A 10-15 year Modulation Cycle of ENSO Intensity

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ABSTRACT

This study examines the slow modulation of El Niño-Southern Oscillation (ENSO) intensity and its underlying mechanism. A statistically significant 10-15 year modulation cycle of ENSO intensity is identified from historical and multi-proxy paleoclimate data sets using an “envelope function” of cold-season ENSO indices of sea surface temperature (SST). Composite analyses reveal interesting spatial asymmetries between El Niño and La Niña events within this modulation cycle. During the enhanced-intensity periods of the cycle, El Niño SST anomalies center in the eastern tropical Pacific while La Niña SST anomalies center in the central tropical Pacific. The spatial asymmetry is reversed during the weakened-intensity periods of the modulation cycle: El Niño SST anomalies center in the central tropical Pacific while La Niña SST anomalies center in the eastern tropical Pacific. The Eastern-Pacific type of El Niño and La Niña is accompanied with basin-scale surface wind and thermocline anomalies, while the Central-Pacific type of El Niño and La Niña involves more local wind and thermocline anomalies in the central Pacific. The El Niño-La Niña asymmetries allow ENSO to exert a non-zero forcing to and result in the changes of basic states in the tropical Pacific, which in turn favor the alternative types of El Niño and La Niña that manifest as the reversed ENSO asymmetries. The basic state changes associated with this decadal ENSO intensity modulation are characterized by a zonal SST dipole pattern between the eastern and central tropical Pacific that appears as the 2nd leading EOF mode of decadal SST variations in the
tropical Pacific. In association with the SST dipole pattern, significant shifts are found in the mean locations of the rising and sinking branches of Pacific Walker circulation.
1. Introduction

El Niño-Southern Oscillation (ENSO) is known to undergo decadal (and interdecadal) variations in its frequency, intensity, and propagation pattern (e.g., Wang and Wang 1996; An and Wang 2000; Fedorov and Philander 2000; Timmermann 2003; An and Jin 2004; Yeh and Kirtman 2004). The decadal ENSO variability and its potential influences on global climate and weather have prompted extensive research in this area (e.g. Torrence and Webster 1999; Kumar et al. 1999; Power et al. 1999; and many others). Various hypotheses have been put forward to explain the origin of decadal ENSO variability. Initially, the decadal ENSO variability was suggested to be forced by extratropical processes (e.g., Barnett et al. 1999; Pierce et al. 2000) or arise from tropical-extratropical interactions (e.g., Gu and Philander 1997; Wang and Weisberg 1998; Zhang et al. 1998). More recently, it has been suggested that the decadal ENSO variability could originate internally within the tropics. The decadal ENSO variability was described as either an internal mode of the coupled atmosphere-ocean system in the tropics (e.g., Kirtman and Schopf 1998; Timmermann and Jin 2002) or excited by stochastic forcing (e.g., Eckert and Latif 1997; Newman et al. 2003). Newman et al. (2003) and Newman (2007) further suggested that the decadal variability in the extratropics, such as the Pacific Decadal oscillation (PDO, Mantua et al. 1997) could be forced by the decadal ENSO variability via "atmospheric bridge" (Alexander et al. 2002).
Nonlinear ENSO dynamics and the interactions between ENSO and the Pacific basic state have been increasingly emphasized to explain the decadal ENSO variability. Timmermann and Jin (2002) used a low-order tropical atmosphere-ocean model to show that changing the strength of zonal SST advection can alternate ENSO periods between biennial and 4-5 years and result in a slow amplitude modulation. Their study demonstrated that the nonlinearity of ENSO dynamics could allow ENSO properties to change on decadal timescale. By analyzing long-term CGCM (coupled general circulation model) simulations, Timmermann (2003) further suggested that the decadal ENSO modulation could also result from the interactions between ENSO and the Pacific background state. Rodgers et al. (2004) and An and Jin (2004) pointed out that ENSO has strong nonlinearity that can cause asymmetries between its warm (El Niño) and cold (La Niña) phases. As a result of the asymmetries, the ENSO cycle, represented by the sum of El Niño and La Niña, leaves a non-zero net impact on the Pacific basic state from which they grow. These latest studies pointed out that further studies of ENSO-basic state interactions are crucial and needed to better understand ENSO variability on decadal timescales.

It has been noticed that extreme ENSO events happened approximately every 10-20 years, recalling that the last three strongest ENSO events occurred in 1972-1973, 1982-1983 and 1997-1998. Between those strong events, relatively weaker ENSO events happened. Does this nearly 10-20year timescale happen by chance or is there a decadal modulation cycle of ENSO intensity? What is the
underlying generation mechanism? To address these questions, in this study, atmospheric and oceanic data sets are analyzed to examine the existence of slow modulations of ENSO intensity and to describe the changes of ENSO and tropical Pacific basic states during the modulation. The data sets and the analysis methods are outlined in Section 2, followed by the identification of an ENSO modulation cycle in Section 3. In Section 4, the prominent asymmetric spatial structures of ENSO within the modulation cycle are described. In Section 5 a linkage is established between the ENSO asymmetries and the basic state changes in the tropical Pacific. Conclusions and discussions are given in Section 6.

2. Data sets and Methods

Two historical SST data sets are used in this study: the global monthly Extended Reconstructed Sea Surface Temperature data set version 2 (ERSST.v.2) (Smith and Reynolds, 2004) with a spatial resolution of 2° X 2°, and the Hadley Centre Sea Ice and Sea Surface Temperature data set (HadISST) (Rayner et al., 2003) with a spatial resolution of 1° X 1°. The large-scale variations in HadISST are broadly consistent with those in ERSST.v.2, but there are differences between these two data sets due to the use of different historical bias corrections as well as different data and analysis procedures (Smith and Reynolds, 2003). Most of the analyses presented in this paper are based on the ERSST.v.2, and the HadISST is used for verification. ERSST.v.2 is an improved extended reconstruction of the previous version, ERSST
(Smith and Reynolds, 2003), which is constructed utilizing the most recently available International Comprehensive Ocean-Atmosphere Data Set (ICOADS) SST data and the improved statistical methods that allow stable reconstruction using sparse data. The analyzed signal in the historical data sets is heavily damped before 1880 because of the sparsity of data. So the historical data from 1880 to 2006 is analyzed in this study. A 331-year long (1650-1980) ENSO index time series reconstructed by Mann et al. (2000) from multi-proxy paleoclimate data is also used to further verify the decadal signals identified from the historical data sets. This reconstructed ENSO index represents the cold-season (October-March) SST anomalies averaged in the Niño3 region (150°W-90°W, 5°S-5°N) with the long-term climatology removed.

Also used in this study are the monthly surface wind and 200hPa velocity potential data from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al., 1996) and the monthly upper ocean temperature data from SODA (Simple Ocean Data Assimilation) (Carton et al. 2000). The surface wind data is on 2.5° X 2.5° grids and the velocity potential data is on the Gaussian grids (1.875° X ~2°) and both data sets are from 1948 to 2005. SODA assimilates the ocean observations, e.g. World Ocean Atlas, XBT profiles, in-site station data and satellite altimeter-derived sea level data. The upper ocean temperature data from SODA has a resolution of 1° X 0.5°~1° (enhanced resolution in tropics) in horizontal, 15-meter in vertical from the surface to about 160-meter deep (with lower resolution below) and is from 1950 to 2001. The
temperatures are linearly interpolated in the vertical to locate the depth of 20°C isotherms, which is used as a proxy for thermocline depth. The yearly ocean heat content (defined as the averaged temperature between surface and 300-meter deep) data set from Levitus et al. (2005) for the period of 1955-2003 is also used. Monthly anomalies for all the variables are constructed as the deviations from their monthly mean climatologies for the entire time period.

Due to ENSO’s phase locking to the seasonal cycle, the mature phases of El Niño and La Niña tend to occur toward the end of the calendar year (Rasmusson and Carpenter, 1982). In this study, we choose the cold-season (October-March) SST anomalies in the Niño3.4 region (170°W-120°W, 5°S-5°N) to describe the variations of ENSO activity. Both the Niño3.4 and Niño3 (used in the proxy paleoclimate data set) regions are located within the areas where large ENSO SST variability occurs and their time evolutions are highly correlated.

3. The 10-15year Modulation Cycle of ENSO Intensity

Figure 1a shows the cold-season Niño3.4 index (thin-solid line) calculated from the ERSST.v.2. The time series has been highpass filtered with an 8-year cutoff to represent only the SST fluctuations on ENSO timescale. Besides the dominant interannual ENSO events, also apparent in the time series is a slow modulation of ENSO intensity: periods of high and low ENSO intensity alternate on decadal
timescales. We used an “envelope function” adopted from Nakamura and Wallace (1990) to quantify the decadal modulation of ENSO intensity. To construct the envelope function, the cold-season Niño3.4 index was first squared and then filtered with a 10-year lowpass filter. The resulting quantity was multiplied by 2 in recognition of the fact that the “power” of a pure harmonic oscillation of arbitrary frequency averaged over one certain period is just half the squared intensity of the oscillation (Nakamura and Wallace 1990). The resulting time series is defined as the “envelope function” (hereafter ENVF) of Niño3.4 index. The square root of this time series represents the “true” amplitude of the slow (>10 years) modulation. It is shown in Figure 1a that the square-rooted ENVF (thick-solid line, with thick-dashed line the mirror image) portrays reasonably well the slow intensity variations of the Niño3.4 index.

The power spectrum of the standardized ENVF is shown in Figure 2a, together with the best-fit first-order autoregression (AR1) red noise spectrum and associated 99% confidence limit using F-test. It shows that the ENVF has a statistically significant spectral peak around the 10-15year bands. To verify this spectral peak, we also calculated the ENVF from the Niño3.4 index of HadISST and the 331-year reconstructed Niño3 index of Mann et al. (2000). Figure 2b and 2c show the power spectra of the standardized ENVFs from these two data sets. Similar to Figure 2a, spectral peaks near the 10-15year bands are also evident and statistically significant at the 99% confidence level. All the three data sets consistently indicate that ENSO
intensity undergoes a decadal modulation, with a significantly distinct 10-15year cycle.

It should be noted that as indicated by the ENVF curve in Figure 1a, the Niño3.4 intensity increases toward the both ends of the time series compared with the middle periods near 1920-1960. This indicates a secular change of ENSO variance that is far longer than the 10-15year decadal modulation cycle we are interested in. For this reason, a 10-20year bandpass filter is applied to the ENVF to retain only the decadal ENSO modulation. The bandpass filtered ENVF is used as the reference time series for composite analyses in the rest of the study. The standardized bandpass filtered ENVF of cold-season Niño3.4 from ERSST.v.2 is shown in Figure 1b. We also calculated the corresponding bandpass filtered ENVF from HadISST Niño3.4 index (not shown) and found it largely coincides with that shown in Figure 1b, except for the periods around 1910-1920 and 1930-1940. The differences in these two periods may be due to the paucity of the observational data during the two world wars and different historical bias correction methods used in those two data sets.

4. Variations of ENSO Structures in the Modulation Cycle

We examine in this section the variations of El Niño and La Niña spatial patterns within the 10-15year ENSO intensity modulation cycle. The anomalous surface and subsurface structures of El Niño and La Niña were composed for the
enhanced and weakened intensity periods of the modulation cycle. Here, we define the enhanced and weakened intensity periods as the times when the filtered ENVF (Figure 1b) is greater and less than 0.3 standard deviations, respectively. El Niño and La Niña events are defined as the events whose cold-season Niño3.4 index is greater than 0.5°C or less than -0.5°C. It should be noted that our results are not very sensitive to the thresholds used to define the El Niño/La Niña events or the enhanced/weakened intensity periods.

The composite ENSO structures calculated from ERSST.v.2 cold-season SST anomalies are shown in Figure 3 (a)-(d), with the shaded indicating 99% significant level using a two-tailed t-test. There are two major features in the composites. The first is the evident spatial asymmetries in the SST anomaly patterns between El Niño and La Niña events during both the enhanced and weakened intensity periods of the modulation cycle. The second major feature is that the spatial asymmetries in the enhanced and weakened intensity periods are opposite to each other. During the enhanced-intensity periods, El Niño events (Figure 3a) have their largest positive SST anomalies in the eastern tropical Pacific (centered at 130°W) while La Niña events (Figure 3b) have their largest negative SST anomalies in the central tropical Pacific (centered at 150°W). In addition, significant SST anomalies of El Niño events are attached to the South America coast while those of La Niña events are detached from the coast. During the weakened-intensity periods, the spatial asymmetry between El Niño and La Niña events still exists but is reversed from that
in the enhanced-intensity periods: El Niño events (Figure 3c) are now more detached from the South America coast with significant positive SST anomalies centered in the central Pacific (near 160°W) while La Niña events (Figure 3d) have significant negative SST anomalies centered in the far eastern Pacific (near 110°W) and more attached to the coast.

Same composite analyses were repeated with HadISST shown in Figure 3 (e)-(h) and similar results are found. Especially, the composite from HadISST for El Niño events during the enhanced-intensity periods (Figure 3e) shows the largest positive SST anomalies (centered at 100°W) more attached to the coast than those from ERSST.v.2 (Figure 3a). Both data sets show that the spatial asymmetries between El Niño and La Niña are characterized by alternations of ENSO SST anomaly centers between the central and eastern tropical Pacific. To address the concern of general paucity of both ERSST.v.2 and HadISST data sets prior to 1950s, we also performed the composite analyses with only the more reliable SST data after 1950 and qualitatively similar results were found from both data sets (not shown).

The composites in Figure 3 suggest that the 10-15year ENSO intensity modulation cycle is accompanied by alternations of SST anomaly centers between the eastern and central tropical Pacific for both El Niño and La Niña events. The two different types of ENSO structure are similar to the so-called Eastern-Pacific and Central-Pacific types of ENSO recently discussed by Yu and Kao (2007) and Kao and
Yu (2007). They analyzed ENSO events from 1958 to 2001 and argued that there exits two different types of ENSO whose spatial structures and temporal evolutions are distinctly different. Our composite results indicate that alternations between these two different types of ENSO are an essential element of the decadal modulation of ENSO intensity. Figure 3 also indicates that strong El Niño and weak La Niña events tend to appear as the Eastern-Pacific type while weak El Niño and strong La Niña events tend appear as the Central-Pacific type of ENSO.

We further show in Figure 4 the composites of anomalous surface wind vector for the El Niño and La Niña events during the enhanced and weakened intensity periods. Also shown in the figure are the zonal wind anomalies (shaded) that are statistically significant at the 95% significant level using a two-tailed t-test. For strong El Niño (Figure 4a) and weak La Niña (Figure 4d) (i.e., the Eastern-Pacific type of ENSO), significant zonal wind anomalies are located mostly to the east of date line. Westerly and easterly anomalies center slightly to the south of equator (0°-10°S) and are located from 180° to 140°W for El Niño and from 150°W to 120°W for La Niña separately. For weak El Niño (Figure 4c) and strong La Niña composites (Figure 4b) (i.e., the Central-Pacific type of ENSO), significant zonal wind anomalies are located more to the west of the date line with significant westerly anomalies for El Niño and easterly anomalies for La Niña centered at around 150°E-170°W. Figure 4 suggests that the Eastern-Pacific type of ENSO may involve air-sea interactions over a large portion of the tropical Pacific basin while the Central-Pacific type of ENSO
involves air-sea interactions more confined in the central tropical Pacific.

The composite ocean heat content (OHC) anomalies for these strong and weak El Niño and La Niña events are shown in Figure 5. Here the OHC is defined as the ocean temperature averaged over the upper 300 meters, and only anomalies over the 95% significance level are shaded. As shown in Figure 5, for the Eastern-Pacific type of ENSO (i.e., strong El Niño and weak La Niña), significant large OHC anomalies are found across most of the equatorial Pacific from west to east. For the strong El Niño (Figure 5a), the positive OHC anomalies extending from 170°W to the South America coast indicate a deepening thermocline along the equator. For weak La Niña (Figure 5d), negative OHC anomalies show up in far eastern Pacific from 120°W to 90°W indicating a shoaling thermocline. For both cases, there are significant variations of thermocline in the entire equatorial Pacific involving the coastal regions. But for the Central-Pacific type of ENSO (i.e., strong La Niña and weak El Niño), the significant OHC anomalies are only confined in the central Pacific, spanning from 180° to 130°W for strong La Niña (Figure 5b) and from 170°W to 140°W for weak El Niño (Figure 5c), suggesting the variations of thermocline are local. Also, the OHC anomalies for the Eastern-Pacific type of ENSO (Figures 5a and 5d) are out-of-phase between the eastern and western sides of the Pacific basin. This phase relation suggests that this type of ENSO involves basin-wide thermocline variations. It is consistent with the larger zonal extents of surface wind anomaly pattern shown in Figure 4a and Figure 4d for the Eastern-Pacific type of ENSO.
Therefore, Figure 5 further supports our suggestion that the Eastern-Pacific type of ENSO may be resulted from basin-scale air-sea coupling and the Central-Pacific type of ENSO may involve more with local air-sea coupling in the central Pacific.

5. Asymmetric ENSO forcing to the Basic State

Following Rodgers et al. (2004), we quantify the SST asymmetry between El Niño and La Niña by the sum of their SST anomaly composites. Figure 6 shows the sums of composite for the enhanced and weakened periods of the modulation cycle. During the enhanced periods, the sum exhibits large positive anomalies in the far eastern tropical Pacific (around 100°W) centered slightly to the south of equator. Negative SST anomalies are found along the equator between 130°E and the date line. During the weakened periods, the sum exhibits a structure showing negative anomalies in the far eastern Pacific and positive anomalies in the central Pacific, which is nearly out of phase with that found in the enhanced periods. Since the sum of El Niño and La Niña SST anomalies indicates the net impact of ENSO cycle on the SST basic state, the nearly out-of-phase patterns shown in Figure 6 suggest that ENSO’s net forcing on the basis state is reversed during the enhanced and weakened intensity periods of the decadal modulation cycle. During the enhanced-intensity periods, the net ENSO forcing resulted from the El Niño-La Niña asymmetry tends to warm up the eastern but cool down the central tropical Pacific and then decrease the east-west SST gradient along the equator, which could weaken the tropical Pacific
ocean-atmosphere coupling and gradually push the coupled climate system into periods of weakened ENSO intensity. The reverse is true for the net ENSO forcing during the weakened-intensity periods of the modulation cycle, which tends to cool down the eastern tropical Pacific but warm up the central Pacific, increase the east-west SST gradient, and gradually push the coupled system into periods of enhanced ENSO intensity.

Figure 7 shows the sums of surface wind vector and convergence/divergence anomalies between El Niño and La Niña in the enhanced and weakened ENSO intensity periods, which can be considered as the asymmetric ENSO forcing on the mean surface wind. In the enhanced-intensity periods (Figure 7a), the asymmetric ENSO forcing tends to produce northwesterly anomalies in the eastern equatorial Pacific opposite to the southeasterly climatology, representing a relaxation of the trade winds in that region. In the weakened period (Figure 7b), the asymmetric ENSO forcing tends to produce southeasterly anomalies in that region that strengthens the climatologic trade winds. Figure 7 also shows that the asymmetric ENSO forcing produces surface wind convergence anomalies in the far eastern Pacific from 15°S to the equator in the enhanced-intensity periods but divergence anomalies in that region in the weakened-intensity periods. In association with the asymmetric wind forcing and the resulting changes of the mean convergence and divergence, Figure 8a shows that the asymmetric ENSO forcing tends to increase the thermocline depth in the tropical eastern Pacific but decrease that in the central Pacific in the
enhanced-intensity periods. But in the weakened-intensity periods, the ENSO forcing tends to decrease the thermocline depth along the coast while increase that in the central Pacific. The significant thermocline variations in the tropical Pacific cover a region extending from around $10^\circ$S to $10^\circ$N and more-or-less coincide with the areas of the large asymmetric surface wind anomalies shown in Figure 7 and the large asymmetric SST anomalies shown in Figure 6. The anomalous features shown in Figures 6-8 indicate that the SST, surface wind, and thermocline depth anomalies induced by the asymmetric ENSO forcing are dynamically consistent with each other. For example, in the enhanced-intensity periods, the asymmetry between El Niño and La Niña SST anomalies tends to increase the mean SST in the eastern Pacific that in turn relaxes the mean surface trade wind in the region. The relaxed surface trade wind, together with the anomalous convergence, tends to deepen the mean thermocline there and therefore further warm up the eastern Pacific.

To further quantify the tropical Pacific basic state changes related to the asymmetric ENSO forcing through the modulation cycle, we regress the ENSO intensity modulation cycle (i.e. ENVF) against the lowpassed (>10year) cold-season averaged climate variables (SST, surface wind and thermocline depth) in Figure 9. The regression with SST anomalies (Figure 9a) is characterized by a significantly nearly zonal dipole structure between the far eastern centered near $(90^\circ$W, $10^\circ$S) and the central $(175^\circ$E) tropical Pacific along the equator. It is also noticeable that the center of the regression dipole in the central equatorial Pacific is symmetric with
respect to the equator, while the other center in the far eastern Pacific is located to the south of equator. Figure 9a indicates that associated with the enhanced ENSO intensity periods, the mean SST in the far eastern Pacific along to the coast is warmer while colder in central equatorial Pacific and vice versa for the weakened ENSO intensity periods, which is similar to the asymmetric ENSO SST forcing shown in Figure 6a. Quantitatively, when the decadal ENSO intensity increases one standard deviation, the ENSO asymmetry warms up the eastern tropical Pacific and cools downs the central tropical Pacific by about 0.1-0.2°C.

The regressed surface wind pattern shown in Figure 9b is also similar to the asymmetric ENSO wind forcing shown in Figure 7, which indicates that the climatologically prevailing southeasterly in the eastern tropical Pacific are relaxed in the enhanced-intensity periods, while in the central tropical Pacific, the climatologic trade winds are locally strengthened. The regressed 20 °C isotherm depth is shown in Figure 9c. Opposite variations appear between the thermocline depth anomalies in the far eastern tropical Pacific (centered at 90°W, 10°S) attached to the South America coast and those in the central equatorial Pacific (centered at 130°W). In the enhanced ENSO intensity periods, the mean thermocline deepens in the far eastern tropical Pacific adjacent to South America coast while it shoals in the central Pacific. This basic state variation pattern is in general consistent with the asymmetric ENSO forcing pattern shown in Figure 8.
The similarity between the asymmetric ENSO forcing patterns shown in Figures 6-8 and the ENVF-associated basic state variation patterns shown in Figure 9 suggests that the asymmetric ENSO forcing leads to basic state changes within the ENSO intensity modulation cycle. So how important is the ENSO forcing to the decadal basic state changes in the tropical Pacific climate system? To address this issue, we examined the leading decadal modes of the tropical Pacific SST using the Empirical Orthogonal Function (EOF) analysis. The EOF analysis is applied to the 10-20-year bandpass filtered cold-season SST anomalies in the tropical Pacific (120°E-70°W, 30°S-30°N). The first two leading EOF modes are shown in Figure 10, which together explain more than 75% of the filtered SST variance. The first EOF (Figure 10a) has a spatial structure similar to PDO or the so-called ENSO-like decadal variability (Zhang et al., 1997). This structure is characterized by a broad horseshoe pattern in the tropical central and eastern Pacific, flanked by opposite structures in the mid-latitudes of western and central Pacific in both hemispheres. The correlation coefficient between the principal coefficient of this EOF mode and the band-pass filtered ENVF is small (correlation coefficient: -0.34) and does not pass the 95% significance test. This indicates that the 10-15-year ENSO intensity modulation cycle is probably not directly related to this first EOF.

The second EOF mode (Figure 10b) exhibits zonal out-of-phase structures between the central and eastern tropical Pacific. This EOF pattern is characterized by out-of-phase of SST anomalies in the far eastern tropical Pacific attached to the South
America coast and in the central Pacific extending to the Northeast Pacific and Baja California. This EOF pattern is spatially similar to Figure 9a. The correlation coefficient between the principal component of this EOF pattern and the band-pass filtered ENVF is as large as 0.70 and is statically significant at the 95% level. Therefore, the second EOF mode of the decadal SST variations is likely related to the basic state changes caused by the ENSO asymmetry forcing within its intensity modulation cycle. It also indicates that basic state changes caused by the ENSO asymmetry forcing are an important part of the decadal SST variations in the tropical Pacific.

To allow the changes of Pacific SST basic state caused by the ENSO asymmetric forcing to modulate the ENSO intensity, the SST anomalies have to be strong enough to affect the Pacific Walker circulation, whose location, intensity, zonal extent and structure exert important influence on the strength of atmosphere-ocean coupling in the tropical Pacific (Deser and Wallace 1990). Following Tanaka et al. (2004), we measure the strength of the Walker circulation by the cold-season velocity potential at 200 hPa with its zonal mean removed. The Pacific Walker circulation climatology is shown in Figure 11a, negative values indicating rising motion with wind divergence in the upper troposphere and positive values sinking motion with wind convergence. The climatology is characterized by a rising branch centered over the Philippine Sea and Maritime continent near 150°E and a sinking branch centered over the far eastern tropical Pacific and Central American continents around (100°W,
The variations of Walker circulation associated with the decadal modulation of ENSO intensity is examined in Figure 11b by regressing the ENVF against the 10-20year bandpass filtered 200 hPa velocity potential. The regression structure exhibits a sea-saw anomalous structure to the west and east of the climatological rising center of Walker circulation. The rising branch center in the western Pacific moves further westward to 120°E during the enhanced ENSO intensity periods and eastward to the date line during the weakened periods. Figure 11b also shows the migration of the sinking branch of Walker circulation in the eastern Pacific associated with the ENSO intensity modulation cycle. Compared with the climatology, the sinking branch shifts northwestward during the enhanced ENSO intensity periods. Figure 11b suggests that the locations of both the rising and sinking branches of the Walker circulation in the tropical Pacific are slowly shifted by the ENSO intensity cycle. It appears that the Pacific Walker circulation is shifted further westward during the enhanced periods and further eastward during the weakened periods. It is noteworthy that this pattern is dynamically consistent with the surface wind pattern in Figure 9b, in which easterlies in western equatorial Pacific, e.g. over Indonesia is strengthened (relaxed) corresponding to the stronger and westward (weaker and eastward) Walker circulation during the enhanced (weakened) ENSO intensity periods.
6. Conclusions and Discussions

As one of the most pronounced interannual climate signal in tropical Pacific, ENSO properties show decadal variations, which have captured more and more attentions in the climate research community. By analyzing historical and paleo-proxy climate data sets, we investigated the decadal modulation of ENSO intensity and the associated ENSO forcing to the Pacific basic state. Our major findings are as follows:

1. ENSO intensity exhibits a prominent 10-15 year modulation cycle;
2. There is a strong spatial asymmetry between El Niño and La Niña that reverses from the enhanced- to weakened-intensity periods of the modulation cycle.
3. The El Niño-La Niña asymmetry is manifested as the alternations of ENSO SST pattern between an Eastern-Pacific type and a Central-Pacific type;
4. The asymmetry allows ENSO to leave a non-zero impact onto the basic state changes in the tropical Pacific;
5. The SST basic state changes associated with this modulation cycle appears as the 2nd leading EOF mode of the decadal SST variations in the tropical Pacific;
6. The SST basic state changes are strong enough to lead to the slow migration of Pacific Walker circulation’s locations, which modifies the mean wind and thermocline patterns in the tropical Pacific.

Our study concludes and suggests that El Niño-La Niña asymmetry plays an important role in determining the changes of the tropical Pacific basic state. Figure 12
is sketched to illustrate the major features in the changes of Pacific basic state induced by the asymmetric ENSO forcing. In the enhanced-intensity periods of the modulation cycle (Figure 12a), the El Niño-La Niña asymmetry forcing causes a westward shift of Walker circulation compared to its climatology, which strengthens the trade winds and favors cooling in the central tropical Pacific but relaxes the trade winds and favors warming in the eastern tropical Pacific. Accompanied with the circulation shift is the flattened zonal thermocline in the tropics compared to the climatology, with a deepening thermocline in the far eastern while a shoaling one in the central Pacific. The resulted basic state changes related with the weakened atmosphere-ocean coupling processes could cause the coupled system to shift into the weakened ENSO intensity periods. When El Niño (La Niña) happens in the weakened periods, the already deepened thermocline in the eastern tropical Pacific makes local SSTs more sensitive to upwelling anomalies than to downwelling anomalies. As a result, this basic state favors La Niña (associated with upwelling) but prohibits El Niño (associated with downwelling) to occur in the eastern Pacific. This could explain, at least partially, the El Niño-La Niña asymmetry during the weakened-intensity periods. Figure 12b show in the weakened ENSO intensity periods the basic state changes caused by the ENSO asymmetry forcing: a gradual cooling in the far eastern Pacific and a warming in the central-western Pacific, together with strengthened and relaxed trade winds in these two regions respectively via the eastward migration of Walker circulation from its climatology locations. The SST changes lead to the rebuilding of the zonal SST gradient and concurrently deepening and shoaling of thermocline in the
central and eastern tropical Pacific, respectively. The atmosphere-ocean coupling is enhanced by the ENSO forcing and gradually pushes the coupled system back into the enhanced ENSO intensity periods. In the enhanced periods, the shallow thermocline in the eastern tropical Pacific allows local SST to be more sensitive to downwelling than upwelling anomalies. Therefore, the basic state favors El Niño to happen in the eastern Pacific but prohibits La Niña there. This could be used to explain why eastern-Pacific type of El Niño tends to happen in the enhanced-intensity periods.

This study suggests that the ENSO-basic state interactions in the tropical Pacific are capable of producing decadal ENSO variability, without the need of the external forcing from the extratropics. Furthermore, it substantiates the importance of emphasizing the ENSO asymmetry to the decadal ENSO variability (e.g. An and Jin (2004) and Rodgers et al. (2004)), and it is also in agreement with the recent numerical modeling studies (Sun and Zhang, 2006; Schopf and Burgman, 2006) that suggested ENSO can have regulatory effects on the tropical Pacific basic state. Our results suggest that a better understanding of the ENSO asymmetry and its forcing to the basic state changes is important to the study of the decadal ENSO variations. Further numerical modeling studies are needed to better understand and verify the self-sustained modulation mechanism of the tropical Pacific to explain the decadal modulation of ENSO intensity.
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Torrence, C. and P. J. Webster, 1999: Interdecadal changes in the ENSO-monsoon


Figure 1. Upper panel (Figure 1a): time series of cold-season (October-March) Niño3.4 SST anomaly index (thin line), decadal amplitude (square root of envelope function, thick solid line) and its mirror (thick dashed line); Lower panel (Figure 1b): standardized 10-20year bandpass filtered envelope function (ENVF).
Figure 2. Power spectrum of standardized ENVF of cold-season Niño3.4 index for (a) ERSST.v.2, (b) HadISST and (c) cold-season Niño3 index reconstructed from the paleoclimate proxy data of Mann et al. (2000). Dotted line is the best-fit AR1 red noise power spectrum and dashed line is the 99% significance level using F-test.
Figure 3. Composite cold-season SST anomalies (ERSST.v.2) for (a) El Niño and (b) La Niña events for the enhanced ENSO intensity periods. (c) and (d) are the same as (a) and (b), but for the weakened ENSO intensity periods. Contour interval is 0.2 °C and the shaded indicates 99% significance level using two-tailed t-test. (e)-(h) are the same separately as (a)-(d) but for the HadISST.
Figure 4. Composite cold-season surface zonal wind (shaded, unit: m/s) and wind vector anomalies for (a) El Niño and (b) La Niña events for the enhanced ENSO intensity periods. (c) and (d) are the same as (a) and (b), but for the weakened ENSO intensity periods. Shaded is the 95% significance level using two-tailed t-test.
Figure 5. Composite cold-season ocean heat content anomalies (unit: $10^{18}$ joules) for
(a) El Niño and (b) La Niña events for the enhanced ENSO intensity periods. (c) and
(d) are the same as (a) and (b), but for the weakened ENSO intensity periods. Shaded
is the 95% significance level using two-tailed t-test.
Figure 6. The asymmetric (El Niño+La Niña) structures of cold-season SST anomalies for the enhanced ENSO intensity periods (a) and the weakened ENSO intensity periods (b). Shaded is the 99% significance level using two-tailed t-test.
Figure 7. Same as Figure 6, but for the cold-season surface wind vector (unit: m/s) and divergence (red) and convergence (blue) anomalies (unit: m/s$^2$). Shaded is the 90% significance level using two-tailed t-test.
Figure 8. Same as Figure 6 but for the cold-season 20 °C isotherm depth anomalies (unit: meter). Shaded is the 90% significance level using two-tailed t-test.
Figure 9. Upper panel (Figure 9a): linear regression between 10-20year bandpass filtered ENVF (Figure 1b) and lowpass (>10year) filtered cold-season SST anomalies (unit: °C per standard deviation of ENVF); Middle panel (Figure 9b): same as upper panel but for the surface wind (unit: m/s per standard deviation of ENVF); Lower panel (Figure 9c): same as upper panel but for the 20 °C isotherm depth (unit: meter per standard deviation of ENVF). Shaded is the 90% significance level using F-test.
Figure 10. The first (a) and second (b) leading EOF mode of 10-20yr bandpass filtered cold-season SST anomalies in the tropical Pacific (120°E-70°W, 30°S-30°N).
Figure 11: Upper panel (Figure 11a): long term mean climatology of 200 hPa velocity potential (unit: $10^6\text{m}^2\text{s}^{-1}$) with zonal mean removed. Positive indicates sinking motion and negative rising motion. Lower panel (Figure 11b): linear regression between 10-20year bandpass filtered ENVF and lowpass (>10year) filtered cold-season 200 hPa velocity potential (unit: $10^6\text{m}^2\text{s}^{-1}$ per standard deviation of ENVF). Shaded is the 90% significance level using F-test.
Figure 12. Schematic diagram showing the oceanic and atmospheric variations in the tropical Pacific caused by El Niño-La Niña asymmetry forcing during the enhanced (a) and weakened (b) ENSO intensity periods. Dashed lines show the climatology.