January 1980 to December 1999. The green solid line in (b) denotes the averaged thermocline in January 2000 to December 2015. The yellow dashed line in (b) denotes the averaged thermocline in January 1980 to December 1999. The units are N m⁻² in (a) and °C in (b).
have weakened markedly in the eastern tropical Pacific, contributing to the remarkable suppression of the QQ mode or EP type ENSO since that time. However, the deepened thermocline and intensified surface trade winds in the western-central tropical Pacific may cancel out each other’s influences on the QB mode. It is difficult to conclude whether or not the QB mode or CP type ENSO could be weakened under such conditions. The influences of both the surface winds and thermocline depth on both modes need to be further validated in future studies. ENSO is important in modulating global weather and climate. And, EP and CP ENSO have quite different impacts on the atmospheric circulation over the western North Pacific during boreal autumn, and thus on autumn rainfall over southern China. More autumn droughts have happened over southern China in recent decades, most notably in 2004 and 2009, which is possibly associated with the higher frequency of CP El Niño events (Zhang et al. 2011). To understand this interdecadal change and the two ENSO types/modes in more depth remains an important issue and requires further research.

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