The 1970’s shift in ENSO dynamics: A linear inverse model perspective

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In this paper, we investigate whether the observed changes in El Niño–Southern Oscillation (ENSO) character since the 1970’s climate shift are consistent with a change in the linear ENSO dynamics. Linear Inverse Models (LIMs) are constructed from tropical sea surface temperature (SST), thermocline depth, and zonal wind stress anomalies from the periods 1958–1977 and 1978–1997. Each LIM possesses a single eigenmode that strongly resembles the observed ENSO in frequency and phase propagation character over the respective periods. Extended stochastically forced simulations using these and the LIM from the combined period are then used to test the hypothesis that differences in observed ENSO character can be reproduced without changes in the linear ENSO dynamics. The frequency and amplitude variations of ENSO seen in each period can be reproduced by any of the three LIMs. However, changes in the direction of zonal SST anomaly propagation in the equatorial Pacific cannot be explained within the paradigm of a single autonomous stochastically forced linear system. This result is suggestive of a possible fundamental change in the dynamical operator governing ENSO and supports the utility of zonal phase propagation, rather than ENSO frequency or amplitude, for diagnosing changes in ENSO dynamics. Citation: Aiken, C. M., A. Santoso, and M. H. England (2013), The 1970’s shift in ENSO dynamics: A linear inverse model perspective, Geophys. Res. Lett., 40, doi:10.1002/grl.50264.

1. Introduction

The observational record of tropical sea surface temperature (SST) is suggestive of a significant change in the character of El Niño–Southern Oscillation (ENSO) since the late 1970s. The following decades saw a decrease in the frequency of ENSO events and an increase in their intensity, plus a change in the predominant direction of ENSO SST anomaly phase propagation along the equator (e.g., An and Wang, 2001; Wang and An, 2002). During the 1960s and 1970s warm anomalies appeared first in the eastern Pacific and expanded westward, but since then they have developed in the central Pacific either prior to or concurrently with the eastern Pacific (Fedorov and Philander, 2000; Wang and An, 2002; Trenberth et al., 2002).

2. Linear Inverse Models of ENSO

The theory of linear inverse models and their application to ENSO is thoroughly developed in Penland and...
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Matrosova [1994] and Penland and Sardeshmukh [1995]. The method used to generate LIMs here follows closely that described in Newman et al. [2011a]. The principal assumption made is that ENSO variability may be modeled as a linear system driven by additive Gaussian white noise of the form

$$\begin{aligned}
dx/dt &= Bx + \xi(t), \\
\end{aligned}$$

where $x$ is the state vector, $B$ is an autonomous linear operator, and $\xi$ is a Gaussian white noise process. Knowledge of the covariance properties of the observations of $x$ allows the best fit estimate of $B$ in the least squares sense to be determined as follows:

$$
B = t_0^{-1} \ln \left( C(t_0) C(0)^{-1} \right),
$$

where $C(t_0)$ and $C(0)$ are the covariance matrices at lags of $t_0$ and zero, respectively. Following Newman et al. [2011a], the 23 element state vector

$$
x = [T_0, Z_{20}, \tau_c]
$$

contains the projections of the anomalies onto the first 13 empirical orthogonal functions (EOFs) of sea surface temperature ($T_0$), the first 7 EOFs of 20°C isotherm depth ($Z_{20}$), and the first 3 EOFs of zonal wind stress ($\tau_c$). $T_0$ was taken from the International Comprehensive Ocean-Atmosphere Data Set Project (ICOADS) [Woodruff et al., 2011], $Z_{20}$ from the Simple Ocean Data Assimilation 2.2.4 global ocean reanalysis [Carton and Giese, 2008; Giese et al., 2011], and $\tau_c$ from ERA-40 [Uppala et al. 2005]. LIMs were generated corresponding to the periods 1958–1977, 1978–1997, and 1958–1997 (referred to hereafter as LIM1, LIM2, and LIM0, respectively). In order to address the possible high sensitivity of the results to individual features in the short records, an ensemble of estimates of each LIM was constructed using a jackknife technique in which each consecutive 2-year period was removed sequentially from the analysis. All results that follow are based on these jackknife estimates of each LIM. All data were subjected to a 3-month running mean prior to removing the seasonal cycle and linear trend. These filtered anomalies were then consolidated into bins of 2° latitude by 5° longitude within the region between the 25°N and 25°S parallels. The resulting binned anomalies were then projected onto the state vector (3) and used to generate the linear inverse model $B$ via (2). The covariance timescale $\tau$ used for calculating the LIMs was 3 months in each case. The results that follow are not sensitive to this choice.

A significant degree of uncertainty exists in the trends present in historical observational data sets due to sparse sampling and changes in observational methods over time. In particular, the apparent change in ENSO character coincides roughly with the availability of satellite SST, producing a sudden increase in the quantity and quality of SST observations from the tropics. By removing the mean and seasonal cycle independently from each period, the following analysis is less sensitive to any such artifacts in the observational record. Only observational errors that affect the covariance will degrade the LIM.

Each LIM satisfies reasonably well the criteria of Penland and Sardeshmukh [1995] and reproduces the major characteristics of the corresponding observations, suggesting that they capture much of the principal dynamics of ENSO and hence represent useful analogues with which to investigate the real system. The cross-validated skill of Niño3 forecasts averaged over the jackknife estimates of each LIM, shown in Figure 1, reveal that each LIM beats persistence and climatology forecasts on lead times out to 24 months. In addition, it indicates that LIM1 (LIM2) is more skillful than LIM0 for the former (later) period on all lead times. As discussed below, the LIMs recover the observed spatial structure and frequency of the coupled ENSO mode and the propagating character of the coupled dynamics.

Figure 1. Mean (solid) and standard deviation (shaded) of the RMS error in cross-validated LIM forecasts of Niño3 as a function of lead time for the periods (a) 1958–1977 and (b) 1978–1997. Cross-validation involved performing forecasts for each of the two consecutive years using the LIM recalculated with those years removed from the analysis. The persistence forecast is shown by the dashed line. The RMS error is normalized by the standard deviation, such that a climatology forecast corresponds to an error of 1 at all lags.

Eigenanalysis of the operator $B$ yields the spectrum (eigenvalues) and modes (eigenvectors) corresponding to each period. Each of the LIMs possesses one eigenmode that closely resembles the observed ENSO in both structure and frequency. The quadrature phases of these modes are shown in Figure 2 and are hereafter referred to as the ENSO modes. The evolution of both ENSO modes is consistent with the classical Bjerknes-type mechanism and the recharge oscillator paradigm [Bjerknes, 1969; Jin, 1997; Meinen and McPhaden, 2000]. The basin-wide equatorial thermocline deepens at the initial state of developing El Niño (Figures 2a, 2c, and 2e). This is followed by a shoaled and deepened thermocline in the west and east, respectively, enhanced by anomalous westerlies that are further reinforced by the eastern Pacific surface warming (Figures 2b, 2d, and 2f). These modes also encapsulate much of the lagged correlation structure of the observations (Figures 2g–2l), illustrating the propagating character of the coupled dynamics. The most notable difference is seen in the westward and eastward propagating correlation between the zonal wind stress and Niño3 before and after the climate shift, respectively. Although damped, noise forcing sustains these ENSO modes through linear interference with other nonorthogonal modes [Penland and Sardeshmukh, 1995; Newman et al., 2011].

3. Can a Single LIM Explain the Observations?

Even if the dynamics of ENSO were identical in both periods and perfectly explained by (1), one would...
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Figure 2. Quadrature phases of the principal ENSO mode of the LIMs corresponding to the periods (a–b) 1958–1977, (c–d) 1978–1997, and (e–f) 1958–1997. SST is shaded, $z_{20}$ is contoured (with negative contours in green), and $t_{20}$ is indicated by arrow heads. The spacing in arrow head and contour increments is equivalent to a normalized anomaly of magnitude 0.2 on the SST scale. The modes evolve as (a), (b), (-a), (-b), (a), etc. Figures 2g–2l display the lagged correlation between the Niño3 index and $t_{20}$ (g, i, k) and $z_{20}$ (h, j, l) as a function of equatorial Pacific longitude. The values determined from the observations are shaded and those corresponding to the the ENSO modes contoured (with negative contours in green).

still expect our estimates of those dynamics to differ to some degree due to variations in the applied forcing alone. Thus, the differences between the LIMs may not indicate a real change in dynamics. In the following, we test the null hypothesis that the observed ENSO frequency and propagation character can be reproduced by a single dynamical system and hence that LIM1 and LIM2 represent estimates of this same unique dynamical operator. For this purpose, a series of 20,000-year simulations of (1) were performed for each jackknife estimation of each LIM, and the resulting time series used to generate an ensemble of estimates of the dynamical operator by performing the LIM analysis on each of the 1000 independent 20-year segments. Although each time series is generated by a single autonomous dynamical operator that obeys (1) exactly, it may be anticipated that the properties of each of the estimates of that operator based on short records will tend to differ from the original $\mathbf{B}$. We investigate whether this variability in the inferred dynamics is sufficient to explain the observed changes in ENSO character.

\[ y(t + \delta) = y(t) + \delta \mathbf{B}y + \mathbf{P} \mathbf{r}(t)/\delta^{1/2}, \]  

where the time step $\delta = 6$ h, $\mathbf{P}$ contains the eigenmodes of the forcing covariance matrix multiplied by the square root of their corresponding eigenvalues, and $\mathbf{r}(t)$ is a vector of independent Gaussian deviates of unit variance. In order to remove the effect of differences in the forcing $\mathbf{P}$, the simulations were repeated using a randomly generated $\mathbf{P}$ constrained to have orthonormal columns. The differences due to the form of $\mathbf{P}$ were in all cases found to be minor. The final state vector $x(t)$ is then given by

\[ x(t + \delta/2) = (y(t) + y(t + \delta))/2. \]

The initial condition for each simulation was determined by spinning up the model from rest for 10 years. All analysis
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Figure 3. Probability density functions calculated from the ensemble of 20,000-year stochastically forced simulations for (a) the period of the ENSO mode, (b) the e-folding decay time of the ENSO mode, (c) the period of maximum power spectral density of the Niño3 index, and (d) the standard deviation of the principal component of the first EOF of SST, representing the amplitude of ENSO variability. Vertical lines in each panel indicate the values derived from the observations.

that follows was based on the monthly mean values of the state vector.

Figure 3 presents the probability density functions for the estimates of the imaginary and real components of the eigenvalue corresponding to the ENSO mode (Figures 3c and 3d), together with those for the peak frequency of Niño3 power spectral density (Figure 3a) and for the standard deviation of the first principal component of SST (i.e., of the first element of the state vector; EOF1; Figure 3b). The latter two quantities represent commonly used metrics of ENSO character (frequency and amplitude, respectively) that are determined directly from the time series. The former two represent indirect, dynamically based, estimates of ENSO frequency and amplitude inferred from the LIM. Despite the fact that each of the simulations was generated by a distinct autonomous dynamical operator, there is substantial overlap in the distributions in each of these measures of ENSO character. The observed frequency and decay timescale of the pre-1977 and post-1977 ENSO modes (marked by vertical lines in Figures 3c and 3d) are located well within the intersection of distributions of estimates from the extended simulations, such that both could plausibly have resulted from a single stochastically forced system governed by any of the three LIMs. The distributions of the frequency of peak power spectral density of Niño3 reflect those for modal frequency, with substantial overlap between the pre-1977 and post-1977 periods. Similarly, there is substantial overlap in the distributions of EOF1 amplitude (Figure 3b) and modal decay time (Figure 3d), such that changes in ENSO amplitude also do not necessarily indicate changes in the underlying ENSO dynamics. These results suggest that the observed change in ENSO amplitude and frequency could conceivably be explained by a stochastically forced system with a single dynamical operator. Specifically, the hypothesis that the observed ENSO frequencies corresponding to the pre-1977 and post-1977 periods resulted from the single dynamical operator represented by LIM0 cannot be rejected.

The inferred direction of propagation of SST anomalies in the equatorial Pacific does not, however, vary sufficiently during the simulations to explain the observed change since the 1970s. The propagation direction can be diagnosed by calculating the lagged correlation between central Pacific SST and the difference between eastern and western Pacific SST [e.g., Gualtieri, 2006; Santos et al., 2012]. Following Santos et al. [2012] (see their Figure 7),

Figure 4. (a) Lagged correlation between Niño3 and the east-west index for the periods 1958–1977 (blue), 1978–1997 (red), and 1958–1997 (green). Dashed lines correspond to observations and solid to the average over all 20-year segments from the ensemble of simulations. Shading indicates the correlation within one standard deviation of the mean value. (b) Probability density functions for the gradient of the correlation in Figure 4a evaluated at zero lag from the ensemble of 20-year segments, used to quantify the propagation direction. Vertical lines indicate the observed value.
the former is determined by the Niño3 index, and the latter by the east-west index, defined as the area-averaged SST in the far eastern Pacific (5°S–5°N, 91°W–80°W) minus that in the Niño4 region (5°S–5°N, 160°E–150°W). Eastward (westward) propagation is indicated by positive correlations at negative (positive) lags. As is the case for ENSO amplitude and frequency, the propagation character of ENSO is encapsulated within the corresponding ENSO mode from each LIM. The fact that the ENSO modes mirror the dominant phase propagation character of the observations is illustrated in Figures 2g–2l. Figure 4a demonstrates that the ensemble average from each LIM agrees closely with the observations, and hence the LIMs accurately recover the propagation character of equatorial Pacific SST anomalies: prominent westward propagation in LIM1 and somewhat eastward in LIM2. The probability density functions of the gradient in the correlation curve evaluated at zero lag, used to quantify phase propagation character, demonstrate no intersection between the distributions of LIM1 and LIM2 (Figure 4b). Moreover, even though LIM0 spans periods of eastward and westward propagation, no 20-year period in the LIM0 simulations reproduces the propagation characteristic of the pre-1977 period. As such, we can reject the hypothesis that the change in propagation characteristic can be explained by LIM0.

[14] Although the LIMs are contrived to best fit the observed covariance structure at a given lag, they are not constrained to reproduce the phase structure at all lags. In fact, it is possible to manipulate the forcing in such a way as to alter the propagation character (such as by removing the projection of the forcing onto ENSO modes). However, the results were not altered qualitatively when the spatial forcing P was white; in both cases, the estimates of the ENSO mode propagation direction derived from the extended simulations do not vary sufficiently to produce differing ENSO phase propagation characters consistent with the observations. As a result, insofar as the LIM captures the physics of ENSO phase propagation, the observed change in propagation direction demands a fundamental change in the underlying dynamical operator, such as due to changes in the mean state.

4. Conclusions

[15] An empirical investigation of ENSO dynamics either side of the 1970's shift was performed using linear inverse models. Consistent with a series of previous studies, ENSO in both periods can be well described as a stochastically forced damped linear system, with dominant ENSO modes whose spatial structure and complex frequencies agree well with observations. While an altered mean state has been shown to possibly explain the observed differences in ENSO frequency, here we find that such changes may also arise without a change in ENSO dynamics and due solely to variability in the forcing and to the relatively short observational record.

[16] Even though the underlying dynamical operator and statistics of the forcing were fixed, estimates of the complex ENSO mode frequency taken from independent 20-year segments of extended stochastically forced simulations vary significantly. In particular, there was substantial overlap between the sets of estimated ENSO complex eigenvalues from the simulations using each LIM. This suggests that the observational record may be too short to determine what component of the observed changes in the frequency and amplitude of ENSO can be attributed to dynamical changes (i.e., related to changes in the mean state) and how much is simply a consequence of forcing variability.

[17] In contrast, the observed change in the direction of zonal SST propagation in the equatorial Pacific does appear to be symptomatic of altered ENSO dynamics. The SST propagation character simulated by each LIM varied little over the course of the stochastically forced simulations, and no single LIM could reproduce the propagation characteristics of both periods. Our study therefore suggests that the direction of the zonal phase propagation of SST anomalies may provide a more useful diagnostic for changes in ENSO behavior, rather than ENSO frequency and amplitude. These results may partially explain the disagreements across Coupled Model Intercomparison Project Phase 3 models in terms of the response in ENSO frequency and amplitude under global warming, despite a more consistent picture in terms of zonal phase propagation [Guilyardi 2006].

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References


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