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Short Communication

Identifying the types of major El Niño events since 1870

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ABSTRACT: This study develops a pattern correlation method to determine the type of major El Niño events since 1870 from a reconstructed sea surface temperature dataset. Different from other identification methods, this method allows an El Niño event to be of the Central-Pacific (CP) type, the Eastern-Pacific (EP) type, or the Mixed type (i.e. the both types coexist). Application of this method to the 39 major El Niño events identified by the Ocean Niño Index during the period 1870–2010 results in 8 events that are categorized to be of the EP type, 16 of the CP type, and 15 of Mixed type. Before the 1910s, the El Niño events are mostly of the EP type, but are mostly the CP type after 2000, while in between both types occurred. The consistencies and inconsistencies between the El Niño types identified by this method and other three methods, which have been proposed recently for El Niño-type classification, are examined and discussed. All four methods consistently identify the El Niño events occurring in the following years to be of the EP types: 1876–1877, 1881, 1884–1885, 1895–1896, 1896–1897, 1918–1919, 1982–1983, and 1997–1998; and the events occurring in the following years to be of the CP type: 1968–1969, 1977–1978, 1994–1995, 2004–2005, and 2009–2010. It is evident that the characteristics of the EP type of El Niño are more robust in the 19th century and the early part of the 20th century, whereas the characteristics of the CP type of El Niño is more robust in the late 20th century and the early 21st century. The list of the El Niño types produced by this study can be used for selecting El Niño events to further study the dynamics and climate impacts of the EP, CP, and Mixed types of El Niño. Copyright © 2012 Royal Meteorological Society

KEY WORDS Central-Pacific El Niño; pattern correlation method; identifying El Niño types; Eastern-Pacific El Niño

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1. Introduction

It has been increasingly recognized that different types or flavours of El Niño exist (e.g. Trenberth and Stepaniak, 2001; Larkin and Harrison, 2005; Ashok *et al*., 2007; Yu and Kao, 2007; Guan and Nigam, 2008; Kao and Yu, 2009; Kug *et al*., 2009). The two types, which have recently been emphasized, are the Central-Pacific (CP) type that has sea surface temperature (SST) anomalies near the Date Line and the Eastern-Pacific (EP) type that has anomalies centred over the cold tongue (Yu and Kao, 2007; Kao and Yu, 2009). The EP type has been considered as the conventional type of El Niño (Rasmusson and Carpenter, 1982), but the CP type has been occurring more frequently in recent decades (e.g. Ashok *et al*., 2007; Kao and Yu, 2009; Kug *et al*., 2009; Lee and McPhaden, 2010; McPhaden *et al*., 2011; Newman *et al*., 2011).

To better understand these two types of El Niño, particularly the non-conventional CP type, it is important to be able to identify the type of major El Niño events. Several identification methods have been proposed. Some of them determine the El Niño type based on the central location of surface or subsurface ocean temperature anomalies (e.g. Kug *et al*., 2009; Ren and Jin, 2011; Yeh *et al*., 2009; Yu *et al*., 2011). In Kug *et al*. (2009) and Yeh *et al*. (2009), e.g. an El Niño event is classified as a CP type if SST anomalies averaged over the Niño4 region are greater than those averaged over the Niño3 region and vice versa for the EP type. Ren and Jin (2011) considered that Niño3 and Niño4 indices cannot effectively separate the two types of El Niño, because these two indices are highly correlated in time. They proposed a new set of indices, which has little simultaneous correlation, by performing a simple transformation of the Niño 3 and 4 indices. These transformed indices are then used to identify the two types of El Niño. These new indices are termed Cold Tongue (CT) and Warm Pool (WP) indices for identifying, respectively, the EP and CP El Niño events. Other methods (e.g. Ashok *et al*., 2007; Kao and Yu, 2009) examined the spatial pattern of tropical Pacific SST anomalies to determine the type. Ashok *et al*. (2007), for example, argued that the CP type is characterized by an out-of-phase relation between the SST anomalies in the central Pacific and those in the eastern and western Pacific. An El Niño Modoki Index (EMI) was defined to quantify this out-of-phase relationship, in which half of the SST anomalies averaged over the eastern Pacific

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(110 °W–70 °W, 15 °S–5°N) plus half of those averaged over the western Pacific (125 °E–145 °E, 10 °S–20°N) are subtracted from the anomalies averaged over the central Pacific (165 °E–140 °W, 10 °S–10°N). An El Niño event is considered to be of the CP type if the EMI is greater than a threshold value. Kao and Yu (2009) argued that the EP and CP types have different generation mechanisms and can coexist to contribute to the tropical Pacific SST anomalies, and that contrasting SST anomalies in specific regions of the tropical Pacific cannot fully separate the two types of El Niño. Instead, they used a regression method to separate the SST anomalies into the components associated separately with the EP and CP types and then applied an Empirical Orthogonal Function (EOF) analysis to each of the components to extract the leading spatial patterns of these two types. They then projected tropical Pacific SST anomalies onto these two EOF patterns to determine the El Niño type.

In this study, a pattern correlation method (i.e. the PTN method hereafter) is developed to identify the El Niño type that is also based on the spatial pattern of El Niño SST anomalies but does not require the EOF analysis used in Kao and Yu (2009). This method is then used to determine the types of the major El Niño events observed in the Extended Reconstruction of Historical Sea Surface Temperature version 3b (ERSST; Smith *et al*., 2008) during 1870–2010. The El Niño types identified by this new method are compared with those obtained by other three identification methods: the central-location method (i.e. the NINO method hereafter) used in Kug *et al*. (2009) and Yeh *et al*. (2009), the EMI method used in Ashok *et al*. (2007), and the CT and WP index method (CT/WP method hereafter) proposed by Ren and Jin (2011). A comprehensive list of the El Niño types during the past 141 years is produced from this comparison. Here, it should be noted that the goal of such a comparison is not to determine which method is better than the others, rather it is to demonstrate how different and similar the type classification for major El Niño events produced by the PTN method can be with other methods and the possible reasons for the differences are examined. Although uncertainties are known to exist in the reconstructed SST data, such a comprehensive list should be still useful for the further studies of the different types of El Niño.

2. Results

Our PTN method adopts the view that the EP type of El Niño typically originates in the eastern Pacific near the Niño 1 + 2 region and the CP type originates in the central Pacific near the Niño4 region (Kao and Yu, 2009; Yu and Kim, 2010; Yu *et al*., 2010). To assess the SST anomalies contributed by, for example, the CP type of El Niño, SST anomalies that are regressed with the Niño 1 + 2 SST index are removed. Here, the regression with the Niño 1 + 2 index is considered as a conservative estimate of the influence of the EP El Niño on tropical Pacific SST anomalies, which should be removed to better reveal the SST anomalies associated with the CP El Niño. Similarly, SST anomalies contributed by the EP type are assumed to be better revealed in the residual SST anomalies after the anomalies regressed on the Niño4 SST index (i.e. representing the influence of the CP El Niño) are removed. The use of Niño 1 + 2 and Niño4 indices to separate the two types of El Niño can be supported by Takahashi *et al*. (2011). They found that the evolution of El Niño events tends to cluster around two indices, which are termed C- and E-index; the former is closely related to the Niño4 index and the latter to the Niño 1 + 2 index. We show in Figure 1 the evolution of the SST anomalies along the equatorial Pacific (10 °S–10°N) for five selected El Niño events, which will be used later in the discussion. Also shown in the figure are the residual SST anomalies related to the CP type (i.e. after the regressions with Niño 1 + 2 are removed; the CP residual hereafter) and the residual anomalies related to the EP type (i.e. after the regressions with Niño4 are removed; the EP residual hereafter) during the events. Here, the anomalies are computed by removing the monthly mean climatology and the trend. The monthly mean climatology is calculated based on the same period (1971–2000) that the National Oceanic and Atmospheric Administration (NOAA) uses to define anomalies for their Ocean Niño Index (ONI; 3 month running mean of SST anomalies averaged in the Niño3.4 region). Figure 1(d) shows that the evolution of the SST anomalies associated with the 1997–1998 El Niño, for example, is similar to the evolution of the EP residual but not to the CP residual. Naturally, this major El Niño event should be considered to be EP type. As another example, the evolution of the SST anomalies in the 1994–1995 El Niño (Figure 1(c)) is more similar to the CP residual but less similar to the EP residual and, therefore, this event should be considered to be CP type.

To quantify the spatial similarity, we calculate the pattern correlations between the original SST anomalies and the residual anomalies related to the CP and EP types in each of months over the Pacific between 10 °S and 10°N. We then subtract the pattern correlation with the CP residual from that with the EP residual. A positive difference in the correlation coefficients indicates that the El Niño event is dominated by EP type anomalies, and a negative difference indicates the event is dominated by CP type anomalies. Figure 2 shows the time series of the monthly pattern correlation differences from 1870 to 2010. One obvious feature in Figure 2 is a shift of the correlation difference from positive values in earlier periods to negative values in later periods, indicating that El Niño events have changed from mostly EP type to more CP type over the past 141 years.

Using the pattern correlation difference, we classify all major El Niño events that have occurred since 1870 into three types: EP, CP, or Mixed type. The El Niño events are selected based on NOAA's criterion that the ONI be greater than or equal to +0.5 °C for a period of at least five consecutive overlapping 3 month seasons. Figure 3

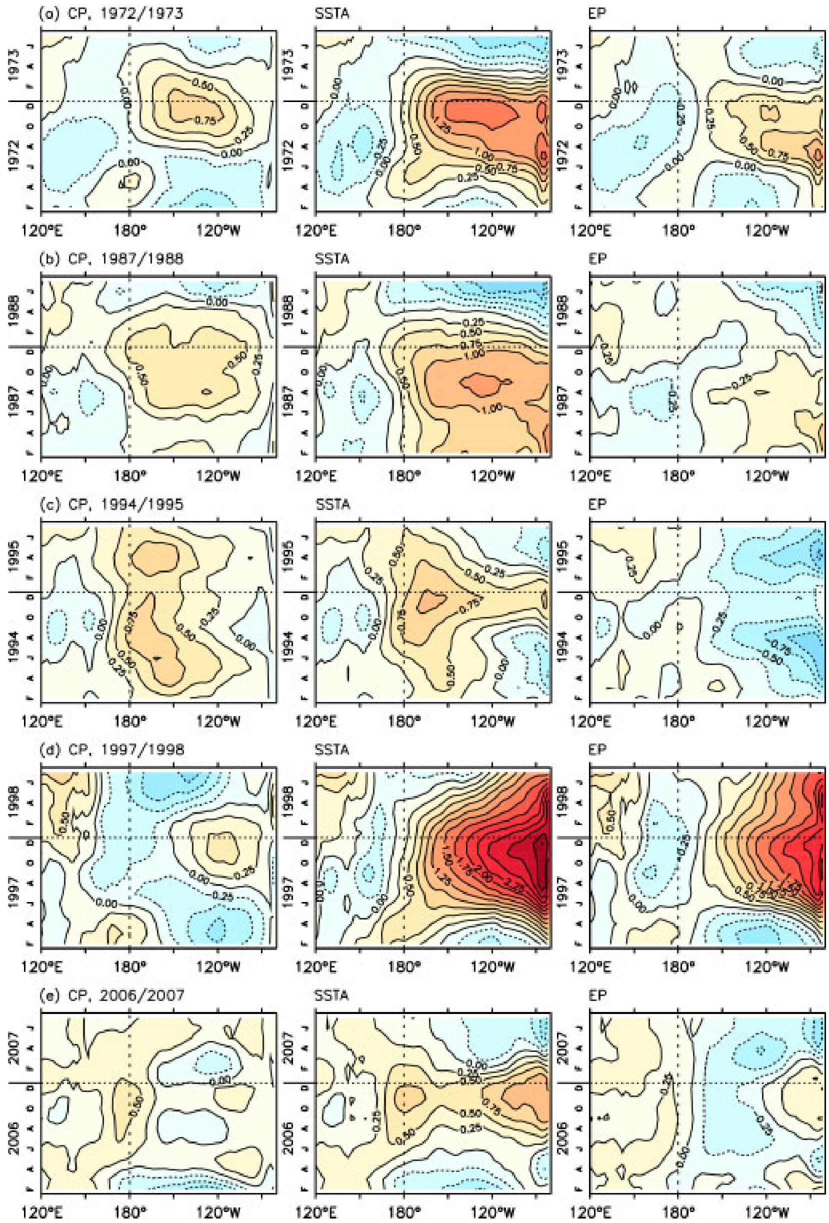

Figure 1. Longitude-time evolution of residual sea surface temperature (SST) anomalies for the CP type (left panels), total SST anomalies (middle panels), and residual anomalies for the EP type (right panels) averaged between 10°N and 10°S for (a) 1972/1973, (b) 1987/1988, (c) 1994/1995, (d) 1997/1998, and (e) 2006/2007 El Niño events.

shows the ONI time series during 1870–2010. In the figure, when the pattern correlation difference is >0.1, the curve is coloured red to indicate the dominance of the EP type. Conversely, the curve is coloured blue indicating dominance by the CP type if the correlation difference is less than -0.1. When the difference is small, namely between 0.1 and -0.1, the curve is coloured in a blend of blue and red to indicate a Mixed type in which both the EP and CP types have comparable contributions to the event. The values of ± 0.1 are subjectively chosen to represent a range of small difference between the pattern correlations. We have repeated the analysis with ± 0.05 and ± 0.15 for Figure 3 and obtained similar results. Figure 3 offers a straightforward way to visualize the El Niño type during 1870–2010. For example, the figure shows that the extraordinary 1997–1998 El Niño is an EP type. The ONI curve is coloured red from the onset to the termination of this event. For the 1994–1995 El Niño, which we noted previously in Figure 1(c) as a CP type event, the ONI curve is coloured blue throughout the event. In another example, the 1972–1973 El Niño is colour-blended, which indicates that both the EP and CP types contribute comparably to the event. This is consistent with Figure 1(a), which shows the SST anomalies during this event resemble the CP residual in the central Pacific and the EP residual in the eastern Pacific. These three examples demonstrate that the PTN method provides a reasonable assessment of the relative contributions of the EP and CP types to El Niño events.

To assign a single type (EP, CP, or Mixed) to each El Niño event, we choose to look at the pattern correlation difference averaged in December–January–February

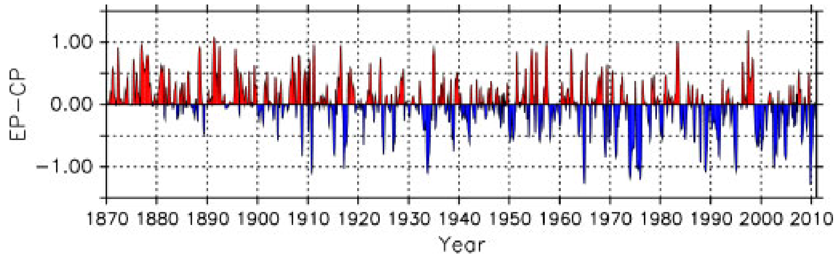

Figure 2. Time series of pattern correlation difference (EP−CP). The pattern correlations are estimated for the regions 120°E–70°W and 10°N–10°S.

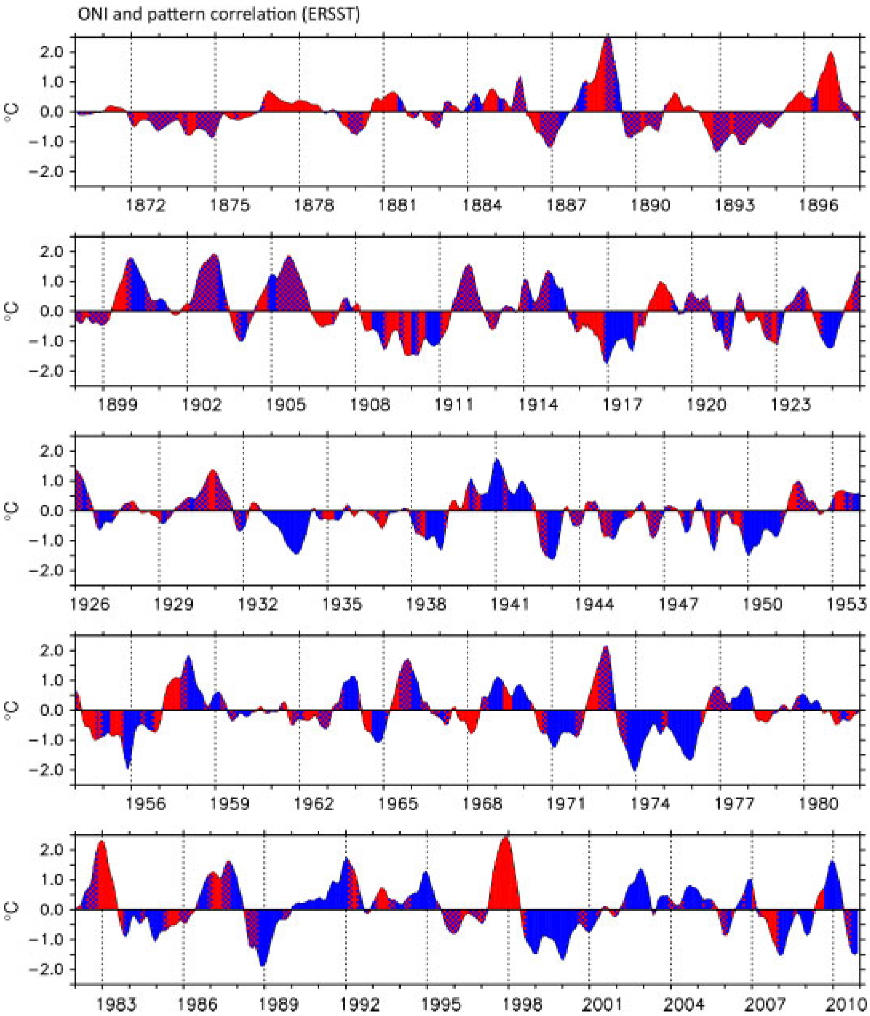

Figure 3. Time series of the ONI with pattern correlation difference superimposed. The red colour indicates EP type, blue colour CP type, and bl0ended colour mixed type.

(DJF), which is the peak season of both the EP and CP types of El Niño (Kao and Yu, 2009). The only exception was the 1881 event, whose large ONI values were not sustained through the winter and a June–July–August (JJA) average was used instead. If the DJF averaged difference is greater (less) than +0.1 (−0.1), the El Niño event is classified as overall an EP (CP) type. If the difference is between 0.1 and −0.1 inclusive, the event is classified as overall a Mixed type. Table I lists the 39 El Niño events and their types as determined by this PTN method. The table shows that 8 of the events are the EP type, 16 of them are the CP type, and 15 of them are the Mixed type. Six of the EP events occurred before the 1910s. Only two such events occurred afterward: the 1982–1983 and 1997–1998 El Niños, which were the two strongest El Niños in the 20th century. This tendency indicates that the EP type used to be the prevailing type of El Niño, particularly before the 20th century, but its dominance decreased throughout the 20th century. On the contrary, the dominance of the CP type has been increasing in the 20th century. Among the 20 El Niño events that occurred after 1950, 12 of them are of the CP

Table I. El Niño events that have occurred during the period of 1870–2010 as identified by the NOAA Ocean Niño Index (ONI) and their type determined by four methods.

	El Niño Years	Type			
		PTN	NINO	EMI	CT/WP
1	1876–1877	EP	EP	EP	EP
2	1881	EP	EP	EP	EP
3	1884–1885	EP	EP	EP	EP
4	1888–1889	MIX	EP	EP	EP
5	1895–1896	EP	EP	EP	EP
6	1896–1897	EP	EP	EP	EP
7	1899–1900	MIX	EP	EP	EP
8	1902–1903	MIX	EP	CP	EP
9	1904–1905	CP	EP	CP	EP
10	1905–1906	MIX	EP	EP	EP
11	1911–1912	MIX	EP	EP	EP
12	1914–1915	CP	EP	CP	EP
13	1918–1919	EP	EP	EP	EP
14	1923–1924	MIX	CP	CP	EP
15	1925–1926	MIX	EP	CP	EP
16	1930–1931	MIX	EP	EP	EP
17	1939–1940	MIX	EP	EP	EP
18	1940–1941	CP	EP	CP	EP
19	1941–1942	CP	EP	EP	EP
20	1951–1952	MIX	EP	EP	EP
21	1953–1954	MIX	EP	CP	CP
22	1957–1958	CP	EP	CP	EP
23	1963–1964	CP	EP	CP	EP
24	1965–1966	CP	EP	CP	EP
25	1968–1969	CP	CP	CP	CP
26	1969–1970	CP	EP	EP	EP
27	1972–1973	MIX	EP	EP	EP
28	1976–1977	MIX	EP	EP	EP
29	1977–1978	CP	CP	CP	CP
30	1982–1983	EP	EP	EP	EP
31	1986–1987	MIX	EP	EP	EP
32	1987–1988	CP	EP	EP	CP
33	1991–1992	CP	EP	CP	EP
34	1994–1995	CP	CP	CP	CP
35	1997–1998	EP	EP	EP	EP
36	2002–2003	CP	EP	CP	CP
37	2004–2005	CP	CP	CP	CP
38	2006–2007	MIX	EP	EP	EP
39	2009–2010	CP	CP	CP	CP

The detailed El Niño-type classification methods are explained in the text: EP stands for Eastern Pacific type, CP for Central Pacific type, and MIX for mixed type

type. Six of the remaining eight events are of the Mixed type, in which the CP type still has important contributions to the SST anomalies. The four El Niño events that have occurred so far in the 21st century are mostly the CP type.

The El Niño types determined by the NINO method (Kug *et al.*, 2009; Yeh *et al.*, 2009) and the EMI method (Ashok *et al.*, 2007) are shown in Table I. For the consistency of the analysis, the identification of El Niño types by those methods were based on the DJF averages of their associated indices as used in the PTN method, although Ashok *et al.* (2007) used both June–July–August–September (JJAS) and DJF averages. In the NINO method, an El Niño event is classified as a CP (EP) type when the DJF-averaged value of the Niño4 index is greater (less) than the averaged value of the Niño3 index, which is close to the method in Yeh *et al.* (2009) except that they used a threshold value (i.e. 0.5 °C) for collecting El Niño years. We do not use the value as the major El Niño years are selected based on NOAA's criterion. In the EMI method, an El Niño event is considered to be the CP type when the amplitude of the DJF averaged EMI is ≥0.7STD. Here, STD is the DJF standard deviation (0.46) of the EMI. Similar to the PTN method, both the NINO and EMI methods in Table I show a tendency for an increasing occurrence of the CP type during recent decades, but the tendency is more obvious in the PTN and EMI methods than in the NINO method. In addition, more El Niño events are determined to be of CP type by the spatial-pattern methods (i.e. the PTN and EMI methods) than by the central-location method (i.e. the NINO method).

Thirteen of the 39 El Niño events in the table have the same type for all three methods. These include the 1876–1877, 1881, 1884–1885, 1895–1896, 1896–1897, 1918–1919, 1968–1969, 1977–1978, 1982–1983, 1994–1995, 1997–1998, 2004–2005, and 2009–2010 events. SST anomalies from the 1876–1877 event are displayed in Figure 4(a), as an example, to show the main characteristics of the EP type of El Niño, which include the onset of anomalies along the South American Coast, the extension of the anomalies towards the equator and westward along the equator during the developing phase, and the retreat of the anomalies back to the coast during the decaying phase. As for the CP El Niño, as shown by the 1968–1969 event in Figure 4(b), the SST anomalies onset from the North American Coast spread southwestward towards the equatorial central Pacific and then intensify and decay locally in the central Pacific.

Among the remaining 26 events whose type varies for the three methods, 8 of them are identified as the CP type by the PTN and EMI methods but as the EP type by the NINO method. This group includes the 1904–1905, 1914–1915, 1940–1941, 1957–1958, 1963–1964, 1965–1966, 1991–1992, and 2002–2003 El Niños. SST anomalies from the 1963–1964 event are shown in Figure 4(c) as an example to explain how the discrepancy occurs. The centre of the SST anomalies of this event is located more towards the Niño3 region and is therefore considered as an EP type by the NINO method, but the spatial pattern and the evolution of the anomalies clearly resemble that of the CP type. Therefore, this event should be considered as a CP type and is reasonably identified by the PTN and EMI methods. There is also another group of three events (i.e. the 1941–1942, 1969–1970, and 1987–1988 El Niños) that are considered to be CP type by the PTN method but are identified as the EP type by the other two methods. SST anomalies from the 1987 to 1988 event are examined in Figure 4(d). In this event, the SST anomalies spread from the eastern to the central equatorial Pacific and do not exhibit the out-of-phase relation between the eastern and central Pacific required by the EMI method to be a CP type event. At the same time, the centre of the maximum SST anomalies is located more towards the Niño3 region and is classified as an EP type by the NINO method. However, the evolution shown in Figure 4(d) indicates that the event started in the central Pacific and developed mostly within that area, although the SST anomalies did spread towards the eastern equatorial Pacific and an EP type of El Niño did try, but failed, to develop during October of 1987. From these features, this event should be classified as a CP type. An inspection of Figure 1(b) also confirms that the equatorial SST anomalies observed during this event are more similar to the CP residual than to the EP residual. A similar evaluation is found for the 1941–1942 and 1969–1970 events (not shown). Therefore, the PTN method is reasonable in classifying these two events as CP type.

Excluding the events discussed in the previous paragraph, there remain 15 El Niño events that the PTN method classifies as the Mixed type but the other two methods classify as either the EP or the CP types. The SST anomalies from the 2006 to 2007 El Niño are shown in Figure 4(e) as an example to argue that they should be considered as the Mixed type. It is obvious from the figure that, during this event, the warming developed simultaneously around the Date Line and in the equatorial eastern Pacific, and that the anomalies associated with each of these two centres are comparable. An inspection of Figure 1(e) also reveals that both the CP residual and the EP residual have comparable contribution to the SST

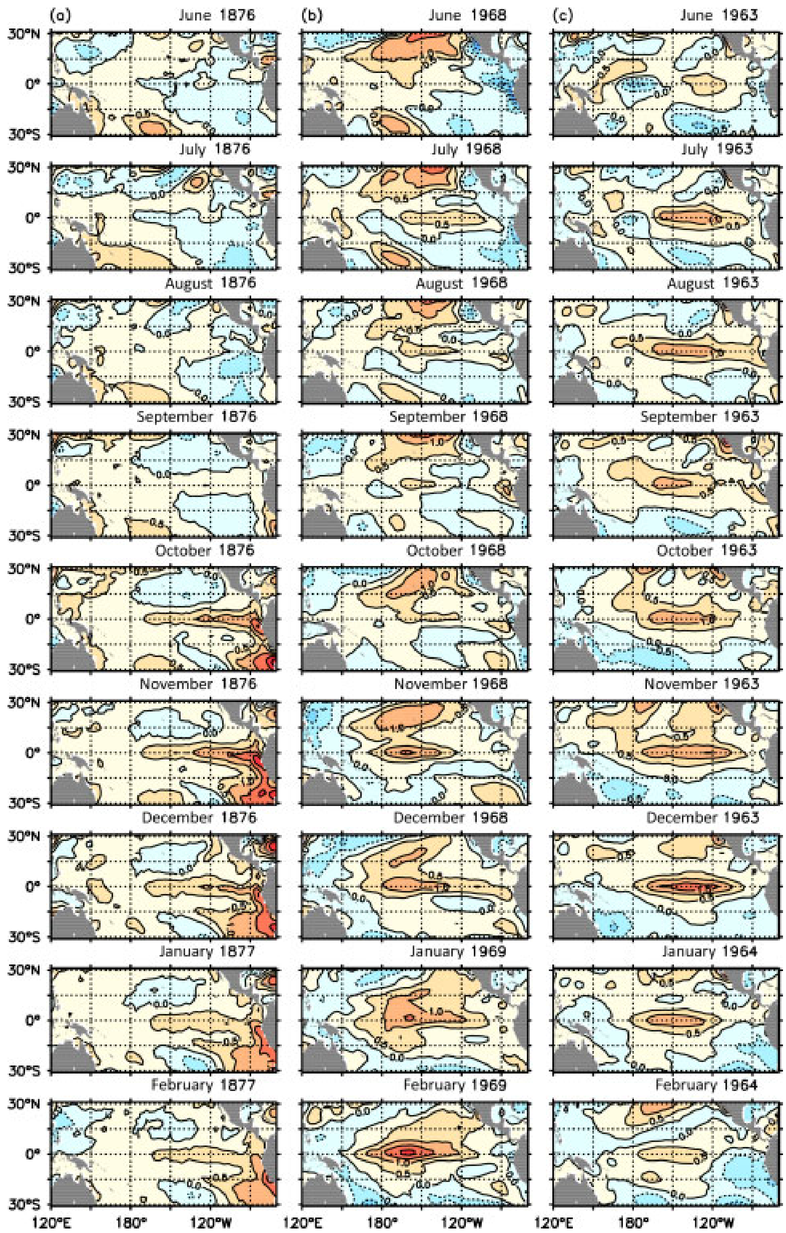

Figure 4. The spatial evolution of tropical SST anomalies from June of the El Niño year to February of the following year for (a) the 1876–1877 and (b) 1968–1969, (c) 1963–1964, (d) 1987–1988, and (e) 2006–2007 events.

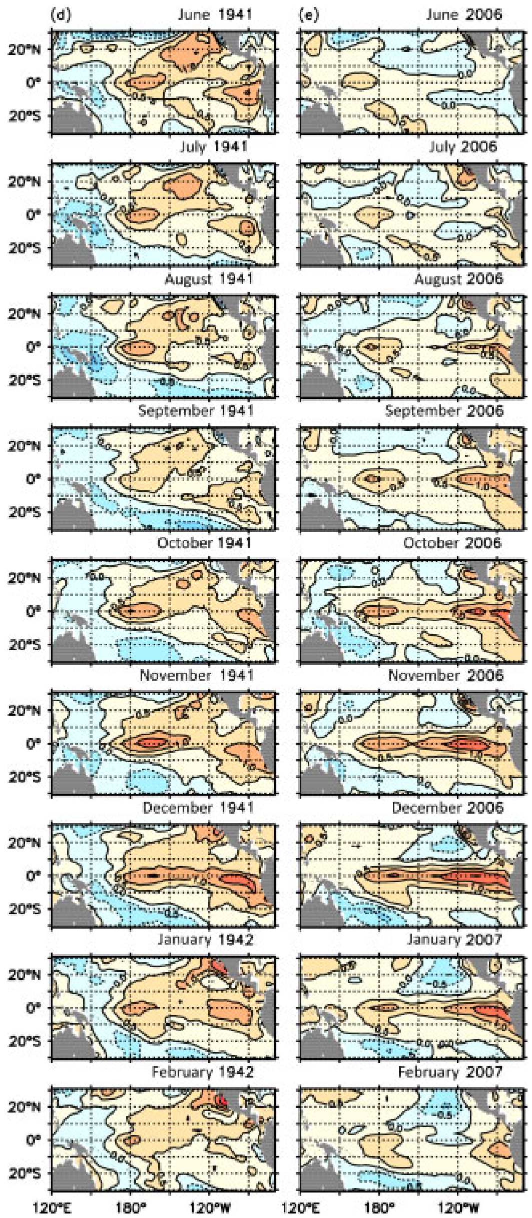

Figure 4. (*Continued*).

anomalies in the equatorial Pacific during the 2006–2007 El Niño event. It is our view that such an event should be classified as a mixture of both the EP and CP types, rather than just an EP type as suggested by the EMI and NINO methods.

We also identified the El Niño types using the CT/WP method of Ren and Jin (2011), where an El Niño event is classified as a CP (EP) type when the DJF-averaged WP index is greater (less) than the DJF CT index. The El Niño types by the CT/WP method are also listed in Table I. As shown in Table I, only four (1923–1924 1953–1954, 1987–1988, and 2002–2003) of 39 El Niño events were classified differently between the CT/WP method and the NINO method, indicating that the simple transformation of the Niño3 and Niño4 indices used in the Ren and Jin (2011) does not affect significantly the classification of El Niño types.

Yeh *et al*. (2009), who also identified the EP and CP types of El Niño events that have occurred since 1870s, found CP El Niño events occurred only after the late 1960s (similar to the result shown in Table I with the NINO method). On the other hand, the PTN method proposed in the study indicates that CP El Niño events can occur before the 1960s. In particular, we find a period from 1940 to 1960 to be a period of frequent occurrence of the CP El Niño events, which deserves further understandings. As mentioned, our PTN method determines the El Niño type based on the spatial pattern of SST anomalies, whereas the method used in Yeh *et al*. (2009) is based on the location of the maximum SST anomalies. The differences in the methods result in different conclusions of whether the CP El Niño began to occur after the late 1960s or there were also periods when it had occurred frequently before the 1960s. The different conclusions have important implications to whether the increasing occurrences of CP El Niño events in the last few decades is a result of global warming or part of multi-decadal variations.

3. Summary and discussion

A pattern correlation method is developed and used in this study to classify types of major El Niño events during the period 1870–2010. The new method is based on the two-type El Niño concept of Kao and Yu (2009), which suggested that the EP El Niño typically originates from the equatorial eastern Pacific near the Niño 1 + 2 region and the CP El Niño originates in central Pacific near the Niño4 region, and that they may be governed by different generation mechanisms and can coexist. The method includes two major steps: (1) linear regression is used to separate the SST anomalies associated with the EP and CP types of El Niño, and (2) pattern correlations between these separated anomalies and the original SST anomalies are compared. This method, therefore, considers SST anomalies in the entire tropical Pacific instead of just a few selected regions. Using this method, we determined that the 39 major El Niño events, which have occurred during 1870–2010, include 8 EP types, 16 CP types, and 15 Mixed types. This classification was compared with those obtained using other three identification methods (i.e. NINO, EMI, and CT/WP methods). Consistencies and inconsistencies in the classification of the El Niño types by all the four methods were further examined. This study produces a comprehensive list of the type of El Niño events since 1870, which can be used to further study the dynamics and climate impacts of the EP, CP, and Mixed types of El Niño.

In this study, all the analyses were conducted with the ERSST data. We also repeated the pattern correlation analysis with the SST datasets from Hadley centre (HadISST; Rayner *et al*., 2003) and Kaplan extended SST version 2 (Kaplan *et al*., 1998) and compared the results (i.e. time series of pattern correlation difference) from all three datasets through a 20 year running window correlation analysis (not shown). As expected, before 1940, the correlation coefficient is greatly decreased relative to correlations after 1950. We also found that there are disagreements even for El Niño years, mainly in the pre-1940 periods. Therefore, for a perfect list of El Niño years and their types since 1870, more improvements are needed to the reanalysis datasets and accordingly we expect that the list of El Niño types that is provided in this study will be updated.

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