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Precursors of ENSO beyond the tropical Pacific

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Precursors of the El Niño-Southern Oscillation (ENSO) are atmospheric or oceanic phenomena that often occur before the onset of ENSO events and offer the potential to predict ENSO events with significant lead times. Most of the well-known ENSO precursors identified, so far, occur within the tropical Pacific, such as the build-up of subsurface ocean heat content anomalies in the tropical western Pacific (e.g., Wyrtki 1985; Meinen and McPhaden 2000) and the appearance of westerly wind bursts in the tropical western-to-central Pacific (e.g., McPhaden 1999; Vecchi and Harrison 2000; Zhang and Gottschalk 2002). These precursors have been suggested to affect ENSO onset through fluctuations in thermocline depths in the equatorial Pacific, which are recognized as a central element of the ENSO generation mechanism. Precursors outside the tropical Pacific have also been shown to exist, including wind and sea surface temperature (SST) variations in the subtropical or extratropical Pacific as well as in the Indian Ocean (e.g., Clarke and van Gorder 2003) and Atlantic Ocean (e.g., Rodriguez-Fonseca et al. 2009). The increasing interest in different flavors of ENSO in recent years has begun to place more emphasis on ENSO precursors outside the tropical Pacific, particularly those in the subtropical Pacific. The US CLIVAR working group on ENSO diversity summarized recent ENSO diversity studies in Capotondi et al. (2015). One view emerging from these studies is that there may exist two different flavors or types of ENSO, which are often referred to as the Eastern Pacific (EP) ENSO and Central Pacific (CP) ENSO (Yu and Kao 2007; Kao and Yu 2009), and that subtropical Pacific precursors may be particularly important to the CP ENSO. As CP ENSO events have occurred more frequently in recent decades (e.g., Ashok et al. 2007; Kao and Yu 2009; Yu et al. 2010; Lee and McPhaden 2010; Yu et al. 2015), the subtropical

Pacific precursors may become more important for predicting ENSO events in the coming decades. This article intends to describe the major features of these precursors, their connections with the two types of ENSO, and a possible reason why they have become more important in recent decades.

Subtropical Pacific precursors and ENSO

Subtropical Pacific precursors for ENSO are most prominent in the northeastern Pacific as a band of SST anomalies extending typically from Baja California toward the equatorial central Pacific. Taking the 1986, 1994, 1997, and 2004 El Niño events as examples (Figure 1), positive SST anomalies appeared off Baja California several months before the onset of these El Niño events in the equatorial Pacific. The SST anomalies then persisted in the subtropical Pacific for several months and at the same time extended southwestward. As the subtropical SST anomalies approached the equatorial Pacific, the El Niño events developed and began to grow. The thought is that the initial warming outside Baja California is forced by atmospheric fluctuations via surface heat fluxes, particularly those associated with the North Pacific Oscillation (NPO; Walker and Bliss 1932; Rogers 1981; Linkin and Nigam 2008) as suggested by several recent studies (e.g., Vimont et al. 2003; Anderson 2004; Yu and Kim 2011). These initial SST anomalies then feedback to modify near surface winds via convection. The wind anomalies induced by the convection tend to be located to the southwest of the initial subtropical SST anomalies (Xie and Philander 1994), where new positive SST anomalies can be formed through a reduction in evaporation. The atmosphere then continues to respond to the new SST anomalies by producing wind anomalies further southwestward. Through this wind-evaporation-SST (WES) feedback (Xie and Philander 1994), the SST anomalies initially induced by the extratropical atmosphere off Baja California can extend southwestward into the deep tropics. This series of subtropical Pacific coupling processes are referred to as the seasonal footprinting mechanism (Vimont et al., 2001, 2003, 2009). This mechanism also offers a way to explain how the subtropical SST anomalies can be sustained from boreal winter, when the extratropical atmospheric variability (e.g., the NPO) is the most active, to the following spring or summer to excite El Niño events.

The SST anomaly pattern of the subtropical precursor strongly resembles the so-called Pacific Meridional Mode (PMM; Chiang and Vimont 2004), which has been shown to be the leading coupled variability mode of the subtropical Pacific. A strong association between the spring PMM index and the following winter ENSO index was demonstrated in Chang et al. (2007). They found that a majority of El Niño events over the past four decades were preceded by SST and surface wind anomalies similar to the PMM.

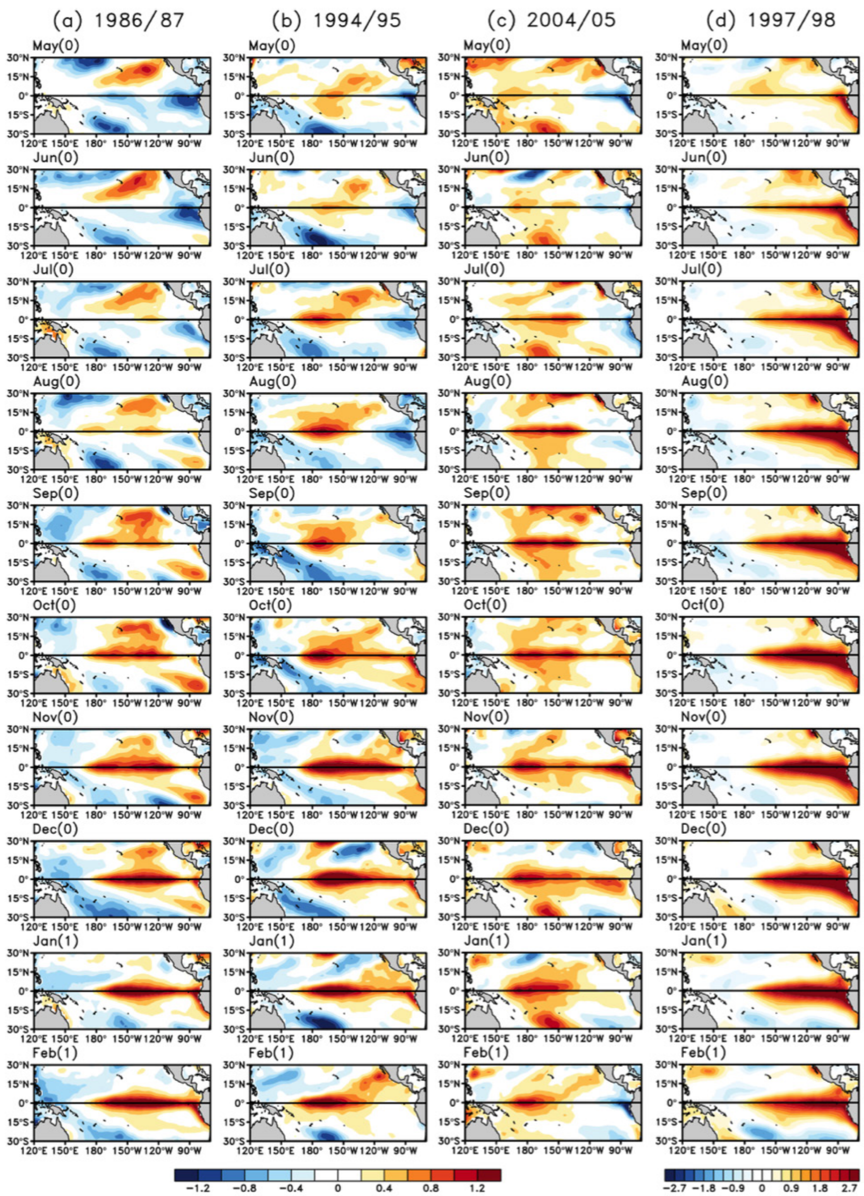

Figure 1. Monthly sea surface temperature anomalies (°C) observed in the developing (0) and peak (1) years of the (a) 1986/87 El Niño event, (b) 1994/95 El Niño event, (c) 2004/05 El Niño event, and (d) 1997/98 El Niño event.

There are a few different ways to explain how the PMM anomalies can generate ENSO events in the equatorial Pacific. One explanation is that the surface wind anomalies associated with the subtropical precursors can directly or indirectly (through the reflection of off-equatorial Rossby wave at the western Pacific) excite downwelling Kelvin waves along the equatorial thermocline that propagate eastward to trigger El Niño events in the eastern Pacific (e.g., Alexander et al. 2010). The subtropical precursors have also been suggested to be capable of directly increasing the ocean heat content in the equatorial Pacific via modulations in the strength of the trade winds, which then creates a charged state for ENSO in the equatorial Pacific (Anderson 2004; Anderson and Maloney 2006; Anderson et al. 2013). The SST and wind anomalies associated with the subtropical precursors also resemble the optimal structures identified by liner inverse models that are capable of growing into large ENSO events (Penland and Sardeshmukh 1995; Xue et al. 1997).

These earlier studies on the relationship between the subtropical precursors and ENSO did not consider the existence of different types of ENSO. In Figure 1, the subtropical precursors in three of the four examples (i.e., the 1986, 1994, and 2004 events) were followed by an El Niño event in the central Pacific (i.e., the CP El Niño). The subtropical precursors seem to be particularly important to the generation of the CP ENSO. The SST anomaly pattern associated with the CP ENSO are characterized by positive anomalies extending from the equatorial central Pacific to the northeastern subtropical Pacific (see Figure 3b of Kao and Yu 2009, for example), which is similar to the SST anomaly pattern of the subtropical Pacific precursors (or the PMM). No such subtropical extension is found in the SST anomaly pattern associated with the EP ENSO. A lead-lagged regression of the Pacific SST anomalies to a CP ENSO index shows that the CP ENSO is preceded by positive SST anomalies off Baja California during the previous winter (Yu et al. 2010), while a lead-lagged regression of the Pacific SST anomalies to a NPO index shows that the CP ENSO pattern peaks in the equatorial Pacific 12 months after the peak in NPO events (Yu and Kim 2011). These studies offer evidence that there exists a close relationship between the subtropical Pacific precursors and the CP ENSO. It is argued that the arrival of the subtropical Pacific precursor in the equatorial central Pacific could trigger local air-sea interactions that intensify local SST anomalies into a CP El Niño event via surface heat fluxes (Yu et al. 2010) or the wind-induced surface ocean advection (Kug et al. 2009; Yu et al. 2010). The earlier view, which links the precursors to ENSO onsets via the eastward propagation of precursor-induced ocean waves along the thermocline, appears more related to the onset of EP ENSO events. Therefore, when the subtropical precursor reaches the equatorial Pacific, it may locally force a CP ENSO event by interacting with the local ocean mixed layer. In this view, the SST and surface wind anomalies in the subtropical Pacific are not just precursors to the ENSO but an essential element of the CP ENSO dynamics.

Figure 2 illustrates our view on the underlying dynamics of the two types of ENSO and how they may be related to the subtropical Pacific precursors. In this perspective, the generation of the CP ENSO is more related to the ocean mixed layer dynamics. Dommenget (2010) and Clement et al. (2011) have demonstrated that ENSO-like events can be produced in coupled models where the ocean component consists of a mixed layer only without any thermocline dynamics. The generation of the EP ENSO is considered more related to the thermocline dynamics depicted by the delayed-oscillator (Suarez and Schopf 1988; Battisti and Hirst 1989) and charge-recharged oscillator theories (e.g., Wyrtki 1975; Zebiak 1989; Jin 1997).

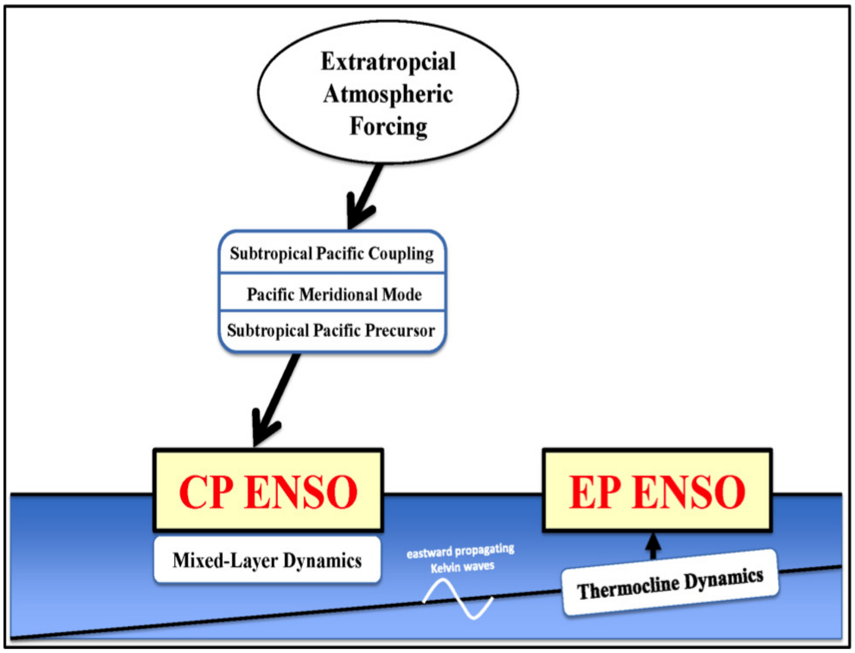

Figure 2. A schematic to illustrate the possible relationships between the subtropical Pacific precursors and the two types of ENSO (CP and EP).

The early-1990s climate shift and the increasing importance of the subtropical Pacific precursors

In order for the subtropical precursors to be able to influence the ENSO events several months later in the tropics, they must rely on subtropical Pacific ocean-atmosphere coupling (i.e., the WES feedback mechanism). The strength of the subtropical Pacific coupling, therefore, plays a key role in determining how efficiently the subtropical Pacific precursors are in generating ENSO events, particularly CP ENSO events. In decades when the subtropical Pacific coupling is strong, more subtropical precursors can penetrate deeper into the equatorial central Pacific to excite CP ENSO events.

The exact time of the recent ENSO shift from the EP type to the CP type has been suggested to be between the 1980s (Ashok et al. 2007) and the beginning of the 21st century (Lee and McPhaden 2010). Yu et al. (2012) showed that the SST variations in the equatorial central Pacific (i.e., the Niño4 index) are more closely related to the SST variability in the equatorial eastern Pacific (i.e., the Niño3 index) before the early-1990s, but more related to sea level pressure variations associated with the NPO (i.e., the NPO index) afterward. Their study suggests that the change of ENSO from the EP type to the CP type to be during the early-1990s.

Yu et al. (2015) further analyzed the subtropical Pacific coupling strength during the past few decades by examining the correlation coefficient between the SST and surface wind stress anomalies associated with the PMM (Figure 3). They find that the coupling strength is indeed stronger after the early-1990s. They argued that the stronger subtropical Pacific coupling makes it easier for the subtropical precursors to influence the deep tropics, and, as a result, the occurrence of CP ENSO events increases. Yu et al. (2015) also noticed that the early-1990s is close to the time that the Atlantic Multi-decadal Oscillation (AMO) changed from a negative phase to a positive phase. They conducted observational analyses and coupled AGCM-slab ocean model experiments to suggest that the recent emergence of the CP El Niño can at least partly be attributed to this AMO phase change via the following chain of events: a switch in the AMO to its positive phase in the early 1990s led to an intensification of the Pacific Subtropical High. The intensified High resulted in stronger-than-average background trade winds that enhanced the WES feedback mechanism, strengthening the subtropical Pacific coupling between the atmosphere and ocean, making the subtropical Pacific precursors more capable of penetrating into the deep tropics, and ultimately leading to increased occurrence of the CP ENSO events. The study of Yu et al. (2015) suggests that an early-1990s climate shift occurred in the Pacific, after which the subtropical Pacific precursors became more important for the generation of ENSO events.

Successful prediction and modeling of the ENSO in the recent and coming decades may depend more on a better understanding and improved skill in the modeling of the subtropical Pacific precursors and their underlying generation mechanisms. Prediction systems based on this framework would be different from the prediction and modeling systems the climate research community has

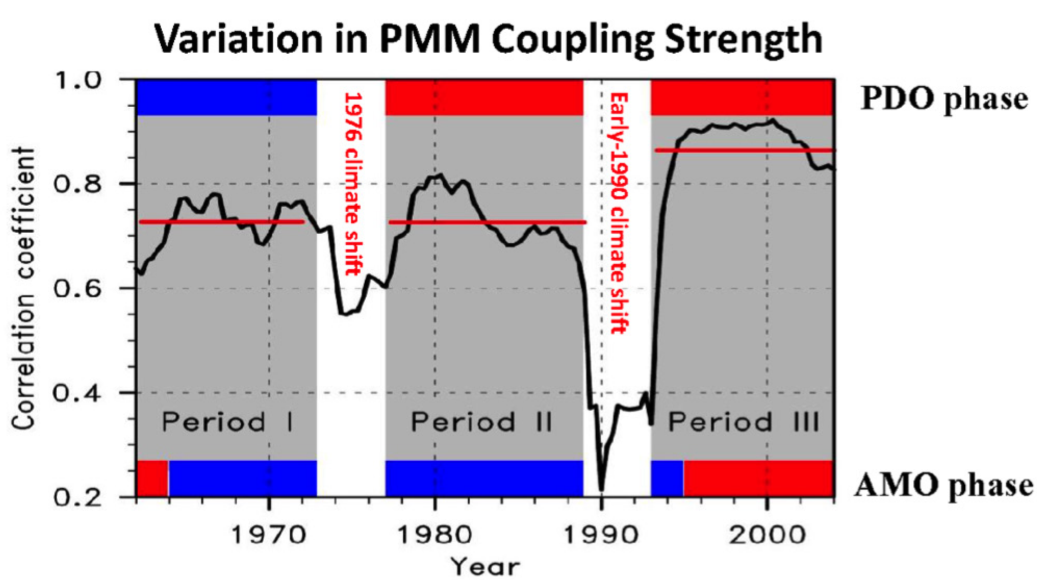

Figure 3. The 10-year running correlation coefficients between the PMM-SST and PMM-wind indices in boreal spring (MAM). NCAR/NCEP reanalysis data is used in the calculation. The red line indicates a mean of the correlation coefficients during each period. The shadings at the top and bottom are the positive/negative (red/blue) phases of the 10-year low-pass filtered PDO and AMO, respectively. (Modified from Yu et al. 2015)

developed in the 1980s and 90s for the conventional ENSO, which emphasize subsurface ocean dynamics in the equatorial Pacific.

Larson and Kirtmann (2014) have reported some skill in using the PMM to forecast ENSO events with the North American Multimodel Ensemble (NMME) Experiments. In order to utilize the subtropical precursors, particularly the PMM, to forecast ENSO events, coupled atmosphere-ocean models have to be able to realistically simulate the precursor events. Lin et al. (2014) examined twenty-three CMIP5 models to conclude that the PMM structure can be reasonably simulated in most of the coupled models. However, the so-called seasonal footprinting mechanism that sustains an equatorward extension of the PMM is not well simulated in a majority of the CMIP5 models. Therefore, it is necessary to improve the subtropical Pacific coupling in coupled models in order for these models to be applied successfully for forecasts of ENSO occurrence.

The views presented in this article assume the existence of the two distinct types of ENSO with different generation mechanisms. It should be noted that there is still an ongoing debate concerning this assumption as reported in Capotondi et al. (2015). Nevertheless, it is generally agreed in the ENSO research community that the characteristics of ENSO seem to be changing in recent decades, including a westward shift in the central location of the ENSO SST anomalies. This shift has motivated efforts to revisit traditional views of ENSO dynamics and its global teleconnections (Wang et al. 2015; Capotondi et al. 2015). The increasing emphasis on the ENSO precursors outside the tropical Pacific is one component of these efforts. This article focuses only on the northeastern subtropical Pacific ENSO precursors. Other regions outside the tropical Pacific have also been emphasized in several recent studies for ENSO precursors, such as the western North Pacific (Wang et al. 2012) and the southeastern subtropical Pacific (Zhang et al. 2014).

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