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A change in the relationship between tropical central Pacific SST variability and the extratropical atmosphere around 1990

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Abstract
A newly released reanalysis dataset covering the period 1979–2009 is analyzed to show that the sea surface temperature (SST) variability in the tropical central Pacific is more closely related to the SST variability in the tropical eastern Pacific before 1990 but more closely related to sea level pressure (SLP) variations associated with the North Pacific Oscillation (NPO) after 1990. Only during the period after 1990 can the NPO excite large SST variability in the tropical central Pacific. Related to this change, El Niño Southern Oscillation (ENSO) SST anomalies tend to spread from the eastern to central tropical Pacific before 1990 in a pattern resembling that associated with the Eastern Pacific (EP) type of ENSO, but are more closely connected to SST variability in the subtropical north Pacific after 1990 with a pattern resembling that of the Central Pacific (CP) type of ENSO. This study concludes that the increased influence of the NPO on the tropical Pacific is a likely reason for the increasing occurrence of the CP type of ENSO since 1990. An analysis of the mean atmospheric circulation during these two periods suggests that the increased NPO influence is associated with a strengthening Hadley circulation after 1990.

Keywords: two types of ENSO, NPO, Walker circulation, Hadley circulation

1. Introduction

While El Niño Southern Oscillation (ENSO) has traditionally been characterized by interannual sea surface temperature (SST) variations in the eastern-to-central equatorial Pacific, it has been noticed that ENSO events with SST anomalies confined near the International Dateline can also occur. This flavor or type of ENSO has been referred to as the Central Pacific (CP) ENSO (Yu and Kao 2007, Kao and Yu 2009), Date Line El Niño (Larkin and Harrison 2005), El Niño Modoki (Ashok *et al* 2007) or warm pool El Niño (Kug *et al* 2009), while the conventional ENSO (e.g., Rasmusson and Carpenter 1982) is referred to as the Eastern Pacific (EP) type. Interest in the non-conventional CP ENSO has been stoked by the observation that this ENSO type has occurred more frequently during the past few decades (Ashok *et al* 2007, Kao and Yu 2009, Kug *et al* 2009, Lee and McPhaden 2010), particularly since the 1990s. Since the start of the 21st century, for example, most of the El Niño events have been of the CP type, including the 2002/03, 2004/05 and 2009/10 events (Yu *et al* 2012). There is a strong interest in understanding the cause(s) of the emergence of the CP ENSO after 1990.

Yeh *et al* (2009) compared the occurrence ratio of the CP to EP events in coupled climate model simulations and noticed that the ratio is projected to increase under a global warming scenario. They argued that the recent increase in the occurrence of the CP El Niño is related to a weakening of the mean Walker circulation and a flattening of the mean thermocline in the equatorial Pacific, which might be results of global warming (Vecchi and Soden 2007). Further, Lee and McPhaden (2010) noticed that not only has the occurrence frequency of the CP El Niño increased in the past three decades but its intensity has also doubled. However, they noticed that the intensity of La Niña events did not change during the same period. The different changes in the intensities of El Niño and La Niña in the recent few decades can be manifested as a warming trend in the mean SST of the tropical central Pacific. Lee and McPhaden (2010), therefore, does not support the suggestion that the recent emergence of the CP El Niño results from mean state changes induced by global warming in the tropical Pacific. Similar suggestions were also made in McPhaden *et al* (2011). Long-term model simulations also suggested that periods when CP variability is high can occur naturally without the need of changes in external forcing (Choi *et al* 2011, Yeh *et al* 2011). Newman *et al* (2011) used a linear inverse modeling technique to suggest that random variations in the atmosphere can excite two particular initial SST anomaly patterns, each of which can eventually develop into either the EP or CP type of ENSO. They argued that such natural random variations can result in slow alternations of the ENSO type without the need for anthropogenically forced changes in the background states. These diverse arguments indicate that there is no clear consensus on the cause of the increasing occurrence of the CP ENSO in recent decades.

In this study, we perform analyses aimed at showing that the increasing influence from the extratropical atmosphere on the tropical Pacific is a possible cause for the recent emergence of the CP ENSO. The importance of extratropical forcing to the generation of the CP ENSO has been demonstrated in several recent studies (e.g., Yu *et al* 2010; Yu and Kim 2011; Kim *et al* 2012). Yu *et al* (2010), for example, performed a mixed-layer heat budget analysis to show that SST anomalies associated with the CP ENSO undergo rapid intensification through ocean zonal advection processes, consistent with the suggestion of Kug *et al* (2009). However, Yu *et al* (2010) argued that the initial establishment of SST anomalies in the tropical central Pacific is related to forcing from the extratropical atmosphere and subsequent atmosphere–ocean coupling in the subtropics. They suggested that SST anomalies appear first in the northeastern subtropical Pacific and later spread toward the tropical central Pacific, leading to the development of the CP ENSO. The initial subtropical SST anomalies were shown to be induced by sea level pressure (SLP) variations associated with the North Pacific Oscillation (NPO; Walker and Bliss 1932; Rogers 1981). Therefore, in this study we focus on examining how the influence of the extratropical atmosphere on the tropical Pacific has changed in the past three decades (1979–2009) using the latest reanalysis dataset from National Centers for Environmental Prediction (NCEP).

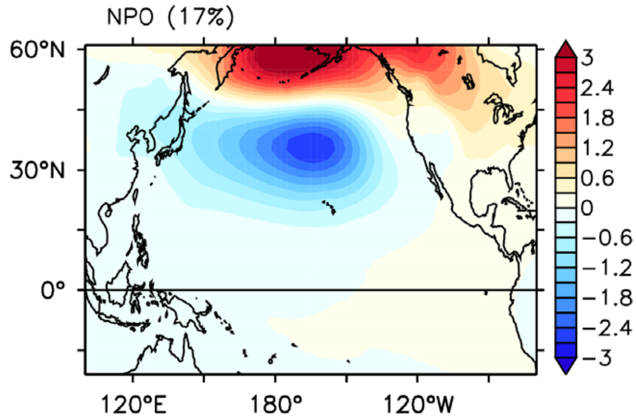

Figure 1. The Pacific SLP anomalies regressed with the principal component of the second EOF modes of SLP anomalies (20°–60°N and 120°E–80°W) from the CFSR. This second mode explains 17% of the total variance.

2. Data

In this study, monthly SST and SLP data are taken from the reanalysis produced by the NCEP's Climate Forecast System (CFS) version 2 (CFSv2), which is referred to as the CFS Reanalysis (CFSR; Saha *et al* 2010). The data set covers the period 1979–2009. It has been suggested that the CFSR is more accurate than the NCEP global reanalysis produced in the 1990s (Saha *et al* 2010). Monthly anomalies of SST and SLP are obtained by removing their climatological seasonal cycles.

3. Results

Our analysis focuses on three quantities: the NPO index, the Niño4 SST index, and the Niño3 SST index. The NPO index is obtained as the principal component of an empirical orthogonal function (EOF) mode of SLP anomalies. The EOF analysis is applied to the covariance matrix of monthly SLP anomalies between 20°–60°N and 120°E–80°W. The NPO appears as the second EOF mode and explains 17% of the total SLP variance. The NPO mode (figure 1) is characterized by an out-of-phase variation between SLP anomalies in the subtropics (20°–40°N) and those in the higher latitudes (50°–60°N). The evolution of the NPO index during the period 1979–2009 is shown in figure 2, together with the evolution of the Niño3 and Niño4 SST indices. All values shown have been filtered using a five-year low-pass filter (Parzen smoother) to retain only the slowly varying components. It can be seen that the general relationships among these three time series changed around 1990. In the post-1990 period (i.e., 1991–2009), the variation of the Niño4 index is less related to the Niño3 index, but more closely related to, and almost in phase with, the NPO index. In contrast, in the pre-1990 period (i.e., 1979–1990), the Niño4 index is more related to, and in phase with, the Niño3 index, but is less related to the NPO index. This figure indicates that, qualitatively, SST variability in the tropical central Pacific (i.e., represented by the Niño4 index) is more related to the

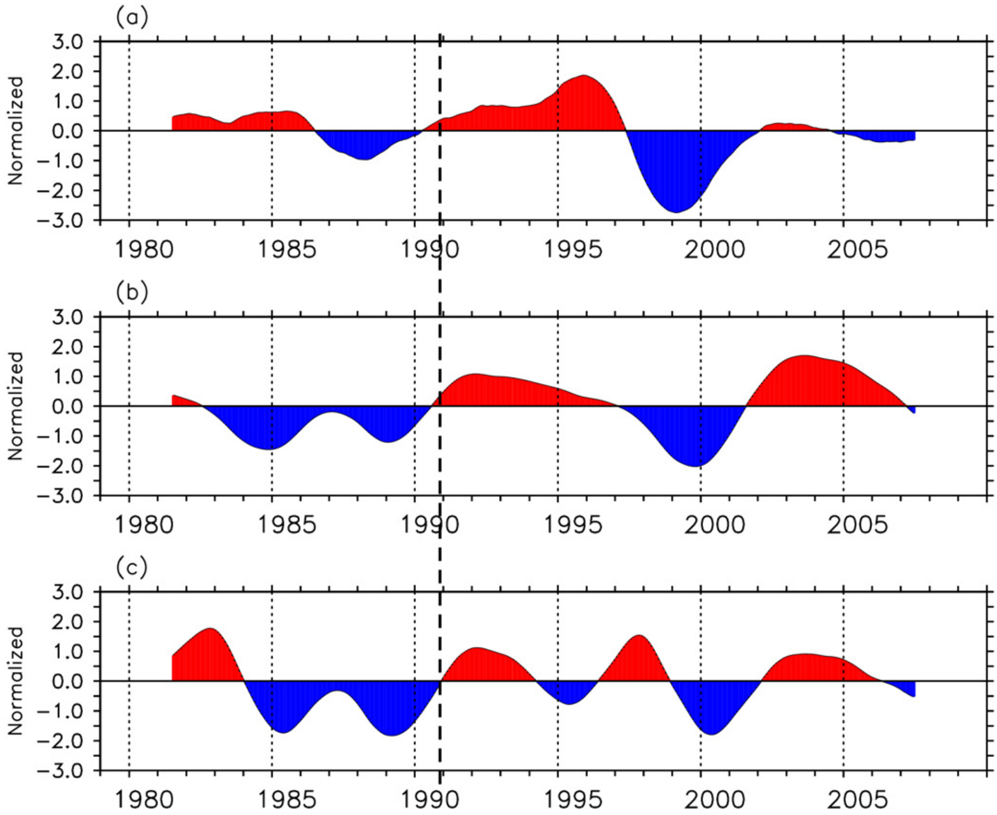

Figure 2. Time series of (a) NPO, (b) Niño4 and (c) Niño3 indices which are five-year low-pass filtered. Values shown are normalized by their standard deviations.

SST variability in the tropical eastern Pacific (i.e., represented by the Niño3 index) before 1990 but more related to the extratropical atmospheric variations (i.e., represented by the NPO index) afterward.

We examine in figure 3(a) the lead–lag regression of Pacific SST anomalies to the NPO index during the post-1990 period using the unfiltered monthly anomalies. During the development phase (Lags −8 to −2 months) of the NPO, positive SST anomalies were induced in the northeastern Pacific underneath the southern lobe of the NPO, where an anomalous, cyclonic atmospheric circulation weakens the trade winds and reduces latent heat flux out of the ocean (not shown). The subtropical SST warming is sustained after the NPO peak (i.e., Lags 2–8) and spreads southwestward toward the tropical central Pacific. A CP type of El Niño develops in the tropical Pacific 6–8 months after the peak of the NPO. A similar regression analysis for the pre-1990 period (i.e., 1979–1990) is shown in figure 3(b). In the pre-1990 period, positive SST anomalies can also be induced by the NPO during its development and peak phases (Lags −8–0). However, the subtropical SST anomalies do not spread into the tropical Pacific and there is no significant warming in the tropical central Pacific afterward. In short, the NPO is more capable of inducing major CP El Niño events during the post-1990 period, but less so during the pre-1990 period. Therefore, interannual variations in the extratropical atmosphere have a stronger influence on the tropical Pacific SST variability after 1990, and this increased influence contributes to the more frequent occurrence of CP ENSO events.

We note that the ENSO SST variability pattern also changed around 1990. Figure 4 shows the standard deviation of the interannual SST anomalies calculated from the pre-1990 period minus the standard deviation calculated from the post-1990 period. As indicated by the red dashed line in the figure, the interannual SST variability in the pre-1990 period was large from the South American coast to the equator and then to the central Pacific along the equator, which closely resembles the SST anomaly pattern associated with the EP ENSO shown in Kao and Yu (2009), their figure 4(a). The negative differences enclosed by the blue dashed line in figure 4 indicate the regions of increased SST variability in the post-1990 period. The line indicates that the increased variability in the tropical central Pacific is connected to increased SST variability extending from the northeastern Pacific. The pattern of negative difference is close to the SST anomaly pattern associated with the CP ENSO shown in Kao and Yu (2009), their figure 4(b). Also, the SST variability in the northeastern subtropical Pacific is similar to the NPO-regressed SST anomaly pattern shown in figure 3(a). Therefore, figure 4 indicates that the tropical central Pacific SST variability in the pre-1990 period is related to the variability in the tropical eastern Pacific and the EP type of ENSO. In the post-1990 period, however, the SST variability in the tropical central Pacific is more related to the SST variability induced by the NPO in the northeastern

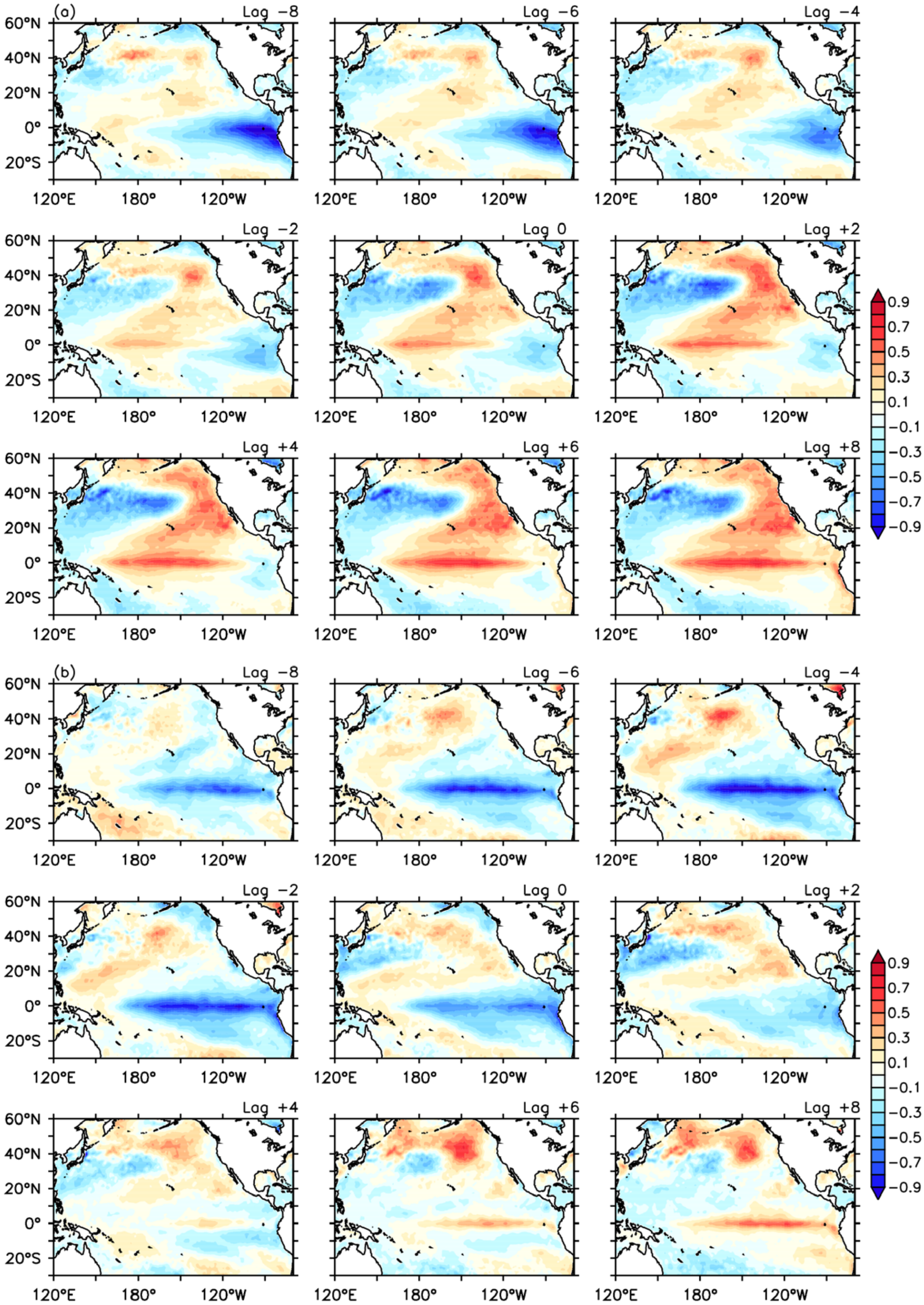

Figure 3. Lead-lagged regression of SST anomalies onto the NPO index in period (a) 1991–2009 and (b) 1979–1990. The lag values shown in the panels are in unit of months.

subtropical Pacific and they appear together as the CP type of ENSO.

Figures 3 and 4 together suggest that the increased influence of the extratropical atmosphere is likely a reason why the CP type of ENSO has occurred more frequently since 1990. We next explore the possible reasons why the extratropical atmosphere became more effective in influencing the tropical Pacific after 1990. Figure 5(a) shows

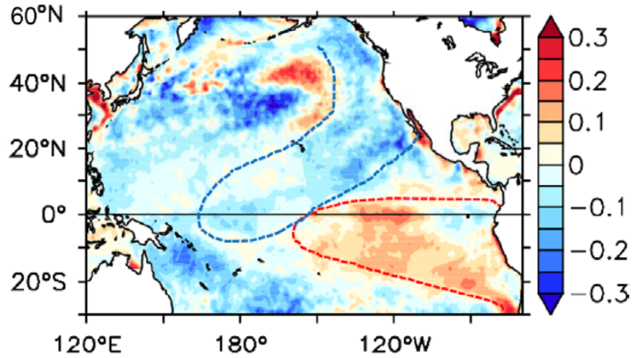

Figure 4. The difference between the standard deviations of SST anomalies calculated from 1979 to 1990 and those calculated from 1991 to 2009.

the deviations of the mean SLP for the pre-1990 period from the mean of the entire period (i.e., 1979–2009; the long-term mean, hereafter). Over the tropical Pacific, the deviations show that the pre-1990 SLP is lower than the long-term mean in the western Pacific but higher than the long-term mean in the eastern Pacific. This deviation pattern implies that the Walker circulation in the pre-1990 period is stronger than the long-term mean. The figure also shows that there is a negative deviation over the subtropical Pacific, which implies that the Hadley circulation in the pre-1990 period is weaker than the long-term mean. In contrast, the SLP deviations calculated from the post-1990 period (figure 5(b)) are positive over the tropical western Pacific and negative over the tropical eastern Pacific, which is an indication of a weakened Walker circulation. Also, the positive deviation in the north subtropical Pacific indicates a strengthened Hadley circulation. Therefore, figure 5 suggests that, over the Pacific Ocean, the post-1990 period has a stronger mean Hadley circulation and a weaker mean Walker circulation than the pre-1990 period.

To further quantify the changes in the strengths of the Walker and Hadley circulations during these two periods we calculated the circulation indices defined by Oort and Yienger (1996). The Hadley circulation strength is defined as the vertical shear of the meridional wind between 200 and 800 mb over the tropical Pacific (120°E–80°W) along 10°N. Our calculation shows that the shear (i.e., the Hadley circulation strength) increases dramatically from 0.12 m s^{-1} in the pre-1990 period to 0.62 m s^{-1} in the post-1990 period. As for the Walker circulation, its strength is defined as the difference in 500 mb vertical velocity between the eastern (180°W–100°W) and western (100°E–150°E) regions of the equatorial Pacific (10°S–10°N). We found that the Walker circulation strength slightly decreases from 3.8×10^{-2} Pa s^{-1} during the pre-1990 period to 3.6×10^{-2} Pa s^{-1} during the post-1990 period. Therefore, the circulation indices confirm the suggestion from figure 5 that the strength of the mean Hadley circulation increases from the pre-1990 period to the post-1990 period, while the reverse is true for the Walker circulation. Our analyses suggest that the increased influence of NPO on tropical central Pacific SST variations in the post-1990 period is associated with a strengthened Hadley circulation and a weakened Walker circulation. However, the strength decrease in the Walker circulation is relatively small and not statistically significant.

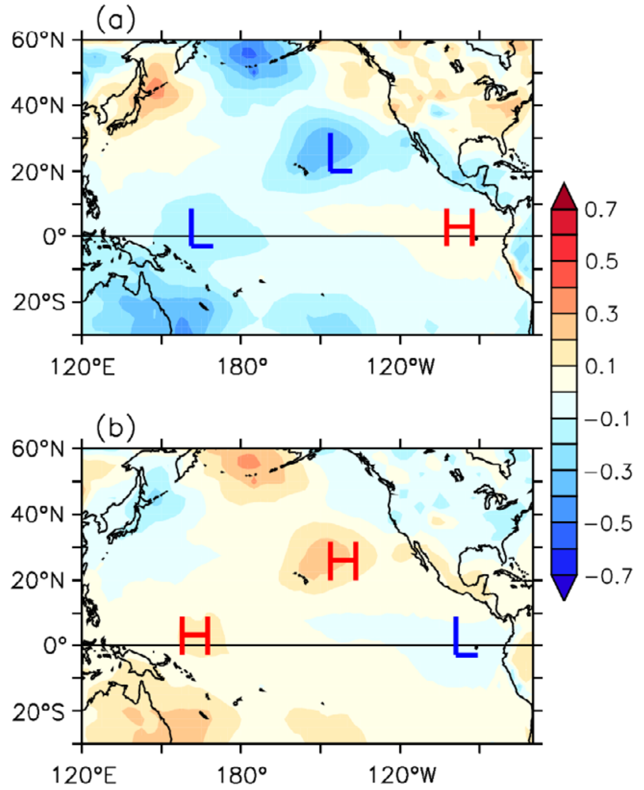

Figure 5. Deviations of the mean SLP in (a) 1979–1990 and (b) 1991–2009 from the long-term mean (1979–2009). Symbols, 'H' and 'L', indicate positive deviations and negative deviations, respectively.

4. Summary and discussion

In this study, we examined the relationship between SST variations in the tropical Pacific and SLP variations over the extratropical Pacific during the past three decades using NCEP's CFSR data. We conclude that the NPO mode of extratropical SLP variations has exerted a stronger influence on SST variations in the tropical central Pacific since 1990. This stronger influence is likely a cause for the shift of ENSO from a predominantly EP type before 1990 to a predominantly CP type afterward. The increased influence of the NPO on tropical central Pacific SST variations is suggested to be related to a strengthening of the Hadley circulation. The stronger Hadley circulation could help the NPO-induced SST variations to spread into the tropical central Pacific. In association with the changes in the strengths of the mean atmospheric circulations, the tropical central Pacific has become more responsive to the forcing and influence from the extratropical atmosphere, which has resulted in more frequent occurrences of CP ENSO events. The results obtained in this study indicate that the relative dominance of the two types of ENSO may be related to the relative strengths of the Hadley and Walker circulations, which warrants further study.

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