Central-Pacific El Nino: Pattern, Evolution, and Generation

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1. Introduction

Recent studies have suggested that there are two different types of interannual sea surface temperature (SST) variability in the tropical Pacific (Larkin and Harrison 2005; Yu and Kao 2007; Ashok et al. 2007; Kao and Yu 2009; Kug et al. 2009). One of them is the conventional type that has most of its SST anomalies centered in the eastern Pacific, and the other is a non-conventional type that has SST anomalies confined more to the central Pacific. Kao and Yu (2009) refer to these two types as the Eastern-Pacific (EP) and Central-Pacific (CP) types of El Nino-Southern Oscillation (ENSO), respectively. Studies have shown that these two types have different impacts on global weather and climate (e.g., Larkin and Harrison 2005). It was argued that the CP El Niño events have become more frequent during recent decades (Ashok et al. 2007; Kao and Yu 2009; Yu et al. 2010a). Thus, interest in the dynamical processes responsible for the CP ENSO events has been increasing rapidly.

By examining the associated subsurface ocean temperature variations, Kao and Yu (2009) concluded that the EP type is produced by basin-wide thermocline variations similar to those described by the recharge-discharge oscillator (Jin 1997) theory, while the CP type involves only local air-sea interactions. According to the recharge-discharge theory, the EP ENSO acts as a mechanism to remove excess ocean heat content from the equatorial to the off-equatorial Pacific. After an EP El Niño event, the equatorial thermocline is in a discharged state that is characterized by above-normal depths and is ready to produce an EP type of La Niña event. After an EP La Niña event, the thermocline is recharged to below-normal depths, and is ready to produce the EP type of El Niño again. As for the CP ENSO, its specific generation mechanism is not fully understood yet. Yu et al. (2009) used numerical experiments to argue that the CP type can be linked by Asian and Australian monsoon forcing. In this study, we further show that the atmospheric forcing from the extratropical Pacific is another generation mechanism for the CP ENSO. Furthermore, the evolution pattern of the CP ENSO is determined by its interaction with the EP ENSO.

2. Data

For SST information, we use the National Oceanic and Atmospheric Administration Extended Reconstruction of Historical Sea Surface Temperature version 3 (ERSST V3) data from the National Climate Data Center (NCDC) and the Met Office Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST). For subsurface ocean temperature information, we use the dataset taken from the Simple Ocean Data Assimilation Reanalysis. We choose to analyze the period 1958-2007, during which both the ERSST and SODA are available. Anomalous quantities are computed by removing the monthly-mean climatology and the trend. We also use the observed anomalous 20°C isothermal depth from the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON) arrays from June 1986 to February 2010.

3. An upper Ocean heat budget analysis

We first analyze the interannual SST variability in the central equatorial Pacific, which is most related to the CP type of ENSO. We separate the central-Pacific SST variability into a Type-1 variability that is directly correlated to the eastern Pacific SST variation and a Type-2 variability that is not. Analyses of the surface-layer ocean temperature budget are performed to identify the leading physical processes for these two types of SST variability. Results show that Type-1 variability is part of the conventional ENSO, which is characterized by SST anomalies extending from the South American coast to the central Pacific, is coupled with the Southern Oscillation, and is associated with basin-wide subsurface ocean variations. This type of variability is dominated by a major 4-5 year periodicity and a minor biennial (2-2.5 years) periodicity. In contrast, Type-2 variability is dominated by a biennial periodicity, is associated with local air-sea interactions and lacks a basin-wide anomaly structure. In addition, Type-2 SST variability exhibits a strong connection to the subtropics of both hemispheres, particularly the Northern Hemisphere. As shown in Figure 1, Type-2 SST anomalies appear first in the northeastern subtropical Pacific and later spread toward the central equatorial Pacific, being generated in both regions by anomalous surface heat flux forcing associated with wind anomalies. The SST anomalies undergo rapid intensification in the central equatorial Pacific through ocean advection processes, and eventually decay as a result of surface heat flux

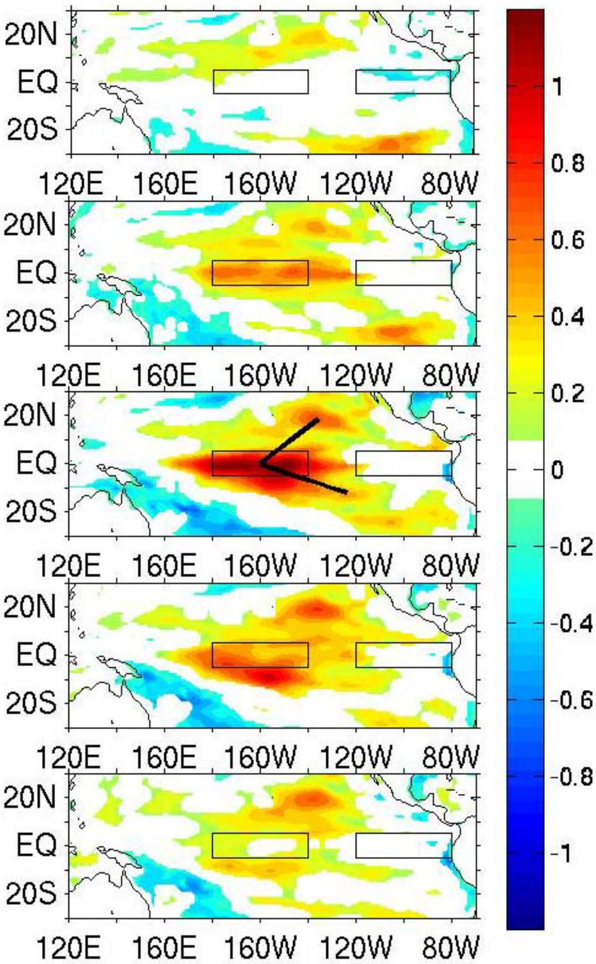

Figure 1. Lead-lagged regression coefficients between SST anomalies in the tropical Pacific and the Type-2 SST index (SST anomalies averaged in the box in the central Pacific). Contour intervals are 0.2ºC/month*ºC. The values in the parenthesis at the upper left of the panels indicate the lag months. The black lines in (h) connect local maximum variability centers at 12ºS and 18ºN. Only coefficients exceeding the 95% confidence interval are shown.

damping and zonal advection. We find that the southward spreading of the trade wind anomalies within the northeastern subtropics-to-central tropics pathway of Type-2 variability is associated with intensity variations of the subtropical high. We conclude that Type-2 interannual variability represents a subtropical-excited phenomenon that is different from the conventional ENSO Type-1 variability.

The Type-2 SST variability discussed here is basically the CP ENSO. This study further confirms that the CP ENSO has a different generation mechanism from the EP ENSO. Our temperature budget analyses not only identify the relative importance of the various local coupling processes in the evolution of the CP El Niño but also demonstrate that those local processes are triggered by remote forcing from the subtropical Pacific. This view is different from the generation mechanism suggested by other groups for the CP ENSO. These other groups either emphasized wind-induced thermocline variations within the tropical Pacific or the zonal ocean advection in the equator for the SST evolution. Our results indicate that the ocean advection processes are important only after the CP type SST anomalies onset at the equator, and that the initial establishment of the equatorial SST anomalies is forced by subtropical atmospheric forcing.

4. Role of extratropical SLP variability

To further examine the extratropical connection for the CP ENSO, we perform Empirical Orthogonal Function (EOF) analysis on sea level pressure (SLP) anomalies between 10ºN and 60ºN (not including the equatorial Pacific to avoid any direct El Niño influences). The principal components of the leading EOF modes are then correlated with interannual SST anomalies in the Pacific to reveal the SST pattern associated with each SLP mode. The first EOF in SLP is found characterized by an Aleutian low variation pattern. Its correlated SST anomalies are typical of the EP ENSO with SST anomalies extending from the eastern to central equatorial Pacific. The second EOF mode is characterized by a meridional SLP anomaly dipole pattern with a nodal point near 50°N. Its correlated SST anomalies extend from the northeastern subtropical Pacific toward the central equatorial Pacific, but show little tropical SST connection.

However, lagged correlation analyses show that the subtropical SST anomalies associated with the second SLP mode continue to expand and spread toward the central equatorial Pacific (Figure 2). Equatorial SST anomalies are established in the central equatorial Pacific a few months after the SLP mode peaks in the Extratropics. The SST anomalies then intensify in the central Pacific and eventually develop into a CP type of El Niño or La Niña. The results obtained from this SLP analysis suggest that the extratropical forcing is a possible generation mechanisms for the CP type of ENSO. This suggestion has an important implication for the study of tropical Pacific SST variability, because it raises the possibility that the meridional atmospheric circulation (i.e., Hadley circulation) can interact with the tropical Pacific Ocean to generate interannual SST variability. El Niño and La Niña events may be results of tropical ocean interactions with not only the east-west Walker circulation but also the north-south Hadley circulation.

Another interesting finding we obtain is that the EP ENSO can excite the 2nd SLP mode during EP's decay phase (see Fig. 2 from lag -10 to lag 0). That means the EP ENSO is one of the forcing mechanisms capable of producing the north-south SLP anomaly dipole in the extratropical atmosphere (i.e., NPO). Since the largest correlation between the 2nd SLP mode and the EP type is -0.47, about 22% of the NPO can be attributed to the EP ENSO. Since we have already pointed out the 2nd SLP mode can lead to the CP ENSO, it becomes reasonable to conclude that some of the CP events are excited after the demise of the EP events through the 2nd EOF mode of extratropical SLP variations. This extratropical linking mechanism may be a reason why a strong CP type of La Niña event tends to occur after a strong EP type El Niño event, as noted in Yu et al. (2010b). For instance, the strong CP-type La Niña events of 1973/74, 1983/84, and 1998/99 came after the strong EP-type El Niño events of 1972/73, 1982/83, and 1997/98, respectively. We verify this linking mechanism in Figure 3, which displays the evolution of SST anomalies along equator (5°S-5°N) from these three sets of events and the values of the principal components of the first two leading extratropical SLP modes. The figure shows all three CP La Niña events (1973, 1983, 1998) were preceded by a negative PC2 value (red lines) in the previous spring, and all these negative PC2 values began to develop after the EP El Niños (1972, 1982, 1997) began to decay. All the three sets of events show a sequence of EP El Niño, 2nd SLP mode, and CP La Niña, consistent with the extratropical linking mechanism uncovered in this study.

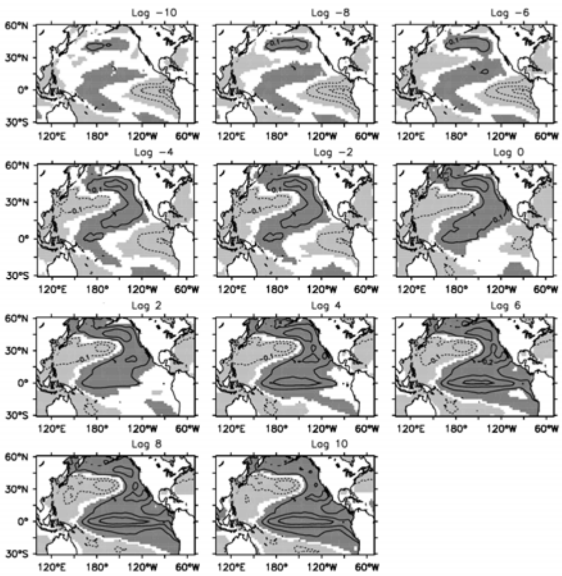

Figure 2. SST anomalies regressed with the 2nd SLP mode from time lag -10 months to time lag +10 months. Contour intervals are 0.1 and the regression slopes significant at the 99 % level according to a student *t*-test are shaded. (+) lags indicate that the principal component leads the SST anomalies.

5. Identify the evolution patterns of the CP ENSO

We next turn our attention to the evolution of the CP El Niño. We analyze

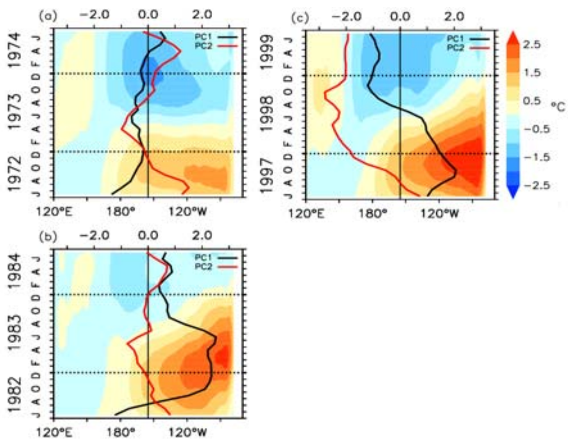

Figure 3. The longitude-time diagram of SST anomalies along the equator for three strong EP type El Niño events followed by CP type La Niña events: (a) 1972/73 El Niño and 1973/74 La Niña, (b) 1982/83 El Niño and 1983/84 La Niña, and (c) 1997/98 El Niño and 1998/99 La Niña. Time series of the first (black line) and second (red line) principal component during the evolution of the El Niño and La Niña are also superimposed.

observed CP El Niño events to better understand their underlying dynamics and their interactions with the EP type of ENSO. We identify nine (9) CP El Niño events during 1958-2007. We inspect the evolution of SST anomalies along the equatorial Pacific (averaged between 5°S and 5°N) for these nine events and notice that their evolutions can be separated into three different groups. A composite analysis is then performed from July of the CP El Niño year (year 0) to June of the following year (year +1) for all these three groups. Figure 4 shows the composite SST anomalies along the equatorial Pacific (5°S-5°N). In the first group, the CP El Niño events are followed by a significant warming in the eastern Pacific. This group includes the 1968/69, 1990/91, and 1991/92 events. All three events reached their peak intensities in boreal winter and decayed during the following spring. During their decaying phase, an EP type of El Niño emerged and produced significant positive SST anomalies during boreal summer off the South American coast. This group has a slow and prolonged decay phase compared to the duration of warming in its growth phase. We name this evolution the prolonged-decaying pattern. In the second group, the CP El Niño events are followed by significant cooling in the eastern Pacific. This group includes the 1963/64, 1977/78, and 1987/88 CP events. These events reached their peak intensities near boreal winter (except the 1987/88 event) and the EP type of cooling developed after the demise of the CP events. These events terminate rapidly after reaching its peak intensity. We name this evolution the abrupt-decaying pattern. The third group has warming occurring more-or-less simultaneously in both the central and eastern Pacific. This group includes the 1994/95, 2002/03, and 2004/05 CP El Niño events. For this group, its decay and growth phases tend to be more symmetric with respect to the peak phase. We name this evolution the symmetric-decaying pattern. All three groups show similar warm peak timing for most of the CP events but very different SST evolutions during the decaying phase. Therefore, our analysis focuses on understanding what determines the different decaying patterns.

We examine the composite thermocline evolution, (represented by the 20°C isotherm depth; D20C) in the equatorial Pacific for the three groups of CP El Niño events. As shown in Figure 5, we find that the depth of the equatorial thermocline determines which evolution pattern should occurs for a CP El Niño event. If the CP El Niño occurs in a recharged thermocline state (i.e., deeper-than-normal depth), an EP warming may appear in the decaying phase of the CP event to slow down the decay, giving rise to the prolonged-decaying pattern. If the thermocline is

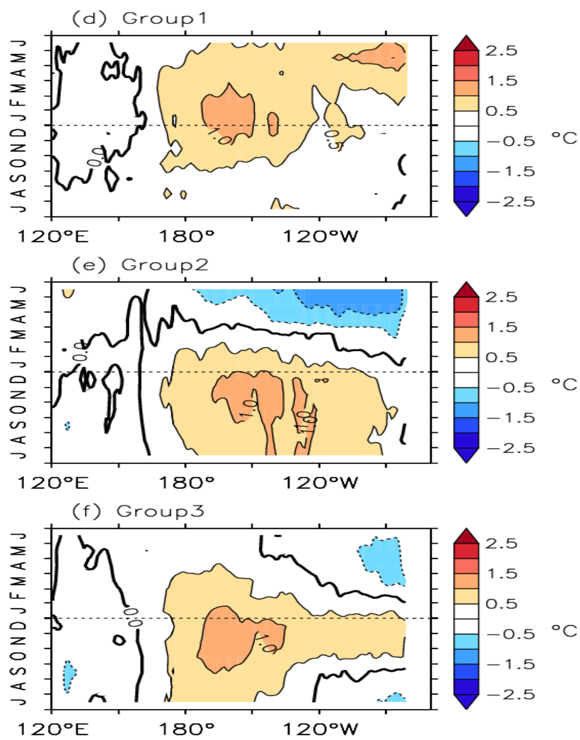

Figure 4. Evolution of equatorial Pacific (5°S-5°N) SST anomalies composite for the three groups of CP El Niño from July of the El Niño year (0) to June of the following year (+1) calculated from the HadISST datasets.

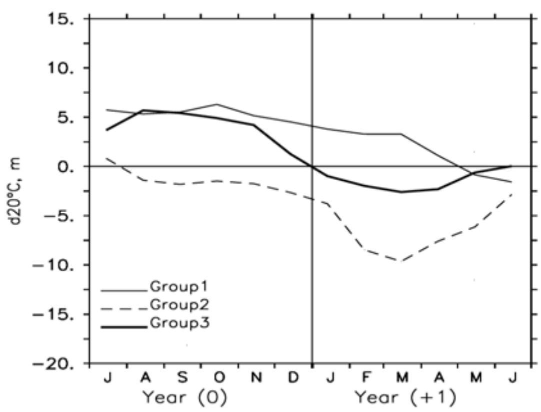

Figure 5. Evolution of the depth anomalies of the zonal-mean 20°C isotherm (D20°C) at the equator (5°S-5°N) calculated from the SODA reanalysis data. A composite for each group is displayed. The zonal mean is averaged between 120°E and 80°W. The evolution is shown from July of El Niño year (0) to June of the following year (+1).

in a discharged state (i.e., shallower-than-normal depth), an EP cooling may occur to abruptly terminate the CP El Niño. If the thermocline is in a neutral state (i.e., normal depth), the CP event may have a symmetric pattern of growth and decay. Our results indicate that the equatorial thermocline state at the peak phase of a CP El Niño event can be a potential predictor of the way the event may decay.

Our findings do not contradict our previous suggestion that the CP ENSO does not rely on the subsurface ocean processes for their generation. Rather, our results confirm that thermocline variations control only the generation of the EP type of SST variability but not the CP type of SST variability. CP El Niño events can occur in the presence of a deeper-than-normal (i.e., recharged state), shallow-than-normal (i.e., discharged state), or near-normal (i.e., neutral state) thermocline depth. However, these different thermocline structures do affect whether a warming, cooling, or neutral event may occur in the eastern Pacific as the CP event decays. Depending on the thermocline structure, the eastern Pacific warming, cooling, or neutral event may interfere with the SST evolution of the CP event and give rise to the three distinct CP El Niño SST decay patterns. It is the interplay between the dynamics of the CP and EP types of tropical SST variability makes the thermocline information useful for the prediction of both types of SST variations.

6. Conclusion

Our analyses indicated that CP events are excited primarily by extratropical atmospheric forcing (via the lower returning branch of the Hadley circulation) and then intensify in the central equatorial Pacific via local air-sea interactions, particularly zonal ocean advection. Successful prediction and modeling of the CP ENSO may depend more on a better understanding, and improved skill in the modeling, of extratropical processes. This is very different from the prediction and modeling systems the climate research community has developed for the conventional EP ENSO, which emphasize tropical subsurface ocean dynamics.

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