On the Relationship between the North Pacific Climate Variability and the Central Pacific El Niño

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(Manuscript received 17 February 2014, in final form 9 September 2014)

ABSTRACT

This study examined connections between the North Pacific climate variability and occurrence of the central Pacific (CP) El Niño for the period from 1950 to 2012. A composite analysis indicated that the relationship between the North Pacific sea surface temperature (SST), along with its overlying atmospheric circulation, and the CP El Niño during the developing and mature phases was changed when the occurrence frequency of the CP El Niño significantly increased after 1990. Empirical orthogonal function (EOF) and singular value decomposition (SVD) analyses of variability in the tropical Pacific and its relationship to the North Pacific show that the North Pacific anomalous SST and the atmospheric variability are more closely associated with the occurrence of the CP El Niño after 1990 than before 1990. There were noticeable differences in terms of the atmospheric variability conditions over the North Pacific, such as the North Pacific Oscillation (NPO)-like atmospheric variability during the spring and its associated SST anomalies during the following winter before 1990 and after 1990. In addition, combined EOF analysis also indicated that the NPO-like atmospheric circulation becomes more effective at playing a role in initiating El Niño after 1990. Consequently, such a change might have been associated with the frequent occurrence of the CP El Niño after 1990.

1. Introduction

The El Niño–Southern Oscillation (ENSO) phenomenon significantly affects the weather and climate variability over the globe through atmospheric teleconnections (Lau 1997; Alexander et al. 2002; McPhaden et al. 2006). The properties of ENSO, including the amplitude, frequency, and spatial structure, change on decadal-to-multidecadal time scales (Wittenberg 2009; Li et al. 2011; McGregor et al. 2013). In addition, such changes in the ENSO properties can be modulated by both natural external forcings, including solar forcing and volcanic eruption, and anthropogenic external forcing (White and Liu 2008a,b; Collins et al. 2010; Stevenson et al. 2012).

Recent studies have suggested that a different type of El Niño, the so-called "date line El Niño," "El Niño Modoki," "warm pool El Niño," or "central Pacific El Niño" has occurred more frequently during recent decades (Larkin and Harrison 2005; Kao and Yu 2009; Ashok et al. 2007; Kug et al. 2009; Yeh et al. 2009; Lee and

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DOI: 10.1175/JCLI-D-14-00137.1

McPhaden 2010; Yeh et al. 2011; J.-S. Kim et al. 2012). This type of El Niño also has different characteristics in terms of the location of the maximum sea surface temperature (SST) anomalies in comparison to the conventional El Niño, which typically exhibits warming in the eastern Pacific. In this paper, we will refer to the different type of El Niño as the central Pacific (CP) El Niño and the conventional El Niño as the eastern Pacific (EP) El Niño, because this terminology reflects the location of the center of the maximum SST anomalies in El Niño events well. After several studies (Yeh et al. 2009; Lee and McPhaden 2010; McPhaden et al. 2011), the CP El Niño received a lot of attention in terms of its mechanisms (Kug et al. 2009; Newman et al. 2011; Yu et al. 2012; Dommenget et al. 2013; Dewitte et al. 2012; Xiang et al. 2013; Chung and Li 2013; Yeh et al. 2014a,b), its influence on weather and climate variability (Kim et al. 2009; Cai and Cowan 2009; Lee et al. 2010; Larson et al. 2012), its teleconnections from the tropics to the midlatitudes (Song et al. 2011; Graf and Zanchettin 2012; Yoon et al. 2012; Yu et al. 2012; Wang and Wang 2013; Wang and Wang 2014), its prediction in climate models (Hendon et al. 2009; S.-T. Kim et al. 2012), and its future changes under global warming (Yeh et al. 2009; Kim and Yu 2012). Among these, it is of great importance to understand the triggering and developing mechanisms of the CP El Niño, because such understanding may guide the development of current climate models to correctly simulate the CP El Niño and predict its future changes under global warming. In particular, an understanding of its mechanism may provide insight for addressing current concerns regarding the changes in the spatial structure of the El Niño events observed in recent decades and, more specifically, to answer the question of why the CP El Niño has occurred more frequently since 1990.

Several mechanisms have been proposed to explain the dynamics of the CP El Niño [see a recent ENSO review by Wang et al. (2012)]. For example, Kug et al. (2009) argued that zonal advective feedback plays a role in the development of a decaying SST anomaly associated with the CP El Niño. Xiang et al. (2013) showed that the recent predominance of the CP El Niño was associated with a significant decadal change characterized by a La Niña–like background pattern and a strong divergence in the atmospheric boundary layer in the central Pacific, which, in addition to favoring the zonal advective feedback, may also involve a nonlinear process associated with the asymmetrical response of the low-level circulation to the SST. Chung and Li (2013) also argued that a shift in the La Niña–like interdecadal mean state was responsible for the more frequent occurrence of the CP El Niño. Likewise, McPhaden et al. (2011) showed that the recent decade was characterized by a slightly deeper thermocline in the central equatorial Pacific in comparison to the previous period, which could be the result of the rectification of the CP El Niño variability onto the mean vertical stratification, and is similar to the result suggested from the analysis of the GFDL CM2.1 (Choi et al. 2011, 2012). On the other hand, Thual et al. (2013) indicated that the La Niña–like conditions, through their manifestation of the vertical stratification (i.e., more diffuse thermocline in the central Pacific) after the 2000s, may have marginally changed the stability of the ENSO and attributed the change in stability to the difference in the characteristics of the atmospheric modes between the periods before and after 2000. All of these studies, although not conclusive, indicate that the occurrence of the CP El Niño was closely associated with the mean state of the tropical Pacific.

Furthermore, several subsequent studies by Yu et al. (2010), Yu and Kim (2011), and Yu et al. (2012) suggested that the occurrence of the CP El Niño may be associated with forcings from the extratropics, such as the North Pacific Oscillation (NPO), which is characterized by the second leading internal atmospheric mode over the North Pacific with a meridional dipole in the sea level pressure anomalies (Rogers 1981). In particular, Yu et al. (2012) argued that the El Niño events after 1990 were more closely connected to the SST variability in the subtropical North Pacific, indicating that the North Pacific Ocean may have played a role in inducing the CP El Niño during recent decades through the so-called North Pacific meridional mode with the seasonal footprinting mechanism (Vimont et al. 2003; Wang et al. 2013). Consequently, these results indicate that the changes in the state of both the tropical and North Pacific Oceans should be examined in order to understand the mechanisms associated with the occurrence of the EP and CP El Niños (Furtado et al. 2011; Stevenson et al. 2012; Wang et al. 2013).

The purpose of this paper is to explore the connections between the climate variability over the North Pacific and the occurrence of the CP El Niño in order to improve our understanding of its mechanism. We report that a change in the relationship between the North Pacific Ocean and the CP El Niño takes place during recent decades, concurrent with the changes in the atmospheric variability over the North Pacific before 1990 and after 1990.

2. Data and methodology

The monthly SST from the Hadley Centre Sea Ice and SST dataset (HadISST) with a $1.0^\circ \times 1.0^\circ$ resolution from 1950 to 2012 is used (Rayner et al. 2003). The atmospheric variable used in this study is the monthly sea level pressure (SLP) obtained from the National Centers for Environmental Prediction–National Center for

TABLE 1. The years for the CP El Niño-B90 and CP El Niño-A90 used in the present study.

CP El Niño before 1990 (B90)	CP El Niño after 1990 (A90)
1963/64, 1968/69, 1977/78, 1979/80, and 1987/88	1990/91, 1991/92, 1992/93, 1993/94, 1994/95, 2002/03, 2004/05, and 2009/10

Atmospheric Research (NCEP–NCAR) Reanalysis 1 (Kalnay et al. 1996). It should be noted that all of the data in the present study were detrended by removing the linear trend before analyzing.

We first define the years of the EP El Niño and the CP El Niño, respectively. As in other studies, including those by the Japan Meteorological Agency (e.g., Weng et al. 2009), the EP El Niño is defined by the Niño-3 (150°–90°W, 5°N–5°S) SST anomalies such that the 5-month running mean Niño-3 SST anomalies are +0.5°C or higher for 6 consecutive months or longer. According to this definition, eight of the EP El Niño events in the period of 1950 to 2012 can be identified as follows: 1951/52, 1957/58, 1965/66, 1972/73, 1976/77, 1982/83, 1986/87, and 1997/98. To define the CP El Niño, we follow the studies by Kao and Yu (2009) and Yu and Kim (2010). In other words, we determine the CP El Niño pattern by first removing the portion of the tropical Pacific SST anomalies that are regressed with the Niño-1+2 SST index and then applying an empirical orthogonal function (EOF) analysis to the residual SST anomalies. The regression with the Niño-1+2 index is considered to be an estimate of the influence of the EP El Niño, which should be removed in order to better reveal the SST anomalies solely associated with the CP El Niño. The CP El Niño events during the second half of the twentieth century are identified, which agree with those identified by using the other El Niño Modoki indices (Ashok et al. 2007; Ren and Jin 2011).

We identified 13 CP El Niño events for the period of 1950 to 2012, as follow: 1963/64, 1968/69, 1977/78, 1979/80, 1987/88, 1990/91, 1991/92, 1992/93, 1993/94, 1994/95, 2002/03, 2004/05, and 2009/10. To examine the change in the relationship between the North Pacific Ocean and the CP El Niño, we classify the two groups of the CP El Niño as before 1990 (CP El Niño-B90) and after 1990 (CP El Niño-A90). Table 1 displays the years for the CP El Niño-B90 and CP El Niño-A90, respectively. The reason why we separate the periods before and after 1990 is that most of previous studies found that the CP El Niño events occurred more frequently after 1990 than before 1990 (Xiang et al. 2013; Wang et al. 2013; Yeh et al. 2014b). The occurrence frequency of the CP El Niño before 1990 is around 0.13 yr^{-1}, while it is around 0.35 yr^{-1} after 1990. Therefore, the occurrence frequency of the CP El Niño increases after 1990 by as much as approximately 3 times the frequency during the period before 1990. On the other hand, the occurrence frequency of the EP El Niño before 1990 is approximately 0.17 yr^{-1}, which is similar to the frequency of the CP El Niño before 1990. However, the occurrence frequency of the EP El Niño after 1990 is approximately 0.04 yr^{-1}, which is much smaller than that of the CP El Niño after 1990. In other words, the CP El Niño also occurs more frequently than the EP El Niño after 1990.

3. Results

a. Composite analysis

Figures 1a and 1b display the anomalous SST composites of the CP El Niño-B90 and CP El Niño-A90, respectively, during the boreal winter {December(0)–January(+1)–February(+1), represented as [D(0)JF(+1)]}. The 0 denotes the year when the CP El Niño occurred, and +1 indicates the following year of the CP El Niño occurrence. In both the anomalous SST composites, a distinct spatial structure of the CP El Niño could be found in which a center of the maximum anomalous SST was observed in the central equatorial Pacific, not in the eastern equatorial Pacific, consistent with the results of most previous studies (e.g., Larkin and Harrison 2005; Kao and Yu 2009; Ashok et al. 2007; Kug et al. 2009). Note that there is little difference in the case of the EP El Niño before and after 1990 in the Pacific, except the magnitude (figure not shown).

There were some differences in the case of the CP El Niño-B90 and the CP El Niño-A90 in the tropical Pacific. For example, the meridional scale of the anomalous SST averaged in 120°E–90°W in the case of CP El Niño-A90 is smaller than that of the CP El Niño-B90 in the eastern Pacific (Fig. 1c). The CP El Niño-B90 is characterized by a broad triangular structure in the eastern subtropical Pacific at both the hemispheres in comparison to the CP El Niño-A90, in which an anomalous cold SST is observed. In other words, the anomalous warm SST is more zonally confined in the central equatorial Pacific in the CP El Niño-A90 than in the CP El Niño-B90. To examine details of the differences between individual cases during each period, we compare the SST map for each individual CP El Niño before and after 1990 (figure not shown). In spite of some differences among individual cases in each period, it is found that the CP El Niño before 1990 is characterized by an anomalous cool SST in the North Pacific; in contrast, the CP El Niño after 1990 is accompanied by an anomalous warm SST in the North Pacific. Furthermore, it is evident that the individual CP El Niño

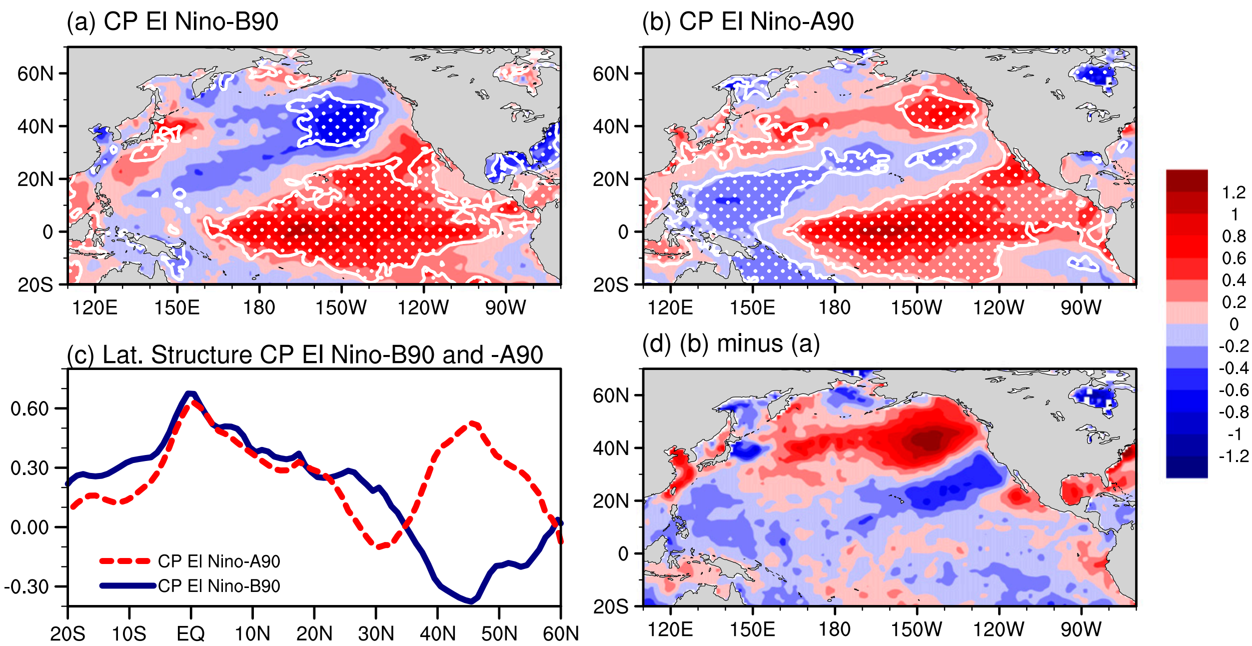

FIG. 1. SST composite of the (a) CP El Niño-B90 and (b) CP El Niño-A90 during the winter [D(0)JF(+1)]. The white thick contours indicate statistical significance at a 90% confidence level based on a Student's t test. (c) The latitudinal structure of anomalous SST averaged between 120°E–90°W for CP El Niño-B90 (solid line) and CP El Niño-A90 (dashed line). (d) The composite SST difference between CP El Niño-B90 and CP El Niño-A90 (i.e., CP El Niño-A90 − CP El Niño-B90).

before 1990 is characterized by a broad triangular structure of SST anomalies in the eastern subtropical Pacific at both the hemispheres in comparison to the CP El Niño after 1990.

The most striking differences between the two cases are found in the North Pacific (Fig. 1d), which is also true in the previous winter [D(−1)JF(0)] between the two cases (see Fig. 3). It is evident that the CP El Niño-A90 is accompanied by an anomalous warm (cool) SST north (south) of 40°N in the central and eastern North Pacific, which is characterized by a dipole-like structure in the meridional direction (Fig. 1b). In the CP El Niño-B90, in contrast, the composited anomalous SST in the North Pacific is characterized by an anomalous cool SST peaking in the southern flank of the Gulf of Alaska and extending southwestward (Fig. 1a). Consequently, a significant difference in the composited SST between the two periods of the CP El Niño is found in the central and eastern North Pacific around the west coast of the USA. This result indicates that the relationship between the North Pacific and the CP El Niño is significantly changed after 1990. In other words, Fig. 1 indicates that the mean state of the North Pacific SST might be associated with a frequent occurrence of the CP El Niño. The difference of EP–CP El Niño frequency before and after 1990 may influence the mean state in the North Pacific through the rectification processes, which in turn affects the EP–CP El Niño occurrence.

This result raises an important question of whether the Pacific decadal variability, such as the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO), is associated with the frequency changes in the CP El Niño occurrence before and after 1990. To examine this, we display the first two EOFs of SST in the North Pacific for the period of 1950–2012 and their corresponding principal component (PC) time series (Fig. 2). Both the PDO and NPGO indices, which are represented by the first two EOF PC time series, are characterized by the low-frequency variability on quasi-interannual-to-decadal time scales. In other words, the phase of both PDO and NPGO shifts from the positive to the negative on low-frequency time scales without any covariability. In particular, there exist several phase shifts of both the PDO and the NPGO that are not associated with the periods of before and after 1990. This suggests that the Pacific decadal variability does not influence a frequent occurrence of the CP El Niño after 1990.

To examine more details regarding the distinctions in the CP El Niño-B90 and CP El Niño-A90, we display the seasonal evolution of the anomalous SST along with the SLP from the previous winter [D(−1)JF(0)], the spring {March(0)–April(0)–May(0), i.e. [MAM(0)]}, the summer {June(0)–July(0)–August(0), i.e. [JJA(0)]}, and the fall {September(0)–October(0)–November(0), i.e. [SON(0)]} (Fig. 3). It is worth noting that the seasonal SST evolution, along with the seasonal mean SLP, has some

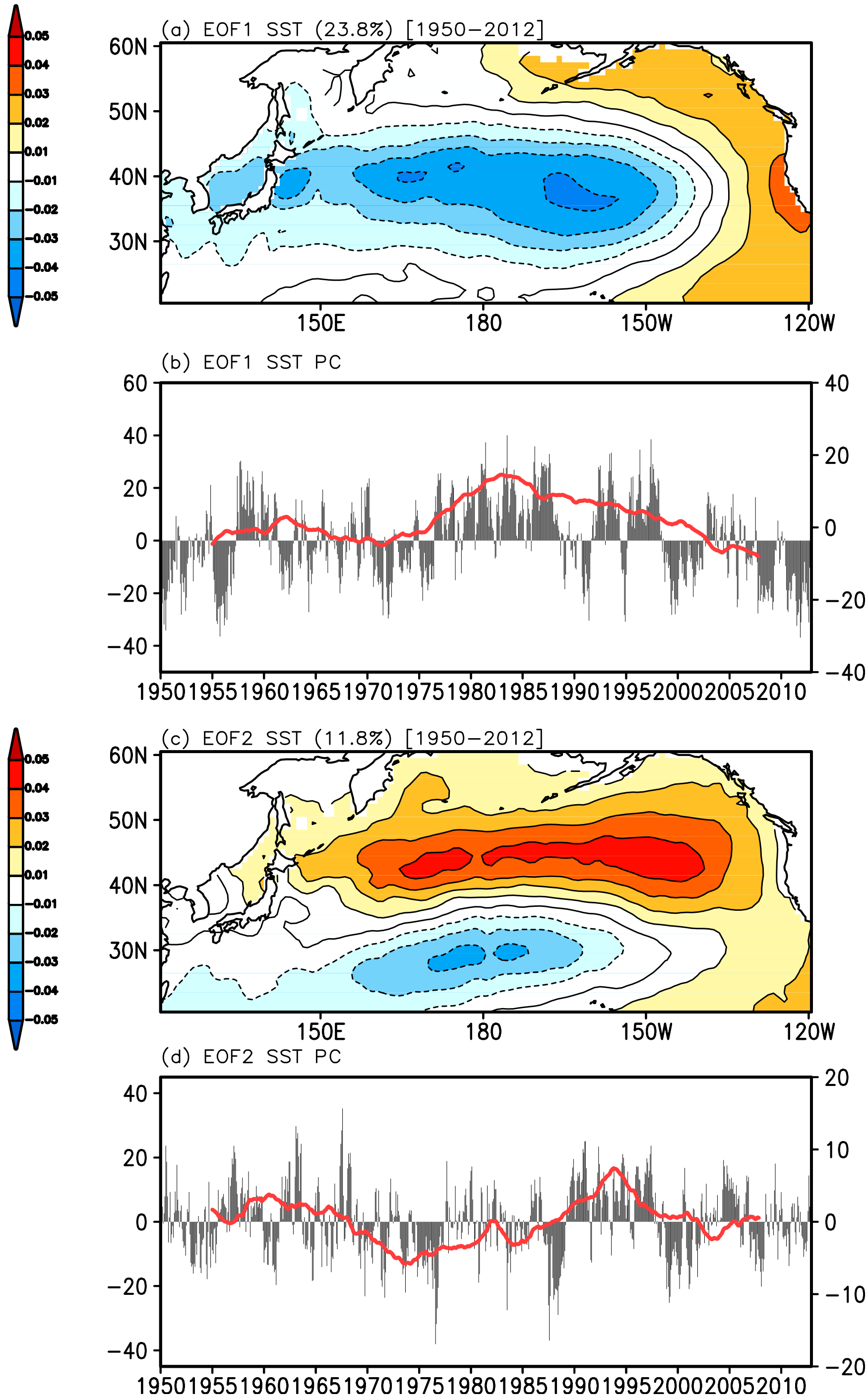

FIG. 2. The (a) first and (c) second EOFs of SST (°C) in the North Pacific for the period of 1950–2012. The PC time series of the (b) first and (d) second EOF. Red lines in (b),(d) are the 10-yr running mean PC time series.

similarities and differences in the cases of the CP El Niño-B90 and CP El Niño-A90.

In the case of the CP El Niño-B90 (left column in Fig. 3), a significant anomalous warm SST develops in the central and eastern tropical Pacific during JJA(0). In particular, the maximum of the anomalous warm SST is located in the southeastern tropical Pacific during JJA(0). As the CP El Niño-B90 develops further during SON(0), the anomalous warm SST moves to the west and extends to the central equatorial Pacific. In addition,

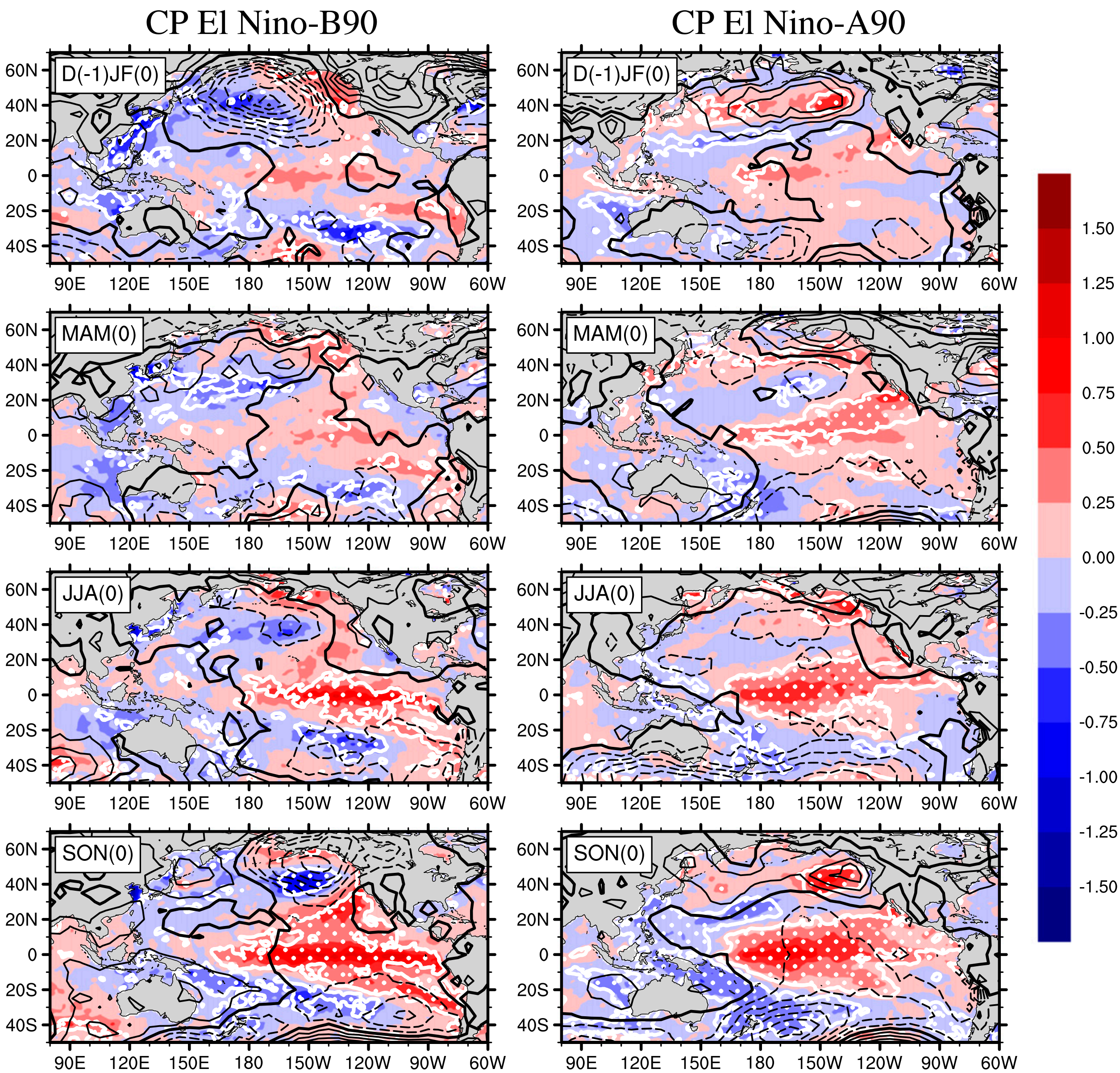

FIG. 3. (top to bottom) Evolution through D(−1)JF(0), MAM(0), JJA(0), and SON(0) for the SST (color shading, °C) and SLP (contours with interval of 0.4 mb) composites for (left) CP El Niño-B90 and (right) CP El Niño-A90. The white thick contours indicate 90% statistical significance for the SST composites based on a Student's *t* test. The Second Hadley Centre Sea Level Pressure dataset (HadSLP2) during 1950–2012 was used for SLP (Allan and Ansell 2006).

the anomalous SST shows an extension of the warm anomalies form the subtropics to the central equatorial region from MAM(0) to SON(0) in both the hemispheres. Note that the statistically significant anomalous warm SST in the northern subtropics during SON(0) is observed after the large warming in the central and eastern tropical Pacific occurs during JJA(0). This indicates that such warming in the northern subtropics might be due to a Gill-type atmospheric response to SST anomalies in the equatorial Pacific (Gill 1980). On the other hand, the anomalous cool SST in the North Pacific exists persistently from D(−1)JF(0) to SON(0). In general, such anomalous cool SSTs can be explained by a response to the tropical SST forcing (i.e., El Niño) through atmospheric teleconnections (Alexander et al. 2002). That is, the anomalous low SLP is dominant over the central and eastern North Pacific during JJA(0) and SON(0), which is indicative of a strengthening of the Aleutian low pressure. It should be noted that the minimum SLP of the Aleutian low pressure, which represents the strengthening of the Aleutian low, is 1008.4 hPa during JJA(0), 1000.1 hPa during SON(0), and 997.9 hPa during DJ(0)F(+1).

In the case of the CP El Niño-A90 (right column in Fig. 3), on the other hand, significant SST anomalies already exist from the eastern subtropics to the central equatorial Pacific during MAM(0), which is strikingly different from the case of the CP El Niño-B90. It should be noted that a similar structure of SST anomalies already exist during D(−1)JF(0). As the CP El Niño-A90 develops further from JJA(0) to SON(0), it is evident that the anomalous warm SST in the central equatorial Pacific becomes stronger, and the center of the maximum anomalous SST is persistently located in the central equatorial Pacific. Consequently, a strong anomalous warm SST is more confined in the central equatorial Pacific in the case of the CP El Niño-A90 from JJA(0) to SON(0), in comparison with the CP El Niño-B90. In addition, there is no clear evidence that the anomalous SST propagates from the eastern equatorial Pacific to the central equatorial Pacific, unlike the evolution of the CP El Niño-B90. Overall, the seasonal evolution of the CP El Niño-A90 during the developing phase [MAM(0)–JJA(0)–SON(0)] is characterized by a close link between the central equatorial Pacific and the eastern subtropical Pacific. In addition, unlike the CP El Niño-B90, the spatial pattern of the anomalous SST in the North Pacific is characterized by a dipole-like structure in the meridional direction from D(−1)JF(0) to SON(0) [i.e., an anomalous warm (cool) SST in the northern (southern) part of the North Pacific], which is also observed during the mature phase [DJ(0)F(+1)] of CP El Niño-A90 (see Fig. 1b). In other words, such a dipole-like pattern of the anomalous SST in the North Pacific could not be explained simply by the response to the tropical SST forcing, which is unlike the CP El Niño-B90. We speculate that the North Pacific SST after the 1990s does not respond to the CP El Niño, but it plays a role in association with the occurrence of the CP El Niño.

It is also found that the seasonal evolution of the composited anomalous SLP in the case of the CP El Niño-A90 was quite different from that of the CP El Niño-B90. It is difficult to observe that the Aleutian low pressure became stronger as time progressed from JJA(0) to SON(0) for the CP El Niño-A90, whereas a dipole-like structure of the anomalous SLP in the meridional direction is dominant from MAM(0) to SON(0) over the North Pacific. In detail, the anomalous high (low) pressure is observed in the northern (southern) part of the North Pacific. That is, the NPO-like structure of the atmospheric circulation over the North Pacific is dominant in the case of the CP El Niño-A90 in comparison to the CP El Niño-B90, especially during the springtime [MAM(0)]. This result also indicates that the atmospheric circulation over the North Pacific seems to be associated with the occurrence of the CP El Niño after 1990, which is consistent with previous studies (Yu et al. 2010; Yu and Kim 2011; Yu et al. 2012). In other words, the atmospheric variability may play a role in leading the CP El Niño after 1990. Overall, these results indicate that the North Pacific climate variability, including both the SST and the atmospheric circulation, is associated with the occurrence of the CP El Niño after 1990, in comparison to before 1990.

b. *Analysis on the role of North Pacific climate variability*

To investigate the above argument, we examine the SST variability and atmospheric circulation during the spring, because noticeable differences exist then in terms of ocean and atmospheric conditions between the CP El Niño-B90 and the CP El Niño-A90 compared to any other season, as shown in Fig. 3. Figures 4a and 4b display the first two EOFs' SLPs over the North Pacific for the period from 1950 to 2012 during the spring, respectively. It is noteworthy that the spatial patterns of the first two EOFs' SLPs (Figs. 4a,b) are reminiscent of the composited SLP during MAM(0) in the cases of the CP El Niño-B90 and the CP El Niño-A90, respectively (Fig. 3). While the first EOF (Fig. 3a) is characterized by a single atmospheric cell in a basin scale (i.e., Aleutian low pressure), the second EOF (Fig. 4b) shows a dipole-like structure in the meridional direction over the North Pacific (i.e., NPO-like pattern). However, the regressed SST against the first EOF PC time series (Fig. 4c) is quite different from the composited anomalous SST during MAM(0) in the case of the CP El Niño-B90. In contrast, the spatial pattern of the regressed SST against the second EOF PC time series (Fig. 4d) is similar to that of the composited SST during MAM(0) in the case of the CP El Niño-A90. In other words, the spatial pattern of the regressed SST is characterized by a dipole-like structure in the meridional direction [i.e., anomalous warm (cool) SST in the southern (northern) part of the North Pacific]. The anomalous warm (cool) SST in the southern (northern) part of the North Pacific could be explained by the easterlies (westerlies) in the southern (northern) North Pacific through the wind–SST interactions in the midlatitudes (Cayan 1992), which are primarily associated with a dipole-like structure of the SLP (Fig. 4b).

Therefore, we argue that the anomalous SST in the North Pacific during the spring after 1990 is primarily explained by a linear forcing of the dipole-like pattern of the SLP when the CP El Niño occurred during the following winter. Such a close relationship between the anomalous SLP and SST during the spring might be

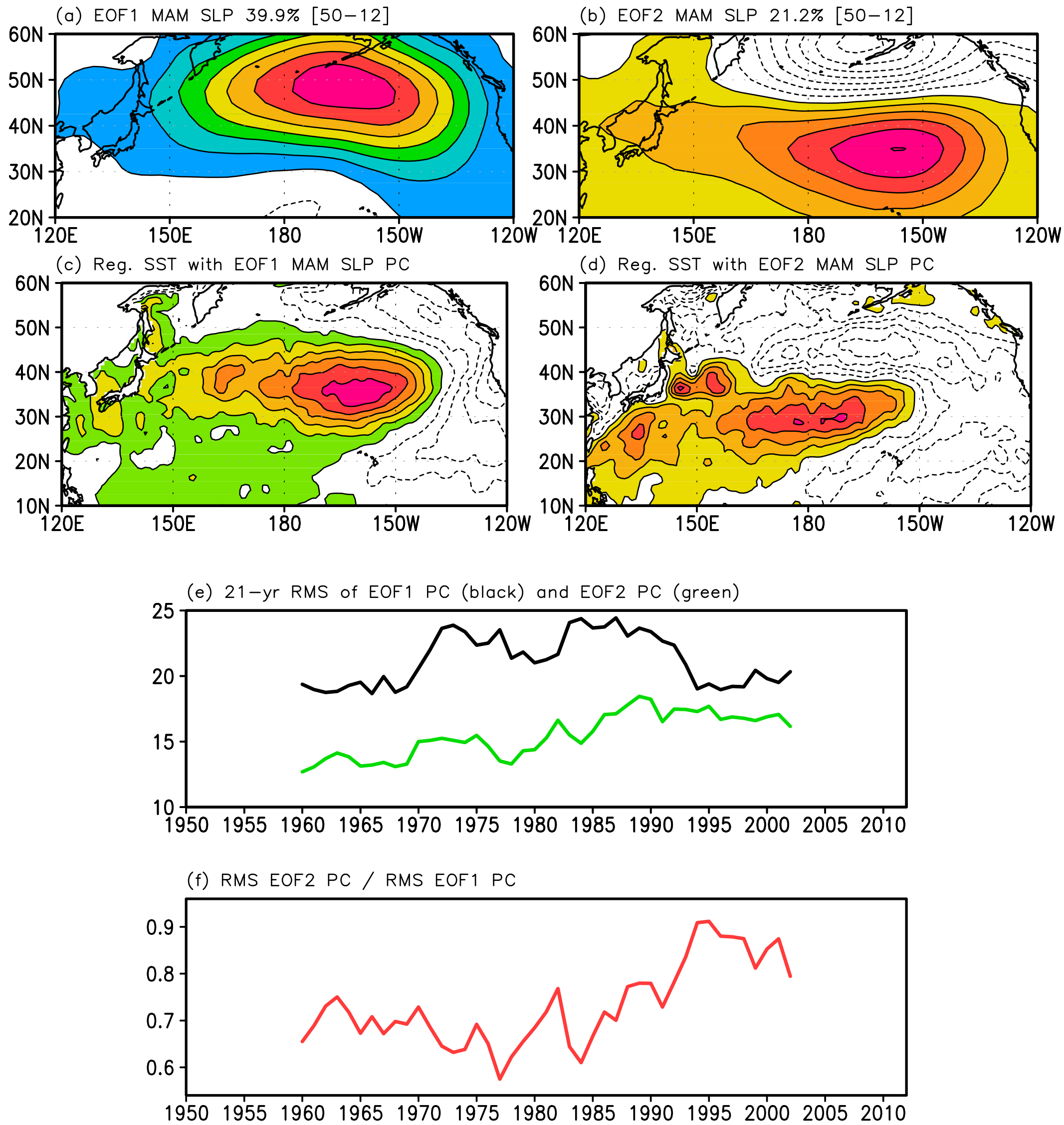

FIG. 4. The (a) first and (b) second EOFs of SLP over the North Pacific for the period between 1950 and 2012 during the spring. (c),(d) The anomalous SST regressed against the PC time series of the first and second EOFs, respectively; the contour interval is 0.02, and the unit is nondimensional. Dashed line contours are for negative values. (e) The 21-yr running mean time series of the RMS (hPa) of the PCs of the first (black) and second (green) EOFs. (f) The ratio between these RMSs, EOF2 PC/EOF1 PC.

associated with an occurrence of the CP El Niño during the following winter. Why such a feature occurs after 1990 is beyond the scope of the current study. However, in order to get insights on the characteristics of the changes in variability over the North Pacific, we show the 21-yr running mean time series of the root-mean-square (RMS) of the PCs of the first and second EOFs (Fig. 4e). In spite of removing a linear trend, the RMS of the second EOF's PC gradually increases. In addition, the ratio of the RMS of the PCs of the first and second EOFs becomes large during the most recent decades in particular (Fig. 4f). This result indicates that the atmospheric forcing over the North Pacific during the spring, such as the NPO-like forcing, becomes dominant during recent decades. Subsequently, this plays a role in inducing the more frequent occurrence of the CP El Niño after 1990.

As a consistency check of the previous statement, we also provide the SLPs of the first two EOFs before and after 1990 (Fig. 5). Figures 5a and 5b are the first two EOFs' SLPs during the spring for the period between 1950 and 1989, and Figs. 4c and 5d are as in Figs. 5a and 5b, but for the period between 1990 and 2012. It is evident that the second EOF before 1990 (Fig. 5b), which is characterized by a dipole-like structure in the North

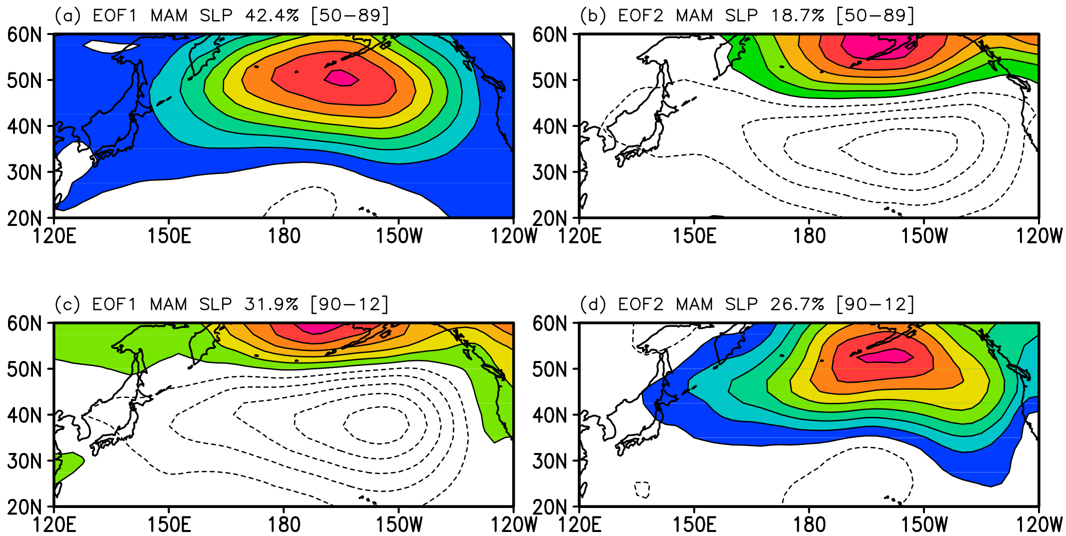

FIG. 5. The (a),(c) first and (b),(d) second EOFs of SLP during the spring (top) before 1990 and (bottom) after 1990. The contour interval is 0.02, and the unit is nondimensional.

Pacific, becomes the most dominant mode of atmospheric circulation after 1990 (Fig. 5c). The total explained variance in the second EOF before 1990 was 18.7%, which significantly increases to 31.9% after 1990. In contrast, the total variance in the first EOF before 1990 is 42.4%, which is greatly reduced to 26.7% after 1990. It should be noted that we also conduct the same calculation using the SLP during the summer, fall, and winter before and after 1990 and found that there is not such a significant change as that found during the spring (not shown). Therefore, we argue that the atmospheric variability and its associated SST variability over the North Pacific during the spring are changed significantly from before 1990 to after 1990. Subsequently, such a change might be associated with a more frequent occurrence of the CP El Niño after 1990.

To statistically support the argument that the NPO-like atmospheric forcing and the anomalous warm SST north of 40°N in the central and eastern North Pacific during the spring is associated with the more frequent occurrence of CP El Niño during the following winter, we conduct the singular value decomposition (SVD) analysis using the SST and SLP in the North Pacific and the tropical Pacific before and after 1990 Figure 6 shows the leading SVD modes between the North Pacific SST during MAM(0) and the tropical Pacific SST during D(0)JF(+1) before and after 1990. Note that the SST in the tropical Pacific has been previously filtered out from the influence of the Niño-1+2 index following Kao and Yu (2009), which ensures that the SVD modes mainly capture variability not associated with EP El Niño events. The spatial structure of the first SVD modes before 1990 (left panel in Fig. 6) is similar to the North Pacific SST composite during MAM(0) and the tropical Pacific SST composite during D(0)JF(+1) in the CP El Niño before 1990, respectively. It is also true that the spatial structure of the first SVD modes after 1990 (right panel in Fig. 6) is similar to the North Pacific SST composite during MAM(0) and the tropical Pacific SST composite during D(0)JF(+1) in the CP El Niño after 1990, respectively. Furthermore, the explained covariance of the first SVD mode and the explained variance of the associated SST mode over the equatorial Pacific are largely enhanced from before 1990 to after 1990, indicating that connections of the North Pacific SST during MAM(0) and the CP El Niño during D(0)JF(+1) increase after 1990.

Figure 7 is as in Fig. 6, but for the SLP during MAM(0). It should be noted that the spatial structure of the first SVD SLP mode in the North Pacific during MAM(0) after 1990 is characterized by a dipole-like structure of the anomalous SLP in the meridional direction, which is quite similar to that of the composited SLP in the North Pacific during MAM(0) after 1990 in the CP El Niño. Furthermore, the explained covariance of the SVD mode and the explained variances of the associated SST and SLP fields are largely enhanced from before 1990 to after 1990, indicating that the NPO-like pattern of atmospheric circulations in the North Pacific is more coupled with the CP El Niño after 1990 than before 1990. Overall, Figs. 6 and 7 indicate that the North Pacific climate variability, including both the SST and the NPO-like atmospheric circulation, is more associated with the occurrence of the CP El Niño after 1990 than before 1990. The external forcing to the tropics that may have favored the generation mechanism for the CP El Niño before 1990 is not studied here.

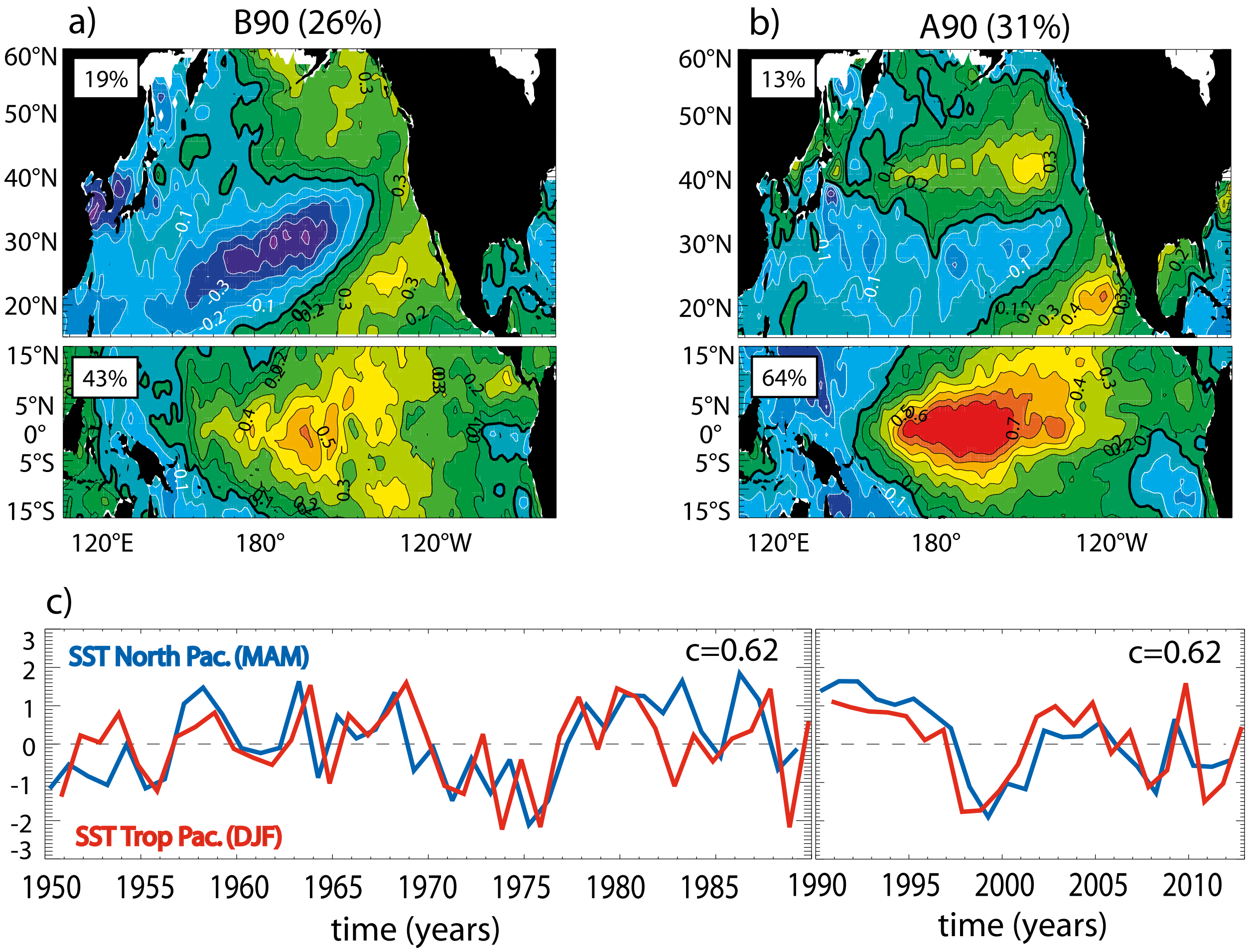

FIG. 6. Patterns of the leading SVD mode between the SST in the North Pacific (15°–60°N, 120°E–70°W) in MAM(0) and the SST in the tropical Pacific (15°S–15°N, 120°E–70°W) in D(0)JF(+1) for (a) before 1990 and (b) after 1990. (c) The associated time series for both periods. The SST in the tropical Pacific has been previously filtered out from the influence of the Niño-1+2 index following Kao and Yu (2009). The percentage of covariance is indicated at the tops of (a) and (b). The mean explained variance is also displayed on each map. The SST datasets were previously detrended for the period 1950–2012.

Still, we can speculate that since CP El Niño events are tightly linked to various components of the intraseasonal tropical variability (Gushchina and Dewitte 2012), and there is the possibility that the intraseasonal tropical variability is enhanced after 1990 compared to before 1990 because of the influence of the NPO on the mean SST state in the equatorial region. In particular, Madden–Julian oscillation activity has been increased from the mid-1990s (Jones and Carvalho 2006). This deserves further investigation, which is beyond the scope of the present study.

c. *Further analysis*

To answer how the NPO-like atmospheric forcing is associated with the more frequent occurrence of the CP El Niño after 1990 than before 1990, we conduct a combined EOF (CEOF) analysis based on the surface wind and anomalous SST in the Pacific Ocean before and after 1990 during the spring (Fig. 8). The first CEOF modes during both periods (Figs. 8a,c) are associated with the ENSO-related mode of SST variability and the surface wind during the spring, which is mostly due to the decaying phase of ENSO from the previous winter. On the other hand, the second CEOF modes during both periods (Figs. 8b,d) may represent the surface wind–evaporation–SST (WES) feedback processes in the subtropical northeastern Pacific, which are also associated with the NPO-like atmospheric circulation in the North Pacific (see Fig. 9).

It is evident that anomalous southwesterly wind is associated with anomalous warm SST in the subtropical northeastern Pacific, which might be associated with the WES feedback processes in the second CEOF model in both periods. However, there exist some

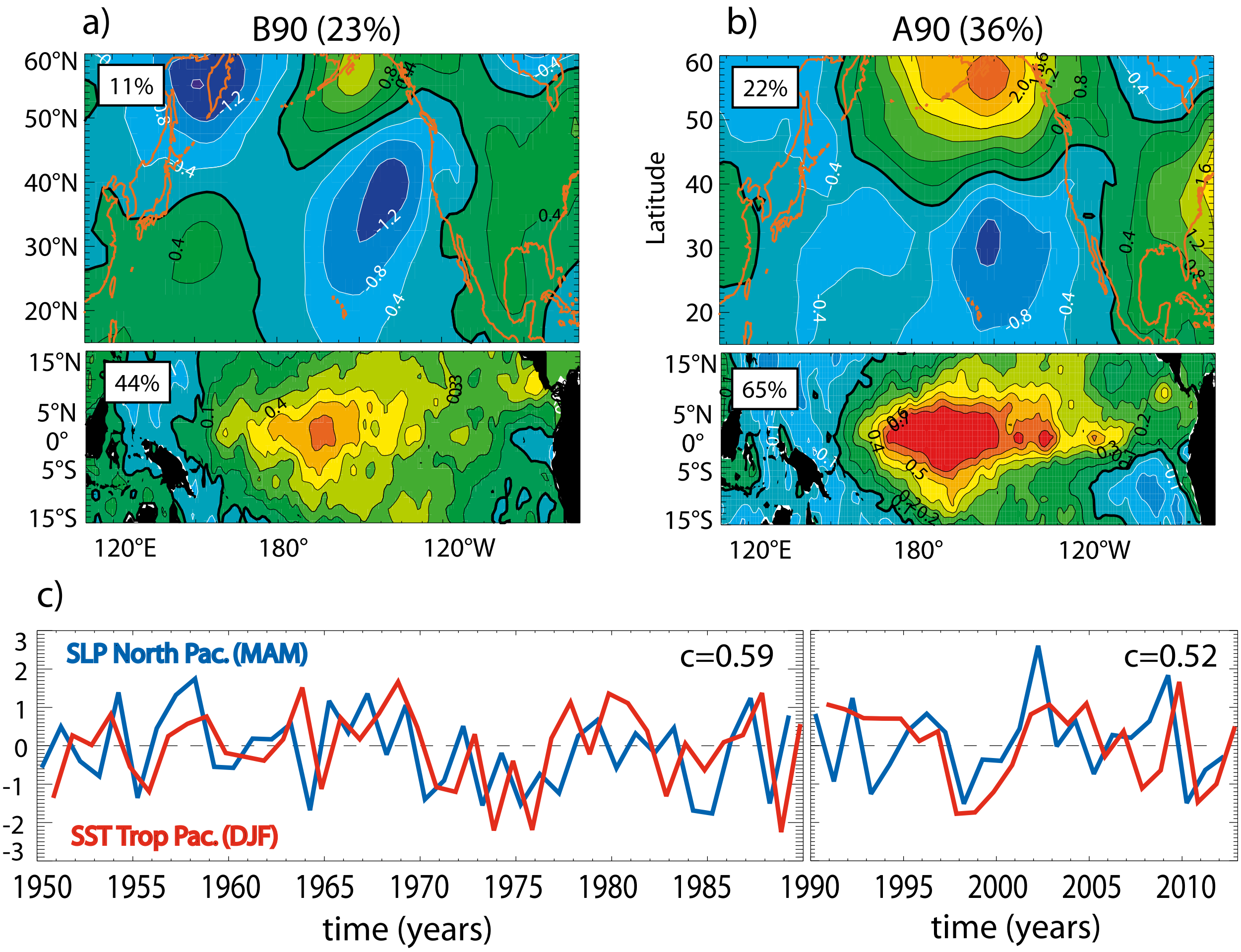

FIG. 7. As in Fig. 6, but for SLP.

differences between the second CEOF modes before and after 1990. That is, the location of maximum SST variance in the subtropical northeastern Pacific is slightly shifted to the south after 1990, compared to before 1990 (Fig. 8e). A southward shift of anomalous warm SST might be associated with an effectiveness to generate the westerly wind anomaly close to the equatorial Pacific during the following summer and fall (Vimont et al. 2003), which plays a role to initiate an ENSO event and, finally, the occurrence of El Niño in the following winter through the air–sea interactions in the tropical Pacific. Furthermore, it should be noted that the explained variance of the second CEOF mode also significantly increases from before 1990 (9.1%) to after 1990 (16.7%), indicating that the SST variance in relation to the second CEOF is enhanced in the subtropical eastern Pacific after 1990 (not shown).

We hypothesize that the WES feedback processes in the subtropical northeastern Pacific, which is associated with the NPO-like atmospheric circulation, become more effective at playing a role in initiating ENSO after 1990 (i.e., CP El Niño). This may explain how the NPO-like atmospheric forcing is associated with the more frequent occurrence of the CP El Niño after 1990 than before 1990 (Yu et al. 2012). Wang et al. (2013) also point out a likely change in ENSO precursors from before and after 1990. According to Wang et al. (2013), in particular, the SST anomalies in the western North Pacific have increased since the 1990s, which may have favored the increased low-level zonal wind anomalies in recent decades over the western equatorial Pacific, implying an increased activity of oceanic Kelvin waves for the development of ENSO. They also note that their western North Pacific index also correlates more to the Pacific meridional mode after 1990, which is consistent with our results. Therefore, there is the possibility that both the influences (i.e., Pacific meridional mode preconditioning and increased oceanic Kelvin wave activity associated to the amplification of the western North Pacific dipole

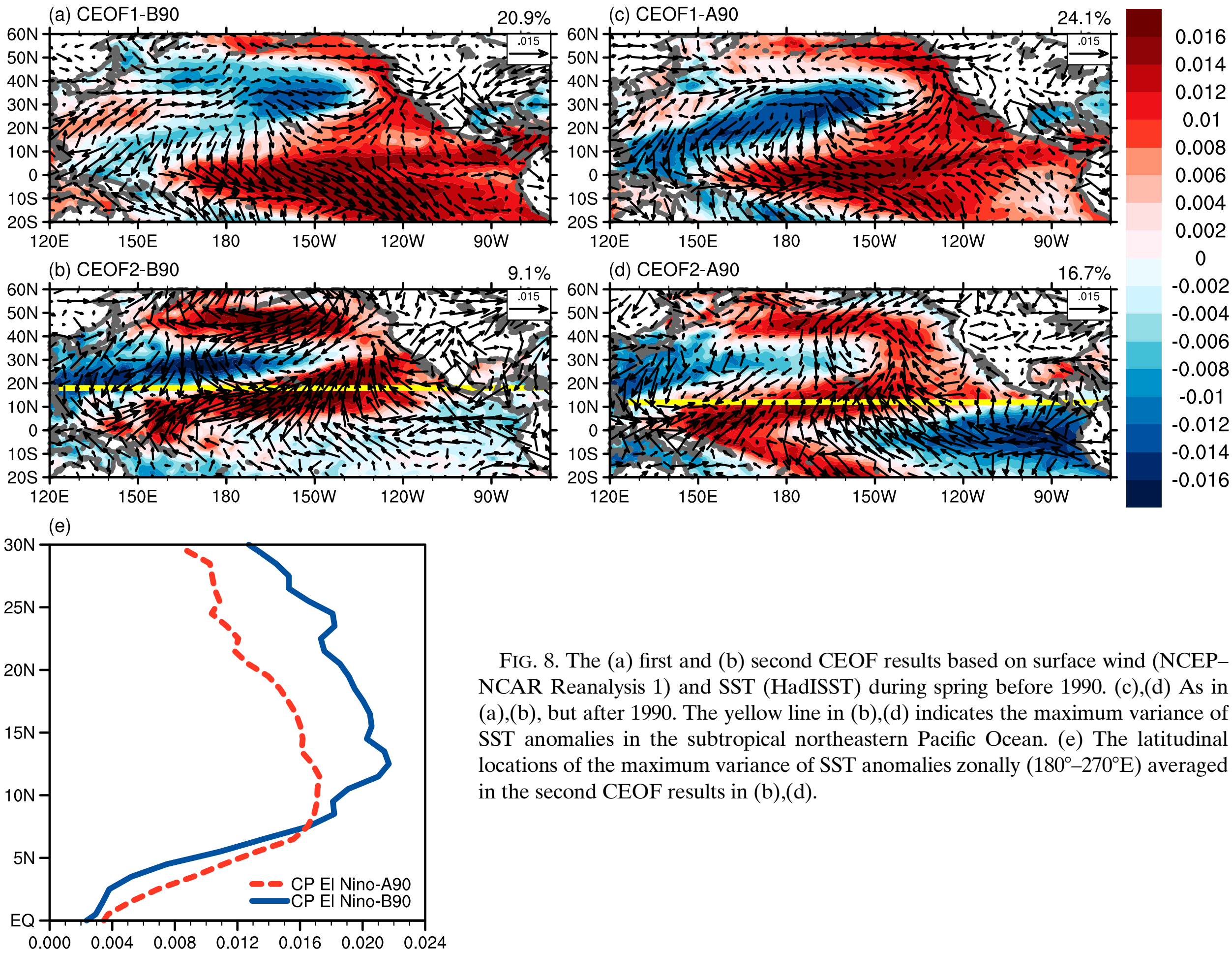

FIG. 8. The (a) first and (b) second CEOF results based on surface wind (NCEP–NCAR Reanalysis 1) and SST (HadISST) during spring before 1990. (c),(d) As in (a),(b), but after 1990. The yellow line in (b),(d) indicates the maximum variance of SST anomalies in the subtropical northeastern Pacific Ocean. (e) The latitudinal locations of the maximum variance of SST anomalies zonally (180°–270°E) averaged in the second CEOF results in (b),(d).

after the 1990s) combine to produce increased occurrence of the CP El Niño events. This deserves further investigation, which is beyond the scope of the present paper.

Figure 9 shows the SLP regressed against the second CEOF PC time series during both periods. It is evident that the second CEOF modes during both periods are associated with the NPO-like atmospheric circulation, which is characterized by a dipole-like structure of SLP in the North Pacific. However, the detailed structures of the regressed SLP are different between the two periods. While the NPO-like atmospheric circulation is confined in the North Pacific before 1990 (Fig. 9a), its southern lobe is extended in the western tropical Pacific after 1990. This indicates that the NPO-like atmospheric variability becomes more coupled to the variability of SLP in the western tropical Pacific during the spring, which might be associated with the El Niño occurrence in the following winter by increasing low-level wind anomalies over the western equatorial Pacific, which is consistent with the results in Wang et al. (2013).

4. Summary

Recent studies have paid much attention to the CP El Niño, in terms of understanding its mechanisms to improve current climate models so that they can correctly simulate the CP El Niño and predict the El Niño's changes under global warming. To understand the mechanisms associated with the frequent occurrence of the CP El Niño, we explored the connections between the North Pacific climate variability and the occurrence of the CP El Niño for the period between 1950 and 2012 by using observational data. First, we separated the period into two periods—before and after 1990—because the occurrence frequency of the CP El Niño after 1990 increased by as much as 3 times in comparison to before 1990. It was found that the relationship between the state of the North Pacific SST and the CP El Niño during the winter changed before 1990 and after 1990, a change that is not associated with Pacific decadal variability, such as the PDO and the NPGO. While the CP El Niño after 1990 was accompanied by an anomalous warm (cool) SST north (south) of

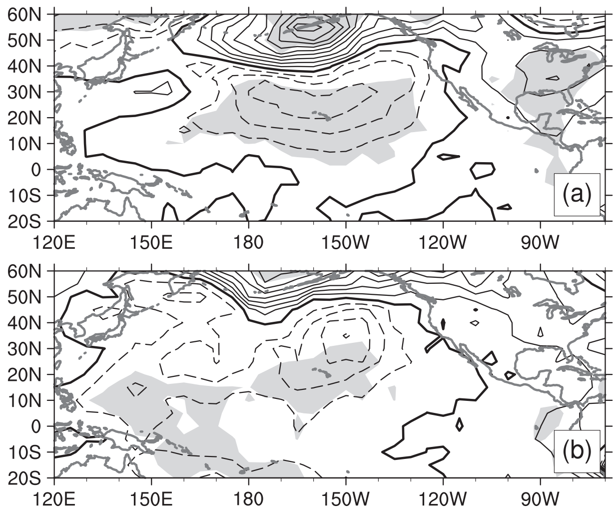

FIG. 9. The SLP regressed against the second CEOF PC time series (a) before 1990 and (b) after 1990. The shadings represent values exceeding the 90% significant level. The contour interval is 0.004 and the zero contour lines are thickened.

40°N in the central and eastern North Pacific, the CP El Niño before 1990 was associated with an anomalous cool SST in the North Pacific.

Our analysis indicated that the seasonal SST evolution, along with the seasonal mean SLP, which was associated with the occurrence of the CP El Niño, was quite different before 1990 and after 1990. Before 1990, the anomalous SLP and SST over the North Pacific during the developing phase of the CP El Niño could be explained by the tropical SST forcings, but not after 1990. We found that the anomalous SST in the North Pacific after 1990 during the spring was primarily explained by the atmospheric forcing of the dipole-like pattern of the SLP. Further statistical analysis indicated that both the North Pacific anomalous SST and the SLP acted to lead the occurrence of the CP El Niño after 1990. It was also found that noticeable differences existed in terms of the atmospheric variability conditions during the spring before and after 1990. The second EOF of the SLP in the North Pacific before 1990, which was characterized by a dipole-like structure in the North Pacific, became the most dominant mode of atmospheric variability after 1990. We proposed the hypothesis that the WES feedback processes in the subtropical northeastern Pacific, which is associated with the NPO-like atmospheric circulation, become more effective at playing a role in initiating the El Niño after 1990. Subsequently, such a change might be associated with a frequent occurrence of the CP El Niño after 1990. However, our results heavily depend on the statistical analysis, which cannot fully support the details of physical processes in relation to the WES feedback processes in the subtropical northeastern Pacific. In addition, the short length of the observational data and the limited sampling should be overcome by conducting an analysis of a long-term coupled model that realistically simulates the ENSO diversity.

Acknowledgments. This work was funded by the Korea Meteorological Administration Research and Development Program under Grant CATER 2012-3041, a National Research Foundation of Korea grant funded by the Korean Government (MEST) (NRF-2009-C1AAA001-2009-0093042), the National Basic Research Program of China (2013CB430301), the National Natural Science Foundation of China (Grants 41422601 and 41376025), and the CAS/SAFEA International Partnership Program for Creative Research Teams. The CNES (Centre National d'Etudes Spatiales) is also acknowledged for its support (Modokalt project).

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