1. Introduction

[2] El Niño, which is characterized by unusually warm sea surface temperature (SST) in the eastern Pacific and positive and negative sea level pressure anomalies in the western and the eastern Pacific, respectively, is known as a conspicuous phenomenon of ocean-atmosphere interactions in the equatorial climate system [McPhaden et al., 2006]. National Oceanic and Atmospheric Administration (NOAA) defines El Niño as the occurrence of 3 month averaged SST anomaly above 0.5°C in the Niño3.4 region (5°S–5°N, 170°–120°W). Recent studies, however, show that there are different ‘flavors’ or ‘types’ of El Niño in terms of their spatial patterns. In many conventional El Niño cases, maximum SST anomaly is observed in the eastern Pacific (hereafter, Eastern Pacific (EP) El Niño). In other cases, however, maximum SST anomaly is observed in the central Pacific rather than the eastern Pacific. This nonconventional type has been referred to as “Dateline El Niño” [Larkin and Harrison, 2005a, 2005b], “El Niño Modoki” [Ashok et al., 2007], “Central Pacific El Niño” [Kao and Yu, 2009], or “Warm pool El Niño” [Kug et al., 2009]. Since there is no consensus in the terminology of the nonconventional type of El Niño, it will be called the ‘Central Pacific (CP) El Niño’ in the present study.

[3] The two types of El Niño have significantly different ocean-atmosphere interactions and different tropics–midlatitude atmospheric teleconnection in both hemispheres [Weng et al., 2009; Song et al., 2011]. Many recent studies, therefore, investigated why CP El Niño occurs more frequently and strongly during recent years [Ashok et al., 2007; Yu and Kao, 2007; Kao and Yu, 2009; Kug et al., 2009; Yeh et al., 2009; Lee and McPhaden, 2010]. Despite many recent studies, the reason why CP El Niño is more frequent and stronger in recent years is still unclear.

[4] Climate models, under the anthropogenic greenhouse gas forcing, show a weakening of the trade winds and shoaling of the equatorial thermocline in the central and western Pacific. Therefore, an increasing frequency of the CP El Niño during the recent decade appears to have connection with global warming caused by the anthropogenic forcing [Yeh et al., 2009; Collins et al., 2010; Na et al., 2011]. On the other hand, some studies support that a peculiar trend of the recent CP El Niño is just of natural
origin. Using high-quality satellite observations, McPhaden et al. [2011] argued that the characteristic of El Niño events has varied naturally and their disparate spatial structures are able to cause change in the background state. Also, Newman et al. [2011], using a multivariate red noise approach, argued that the recent change in the occurrence ratios of the two types of El Niño could come from natural variability rather than the anthropogenic forcing. Occurrence ratio of CP El Niño to EP El Niño has been vigorously examined using coupled general circulation models (CGCMs) and the results show that the variation of CP El Niño occurrence is a part of natural climate variability [Kug et al., 2010; Yeh et al., 2011]. Then, it is debatable whether the global warming or natural variation affects the frequency and the types of El Niño. In this paper, we extract two primary SST patterns from various data sets employing cyclostationary empirical orthogonal function (CSEOF) analysis to explain why the characteristic change of the two types of El Niño has occurred during the past decade.

2. Data and Method

[6] The SST data sets used in this study are the 60 year (1951–2010) NOAA extended reconstruction of historical sea surface temperature version 3 (ERSST V3) [Smith and Reynolds, 2004] from the National Climate Data Center, the Met Office Hadley Centre sea ice and sea surface temperature data (HadISST) [Rayner et al., 2003], and the 49 year (1958–2006) simple ocean data assimilation reanalysis (SODA) data [Carton et al., 2008]. Subsurface temperatures were derived from the SODA data set, and precipitation values used are the satellite products from Global Precipitation Climatology Project (GPCP) [Adler et al., 2003]. Also used was the Geophysical Fluid Dynamics Laboratory (GFDL) Climate Model version 2.1 (CM 2.1) preindustrial 500 year control data set [Delworth et al., 2006], which was analyzed to understand the CP El Niño in previous studies [Kug et al., 2009; Choi et al., 2011a, 2011b]. At each grid point, monthly mean values were removed from respective months to obtain anomalies from the climatological seasonal cycle.

[7] Recent studies used different methods to separate two types of El Niño: for example, comparison of Niño4 and Niño3 anomalies [Kug et al., 2009; Yeh et al., 2009, 2011], development of new indices [Ashok et al., 2007; Ren and Jin, 2011; Takahashi et al., 2011], combined EOF analysis [Kao and Yu, 2009; Yu and Kim, 2010], and red noise approach [Newman et al., 2011]. These methods capture the occurrence period of El Niño and Southern Oscillation (ENSO) widely known as 3 to 6 years, but do not resolve physical evolution of ENSO varying with the seasons. In order to resolve accurate temporal evolution of ENSO, CSEOF analysis was conducted in this study [Kim et al., 1996; Kim and North, 1997]. As a result, space-time data can be written as

\[ P_n(r, t) = \sum_a B_a(r, t) T_n(t), \]

where \( P(r, t) \) is raw data, \( B_a(r, t) \) are loading vectors (LV), and \( T_n(t) \) are principal coefficient (PC) time series. CSEOF LVs are function of time as well as space. Further, CSEOF LVs are periodic in time. Hence,

\[ B_n(r, t) = B_n(r, t + d), \]

where \( d \) is called the nested period. El Niño cycle has initiation, mature and decay states nearly phase locked to the seasonal variation of equatorial atmosphere-ocean system; therefore, the nested period was set to be 12 months. As a result, each CSEOF LV describes monthly patterns of physical evolution throughout a year. [7] We also used regression analysis in CSEOF space to derive physically consistent evolution of subsurface temperatures and precipitation as follows:

\[ T_n^{(T)}(t) = \sum_{m=1}^M a_m T_m^{(T)}(t) + \varepsilon(t), \]

where \( T_n^{(T)}(t) \) is the target PC time series for mode \( n \), \( a_m \) and \( T_m^{(T)}(t) \) are the regression coefficient and predictor time series for mode \( m \), and \( \varepsilon(t) \) is the regression error. The first 20 PC time series (\( M = 20 \)) of a predictor variable are used in (3). In this study, the target variable is 5 m subsurface temperature and the predictor variables are the subsurface temperatures at all vertical levels from the SODA data set and also the GPCP precipitation. Then, the regressed patterns of the predictor variable, \( R_n^{(P)}(r, t) \), are obtained as shown in (4):

\[ R_n^{(P)}(r, t) = \sum_{m=1}^M a_m R_m^{(P)}(r, t), \]

where \( R_n^{(P)}(r, t) \) is the CSEOF LV for mode \( m \) of the predictor variable. As a result, spatial patterns of the predictor variable are obtained such that they have (nearly) the same PC time series of the target variable. In this sense, the target patterns \( B_n(r, t) \) in (1) and the predictor patterns \( R_m^{(P)}(r, t) \) in (4) are considered physically consistent with each other.

3. Result

3.1. The First Two CSEOF Modes

[8] Using CSEOF analysis, monthly evolution patterns of the first and the second CSEOF modes were derived from the ERSST (Figure 1); the two modes explain about 50% and 10% of the total SST variance, respectively. The spatial patterns of the first mode are characterized by a basin-scale warming from the eastern Pacific to the central Pacific. Its evolution displays westward growing SST anomalies from December to January–February). In contrast, the spatial patterns of the second mode exhibit warming in the central Pacific and the western Pacific, and cooling in the eastern Pacific particularly in spring and summer; the major pattern has an appearance of a dipole structure as already discussed in Ashok et al. [2007] and the noncanonical mode in Guan and Nigam [2008]. In addition, the eastern Pacific negative SST anomaly develops strongly in boreal spring and summer but disappears in winter. Note that we obtain similar results from the other two SST data sets, i.e., HadISST and SODA (see Figures 2b and 2c).
Figure 2a shows the annual mean pattern of the first and second CSEOF LVs extracted from the ERSST. Similarly, Figures 2b and 2c are for the HadISST and the SODA data. The annual mean patterns of CSEOF LVs are quite similar in all three SST data sets, indicating that the two primary CSEOF modes of SST variability are robust. The regressed subsurface temperature patterns from the SODA data set are shown in Figure 2d. The first mode shows the opposite signs of subsurface temperature anomalies between the eastern Pacific and the western Pacific, which is associated with the change in thermocline depth [Kim and Kim, 2004]. This feature suggests that the thermocline feedback mechanism is associated with the first mode in the eastern Pacific. In contrast, the second mode exhibits smaller-scale subsurface warming in the central Pacific, but cooling in the eastern Pacific. The second mode is associated with the thermocline depth in the central and eastern Pacific; this structural difference suggests that the thermocline feedback is less important in the second mode. Moreover, the regressed GPCP precipitation patterns indicate that the atmospheric responses of the two modes are substantially distinct (Figure 2e). These results support that the two modes are physically distinct. In fact, lagged cross correlation between

Figure 1. CSEOF LVs of the (left) first and (right) second modes extracted from the ERSST V3 data set. Contour interval is 0.1°C.
the two PC time series is less than 0.2 for the lag range of 24 months.

The PC time series of the data sets are very similar to each other (Figures 3a and 3b). The PC time series of the first mode has a significant spectral peak in a 4–6 year band (figure not shown). The second mode, on the other hand, has a dominant spectral peak in a 7–11 year band. To verify that the first two modes explain the ENSO variability, we compare the Niño indices provided by NOAA and the reconstructed Niño indices based on the two modes (Figures 3c and 3d). The reconstructed indices based on the first two modes of the ERSST data set are similar to the Niño3 and the Niño4 indices as shown in Figures 3c and 3d. One crucial reason why we used the nested period of 12 months is to establish a firm connection of the first two PC time series with the various ENSO indices used in the present study. While using the nested period of 24 months yields physically reasonable modes, i.e., the low-frequency mode and the biennial mode [Kim, 2002], the PC time series of the biennial mode has little correlation with both the Niño3 to Niño4 time series. Thus, it is difficult to establish that the first two CSEOF modes represent EP El Niño and CP El Niño, respectively.

Table 1 shows correlations between the CSEOF PC time series and various ENSO indices; to characterize the CP El Niño and the EP El Niño, Ashok et al. [2007], Ren and Jin [2011] and Takahashi et al. [2011] developed new pairs of uncorrelated indices. Correlations of the first PC time series

Figure 2. Annually averaged CSEOF LVs of the (left) first and (right) second modes extracted from (a) ERSST V3, (b) HadISST, and (c) SODA data sets. (d) The regressed field of SODA subsurface temperature averaged over 5°S–5°N. Contour interval is 0.1°C. (e) The regressed patterns of GPCP precipitation. Contour interval is 0.2 mm d⁻¹.
with Niño3 and Niño4 are both significantly high since the first mode exhibits significant loading both in the Niño3 and Niño4 regions. As pointed out in previous studies, Niño3 and Niño4 indices are difficult to explain the observed change in the ENSO statistics [Ashok et al., 2007; Ren and Jin, 2011; Takahashi et al., 2011]. The PC time series of the first mode is significantly related with the NCT index [Ren and Jin, 2011] and the C index [Takahashi et al., 2011], which measures the strength of the EP El Niño. In contrast, the PC time series of the second mode is not strongly related with any indices but the El Niño Modoki Index (EMI) defined by Ashok et al. [2007]; this index represents the strength of the CP El Niño. The second PC time series is moderately correlated with the NWP index and the E index, which also measures the strength of the CP El Niño. These results indicate that CSEOF analysis successfully separate the first two modes of the tropical Pacific SST variability in all the three SST data sets.

3.2. Changing Relationship Between the First Two CSEOF Modes

[12] By definition, the PC time series of the two CSEOF modes are nearly independent and they exhibit little lead-lag relationship in the entire analysis period (not shown here). However, sliding correlation with a 10 year window shows that the relationship between the two modes undergoes significant long-term variations. Since the late 1990s, the two modes exhibit a strong in-phase relationship. To examine the characteristic temporal relationship of the two modes on a low-frequency time scale, sliding correlation of the two PC time series is calculated with a 10 year window (Figure 4). The sliding correlation reveals strong decadal variations with significant positive and negative correlations. It is striking that the sliding correlation increases rapidly to 0.87 since the late 1990s in the HadISST and the ERSST data sets. This indicates that the PC time series of the two modes had varied coherently during the recent decade. As a result, a superposition of the first and the second CSEOF modes with the same sign during the recent decade (see Figures 3a and 3b)

<table>
<thead>
<tr>
<th>Niño3</th>
<th>Niño4</th>
<th>EMI</th>
<th>NCT</th>
<th>NWP</th>
<th>E Index</th>
<th>C Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>First mode</td>
<td>0.82</td>
<td>0.80</td>
<td>0.30</td>
<td>0.74</td>
<td>0.54</td>
<td>0.51</td>
</tr>
<tr>
<td>Second mode</td>
<td>0.11</td>
<td>0.37</td>
<td>0.75</td>
<td>0.25</td>
<td>0.58</td>
<td>0.57</td>
</tr>
</tbody>
</table>

*EMI is El Niño Modoki Index (SST averaged over (165°E–140°W × 10°S – 10°N) – 0.5 × SST averaged over (110°W–70°W × 15°S–5°N) – 0.5 × SST averaged over (125°E–145°E × 10°S–20°N) [Ashok et al., 2007]. Cold Tongue El Niño index (NCT; Niño3 – 0.4 × Niño4) and Warm Pool El Niño index (NWP; Niño4 – 0.4 × Niño 3) are defined in Ren and Jin [2011]. Eastern Pacific El Niño index (E index; Niño12 – 0.5 × Niño4) and central Pacific El Niño index (C index; 1.7 × Niño4 – 0.1 × Niño12) are defined in Takahashi et al. [2011].

Figure 3. PC time series of (a) the first and (b) second CSEOF modes from the observational data sets. (c) Niño3 and (d) Niño4 index anomalies from NOAA (black curve) and the reconstruction SST anomalies based on the first two CSEOF modes (red curve).

Figure 4. Sliding correlations between the first and the second PC time series with a 10 year window. Dashed lines denote the 95% significance level based on the t test.
yields a significant warming in the central Pacific but a weak warming in the eastern Pacific. It is argued that the strengthening of the in-phase relationship of the first two CSEOF modes can be a plausible explanation for stronger and more frequent CP El Niños in the recent decade.

[13] In case of 1982/83 and 1997/98 El Niño, the PC time series of the two CSEOF modes are of opposite signs, i.e., positive for the first CSEOF mode and negative for the second mode. The resulting spatial patterns, therefore, appear to be a canonical EP El Niño with a significant warming in the eastern Pacific. Thus, the second mode as well as the first mode contributes significantly to the development of a strong EP El Niño. Not surprisingly, the average amplitude of the first PC time series during boreal winter (DJF) is 1.38 for EP El Niño years (Table 2), but that of the second PC time series is −0.26; this is a favorable condition for canonical EP El Niños. In contrast, the average amplitudes of the first and the second PC time series are respectively 0.65 and 1.04 during DJF for CP Niño years (Table 2), which is a favorable condition for CP El Niños.

[14] Figure 5 displays the composite evolution patterns averaged over 5°S–5°N of the El Niño events (see Table 2) before and after 2000. The SST anomalies in Figure 5 (top) are based on the first two modes by multiplying their LVs with corresponding PCs as in (1). Both plots in Figure 5 (bottom) are based on the actual SST anomalies. Both the actual and the reconstructed SST anomalies show that the center of anomalous SST is located in the central Pacific after 2000, whereas it is located in the EP before 2000. In addition, anomalous SST before 2000 exhibits westward phase propagation with time, which is not seen after 2000. Varying temporal relationship of the two modes causes these evolutionary differences of El Niños before and after 2000. This is an additional support for the in-phase relationship between the two CSEOF modes being the primary reason for more frequent occurrence of CP El Niño since the year 2000.

[15] Figure 6 shows the DJF mean SST anomalies in the Niño3 and the Niño4 regions for the EP El Niño and the CP El Niño years (Table 2). In Figures 6a and 6b, the first bar indicates the DJF Niño3 or Niño4 indices provided by NOAA, the second and the third bars represent the reconstructed Niño3 or Niño4 indices based on the first and the second CSEOF modes, respectively. In Figure 6a, the median values are similar for the first and the second bars while that of the third bar is nearly zero; the first mode explains a significant fraction of Niño3 anomalies while the second mode explains little of the Niño3 anomalies. In contrast, Niño4 index cannot be explained by the first mode alone in CP El Niño years; the second mode explains a significant part of SST variability in the Niño4 region in CP El Niño years. The second mode is as important as the first mode in explaining the occurrence of CP El Niño. While the first mode essentially dictates the occurrence of El Niño or La Niña in the eastern Pacific and its contribution is significantly larger than the second mode, the second mode is essential in determining the central location of ENSO thereby discriminating EP El Niño and CP El Niño.

3.3. GFDL Model Results

[16] Because of the relatively short length of the observational data sets, the varying relationship of the two modes needs to be confirmed from a long coupled GCM simulation. Several studies show that the two types of El Niño are captured well in the GFDL model [Kug et al., 2009; Choi et al., 2011a, 2011b]. Therefore, this model is used to examine the hypothesis above.

[17] The spatial patterns and the PC time series of the first (62.3%) and the second (10.7%) modes were extracted from the GFDL CM2.1 preindustrial 500 year control run. The first mode captures the EP El Niño pattern and the second mode is characterized by a dipole SST anomaly pattern (Figure 7a). The central locations of the spatial patterns, however, are shifted westward by about 20° compared to those of the observations; this is due to model bias as pointed out by Kug et al. [2010]. The subsurface temperature anomaly patterns also show that the first mode is associated with thermocline variability on a basin scale while the second mode is associated with shallower thermocline in the central Pacific (Figure 7b). Despite a westward shift of the SST anomaly patterns, GFDL model results are generally consistent with the observations. The sliding correlation between the two PC time series changes on low-frequency time scales, which further supports that the phase relationship between the two modes undergoes natural variations (black curve in Figure 7c, top). Not surprisingly, difference between the Niño4 m (5°S–5°N, 140°E–170°W) and the Niño3 m (5°S–5°N, 170–110°W), which represents the CP El Niño occurrence ratio in Kug et al. [2010] (black curve in Figure 7c, bottom), coincides reasonably with the sliding correlation (red curve in Figure 7c, top). In contrast, the occurrence of extreme EP El Niños, when the Niño3 m is three times or more than the Niño4 m in magnitude, is tied with the out-of-phase relationship between the two modes (figure not shown). This result indicates that the occurrence ratio of the two types of El Niño fluctuates naturally and is strongly associated with the phase relationship between the two modes.

4. Conclusion Remarks

[18] There are two dominant and independent SST modes of variability in the equatorial Pacific. The first mode captures well the conventional EP El Niño and the second mode exhibits east-west contrast of SST anomalies. Various “flavors” of El Niño and La Niña can be explained as a varying combination of the two modes. The magnitude of the first mode primarily determines the El Niño state. The second mode, on the other hand, dictates the central location

Table 2. EP and CP El Niño Years

<table>
<thead>
<tr>
<th>Years</th>
<th>EP</th>
<th>CP</th>
</tr>
</thead>
</table>

*El Niño years are defined as the years with DJF-averaged SST anomaly above 0.5°C in the Niño3.4 region. EP El Niño is considered to have occurred when Niño3 is greater than Niño4. However, CP El Niño is considered to have occurred when Niño4 is greater than Niño3.
Figure 5. (a and b) Composite maps of SST anomalies averaged over $5^\circ\text{S} - 5^\circ\text{N}$ in El Niño years before 2000 and after 2000 based on the reconstructed SST anomalies using the first two CSEOF modes. (c and d) Composite maps of SST anomalies averaged over $5^\circ\text{S} - 5^\circ\text{N}$ in El Niño years before 2000 and after 2000 based on the actual data. Contour interval is 0.1°C.

Figure 6. Box plots of (a) DJF Niño3 in EP El Niño years and (b) DJF Niño4 index in CP El Niño years. The first bar represents the raw data and the second and third bars represent the first two CSEOF modes, respectively. Each bar shows maximum and minimum of the first, the second (median), and the third quartile values of SST anomalies in Celsius.
of the SST anomalies. When the PC time series of the second mode is negative, the central location of SST anomalies shifts toward the eastern Pacific and EP El Niño may occur. When the PC time series of the second mode is positive, on the other hand, CP El Niño may occur. Thermocline shallows in the eastern Pacific when the amplitude of the second mode is positive. Since the mean thermocline depth is

**Figure 7.** (a) Annually averaged CSEOF LVs of the first and the second modes extracted from the GFDL CM 2.1 500 year run under the preindustrial conditions. The gray boxes denote (left) Niño4 m and (right) Niño3 m regions. (b) The regressed field of subsurface temperature anomalies averaged over 5°S–5°N. Contour interval is 0.2°C for Figures 7a and 7b. (c) The top plot shows sliding correlation between the first and the second PC time series with a 20 year window (black curve) and the 95% significance level based on the t test (dashed lines). The red curve is the 20 year moving averaged difference between the Niño4 m and the Niño3 m anomalies. In the bottom plot, the black curve is the 20 year moving averaged CP El Niño occurrence ratio, which is defined as the number of CP El Niños divided by the number of the both types of El Niños. El Niño years are defined as the years of the Niño3.4 m (5°S–5°N, 170°E–130°W) indices being above 0.5°C. CP El Niño is considered to have occurred when Niño4 m is greater than Niño3 m.

**Figure 8.** Loading vectors of the (left) first and (right) second modes extracted from the 20 year moving mean SST in GFDL CM 2.1 500 year run under the preindustrial conditions. Contour interval is 0.02°C.
relatively shallow in the eastern Pacific, there is a limitation in the extent of shoaling.

[19] The in-phase state of the two modes in recent years leads to a more frequent occurrence of CP El Niño. This tendency also appears in long-term model data; this seems to be a fortifying evidence for the natural variation of the frequency of CP El Niño. This in-phase state can be set up by a change in the mean state as reported in several studies [Yeh et al., 2009; Collins et al., 2010]. In order to confirm this, EOF patterns of the 20 year moving averaged SST were calculated (Figure 8). The PC time series of the second mode, which represents the long-term variation of the zonal SST gradient, is highly correlated with the Niño4 m and Niño3 m (Figure 7c); correlation is 0.80. On the other hand, it is inconclusive that the second EOF denotes a mean state change. Number of El Niño occurrences, particularly the CP El Niño, may vary significantly within a 20 year window; the second EOF may also reflect the temporally varying occurrences of El Niño.

[20] Although the model result suggests the natural fluctuation of the CP El Niño frequency in the absence of global warming, observational data sets do not provide concrete evidence. Thus, we cautiously deduce that the recent change in El Niño statistics is caused simply by positive contributions of the two modes rather than external forcing due to global warming. Henceforth, the null hypothesis that the increased occurrence ratio of CP El Niño is due to natural variability cannot be rejected.

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