Increasing influence of central Pacific El Niño on the inter-decadal variation of spring rainfall in northern Taiwan and southern China since 1980

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Decadal variation of spring (February–April) rainfall in northern Taiwan and southern China was significantly related to the Pacific Decadal Oscillation (PDO) during the 20th century. However, this inter-decadal relationship subsequently weakened, and the sea surface temperature (SST) associated with the central Pacific El Niño (CPEN) has determined the inter-decadal variation of spring rainfall in northern Taiwan and southern China since the 1980s. In this study, the effect of CPEN–SST on the inter-decadal variation of spring rainfall in northern Taiwan and southern China was investigated. We found that a CPEN-associated positive SST anomaly in the eastern North Pacific forced an east–west overturning circulation anomaly in the subtropical North Pacific, the descending motion of which may have generated an anticyclonic circulation anomaly in the Philippine Sea. Simultaneously, the anticyclone associated southerly winds anomaly may enhance the southwesterly in northwest of the anticyclone, which in term enhance the trough extending from Japan to northern Taiwan. The anticyclone and trough associated with the respective southwesterly and northeasterly anomalies created a convergence environment in northern Taiwan. In turn, this convergence environment contributed substantially to an inter-decadal rainfall enhancement in northern Taiwan and southern China. Our results suggest that the effect of CPEN–SST on the inter-decadal variation of spring rainfall in northern Taiwan and southern China has increased since 1980, especially during the transition period from the termination of a warm PDO phase to a cold phase in the late 1990s.

KEYWORDS
central Pacific El Niño, Pacific Decadal Oscillation, spring rainfall

1 | INTRODUCTION

Taiwan is an island located southeast of mainland China, and its climate is strongly influenced by the East Asian monsoon system in both summer and winter seasons. During the transition period from winter monsoon to summer monsoon, the Siberian High is still active (Zhu et al., 2012), and its associated cold front may advance southward to northern Taiwan, resulting in considerable rainfall in the area in springtime (February–April, hereafter FMA). In addition to the Siberian High-associated cold front, cold fronts that originate in southern China affect Taiwan in springtime. These cold fronts, once initiated, generally move rapidly eastward across the Taiwan Strait and northern Taiwan (Yeh and Chen, 1984). These two types of cold fronts associated with spring rainfall account for approximately 20% of the total
annual rainfall in northern Taiwan and therefore strongly affect the amount of water available for agricultural irrigation in this region in springtime.

Using long-term rainfall data from Taiwanese stations, Hung et al. (2004) reported that spring rainfall in northern Taiwan was significantly correlated with the Pacific Decadal Oscillation (PDO) in the 20th century. That is, a surplus of spring rainfall in northern Taiwan occurred during the warm PDO phases in 1925–1946 and 1977–1995, and rainfall was below average during the cold PDO phases in 1890–1924 and 1947–1976.

Jiang et al. (2003) reported that the inter-annual variation of spring rainfall in northern Taiwan was substantially affected by El Niño-associated sea surface temperature (SST); that is, spring rainfall in northern Taiwan was enhanced or diminished in the year following an El Niño or La Niña event, respectively. El Niño events may be classified as central Pacific El Niño (CPEN) or eastern Pacific El Niño (EPEN) based on the zonal location of the maximum SST anomaly (SSTA) at the equator (Ashok et al., 2007; Kao and Yu, 2009; Kug et al., 2009; Lee and McPhaden, 2010). The two El Niño types exert different effects on the weather and climate variations in East Asia and the western North Pacific (WNP) (Kim et al., 2012; Hong et al., 2011; Yuan and Yang, 2012). The effect of El Niño on the East Asian climate has been widely discussed, but the distinct effects of the two El Niño types on spring rainfall in northern Taiwan have not been thoroughly investigated.

The inter-decadal variation of summer rainfall in Taiwan is significantly correlated with the equatorial central Pacific SST (Zhu et al., 2014; Huang et al., 2017; Liu et al., 2017). Based on historical observation and Coupled Model Inter-comparison Project Phase 5 (CMIP5) simulations, Sullivan et al. (2016) reported that the CPEN, rather than the EPEN, contributes substantially to atmospheric low-frequency variability in the eastern Pacific. Moreover, the magnitude of envelop function (i.e., low-frequency variability) of the PDO index has decreased since the 1980s, but the EPEN index has gradually increased (Figure 1). The effect of the CPEN-associated SSTA on the inter-decadal variation of spring rainfall in northern Taiwan and southern China was investigated in this study. We hypothesized that the CPEN-associated warm SSTA in the eastern North Pacific forced an east–west overturning circulation anomaly in the subtropical North Pacific, the descending motion of which may have generated an anticyclonic circulation anomaly in Philippine Sea. The anticyclone anomaly-associated southeastern anomaly transported a considerable amount of warm and humid ocean air to Taiwan and southern China, thereby contributing substantially to an inter-decadal rainfall surplus in northern Taiwan and southern China. Thus, we reported that the effect of CPEN–SST on spring rainfall in northern

**FIGURE 1** Time series of 10-year low-pass filter data in the FMA. (a) Northern Taiwan rainfall index, (b) rainfall at southern China, (c) PDO index, (d) CPEI, (e) EPEI. The NTRI was defined as the averaged TRI of five stations in northern Taiwan: Tamsui, An-bu, Taipei, Chu-tzi Lake, and Keelung. The time series of southern China was identified with southeast of mainland China (110°–122°E, 20°–30°N) of CRU rainfall data which starts form 1960 when adequate observations data was available. The gray line indicates a phase change of the inter-decadal rainfall with NTRI.
Taiwan was enhanced during the transition from a warm PDO phase to a cold phase in the late 1990s.

2 | DATA COLLECTION AND METHODS

Several independent data sets were used in this study. The monthly PDO index defined by Mantua et al. (1997) was retrieved from http://research.jisao.washington.edu/data_sets/pdo/. Monthly CPEN and EPEN indices (Yu et al., 2012a; 2012b) were used to represent the intensities of the two El Niño types. Through regression-empirical orthogonal function analysis, the indices were calculated from monthly SST data (Kao and Yu, 2009; Yu and Kim, 2010). The monthly atmospheric fields from the National Centers for Environmental Prediction-National Center for Atmospheric Research Reanalysis (Kalnay et al., 1996) were also used in analyses in the present study. SST data were collected from the National Oceanic and Atmospheric Administration Extended Reconstructed Sea Surface Temperature version 4 (Huang et al., 2014; Liu et al., 2014; Huang et al., 2015).

The Taiwan rainfall index (TRI) is the most extensive source of rainfall data in Taiwan; since 1900, extensive data for the TRI have been collected from observational stations in Taiwan (1,176 stations are used) (Hung, 2012). In this study, the TRI was used to represent rainfall data for northern Taiwan. The northern Taiwan rainfall index (NTRI; Figure 1a) was defined as the averaged TRI of five stations in northern Taiwan: Tamsui (121.44°E, 25.16°N), An-bu (121.53°E, 25.18°N), Taipei (121.51°E, 25.04°N), Chu-tzi Lake (121.54°E, 25.16°N), and Keelung (121.74°E, 25.13°N). Spring rainfall was defined as rainfall in FMA. In addition, the land precipitation data of the Climatic Research Unit (Mitchell and Jones, 2005) was used to represent large-scale rainfall. For these data, a 10-year Lanczos low-pass filter (Duchon, 1979) was used to isolate the inter-decadal signal. The effective degree of freedom (Quenouille, 1952) of low-pass time series data is considered in the significant test. The effective degree of freedom is defined as

\[
N' = \frac{N}{1 + \sum_{L=1}^{N/2} 2r_L x^2 r_L y^2}, \tag{1}
\]

where \(N'\) is the effective degree of freedom, \(N\) sample size, \(r_L, x^2 r_L, y^2 \) the lag correlation coefficient.

3 | RESULTS

3.1 | Changing relationship between PDO and northern Taiwan spring rainfall

The results of the 10-year low-pass filtering of the FMA rainfall data for northern Taiwan (Figure 1a) depicted a clear inter-decadal variation; spring rainfall was above average from the early 1920s to the mid-1940s and the late 1970s to the late 1990s, and it was below average from the late mid-1940s to the late 1970s. A similar inter-decadal variation was identified in southeast of mainland China (110°–122°E, 20°–30°N) from 1960 onward (Figure 1b), indicating that the inter-decadal variation of spring rainfall in northern Taiwan was a part of a large-scale phenomenon in southeastern Asia. Comparisons between the NTRI and climate indices (the PDO, CPEN, and EPEN indices; Figure 1c–e) revealed that the inter-decadal variation of the NTRI was closely correlated with the PDO (\(r = -0.82\)) during 1961–2010. The NTRI was positively correlated with the CPEN (\(r = -0.52\)) and EPEN (–0.53) indices, but the correlation coefficient was lower relative to that of the PDO comparison. The partial correlation was applied to investigate the individual relationship among the PDO, CPEI, EPEI indices and the NTRI (not shown). It reveals that partial correlation only exhibits a bit change compared with the original correlation coefficient (Figure 1a). Therefore, the inter-decadal increase of CPEI–NTRI correlation since 1990 is primarily resulted from the CPEI index. The 21-year sliding correlation coefficient revealed that the relationship between the PDO and NTRI weakened (\(r = -0.2\)) during the transition period from a warm PDO phase to a cold phase in the late 1990s (Figure S1, Supporting Information). The relationship between the EPEN index and the NTRI changed suddenly from positive to negative and became nonsignificant in the early 1990s. In contrast to the PDO and EPEN indices, the relationship between the CPEN index and the NTRI began increasing in the late 1990s (\(r = -0.7\)). Because the association of the EPEN index with spring rainfall in northern Taiwan was non-significant from 1990s onward, we focused on the associations of the PDO and CPEN indices with the NTRI.

A cross wavelet analysis was used to investigate the coherent spectrum between the PDO (CPEN) index and the NTRI through the time-varying domain. The analysis revealed that the PDO index was characterized by an inter-decadal fluctuation in cycles of more than 16 years (Figure 2a), whereas the CPEN index exhibited inter-decadal variation within periods of 8–12 years from the mid-1970s onward. Considering the inter-decadal timescale, the PDO was significantly coherent with the NTRI approximately in the spectrum window of 8–16-year periods. Whereas part of CPEN–rainfall relationship are located at the boundaries (cone of influence), Figure 2b clearly depicts the significant spectrum from 1980s to the early 1990s exactly falls in the cone of influence. The analysis shows that the low-pass filter of CPEN index and NTRI were significantly correlated since the 1980s. The inter-decadal signal of the CPEN index had been growing from 1980 onward (Figure S2), and the inter-decadal relationship between the NTRI and CPEN had been increasing since the mid-1970s (Figure 2d). As illustrated in Figures S2 and 2, the inter-decadal relationship between the NTRI and the CPEN index grew from 1980 onward;
concurrently, the inter-decadal relationship between the NTRI and PDO was weakening, especially during the transition period of the PDO in the late 1990s.

3.2 Increasing decadal correlation of CPEN and spring rainfall in northern Taiwan

Based on the data presented in Figure 2, the period of 1956–2000 was separated into two sub-periods: prior (1956–1975, referred to as IP1 hereafter) and post (1981–2000, referred to as IP2 hereafter) periods. The background state difference of SSTs and 850-hPa winds between IP1 and IP2 (IP2 subtracted from IP1) in FMA (Figure S3a) revealed a positive PDO-like pattern: a positive SSTA was identified in the tropical Pacific and a negative SSTA in the North Pacific. The SSTA patterns were accompanied by a low-level anticyclone anomaly in the WNP and a cyclone anomaly northeast of the anticyclone. The low-level cyclone anomaly may have contributed to the deepening of the trough in the Taiwan Strait, joining with the anticyclone anomaly-associated southeasterly flows, creating a convergent environment; these events lead to a rainfall surplus in northern Taiwan and southern China (Figure S3b; Hung et al., 2004).

A regression of SST, 850-hPa winds, and 200 hPa velocity potential on the PDO and CPEN indices was calculated to investigate the relative influence of the CPEN and PDO on the inter-decadal variation of spring rainfall in northern Taiwan. The regression map of SST and 850 hPa on the PDO in IP1 exhibited a PDO-like pattern: positive and negative SSTA were, respectively, identified in the eastern tropical Pacific and North Pacific, and an anticyclone anomaly was detected in the WNP (the PDO phase was negative in the IP1; Figure 3a). The regression map of the CPEN index in the IP1 was similar to that of the PDO index (Figure 3c), indicating that the time series of CPEN and PDO indices were closely related (cr = 0.54) in IP1. During IP2, the regression map of the PDO was approximately opposite to that in the IP2, but the signals became insignificant (Figure 3b). Simultaneously, the inter-decadal relationship between the PDO and CPEN indices suddenly decreased to near zero (cr = 0.07) in IP2. By contrast, the inter-decadal relationship between the CPEN and NTRI strengthened in IP2: a significant northeast–southwest tilted Pacific meridional mode (PMM)-like (Chiang and Vimont, 2004) positive SSTA, extending from the coastline of Baja California to equatorial central Pacific, and a negative SSTA and a low-level anticyclone in the WNP (Figure 3d) were clearly observed. Notably, the positive PMM-like SSTA was accompanied by an enhanced westerly anomaly in the equatorial western-central Pacific and a cyclone anomaly in the eastern North Pacific, which resembled the pattern of the CPEN. Because the PDO and CPEN indices were correlated, especially in IP1, a multiple regression was calculated to investigate the net contribution of the PDO and CPEN to the large-scale circulation and rainfall anomalies. Overall, the results of the multiple regression (Figure 3e–h) did not suggest essential distinctions compared with the single regression.

The data presented in Figure 3 indicated that spring rainfall in southern China and northern Taiwan in IP1 was primarily determined by the PDO. However, in IP2, rainfall in these regions was primarily determined by the CPEN. To investigate how the CPEN index modified the effect of
the PDO on spring rainfall in northern Taiwan and southern China, maps of velocity potential and divergent wind at 850 hPa regressed onto the PDO and CPEN indices were analyzed. The regression map of the PDO in IP1 revealed an east–west dipole structure in the Pacific, with descending and ascending anomalies in the respective western and eastern North Pacific (Figure 4a). The east–west dipole structure was not observed in IP2 (Figure 4b), indicating that the effect of the PDO on large-scale convection in the Pacific had declined. This finding was consistent with the regression map of SST and low-level wind anomalies (Figure 3b). The upward motion of the east–west overturning circulation anomaly may have caused an anomalous cyclone in the WNP. The cyclonic circulation anomaly-associated northerly anomaly weakened the prevailing southwesterly in northern Taiwan and southern China. Overall, the regression map of the CPEN index in IP1 resembled that of the PDO (Figure 4a,c), but the CPEI was not always in positive phase during 1956–1975. So, the phase change of spring rainfall in northern Taiwan was not related to the CPEI during 1956–1975. In contrast to the PDO, the east–west dipole structure of the lower-level velocity potential anomaly in the Pacific for the CPEN was enhanced in IP2. Furthermore, the center of anomalous convection shifted southward from south Japan to Maritime Continent in response to the strong
divergent flow anomaly approximately in the region of 120°E. Figure 4d illustrates that the CPEN or PMM-associated SSTA was correlated with an east–west overturning circulation anomaly in the North Pacific in IP2. In turn, the downward motion of the east–west overturning circulation anomaly may have caused an anomalous anticyclone in the WNP. The effect of CPEN–SST on the east–west overturning circulation in the North Pacific was supported by the numerical experiments (Hong et al., 2016). Briefly, the CPEN–SST-associated anomalous anticyclone in the WNP (Figure 3d) may have enhanced the prevailing southwesterly wind in the South China Sea, thus leading to a rainfall surplus in northern Taiwan and southern China in IP2.

4 | SUMMARY AND DISCUSSION

A previous study revealed that the inter-decadal variation of spring rainfall in northern Taiwan was significantly correlated with the PDO (Hung et al., 2004). In the present study, we reported that this relationship has decreased in recent decades, especially during the transition from a warm PDO phase to a cold phase in the late 1990s. In contrast to the PDO, the effect of CPEN–SST on spring rainfall in northern Taiwan exhibited a gradually increase beginning in 1980s and finally exceeded the influence of the PDO from the late 1990s onward (Figure S1). The effects of the PDO and CPEN on spring rainfall in northern Taiwan and southern China in different epochs are illustrated in the schematic (Figure 5) and described subsequently.

During IP1 (1956–1975), a negative PDO-related upward motion of the east–west overturning circulation anomaly may have caused an anomalous cyclone in the WNP. This cyclonic
circulation anomaly induced an anomalous northeasterly wind in the South China Sea, which inhibited the prevailing southwesterly wind, thereby reducing spring rainfall in northern Taiwan and southern China (Figure 5a). During IP2, the effect of the PDO decreased, but the influence of CPEN–SST on spring rainfall in northern Taiwan gradually increased. The CPEN-associated PMM-like SST forced an east–west overturning circulation anomaly in the North Pacific, and the subsidence motion in the WNP may have created a low-level anticyclone anomaly in the WNP (Figure 3d). The anticyclone anomaly-associated southwesterly flow further enhanced the prevailing southwesterly anomaly. Consequently, more humid and warm oceanic air was transported northward to southern China, eventually leading to a rainfall surplus in northern Taiwan and southern China (Figure 5b).

As depicted in Figure 1, the increasing effect of CPEN–SST on the inter-decadal variability of spring rainfall in northern Taiwan was closely related to the strengthening of the CPEN index magnitude. A discussion of the reasons that the CPEN index exhibited an inter-decadal increase from 1990 onward is outside the scope of this study; therefore, the reasons were not examined.

Yu et al. (2015) suggested that the air–sea coupling of the PMM was enhanced by Atlantic Multidecadal Oscillation after the early 1990s. Because the PMM–SST was closely related with CPEN–SST (Figure 3), the rise of CPEN–SST from the 1990s onward was possibly caused by the strengthening of PMM. The response mechanisms underlying the inter-decadal increase of the CPEN index in recent decades deserve additional research attention.

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