Investigation of ENSO variability using cyclostationary EOFs of observational data

K.-Y. Kim

With 12 Figures

Received August 15, 2001; revised March 6, 2002
Published online: August 19, 2002 © Springer-Verlag 2002

Summary

The variability of El Niño-Southern Oscillation (ENSO) on all time scales, ranging from months to decades, has been studied from the perspective of sea-surface temperature anomaly (SSTA), sea-level pressure anomaly (SLPA), and surface wind anomaly (SWA) fields using a statistical tool called cyclostationary empirical orthogonal function (CSEOF) analysis. The analysis indicates that a significant fraction of variability in the tropical Pacific can be explained in terms of an irregular interplay of two dominant modes: the low-frequency mode and the biennial mode. These modes, and in particular the biennial mode, are well defined coupled modes of the tropical ocean-atmospheric circulation system, as suggested by strong correlation (> 0.9) in the evolution of the different physical variables. The low-frequency mode and its PC time series are very similar to the so-called “interdecadal” mode identified by earlier investigators. The corresponding PC time series of the low-frequency mode has a broad spectral peak at 5.3 yrs. The biennial mode represents the oscillation pattern of El Niño and La Niña and has a clear biennial cycle, the amplitude of which varies on a longer time scale. There is a broad spectral peak also at 5.3 yrs in the principal component (PC) time series of this mode. Unlike in earlier studies, this biennial mode is clearly separable from the low-frequency mode, since these two modes have different physical evolution patterns. Results of the present study also indicate that the biennial component, having a clear phase-locking tendency, is not as variable as has been suggested in some previous investigations. It is shown that much of the inter-El Niño variability can be explained in terms of an irregular interplay between the biennial mode and the low-frequency mode. Finally, the role of the low-frequency mode in the tropical Pacific seems to be more important than has been suggested previously. Specifically, recent warming events since 1975 are shown to be associated with the low-frequency mode rather than with the biennial mode.

1. Introduction

Although El Niño and La Niña refer primarily to the occurrence of anomalously warm and cold water in the tropical eastern Pacific, respectively, their influence is far reaching. El Niño and La Niña exert significant impacts on the global atmospheric circulation, weather systems, and the distribution of precipitation as can be observed by the systematic weather changes during these events. The considerable economic value as well as scientific curiosity have stirred vigorous research on El Niño and southern oscillation (ENSO) over the past three decades.

Since the pioneering work of Bjerknes (1969), it is a consensus of the scientific community that El Niño and La Niña are closely linked to the so-called southern oscillation (Walker circulation). It is generally viewed that El Niño and La Niña are the ocean manifestations of the opposite phases of this tropical atmospheric circulation. Basic principles of how the coupled ocean-atmosphere system works have been proposed, and appear to provide reasonable explanations for these phenomena.
The irregularity of El Niño and La Niña, however, has been the source of unresolved controversy and extensive debate. From the viewpoint of data analysis, no two El Niños (and also La Niñas) are the same in terms of the amplitude and the evolving pattern. Moreover, the occurrence of El Niño and La Niña seems to exhibit an irregular behavior. Estimates of the frequency of El Niño and La Niña differ slightly from one investigator to another. In addition to this interannual variability, the starting and terminating times of El Niño and La Niña with respect to the annual cycle seem to fluctuate widely from one event to another. Understanding this inter- and intra-annual variability obviously is of great practical value.

An issue of continuing controversy concerns whether El Niño and La Niña should be viewed as irregular occurrences (events) or as irregular manifestations of otherwise oscillatory behavior of the tropical Pacific ocean. Rasmusson et al. (1990) appear to be the first investigators to have taken the latter view. In the surface wind field of the equatorial eastern Indian Ocean, they identified a well defined standing component of ENSO variability, which is tightly phase-locked with the annual cycle. They proposed that this standing component is part of a larger-scale biennial circulation over the low latitude eastern Indian Ocean-western Pacific sector, and that it is a fundamental element of ENSO variability. They further proposed that ENSO variability consists of biennial mode and low-frequency undulations. Although this two-mode view seems to have gained some acceptance, as seen in recent articles (e.g., Rasmusson and Wallace, 1983; Philander, 1990; Barnett, 1991; Goswami, 1995; Clarke and Van Gorder, 1999), the concept needs to be examined further using more comprehensive analysis tools.

Composite analysis is frequently employed to derive the sea-surface temperature anomaly (SSTA), sea-level pressure anomaly (SLPA), and surface wind anomaly (SWA) patterns associated with El Niño and La Niña (e.g., Rasmusson and Carpenter, 1982; Carton and Huang, 1994; Harrison and Larkin, 1996; and references therein). Nevertheless, composite analysis is unable to delineate the detailed evolution of spatial variability during El Niño and La Niña events, and in particular can not separate different physical modes. In light of the results of Rasmusson et al. (1990), it is not clear whether El Niño and La Niña should be interpreted as a single physical mode or otherwise. Consequently, physical or dynamical interpretation from a composite analysis can be difficult. Although transitional patterns can also be derived via a composite analysis, such patterns might be contaminated significantly. Indeed, since transient phases of El Niño and La Niña are much weaker in strength than their peak phases, analyses of these phases are much more susceptible to contamination than are the peak phases. In some studies, El Niño and La Niña patterns are isolated via a regression analysis between anomaly fields and a time series that measures the ENSO strength such as the southern oscillation index (SOI) time series (Mitchell and Wallace, 1996). This method may also suffer from similar difficulties in interpretation as composite analyses.

In an effort to derive more accurate spatial patterns and transient structure associated with ENSO, advanced eigentechniques have been applied in previous studies with some success. For instance, Graham et al. (1987a, b) and Barnett (1988) applied extended empirical orthogonal function (EOF) analysis to the tropical SST field, and Barnett (1991) used complex EOF analysis to investigate the multiple time scales of variability in the tropical Pacific ocean. Nigam and Shen (1993), and Monttroy (1997) applied rotated EOF analysis to tropical data to investigate the structure of low-frequency variability. Although displaying some success in the desired applications, these tools were not able to provide insight into the currently unresolved issues regarding the nature of variability associated with ENSO.

El Niño and La Niña are generally considered to be strongly phase-locked (Jin et al., 1994; Tziperman et al., 1994; 1998); however, a stationary spectral analysis is frequently employed in ENSO studies to make inferences about the periodicity of El Niño and La Niña occurrences. The phase-locking of El Niño and La Niña is an indication that they are nonstationary phenomena, and hence an estimation of the frequency based on the spectral analysis may be misleading. Indeed, this concern is reflected in the study by Clarke and Van Gorder (1999).

In this study, ENSO variability on all relevant time scales is investigated using a technique