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Inter-decadal signals during the last millennium (AD 1117-1992) in the varve record of Santa Barbara basin, California

Franco Biondi and C.B. Lange
Scripps Institution of Oceanography, University of California-San Diego, La Jolla

M.K. Hughes
Laboratory of Tree-Ring Research, University of Arizona, Tucson

W.H. Berger
Scripps Institution of Oceanography, University of California-San Diego, La Jolla

Abstract. Annual varve thickness (AD 1117-1992) from Santa Barbara basin has been decomposed into orthogonal components using singular spectrum analysis (SSA) to identify and retrieve inter-decadal oscillations. After removing all variability with periods greater than 150 years, leading SSA eigenfunctions (EOFs) identify four oscillatory pairs with periods of ~100, ~58, ~25, and ~12 years respectively. Based on 2500 simulated series and on two-sided confidence intervals, EOFs 1-7 are significant at the 99% level and EOFs 8-9 are significant at the 90% level. Oscillatory signals retrieved from the marine varves show an abrupt change in frequency and amplitude near AD 1600. The largest contribution to this environmental shift is given by the interdecadal components, especially the ~25 and the ~12-year oscillation. The near-AD 1600 change may be related to multi-annual events reported in the stratigraphy of the nearby Santa Monica Basin and in dendrochronological records of the American Southwest.

Introduction

High-resolution laminated systems, such as annual couplets in varved marine or freshwater sediments, dust layers within glacial ice, tree-rings and coral banding, are particularly effective in preserving climatic signals at multiple temporal scales through their response to the annual cycle (Baumgartner et al., 1989). The most extensive and least disturbed record of modern annual varves (light-dark laminations) in the North Pacific is in the central Santa Barbara basin (SBB). Sedimentation rates are of the order of 150 cm/1,000 yrs and are controlled by a combination of terrigenous sediment supply, surface-water productivity, bacterial activity and oxygenation of bottom water (Bull and Kemp, 1995; Kennett et al., 1995; Grimm et al., 1996). The sensitivity of SBB to regional and global changes in climate and the permanent mark that such perturbations leave in the SBB marine sediments have allowed the identification of climate-driven fluctuations in ocean circulation during the past 60,000 years in the North Pacific region that are synchronous with those of the North Atlantic (Kennett and Ingram, 1995; Keigwin, 1995; Behl and Kennett, 1996).

It has been suggested that large climatic shifts have occurred in the past — and may well do so in the future — with transitional periods of only a few decades (Dansgaard et al., 1993). With the goal of investigating abrupt and long-lasting environmental changes recorded in the Santa Barbara basin, we present here the inter-decadal variability contained in the varve record over the last millennium. By restricting our focus to this particular frequency band, we emphasize phenomena well within the human lifespan, as a possible aid to long-range forecasting of climatic change.

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When dealing with noisy data sets of limited length, singular spectrum analysis (SSA) provides a reliable measure of the information content of a discrete time series at different frequencies (Vautard et al., 1992). SSA is among the tools currently used to uncover underlying deterministic properties of climatic and paleoclimatic time series and to investigate the inherently chaotic dynamics of Earth's systems at different timescales (Vautard and Ghil, 1989; Tsonis et al., 1994). As a data-adaptive technique of series decomposition into orthogonal components, SSA has been successfully employed to identify and retrieve low-frequency variability and trends (Ghil and Vautard, 1991) as well as periodic and quasi-periodic oscillations (Dettinger et al., 1995a). In this paper, we apply SSA to the SBB varve record in order to separate signal from noise, identify the leading oscillatory modes, and reconstruct their time-varying strength.

Varve Record

We have used X-radiography of sediment slabs for documenting the sediment structure, for varve counting, and for cross-correlating stratigraphic patterns. The dark and light laminae pairs on an X-radiograph contact print represent single years of deposition and are regarded as annual varves (Soutar and Crill, 1977). Varves are counted from top to bottom of a slab on each contact print and the varve thickness is measured to the nearest 0.1 mm using a hand lens with an integrated scale. Soutar and Crill (1977) constructed the original varve chronology for the SBB, AD 1820-1970. In subsequent publications (Schimmelmann et al., 1990, 1992) the original chronology has been revised and extended to about AD 1400. We have recently obtained additional X-radiographs of high quality from three sediment cores located in the southeastern area of the central basin at depths greater than 580 m (Lange et al., 1996).

The chronology presented here, AD 1117-1992, is averaged over two to three separate cores taken from different sites within the deepest portion of the basin. It is based on our detection and discounting of thin gray layers that may lead to faulty varve counts, as well as on cross-matching among the three new cores and those collected at various times since 1985. Our chronology is consistent with the one for AD 200-1970 used by Baumgartner et al. (1992), with the one for AD 750-1760 from Core 146-893A presented by Lange and Schimmelmann (1995), as well as with the Ocean Drilling Project (ODP) record of radiocarbon-dated sediments at Site 893 (ODP Leg 146; Ingram and Kennett, 1995). We estimate the accuracy of the time scale to be ±1 year for the last century and ±2 years down to AD 1800. Dating accuracy deteriorates with sediment depth, but calendar year assignment most likely remains within ±10 years at AD 1100, corresponding approximately to 180-190 cm in the sedimentary column. This error level is still negligible compared to the accuracy of paleoclimatic time series derived from marine sediments and subjected to interpolation in order to obtain equally-spaced time intervals for singular spectrum analysis (Yiou et al., 1994).

Time Series Methods

Singular spectrum analysis (SSA) is a form of principal component analysis applied to the autocovariance matrix of a time series (Vautard and Ghil, 1989). SSA requires no curve fitting or prewhitening, nor does it rely on prescribed sines and cosines to identify periodic behavior. Rather, SSA gives the principal axes of an M-dimensional sequence of vectors obtained by progressively lagging the original time series up to lag M. Considering the minimum number of replicates needed to compute the eigenspectrum, it is customary to limit the window length (M) to less than $N/3$ (Vautard et al., 1992) or no more than N/5 (Dettinger et al., 1995b). As classical principal component analysis (Preisendorfer, 1988), SSA provides the amount of variance explained by each orthogonal component, whose time-varying strength and phase can be computed in the same units as the original series.

We have employed SSA as a nonlinear trend-removal algorithm to isolate inter-decadal oscillations from lower-frequency signals, including the non-climatic decrease of varve thickness with increasing sediment age (Hamilton, 1976; Cowie and Karner, 1990; Audet, 1995). Given the length of our record (N = 876 years), and the restrictions on M that ensue, we report results for a window length of 150 years; lowering the cut-off time to 130 and 110 years has little impact on the conclusions. The overall time-series trend identified by the combination of slow-varying SSA eigenfunctions (EOFs) has been compared to a natural exponential function. After detrending, we perform signal-to-noise separation of the eigenspectrum according to significance tests based on red-noise assumptions and Monte Carlo simulation (Allen and Smith, 1994). Oscillatory modes are identified by eigenvalue pairs whose EOFs are in quadrature with each other and whose principal components have a single power peak (Penland et al., 1991) of the same frequency. Reconstructed components highlight location and duration of oscillatory spells.

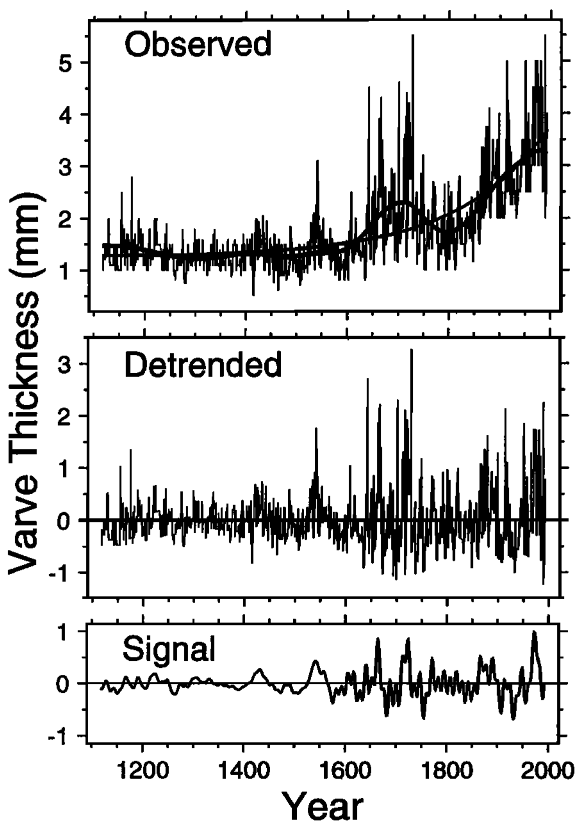

Figure 1. Thickness of annual varves ('Observed') in Santa Barbara basin, AD 1117-1992. SSA components with periods longer than 150 years (heavy line) fit the series better than a natural exponential function (thin monotonic line), and were removed to obtain the 'Detrended' series, whose reconstructed components 1 to 9 ('Signal') summarize statistically significant oscillatory modes.

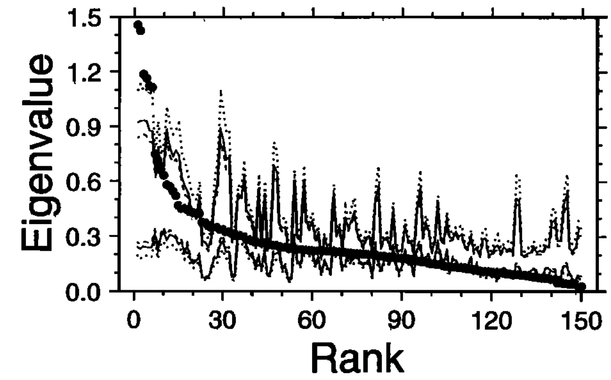

Figure 2. Eigenspectrum of detrended varve thickness with 90% (dashed lines), 95% (solid lines), and 99% (dotted lines) confidence intervals computed from Monte Carlo simulation.

Results

The exponential trend (Fig. 1) for annual varve thickness is consistent with expected patterns in the presence of sediment compaction with time. All variability on timescales longer than 150 years is concentrated in the first two SSA components, which explain 54.3% of the total variance. The sum of the first two reconstructed components follows closely the exponential trend, with the notable exception of a sinusoidal swing from about 1600 to about 1900. Residual series obtained by exponential and SSA detrending are highly correlated (r = 0.93). The exponential trend does not account for all low-frequency variability, hence only the SSA-detrended series (Fig. 1) is analyzed further in this paper.

A total of 2500 surrogate red-noise time series has been randomly generated according to the AR(1) model fitted to the detrended varve thickness series. The eigenspectrum covariance matrices are projected onto an SSA fixed basis (derived from the data) to obtain 90, 95, and 99% two-sided confidence limits for each eigenvalue (Dettinger et al., 1995a; Breitenberger, in press). The hypothesis that the detrended varve record is purely a red-noise series has been rejected because the first seven eigenvalues are significant at the 99% level using two-sided confidence intervals (Fig. 2). Eigenvalues eight and nine are significant at the 90% level, but they would be significant at the 95% level using a one-sided test (M. Dettinger, personal communication, 1996).

The combination of the first nine eigenelements ('Signal') is equivalent to a low-pass filtered version of the detrended series (Fig. 1). The signal series summarizes oscillations whose period is shorter than 150 years and which are significant under red-noise assumptions. As defined, the signal accounts for 25% of the total variance; the remaining components (75% of the variance) are indistinguishable from stochastic noise. The signal series highlights a change in time series properties that occurs near AD 1600. This shift, which is visible in both the original and the detrended time series, is a combination of higher variability and higher frequency in the recent half of the record (Fig. 1). The power density (Fig. 3) of the detrended series is smooth and dominated by red noise, whereas the signal series has three sharp spectral peaks. The highest and sharpest peak corresponds to 12-year oscillations; another sharp peak occurs at 25-year periods. The third peak is less pronounced because power densities greater than 1 range from the 65- to the 92-year period; the local maximum corresponds to the 76-year period.

Each leading eigenelement of the detrended series presents a single power peak, and the first eight eigenelements are organized in four oscillatory pairs with periods of ~100, ~58, ~25, and ~12 years respectively (Fig. 4). The amount of variance explained by pair one to four is 7.3, 6.0, 5.7, and 3.7% respectively. The strong quadrature of the first three pairs of EOFs is superior to the

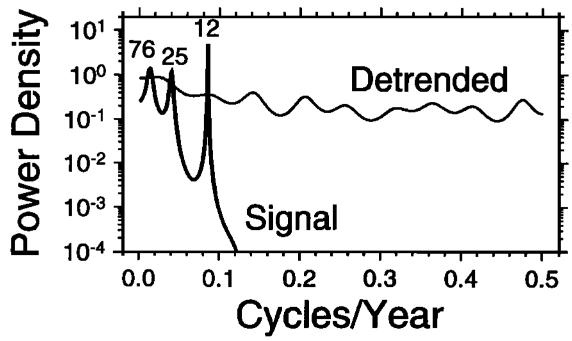

Figure 3. Maximum entropy spectrum of 'Detrended' varve thickness and of its first nine eigenelements ('Signal'; values < 10^{-4} not plotted). The same number (20) of AR components (or poles) was used for both series; the period (years) of spectral peaks greater than 1 is shown above each peak.

quadrature shown by EOFs seven and eight; EOF nine has the same ~12-year frequency as components seven and eight. The number of significant eigenelements is well within the power of SSA, which is usually able to identify about $M/10$ significant components before lumping oscillations together (Dettinger et al., 1995b). For M=80, oscillations with periods of ~58, ~25 and ~12 years are captured by EOFs 1&2, 3&4, and 7&8 respectively. Even though decadal-scale oscillations account for little variance when M=150, their identification is robust to changes in M with regard to the respective eigenvalue order and the shape of the eigenvector.

The time-varying strength of the four oscillatory modes presents remarkable changes over time, especially at the interdecadal scale. The ~25-year and ~12-year oscillations are dampened and negligible before AD 1600, but have undergone much stronger swings since that time (Fig. 4). The same amplitude shift is captured using a much shorter window length (M=80). The negative peak at both ends of RCs 7&8 (Fig. 4) is absent in the corresponding principal components and is not robust to changes in M.

Discussion

The combined amplitude of the first nine SSA eigenelements highlights a major, long-lasting, decadal-scale environmental shift in the marine sediments that occurs near AD 1600. Interdecadal oscillatory modes were 'turned on' around the end of the sixteenth century in a rather abrupt fashion, and have remained in an excited state until the present. At least two global physical mechanisms with interdecadal periodicity could be responsible for these patterns. First, the subtropical Pacific gyre circulation is characterized by a ~20 year cycle in the latitudinal distribution of heat content anomalies (Latif and Barnett, 1994). The reconstructed strength of the ~25-year oscillatory mode could suggest that the Pacific gyre circulation was much more stable during the first half of the second millennium than in recent centuries. Second, solar irradiance is dominated by the 11-year cycle, and recent studies have found a strong correlation between solar irradiance and Northern Hemisphere temperature anomalies from 1610 to 1800 (Rind and Overpeck, 1993; Lean et al., 1995). The near-absence of the 12-year oscillation before AD 1600 cannot be compared with reconstructed solar irradiance, whose annual record ends in AD 1610. However, the absence of any relationship with the Maunder Minimum (AD 1645-1715) cautions against accepting solar variability as a controlling factor of the Santa Barbara basin varve record. Interaction between the above-mentioned mechanisms cannot be ruled out: for instance, a small change in the phase of the North Pacific gyre interdecadal oscillation could greatly modify its resonance with the solar cyclic input, which in turn could either dampen or enhance the amplitude of decadal-scale oscillations.

If the near-AD 1600 shift visible in the last 1000 years of the Santa Barbara basin varve record has any climatic relevance, it should be synchronous with similar long-lasting changes in nearby basins. Marine sediments from Santa Monica Basin, which lies just south of Santa Barbara basin along the inner Continental Borderland of southern California, show a permanent change of state beginning at about AD 1600 (Christensen et al., 1994). Since that time, the laminated structure of the sediments has been preserved, whereas it was destroyed by bioturbation in deeper, older sediments. The onset of lamination — a proxy for near-anoxic conditions in bottom waters — occurs around AD 1600 in the deepest portion of the basin and has spread to increasingly lower depths ever since.

Lange et al. (1990) and Behl and Kennett (1996) have proposed that changes in the circulation off California are linked with the climate of the North Pacific by way of atmospheric forcing. If the Santa Barbara record is tied to large-scale atmospheric circulation in the North Pacific, then terrestrial proxy climatic records used to reconstruct atmospheric phenomena in western North America should contain a near-1600 marker. Tree-ring records and dendroclimatic reconstructions for the American Southwest do include a near-1600 extreme drought of decadal-scale duration (D'Arrigo and Jacoby, 1991; Grissino-Mayer, 1996). The last quarter of the 1500s was characterized by extreme sustained drought in the Upper Colorado River Basin, in the Northern Rio Grande Climatic Division and in the Sacramento River Basin (Meko et al., 1995). Work by Swetnam and Brown (1992) on tree age distributions in Arizona and New Mexico indicates a change of state in forest age structure. Even though trees older than 400 years exist, the vast majority of the old individuals still alive originated after AD 1580, revealing a remarkable shift in age structure caused by either a decrease in mortality rates, an increase in regeneration rates or both.

The varve thickness analysis presented here has uncovered an abrupt environmental change in Santa Barbara basin around AD 1600. That decadal-scale event is concurrent with (a) a similarly sudden change of state in the nearby Santa Monica Basin that triggered the onset of anoxia and the preservation of laminated

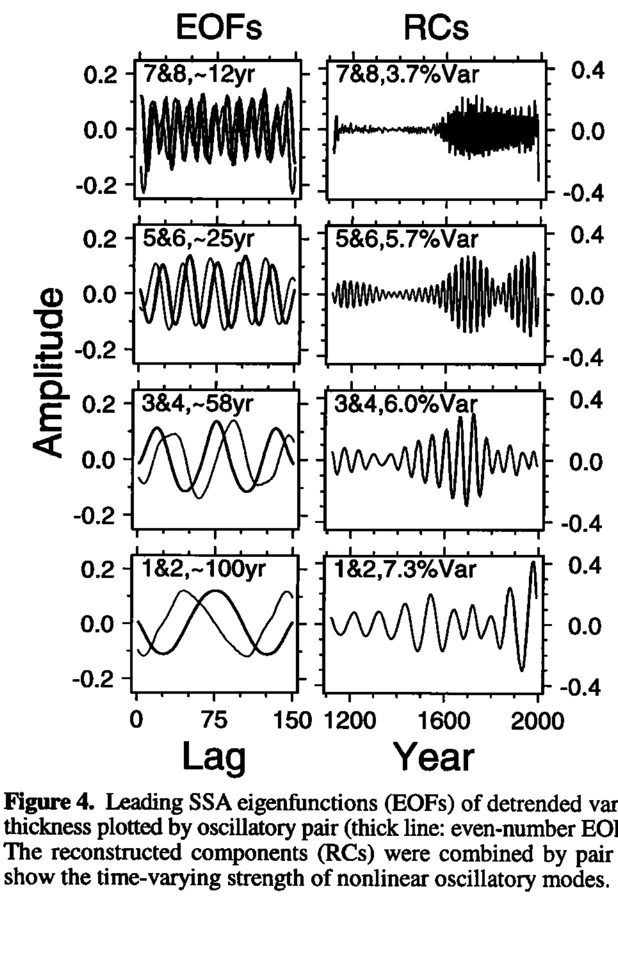

Figure 4. Leading SSA eigenfunctions (EOFs) of detrended varve thickness plotted by oscillatory pair (thick line: even-number EOF). The reconstructed components (RCs) were combined by pair to show the time-varying strength of nonlinear oscillatory modes.

sediments in the deepest portion of the basin, (b) an extreme drought in the American Southwest, (c) a transformation of the age structure in a number of forest populations throughout Arizona and New Mexico. Because published tree-ring records do not indicate a change from one oscillatory pattern to another, the terrestrial events (b) and (c) may be explained by a pulse-like, decadal-scale climatic anomaly. Hence, we entertain the mutually exclusive hypotheses that oceanic and terrestrial evidence of a near-AD 1600 prolonged episode may be (I) linked by a pulse-like climatic event that changed the sensitivity of the marine basins; (II) connected by a shift in the oceanic systems that has sporadic effects on the terrestrial ones; (III) a chance coincidence. It is now our purpose to investigate further the geochemical parameters derived from Santa Barbara basin varves and to refine our understanding of the physical mechanisms that link oceanic circulation and atmospheric processes in the Eastern Pacific on decadal to centennial timescales. As a premise, variability of total organic carbon burial flux in SBB varves has also increased since about AD 1600 (A. Schimmelmann, personal communication, 1996).

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W. H. Berger, F. Biondi, and C. B. Lange, Geosciences Research Division, Scripps Institution of Oceanography, University of California-San Diego, Mailcode 0215, La Jolla, CA 92093-0215 (e-mail: fbiondi@ucsd.edu)

M. K. Hughes, Laboratory of Tree-Ring Research, University of Arizona, Tucson, AZ 85721

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