Interdecadal changes in the El Niño–La Nina asymmetry

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[1] The SST anomalies (SSTA) over the past 148 years have been analyzed to describe the interdecadal change in the skewness of SSTA (ICS) in the tropical Pacific and possible consequence of this change. The first EOF mode of ICS represents the interdecadal changes in the El Nino-La Nina asymmetry. The corresponding PC time series is related to the ENSO predictability, suggesting that ENSOs are more predictable during the positive ICS decades than during the negative ICS decades, and to the propagation characteristics of ENSO such that SSTA during the positive (negative) ICS decades tend to propagate eastward (westward). Moreover, ICS was found to be associated with interdecadal SST variations in the tropical eastern pacific, suggesting a nonlinear positive feedback between ENSO variability and mean climate change. The ICS also is negatively correlated to SSTA over the northern midlatitude oceans and positively correlated to those over the southern midlatitude oceans.

INDEX TERMS: 4520 Oceanography: Physical: Eddies and mesoscales processes; 4215 Oceanography: General: Climate and interannual variability (3309); 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312); 1620 Global Change: Climate dynamics (3309); 4504 Oceanography: Physical: Air/sea interactions (0312).


1. Introduction

[2] The irregularity of occurrence, seasonal locking, and the warm-cold asymmetry are distinctive characteristics of ENSO. On one side, Jin et al. [1994] and Tziperman et al. [1994] showed that by adapting the seasonal cycle into an ENSO model without atmosphere noise, the seasonal locking and the irregularity of ENSO recurrences could be explained by the devil’s staircase scenario. On the other side, several linear models also succeeded in driving the stochastic behavior of ENSO as well as the seasonal locking [Penland and Sardeshmukh, 1995; Thompson and Battisti, 2000]. However, the linear system failed to induce the asymmetric feature, while the nonlinear system produces the warm-cold asymmetry of ENSO as seen in the observation [Burgers and Stephenson, 1999]. In this regard, the survey of the El Nino-La Nina asymmetry – thus, a simple way to measure the nonlinearity of ENSO may provide information regarding how the nonlinearity of ENSO changes, for example, in the interdecadal time scale, and what climate consequence occurs with the ENSO nonlinearity.

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[3] Recently, Wu and Hsieh [2003] objectively identified the El Nino-La Nina asymmetry appeared in the SST anomalies by using the nonlinear canonical correlation analysis and showed that the nonlinearity of ENSO under-went significant interdecadal changes. Interestingly, during the recent half century, the interdecadal changes in the ENSO nonlinearity concurred with those in other ENSO properties including the intensity, period, predictability, propagation characteristics, onset, and so on [e.g., Wang, 1995; Kirtman and Schopf, 1998; An and Wang, 2000], as well as with the late 1970s climate shift [Nitta and Yamada, 1989; Zhang and Levitus, 1997], intuitively implying a linkage between the background climate change and the changes in the ENSO variability. To date, however, no systematic diagnostics have been undertaken that examine the consequences of the interdecadal changes in the nonlinearity of ENSO using the historical data. In this study, thus using the recently released monthly-mean global SST data spanning from 1864 to the present, the interdecadal changes in the El Nino-La Nina asymmetry (a measure of the nonlinearity) and their consequences are examined.

2. Data and Method

[4] The monthly-mean global SST data spanning from 1854 to the present, which were recently released by the National Climatic Data Center, the so-called ‘Extended Reconstruction SST version 2’ (ERSST.v2 [Smith and Reynolds, 2004]), are utilized. These SST data resolve more variance, particularly in the western tropical Pacific, the tropical Atlantic, and Indian Oceans, than the previous analysis, and sea ice concentration data to improve the high-latitude SST analysis and a modified historical bias correction for the 1939–41 period are incorporated. Since Monahan and Dai [2004] already showed that the interde-cal variability of the nonlinear structure - the second EOF mode of tropical Pacific SST – over the period 1871–2003 is broadly the same in the Hadley Centre Sea Ice and SST dataset [Rayner et al., 2003], the Lamont-Doherty Earth Observatory reconstruction SST by Kaplan et al. [1998], and ERSST.v2; and thus, the results from ERSST.v2 are not necessary to be compared with those from other datasets for the verification purpose.

[5] The annual mean SST anomalies are obtained by taking the average from April to following-year March, in which the SST anomaly associated with ENSO usually keeps one sign so that it maximizes the ENSO signal, and then detrended over the 151-year record. From there, two data sets are defined: 21-year running-mean SST anomalies (hereafter, ‘21YR-SST’) and 21-year moving-window skewness of SST (hereafter, ‘21YR-SKN’). For the skew-
negativity, the departures from the local mean, (i.e., the departure from 21-year moving average) are used, and thus the signal of 21YR-SST does not appear in 21YR-SKN.

The skewness is a normalized third statistical moment \([\text{White}, 1980]\). Thus, a small standard deviation may cause large skewness. To avoid this, rather than the normalized skewness, I examine the weighted skewness, \(m_3/m_2\) where \(m_k = \sum (x_i - \bar{x})^k/N\); \(x_i\) is the \(i\)th observation, \(\bar{x}\) the mean, and \(N\) the number of observations.

3. Results

3.1. Spatial and Temporal Patterns of the Interdecadal SST Skewness Variability

In order to identify the dominant pattern representing the long-term changes of the ENSO nonlinearity, the empirical orthogonal function (EOF) analysis (a.k.a. principal component analysis) is applied to 21YR-SKN over the tropical Pacific. Figure 1 shows the first EOF mode, of which the variance fraction to the total variance is 33%.

The first EOF mode (Figure 1) is characterized by a bell-shape pattern centered at the equatorial eastern Pacific and small negatives in the equatorial central and northwestern Pacific. Obviously, this mode represents the asymmetry between El Nino (warm event) and La Nina (cold event), since most of the variance is due to the skewness of ENSO, and the spatial pattern resembles the residual of the sum of El Nino and La Nina. The corresponding principal component (PC) time series indicates that the skewness of ENSO underwent interdecadal variation with about a 20-year period. The positive skewness is dominant during 1890–1910, 1935–1945 (weak), and 1975–1995 (strong), and the negative skewness is dominant during 1860–1880, 1910–1930, and 1945–1975. Note that the mean of 21YR-SKN over the whole data period is slightly positive in the tropical Pacific so that the actual skewness during the negative PC may be close to zero or weakly negative.

To check the robustness of this mode, EOF analysis is applied to the SST skewness with a slightly different moving-window length (e.g., between 15 and 25 years). The results were not changed significantly by changing the window length. In addition, the significance test following \(\text{White} [1980]\) showed that the 21YR-SKN over the tropical eastern Pacific is significant within a 95% confidence level for most of time.

3.2. ENSO Predictability and El Nino-La Nina Asymmetry

\(\text{Chen et al. [2004]}\) forecasted the tropical Pacific SST anomalies over the past 148 years, using the intermediate coupled ocean-atmosphere model. The correlation for the consecutive 20-year periods between the observed and predicted values of the Nino-3.4 index \([\text{Chen et al., 2004}, \text{Figure 2}]\) showed that ENSO predictability varied decade by decade. From \(\text{Chen et al. [2004]}\), the correlations between observed and forecasted Nino-3 index for 9- to 12-month lead times are averaged for the 20-year interval and shown in Figure 1. Although the correlation is not strictly linearly proportional to the PC time series, it is certain that the ENSOs for the positive skewness decades are more predictable (around 0.6 or higher for 1890–1915 and 1976–1995) and those for the negative skewness decades (1865–1875 and 1916–1975) are less predictable. This may be because the background for the cold event is more favorable for the noise to agitate the ENSO cycle (S.-I. An et al., A nonlinear analysis of the ENSO cycle and its interdecadal changes, submitted to \textit{Journal of Climate}, 2004).

3.3. Zonal Propagation of ENSO and El Nino-La Nina Asymmetry

The nonlinear dynamical heating (NDH) in the heat budget of the upper ocean (\(\text{NDH} = -\partial T'/\partial t - \nu' \partial T'/\partial y - w' \partial T'/\partial z\)) can be employed as a measure of the ENSO nonlinearity \([\text{Jin et al., 2003; An and Jin, 2004}], \text{An and Jin [2004]}\) pointed out that NDH strengthens El Nino and weakens subsequent La Nina so that it leads to the El Nino-La Nina asymmetry. They also showed that the eastward propagating ENSO tends to produce large NDH, while the westward propagating ENSO barely produces NDH. In this regard, the zonal propagating features of ENSO may be related to El Nino-La Nina asymmetry.

\(\text{Hayashi, 1977}\) applied to the detrended monthly-mean SST anomalies over the equatorial Pacific band (4°S–4°N) for the 20-year moving segments. Figure 2 shows the temporal evolution of the spectral density associated with the zonal wave number one that has the most variance except the zonal mean. Clearly, the eastward propagating component is dominant since the late 1970s, which coincides with strong El Nino-La Nina asymmetry (positive PC). The ENSOs during 1930–50 and 1950–70 are dominated by the relatively short- and the longer-period westward propagating events, respectively. The 1930–70 corresponds to the weak or negative skewness decades (negative PC). For the negative peak of PC around the 1920s, the short-period westward propagating tendency is dominant. The ENSOs during 1885–1905 – even through the positive skewness decade (positive PC) - have both the westward and eastward propagating tendencies. Overall, the ENSOs during the positive skewness decades tend to propagate eastward,
while those during the negative skewness decades tend to propagate westward.

### 3.4. Nonlinear ENSO Feedback to the Mean State

[13] Jin et al. [2003] suggested that half of the increased tropical Pacific warming after the 1976 climate shift may be attributable to the NDH. Furthermore, Rodgers et al. [2004] showed that the spatial patterns in SST representing El Niño-La Niña asymmetry strongly resembled those associated with the decadal changes in SST, which was supported further by Monahan and Dai [2004] who analyzed several independent historical SST datasets. These studies implied that a part of decadal variability in the tropical Pacific resulted from the nonlinear ENSO feedback to the climate state. On the other hand, An and Jin [2004] pointed out that the interdecadal changes of ENSO nonlinearity were related to the climate state change. In this regard, a positive feedback mechanism between the ENSO nonlinearity and the mean state in the interdecadal time scale can be conjectured.

[14] In order to examine this feedback mechanism, the singular value decomposition analysis (SVD; a.k.a. Maximum Covariance Analysis) is applied to 21YR-SKN and 21YR-SST over the tropical Pacific, and the first SVD mode is shown in Figure 3. The variance fractions explained by this mode are 24% for 21YR-SKN and 61% for 21YR-SST. The patterns associated with 21YR-SKN and 21YR-SST are equally characterized by large amplitude in the tropical eastern Pacific with the same sign, implying that the interdecadal warming/cooling of SST in the tropical eastern Pacific may result from the nonlinear feedback of ENSO or the other way around. This positive feedback, as shown in the corresponding PC time series, is especially dominant during the 1895–1935 and 1975–2003.

### 3.5. Global Impact

[15] The ENSO impact is not only isolated in the tropics but also reaches beyond the tropics. Since the El Nino and La Nina are not symmetric, their impacts seem to be asymmetric. In this sense, the residual of the sum of the El Nino and La Nina impacts may leave the footprint in some places on the globe, as long as the impacts are not heavily damped. The footprint picture can be identified by the correlation map of 21YR-SST against the first EOF PC time series of 21YR-SKN. Figure 4a shows the significant correlation (greater than 0.6) in many places over the global ocean. The positive correlation indicates the increase of SST anomalies for the positive skewness decades, and vice versa for the negative skewness decades. The southwestern Indian Ocean, southeastern Pacific and southwestern Atlantic Ocean SST anomalies are positively correlated, and the

![Figure 2](image2.png)

**Figure 2.** The space-time power spectral density of the equatorial Pacific SST anomalies (4°S–4°N) associated with zonal wave number one. The left- and right-side of contours indicate the spectral densities associated with the westward- and eastward-propagating wave component, respectively.

![Figure 3](image3.png)

**Figure 3.** Distributions of the first SVD mode associated with (left) 21-year moving skewness of SST anomalies and (right) 21-year moving averaged SST anomalies. Solid and dotted lines indicate the PC time series associated with 21-year moving skewness of SST anomalies and the 21-year moving averaged SST anomalies, respectively. The fractions of covariance/variance of normalized data fields explained by this mode are indicated in titles. The values greater than 0.4 are shaded. The correlation between two PC time series (bottom panel) is 0.77.

![Figure 4](image4.png)

**Figure 4.** Correlation map of the 21-year moving averaged SST anomalies against the PC time series associated with the first EOF mode of the interdecadal SST skewness variability (a), and associated with the first EOF mode of the interdecadal SST variability (b). Greater than 0.6 and less than −0.6 are shaded. Contour intervals are 0.2.
interdecadal tropical SST change. It implies that the interdecadal changes in the ENSO nonlinearity could induce an interdecadal impact over the globe. 

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References

4. Concluding Remarks
[17] The global SST data over the past 148 years have been analyzed to describe the dominant spatial and temporal features of the ICS in the tropical Pacific and its consequence. The first EOF mode of the ICS represents the interdecadal changes in the El Nino-La Nina asymmetry. The ICS tend to be positively correlated to the ENSO predictability. During the positive skewness decades, ENSOs tend to propagate eastward, while they tend to propagate westward during the negative/small skewness decades. The SVD pattern between the ICS and the interdecadal SST change suggested a positive feedback between the mean climate state and ENSO variability. The PC time series associated with the first EOF mode are correlated to SST anomalies in northern hemisphere oceans SST negatively and those in southern hemispheric oceans positively. It is also found that the leading EOF modes of the interdecadal tropical Pacific SST anomalies are not correlated to the first EOF mode of the ICS. Furthermore, the global impact of ICS is distinguished from that of the

North Pacific and far North Atlantic Ocean SST anomalies are negatively correlated. For example, it is known that the tropical warm and cold events are associated with the increasing and decreasing SST anomalies over the central North Pacific, respectively [Hoerling et al., 1997; An and Wang, 2004]. In this sense, during the positive skewness decades, overall cold temperature as a residual of the ENSO impact might appear over the central North Pacific, while during the negative skewness decades, the warm temperature might appear. Thus, the negative correlation in the central North Pacific is possible.

[16] Because the interdecadal changes in SST skewness (ICS) are related to the interdecadal SST change as shown in Figure 3, it is unclear whether the correlation in Figure 4a is due to the ICS or due to the interdecadal SST change. To see whether the impact of the ICS is distinguished from that of the slowly varying tropical mean climate state, first I calculate the correlation pattern of the global 21YR-SST against the EOF PC of the 21YR-SST (the first EOF mode of 21YR-SST for the tropical Pacific domain is almost identical to the first SVD mode shown in Figure 3). As shown in Figure 4b, significant correlations (greater than 0.6) are observed in the tropical Pacific and Indian Oceans, near the west coast of South America, and in the Antarctic Ocean. The insignificantly correlated regions are observed in the Indian Ocean between 20°S and 40°S, and in the north Pacific and north Atlantic Oceans. Interestingly, these insignificantly correlated regions seem to match the significantly correlated regions with ICS as shown in Figure 4a. It implies that the global impact of the ICS is distinctive from that induced by the interdecadal SST changes over the tropical Pacific. Note that the correlation between the EOF PC of the 21YR SST and the EOF PC of the 21YR-SKN for the tropical Pacific domain is 0.45, which is below the 95% confidence level.