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Traditional El Niño and El Niño Modoki Revisited: Is El Niño Modoki Linearly Independent of Traditional El Niño?

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Abstract The present study revisited the first two leading modes of tropical Pacific sea surface temperature anomalies (SSTA) during the period of 1979–2008. It is suggested that the so-called El Niño Modoki, which is captured by the second mode, exists objectively and exhibits obvious differences from traditional El Niño, which is captured by the first mode, in terms of its spatial characteristics. Furthermore, the authors found that El Niño Modoki is linearly independent of traditional El Niño; hence, it cannot be described as part of the traditional El Niño evolution, and vice versa.

Keywords: El Niño, El Niño Modoki, linear independence

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1 Introduction

El Niño is a dominant source of interannual climate variability around the world (Trenberth, 1997), and it has received attention in many studies over the last decades (e.g., Bjerknes, 1969; Rasmusson and Carpenter, 1982; McPhaden, 1999; Lin, 2009). In earlier studies, El Niño was portrayed as a tropical sea surface temperature anomalies (SSTA) warming event with an anomalous center in the eastern tropical Pacific (Bjerknes, 1969). In later studies, it was noticed that the El Niño SSTA center could also occur in the central tropical Pacific (Fu et al., 1986). This finding suggested that there might be more than one type of El Niño. Recently, El Niño Modoki has been identified as a new type of El Niño in the tropical Pacific, one that is obviously different from traditional El Niño in terms of its spatial and temporal characteristics as well as its teleconnection patterns (Ashok et al., 2007; Weng et al., 2007, 2009; Ashok and Yamagata, 2009; Taschetto and England, 2009). Therefore, a basic question has been posed: Is El Niño Modoki linearly independent of traditional El Niño?

The primary goal of this study was to obtain a satisfying answer to the aforementioned question. In addition, we outlined the existence of traditional El Niño and El Niño Modoki as well as their spatial differences. The study report is arranged as follows. Section 2 briefly describes the data obtained. Section 3 revisits the first two modes of tropical Pacific SSTA and confirms the existence of traditional El Niño and El Niño Modoki as well as their spatial differences. Section 4 further explores the linear independence of these two types of El Niño. The conclusions and discussion are presented in Section 5.

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2 Data

For SST, we used the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al., 2003). This dataset includes data from 1870 until the present times. In this study, we only used monthly data from 1979 to 2008 because we do know that most El Niño Modoki events have occurred since the late 1970s (Ashok et al., 2007; Yeh et al., 2009; Kug et al., 2009; Kim et al., 2009; Ashok and Yamagata, 2009). For surface wind, National Centre for Environmental Prediction–Department of Energy (NCEP–DOE) Reanalysis 2 data were used for the period from 1979 to 2008 (Kanamitsu et al., 2002). Anomalies were described as deviations from climatology in the above base period.

3 Traditional El Niño and El Niño Modoki

3.1 Climate modes of tropical Pacific variability

Climate modes of tropical Pacific variability have been evaluated previously (Ashok et al., 2007; Kao and Yu, 2009). However, to further study traditional El Niño and El Niño Modoki, as shown in Fig. 1, we revisited the first two Empirical Orthogonal Function (EOF) modes of monthly SSTA over the tropical Pacific (30°S–30°N, 120°E–70°W). The EOF1 pattern (Fig. 1a) associated with its principal component (PC1, Fig. 1b), which explains 44.8% of the total variance, exhibits a traditional El Niño pattern (Rasmusson and Carpenter, 1982) that is centered in the equatorial eastern Pacific and extends into the equatorial central Pacific. The EOF2 pattern (Fig. 1c), which explains 11.4% of the total variance, is composed of an anomalous warming in the central tropical Pacific flanked by an SST to the east and west that is colder than normal. The magnitudes of SSTA in the central and eastern Pacific are comparable. Because the variances explained by the first two EOF modes are well separated (North et al., 1982) and because the first two EOF patterns are supported by results from the composite analyses discussed in Section 3.2, it is reasonable to expect that these two patterns represent significantly different modes of tropical Pacific SSTA variability. Ashok et al. (2007)

referred to the EOF2 SSTA pattern associated with the positive phase of its principal component (PC2, Fig. 1d) as a new type of El Niño called El Niño Modoki. Other names, such as Dateline El Niño (Larkin and Harrison, 2005), Central Pacific El Niño (Kim et al., 2009; Yeh et al., 2009; Kao and Yu, 2009), and Warm Pool El Niño (Kug et al., 2009), have been proposed from slightly different standpoints. Although not emphasized as a new type of El Niño, the existence of this second mode had been implied in earlier studies, including those by An (2003, see his Fig. 1a) and Trenberth et al. (2002, see their Fig. 11(bottom)).

One significant difference between the first two modes involves their unique spatial characteristics. It was noticed that the anomaly center of the first mode is confined along the equator (Fig. 1a), while the second mode has a wider meridional structure that extends toward the subtropics (Fig. 1c). When the EOF analysis was applied by confining the meridional domain to 20°S–20°N (10°S–10°N), the explained variance of the first mode that still captured a traditional El Niño pattern (data not shown) rose to 55.5% (66.9%), but the explained variance of the second mode that still captured an El Niño Modoki pattern (data not shown) did not change significantly. This exercise provides potent corroboration of the aforementioned statement. It should also be noted that the wider meridional horseshoe pattern associated with the second mode is closer to the so-called Pacific decadal oscillation (PDO) (Latif et al., 1997, see their Fig. 1a). Comparing Fig. 1b with Fig. 1d, one can find that the PC1 has just an interannual sign (a period of approximately 2–7 years); by contrast, the PC2 seems to exist some periods more than 10 years (although not statistically significant) in addition to the interannual sign. The internal relationships between the similar horseshoe patterns in the interannual and decadal SST variability are worthy of further study but are beyond the scope of the present study.

3.2 Existence of traditional El Niño and El Niño Modoki

EOF analysis decomposes temporal variations into orthogonal spatial patterns that sometimes reveal independent physical mechanisms (Chen et al., 2002). Nevertheless, the possibility still exists that the climate modes that are obtained through EOF analysis do not exist objectively. To reduce the possibility that traditional El Niño and El Niño Modoki are artificial results due to the EOF analysis, we applied composite analyses to further examine the existence of these two different types of El Niño. We used the two leading PCs to identify traditional El Niño and El Niño Modoki during the period of 1979 to 2008. The events whose PC values exceed one standard deviation (dashed lines in Figs. 1b and 1d) for at least three consecutive months were selected for the composite analysis. The composite was produced according to the peak month of the selected events. A total of four and seven cases were composited for traditional El Niño and El Niño Modoki, respectively. The corresponding results are shown in Fig. 2. Positive (negative) SSTA are shaded dark (light) when they pass a 95% Student's *t*-test. The composite traditional El Niño (Fig. 2a) is remarkable and strongly resembles the positive phase of EOF1 (Fig. 1a), while the composite El Niño Modoki (Fig. 2b) is also remarkable and strongly resembles the positive phase of EOF2 (Fig. 1c). These similarities increase our confidence that traditional El Niño and El Niño Modoki are not artificial results of the EOF analysis and instead exist objectively.

In general, the composite traditional El Niño and El Niño Modoki shown in Fig. 2 do not overlap spatially. One way to summarize the extent of their spatial differences is via the spatial correlation statistics between the composite SSTA associated with traditional El Niño and El Niño Modoki, as shown in the work of Larkin and Harrison (2005). Traditional El Niño and El Niño Modoki

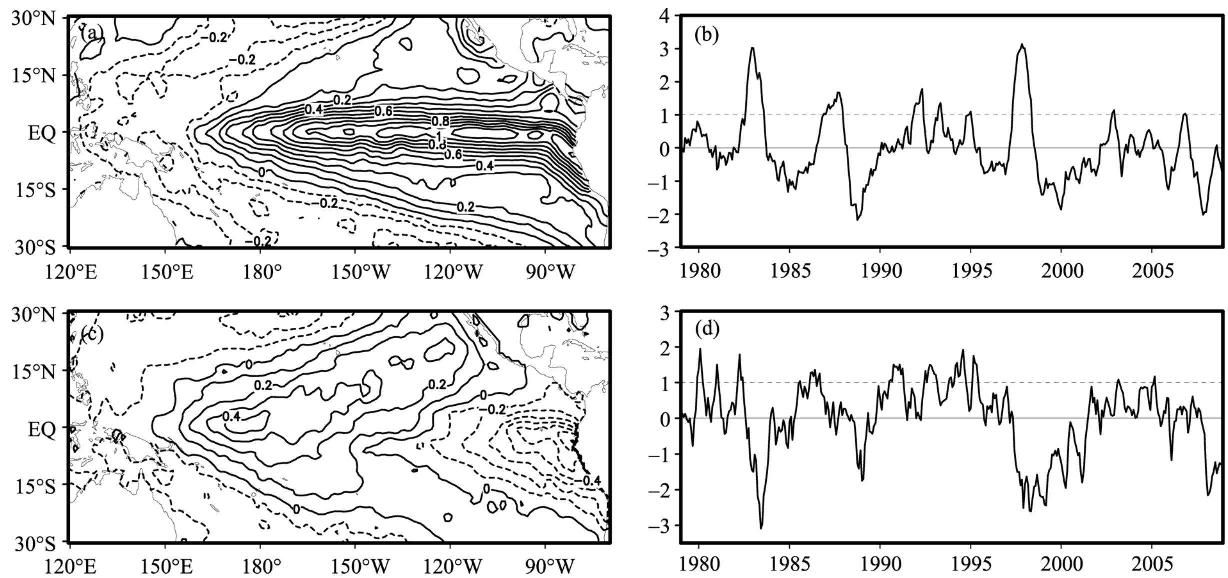

Figure 1 The first (a) EOF pattern (units: °C) multiplied by the standard deviation of its principal component and (b) normalized principal component (PC1); the second (c) EOF pattern (units: °C) multiplied by the standard deviation of its principal component and (d) normalized principal component (PC2) of the tropical Pacific SSTA during the period from 1979 to 2008.

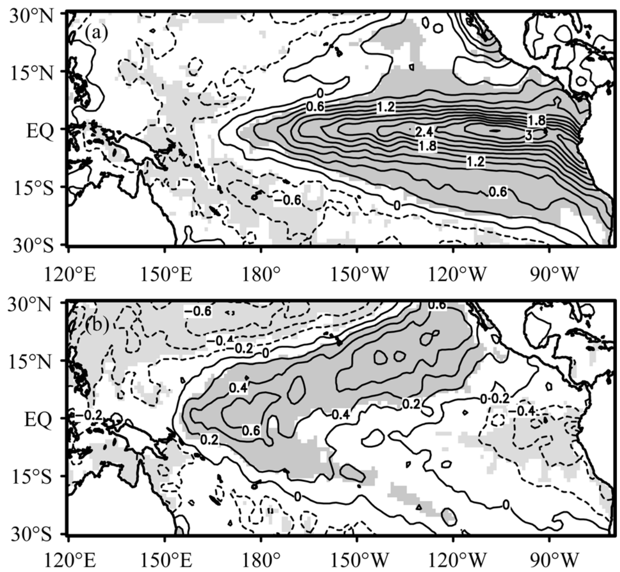

Figure 2 Composite SSTA (units: °C) for (a) traditional El Niño and (b) El Niño Modoki. The contour interval is 0.3°C in (a) and 0.2°C in (b). Negative contours are dashed. Positive (negative) values are shaded dark (light) when they pass the 95% Student's *t*-test.

are significantly different and have near zero correlations. The spatial correlation value between the composite SSTA associated with traditional El Niño and El Niño Modoki is only 0.05, while that between the composite statistically significant SSTA (zeroing non-significant anomalies) associated with traditional El Niño and El Niño Modoki is only 0.06. This finding suggests that traditional El Niño and El Niño Modoki (which exist objectively) are obviously different in terms of their spatial characteristics.

4 Linear independence between traditional El Niño and El Niño Modoki

Trenberth and Stepaniak (2001) and Trenberth et al. (2002) (TST hereafter) were among the first to recognize that the first two modes of tropical Pacific SSTA characterize two different types of El Niño. They indicated that the first two modes are significantly correlated to each other at different lag/lead times; hence, they concluded that these two modes are not linearly independent and that the second mode is simply one phase of traditional El Niño evolution. Later, Ashok et al. (2007) analyzed the relationship between the traditional El Niño index (Niño3.4 index) and the El Niño Modoki indices (TNI and EMI) and argued that the hypothesis of TST does not seem to be supported consistently. For example, the 1982–83 traditional El Niño event may fit the conjecture of TST. However, the 1997–98 traditional El Niño event does not seem to satisfy their hypothesis because the strong traditional El Niño event was preceded by a very weak El Niño Modoki event. In fact, it is still unclear from these previous studies (TST; Ashok et al., 2007) whether El Niño Modoki is linearly independent of traditional El Niño because they only showed a simple relationship between PC1 (or the traditional El Niño index) and PC2 (or the El Niño Modoki index). More analyses are needed to determine if traditional El Niño and El Niño Modoki are linearly independent of each other.

We first performed a lead-lag correlation between the PC1 (Fig. 1b) and the PC2 (Fig. 1d), as in the works of TST. A maximum correlation with PC2 leading PC1 was 0.41 (passing the 95% Student's *t*-test but does not reach statistical significance at the 99% level) at a 12-month lead time, while that with PC1 leading PC2 was −0.20 (not statistically significant) at a 17-month lead time. This result suggests that an EOF1 pattern should occur approximately 12 months after an EOF2 pattern, while an EOF2 pattern with a reversed sign should occur approximately 17 months after an EOF1 pattern, according to the hypothesis of TST. However, it is not known whether this actually happens. On the other hand, the magnitudes of the correlation values between the normalized PC1 and normalized PC2 at different lag/lead times indicate that only 16.8% of the total variance of EOF1 can be explained by EOF2, while only 4% of the total variance of EOF2 can be explained by EOF1. Then, the conjecture of TST in doubt, we further present the regression SSTA and surface wind with a normalized PC1 at a 0-month lag time (Fig. 3a) and a normalized PC2 at a 0-month (Fig. 3b) and 12-month lag time (Fig. 3c).

Not unexpectedly, Figs. 3a and 3b match Figs. 1a and 1b in terms of both SSTA pattern and magnitude, which capture traditional El Niño and El Niño Modoki, respectively. The former is associated with significant westerly wind anomalies over the equatorial central-eastern Pacific, which would deepen (shoal) the thermocline over the eastern (western) Pacific and thus induce SSTA warming over the eastern Pacific through the so-called thermocline feedback (Kao and Yu, 2009). By contrast, the latter accompanies anomalous westerlies over the western-central Pacific and anomalous easterlies over the eastern Pacific. On one hand, those westerly wind anomalies may drive eastward mixed layer warm advection in the western to central Pacific due to the mean temperature gradient and thus develop warming in the central Pacific through the so-called zonal advective feedback (Kug et al., 2009); on the other hand, because these winds cause convergence in the central Pacific, the thermocline in the central Pacific further deepens, which would increase warming in the central Pacific (Ashok et al., 2007). In addition, the anomalous easterlies may cause SSTA cooling over the eastern Pacific through anomalous upwelling, excess evaporation and vertical turbulent mixing (Kug et al., 2009). According to the hypothesis of TST, a traditional El Niño, as shown in Fig. 3a, should appear in Fig. 3c. Does this situation occur? Unfortunately, the statistically significant SSTA warming in Fig. 3c is still confined to the central Pacific that extends toward the northern subtropics rather than propagating into the Niño1+2 region where the variance of SSTA contributing to the traditional El Niño (Fig. 3a) is strongest over the tropical Pacific. Moreover, the anomalous values in Fig. 3c are much lower than those in Fig. 3a. Accordingly, Fig. 3c is fundamentally different from traditional El Niño (Fig. 3a) in

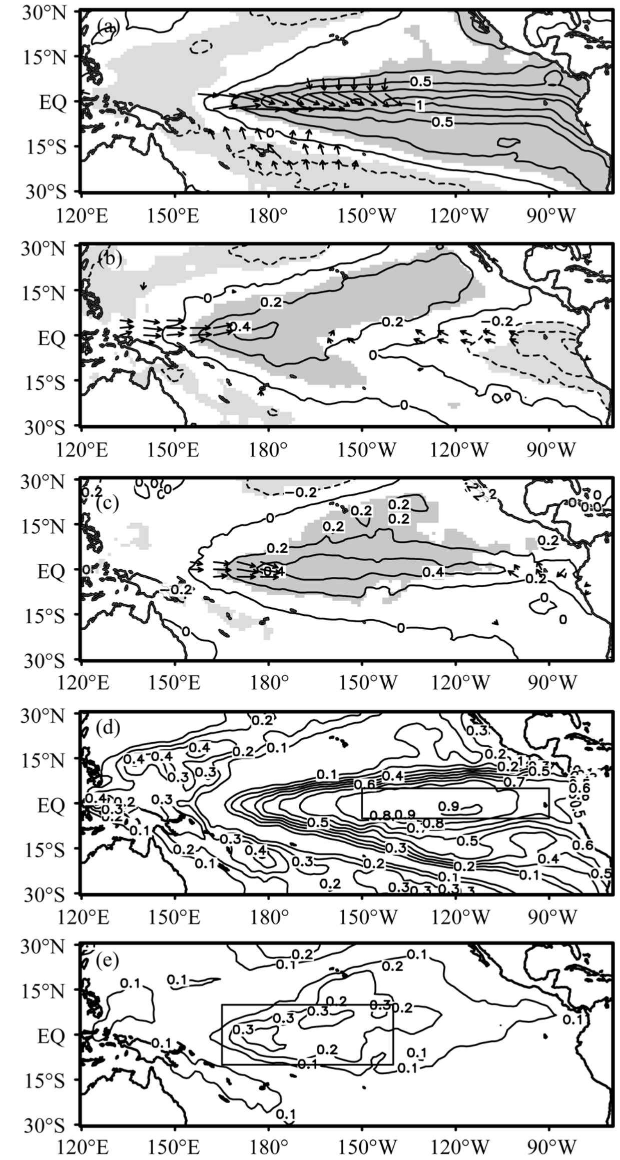

Figure 3 Regression SST and surface wind anomalies with the normalized PC1 (a) at 0-month lag time and with the normalized PC2 (b) at a 0-month lag time and (c) at a 12-month lag time; the percentage of variance of (d) traditional El Niño SSTA signals and (e) SSTA signals in (c) in the total interannual SST variance at each grid over the tropical Pacific. Negative contours are dashed. Wind vectors are shown, and positive (negative) SSTA are shaded dark (light) in (a), (b), and (c) when they pass the 95% Student's *t*-test. The boxes in (d) and (e) mark the Niño3 region (5°N−5°S, 150−90°W) and the central Pacific region (10°S−10°N, 165°E−140°W), respectively.

terms of both SSTA pattern and magnitude; instead, it could be identified as a certain phase of El Niño Modoki evolution (Ashok et al., 2007, see their Fig. 5b) or the residual signals between traditional El Niño and El Niño Modoki (Weng et al., 2007, see their Fig. 2c). This result is supported by the corresponding surface winds with anomalous westerlies over the central Pacific and anomalous easterlies over the eastern Pacific but not with strong westerly wind anomalies in the central-eastern Pacific. In other words, the EOF1 pattern (traditional El Niño) does not occur 12 months after the EOF2 pattern (El Niño Modoki).

To further reveal the differences between traditional El Niño signals and the signals of Fig. 3c, we obtained traditional El Niño signals by multiplying the pattern in Fig. 3a with the normalized PC1 and signals of Fig. 3c by multiplying the pattern in Fig. 3c with the corresponding normalized PC2 at a 12-month lead time. Then, the percentages of variances of these two types of signals in the total SST variance at each grid over the tropical Pacific were performed and are shown in Figs. 3d and 3e, respectively. Figure 3d shows that traditional El Niño SSTA signals explain more than 50% of the total SSTA variance over the equatorial Pacific east of the international dateline, with the maximum (more than 90%) in the Niño3 region (box in Fig. 3d). Figure 3e shows that the percentage of variance of SST signals in Fig. 3c in the total SST variance is much less than that of traditional El Niño signals, as shown in Fig. 3d. Moreover, the maximum (approximately 30%) in Fig. 3e is located in the central Pacific (box in Fig. 3e) but not in the Niño3 region. It is suggested again that the SSTA signals of Fig. 3c are different from traditional El Niño SSTA signals. In other words, traditional El Niño (EOF1 pattern) does not occur 12 months after El Niño Modoki (EOF2 pattern).

As explained above, a maximum correlation with PC1 leading PC2 is only −0.20 (not statistically significant) at a 17-month lead time, which means that only 4% of the total variance of EOF2 can be explained by EOF1. We also believe that an EOF2 pattern with a reversed sign does not occur approximately 17 months after an EOF1 pattern. In fact, the regression SSTA pattern with the normalized PC1 at a 17-month lag time (data not shown) is not statistically significant and is fundamentally different from an EOF2 pattern with a reversed sign in terms of both pattern and magnitude.

The analysis in this section indicates that the hypothesis of TST is flawed, with problems that can be ascribed to their use of a simple relationship between PC1 and PC2. Traditional El Niño and El Niño Modoki, which are represented by the first two modes of tropical Pacific SSTA, cannot be explained by each other. El Niño Modoki is linearly independent of traditional El Niño and cannot be described as part of traditional El Niño evolution, and vice versa.

5 Conclusions and discussion

Two different types of El Niño (traditional El Niño and El Niño Modoki) in the tropical Pacific were revisited through EOF analysis. They are described and contrasted in terms of their spatial structures: traditional El Niño is confined along the equator with a warming SSTA center in the equatorial central and eastern Pacific, while El Niño Modoki has a wider meridional horseshoe pattern with a warming SSTA center in the central tropical Pacific, flanked by opposite SSTA in the western and eastern Pacific. The composite analysis further confirms that traditional El Niño and El Niño Modoki are not artificial results of the EOF analysis and exist objectively. Finally, we performed a regression analysis to study the linear independence between traditional El Niño and El Niño Modoki. It was found that traditional El Niño and El Niño Modoki cannot be explained by each other, and El Niño Modoki cannot be regarded as part of traditional El Niño evolution, and vice versa.

Statistically, this study suggests that there are two different types of El Niño that are linearly independent. They might be understood in terms of two important feedback processes: thermocline feedback and zonal advective feedback. For traditional El Niño, the large SSTA occur in the eastern tropical Pacific, where the thermocline is shallow and interannual SSTA variability is dominated by the upwelling associated with thermocline feedback (An and Jin, 2001). By contrast, for El Niño Modoki, the SST warming occurs in the central tropical Pacific, where the thermocline is relatively deeper and zonal advective feedback usually plays a more important role in governing the interannual SSTA variability than vertical heat (Wang and McPhaden, 2000). More research is needed to better identify the dynamic differences between these two types of El Niño. The authors believe that this work provides potential implications for seasonal prediction as well as stimulating people's interest in the research subject.

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