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A comparison of proxy records of El Niño/Southern Oscillation

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Abstract

Three previously published proxy records of El Niño/Southern Oscillation (ENSO) variability were compared: a documentary record from coastal South America; an ice-core record from the Quelccaya ice cap in Peru; and a tree-ring record record from arid site conifers in the southwestern United States. The records were calibrated with long ENSO instrument records, and all the proxy records showed significant levels of correspondence with the instrument records. In fact, the proxy records appear to capture roughly comparable amounts of ENSO variability as would instrument records from the same regions. The $\delta^{18}O$ ice-core record showed some evidence of missing years, but after adjustment the correlation with the tree-ring record was reasonably consistent back to about A.D. 1630. This result provides additional verification of the two proxy records and also indicates that ENSO variability persisted relatively unchanged through main period of the Little Ice Age. The documentary record does not match the other two proxy records, particularly the tree-ring record, very well prior to the 20th century.

Introduction

One of the most rapidly developing areas in climatology is the study of climate variability on interannual-to-century time scales. Because instrument records are in general only long enough to provide good information on the shorter end of this scale, much of the work has involved the development and interpretation of high resolution proxy climatic records. High-resolution proxy records are taken here to mean either natural or documentary records with annual or almost annual temporal resolution (Baumgartner et al. 1989). Clearly these time scales are the most relevant for determining the potential impacts of climatic changes over the next century, whether produced by increased carbon dioxide or by other causes.

Both paleoclimatic studies and efforts to model future climate have often focussed primarily on reconstructing or predicting changes in mean climate. For example, most studies of the impact of increased carbon dioxide attempt to predict changes in average temperature and precipitation. Similarly, paleoclimatic studies have established that at least some portions of the Northern Hemisphere experienced significantly colder mean temperatures over the last several centuries during the Little Ice Age (e.g. Lamb 1977; Wigley et al. 1981; Grove 1988). In many cases, however, modest changes in mean conditions could be accompanied by much more significant changes in variability. Determining the nature of changing variability is a much more challenging problem, given the inaccuracies of paleoclimatic data and the shortcomings of modern climate models.

One of the main sources of uncertainty in determining future climate changes is how components of modern climate variability would change in response to large-scale changes in mean climate. There is much to be learned about this question from paleoclimatic studies of the behavior of important aspects of modern climate variability during the most recent period of different mean conditions, the Little Ice Age. The El Niño/Southern Oscillation (ENSO) phenomenon is without doubt one of the most striking sources of large-scale variability in the modern climate, and the degree to which its characteristics as observed during the 20th century are a function of the mean climatic conditions of this period is a key issue. How sensitive is ENSO to overall climate? Did it persist through the Little Ice Age or is it closely tied to modern conditions? If it did persist, are there any indications of changes in its frequency or magnitude which might be related to large-scale climate changes? These and other questions relating to the internal workings of the ENSO phenomenon can best be addressed by studies of high-resolution proxy records, since there are detailed ENSO records for only the last few decades and any evidence from instrument records only for the last century.

It is always important to develop the most accurate proxy records possible and to assess the level of accuracy as carefully as possible, but this is especially true in studies of variability. Simply put, it is much more difficult to estimate variances than means. All proxy sources of climatic information, either natural recording systems or documentary evidence, have unique strengths and weaknesses. Each responds only to certain aspects of environmental variability and contains variability, or noise, caused by nonclimatic factors. None is an ideal climate record, so it is important to compare evidence from different sources to reduce the inaccuracies inherent in individual records and to develop more complete pictures of the climate. In addition, each record reflects environmental variations in a single region. Some of these variations are purely regional, while others are related to variability over larger scales. (This attribute is also shared by instrument records, of course, and has led to the common practice of aggregating information over large geographic areas to study large-scale variability.)

Considering the widespread oceanographic and atmospheric impacts of the ENSO phenomenon, there are many possibilities for developing high-resolution proxy climate indicators which could provide information about ENSO fluctuations over the last several centuries. A preliminary analysis of a number of such indicators over a short period of time was presented in Baumgartner et al. (1989), where it was argued that considerable improvements in accuracy and fidelity could be gained by combining proxy records from different sources and regions.

In this report, three such indicators are compared over the last 400 yr: tree-ring chronologies from southwestern United States and northwestern Mexico (Drew 1976; Michaelsen 1989); ice-cores from Quelccaya ice cap in Peru (Thompson et al. 1984, 1985, 1986, 1988; Thompson and Mosley-Thompson 1989; Thompson et al. 1992, this volume); and documentary records (Quinn et al. 1987). The main objectives of the research are (1) to determine the characteristics of the response of each proxy record to ENSO variability and assess the consistency of the response over time; and (2) to study the variability of ENSO over the last 400 yr in order to shed some light on the questions posed above relating to its robustness in the face of large-scale climate changes.

The analysis involved a calibration stage where the proxy ENSO records were compared to relatively long instrument records published by Wright (1989) and a comparison of the three records, themselves, over the period A.D. 1570–1964. Because the documentary record is ordinal, rather than interval scale, two separate analyses were carried out. The tree-ring and ice-core records were compared with the instrument records and with each other using interval-scale statistical techniques. Then the tree-ring, ice-core, and instrument records were converted to categorical datasets recording the occurrence or nonoccurrence of a warm ENSO event for comparison with the documentary record. Analyses of these data were based on statistical point process techniques. In both analyses emphasis was placed on techniques which can identify temporal variations in quantities of interest.

Data

The tree-ring reconstruction (Michaelsen 1989) was based on seven chronologies from New Mexico and nothern Mexico selected from the archived records of the Laboratory for Tree-Ring Research at University of Arizona (Drew 1976). They are from a region which generally shows increased precipitation during ENSO years and during the following year (Ropelewski and Halpert 1986; Kiladis and Diaz 1989). The reconstruction extends only through 1964, the ending date of some of the chronologies.

The ice-core record is from the Quelccaya ice cap, situated in the easternmost glaciated mountain chain of the Peruvian Andes at 14°S and an elevation of 5670 m (Thompson et al. 1984, 1985, 1986, 1988; Thompson and

Mosley-Thompson 1989; Thompson et al. 1992, this volume). Precipitation in this region is concentrated during the November–April high-sun season. It is produced primarily by convective activity in moist, unstable air masses moving out the Amazon Basin. The pronounced seasonality in precipitation produces distinct annual layering in the ice cap, with alternating layers of ice and dust accumulation. In general, southern Peru and the Amazon Basin are warmer and slightly drier during warm ENSO years (Kiladis and Diaz 1989). Two cores were extracted, and the the primary data used in this study are from the summit core. The variables measured include concentrations of three different sized particles, electrical conductivity, $\delta^{18}O$, and accumulation rate. The $\delta^{18}O$ record from core 1, drilled 150 m to the east of the summit core, was also examined in an attempt to clarify possible inaccuracies in dating the ice core. Unless otherwise noted, discussion of the ice-core records will refer to measurements from the summit core. All data are totals for the 'thermal year' running from July of one year through June of the following year.

The documentary ENSO record was compiled by Quinn et al. (1987) based on analysis of a wide variety of sources. The information is concentrated in the coastal areas of Peru and the Pacific along the coast of South America. Terrestrial indicators of warm ENSO events included accounts of heavy rains and flooding, and marine indicators included variations in wind as reflected in the time taken for sailing voyages. Quinn et al. (1987) group warm events into several categories based on strength, ranging from weak to very strong. This study will focus on events described as strong or very strong.

The instrument records utilized in the calibration study are three numerical indices of ENSO derived by Wright (1989). They are (1) an index of rainfall at island stations in the tropical Pacific, 1894–1983; (2) sea surface temperature (SST) averages for the central and eastern Equatorial Pacific, 1881–1986; and (3) a Southern Oscillation sea-level pressure (SLP) index based on the Tahiti and Darwin differences for 1935–1984 and reconstructed back to 1852 using a number of other pressure records. All three instrument records were aggregated to annual averages to match the resolution of the proxy records. A uniform sign convention was adopted so that warm ENSO events were positive deviations. This involved reversing the sign of the Tahiti-Darwin pressure index.

Methods

A detailed description of the tree-ring ENSO reconstruction is given in Michaelsen (1989) and only a summary will be included here. The reconstruction was based on lagged values of the first principal component of the tree-ring records. The component was bandpass filtered to retain variability on time scales from 10 yr to about 3 yr. This approach was taken because ENSO is a band-limited process with variance concentrated between approximately 3 yr and 7 yr (e.g. Doberitz 1968; Julian and Chervin 1978) and because the proxy records are likely to be affected by other phenomena at other frequencies. The explained variance under cross-validation (Michaelsen 1987) was 31%. All the ice-core data used in this study were also bandpass filtered to be comparable with the tree-ring reconstruction.

Since the documentary records are categorical time series, or point processes, two separate analyses were required, both for calibration with instrument records and for intercomparison between the proxy records. The first involved only the continuous tree-ring and ice-core records. In order to include the documentary records in the second phase, all the continuous proxy and instrument records were converted to point processes by establishing a threshold value to define warm events. The thresholds were defined so that all records had the same number of events for the period of overlap between all the proxy and instrument records, 1894–1964. The documentary record listed 12 strong or very strong warm ENSO years during this period, giving an average rate of 0.169 events/yr, or one out of every 5.9 yr. Several other threshold values were tried without appreciably changing the results.

At a more fundamental level some care must be taken in interpreting what is meant by this definition of an warm ENSO event. Ambiguity is introduced by the fact that it is not uncommon for a warm event to span 2 yr. According to the definition of an event based simply on exceeding a threshold, this would constitute two events. A more intuitive approach might be to define a multiyear warm event as a single event. This definition could be particularly useful for identifying changes in the rates of occurrence, or equivalently, in the intervals between events. This idea was implemented by defining a second set of point processes including only the first years of warm ENSO events. Estimates of rates will be presented for the records of all warm ENSO years and the records of warm ENSO onset years.

In an individual record it is almost as easy to define events and analyse rates for warm event onsets as for all warm years, but comparisons between records become much more difficult. Under the straight warm ENSO year definition, a match occurs whenever two records have a warm event during the same year. Attempting to implement this simple matching criterion with the warm event onset definition would present problems in the not uncommon situation when one record has a 2-yr warm event while a second record has only a single-year warm event. If the single-year warm event corresponds to the onset year a match occurs, but if it corresponds to the second year no match is found. It might be possible to come up with a more complicated criterion which would identify a match whenever a single year ENSO in one record occurred in either year of a two year ENSO in the other record, but this would make it difficult to estimate expected numbers of matches required to test the null hypothesis of independence. As a result, comparisons between proxy and instrument records and between different proxy records was only carried out using the original ENSO year event definition.

Standard cross-correlation analyses were utilized to calibrate the continuous records and to compare the tree-ring and ice-core reconstructions. In addition to statistics calculated for the full periods of overlap, time-varying lag correlations were calculated using a sliding window to compare segments of the records. This approach is commonly employed to check the cross-dating of tree-ring records where it is used to identify shifts in one core sample relative to others produced by missing or false growth rings. It can also provide important information about changes in the strength of a relationship between proxy and instrument records or between different proxy records. Consequently, it can be useful for investigating the assumption implicit in most paleoclimatic reconstructions that the characteristics of the recording system do not vary appreciably over time.

The rectangular window,

$$w(s) = \begin{cases} 1/(2h+1) & \text{for } |s| < 1 \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

is most commonly used. In this study a tapered window, or kernel, based on the biweight function,

$$w(s) = \begin{cases} 15/16(1-s^2)^2/h & \text{for } |s| < 1 \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

was used. Tapered kernel functions have the advantage over rectangular ones of producing smoother curves since they have no discontinuities. The correlation for a window centered on some time, t_0, is calculated by applying the kernel function to both records with

$$s = (t - t_0)/h,$$

where h is a kernel width parameter which gives the width of the portion of the kernel with values above 0.5 and must be specified by the user. A window width of 50 yr was arbitrarily selected for the correlation studies.

The basic statistic of interest for an individual point process is the rate function, $m(t)$, (Cox and Lewis 1966) which gives the probability of an event occurring at time t. If the process is stationary, then the rate is constant and can be estimated directly as

$$\hat{m}(t) = \hat{m} = N_T/T, \tag{3}$$

where N_T is the number of events occurring in the time interval of length T. In many cases in may be useful to consider an alternative nonstationary process with a variable rate. This is often done by assuming a particular parametric form for the rate, such as an exponential, but Solow (1991) presents an attractive nonparametric alternative using a kernel estimator. This approach is very similar to the sliding window correlation method described above and is directly comparable to the kernel method of density estimation (Silverman 1986). If the point process has N events occurring at times $t_1, t_2, \ldots, t_N$ in the interval $[0, T]$, then the variable rate estimate at time t is

$$\hat{m}(t) = 1/h \sum_{i-1}^{N} w[(t - t_i)/h], \tag{4}$$

where $w(s)$ is the kernel function. Solow (1991) and Silverman (1986) present a technique for estimating the width parameter, h, using maximum likelihood cross-validation, along with efficient calculation methods in the density estimation context which can be applied here. Cross-validation estimates are obtained by omitting each event in turn, i.e.

$$\hat{m}_{-i}(t) = 1/h \sum_{j \neq i} w[(t - t_i)/h]. \tag{5}$$

The value of h is selected which maximizes the cross-validated log likelihood function,

$$CV(h) = \sum_{i=1}^{n} \log[\hat{m}_{-i}(t_i)]. \tag{6}$$

Using this criterion, window widths of 40 yr were used for the calibration studies and 80 yr for comparisons of the proxy records.

Solow (1991) also presents a method for obtaining approximate confidence intervals for kernel rate estimates under the assumption that the events are generated by a Poisson process. In a Poisson process the intervals between events are independent, identically distributed exponential variates. An examination of the intervals between warm ENSO events suggests that they do appear to be independent but are not exponentially distributed, particularly in the case of intervals between warm event onset years. A somewhat more general model which appears more appropriate is a renewal process with intervals that are independent, identically distributed gamma variates (Cox and Lewis 1966). The gamma distribution,

$$f(x) = \beta^{-\alpha} x^{\alpha-1} e^{-x/\beta} / \Gamma(\alpha), \tag{7}$$

is commonly used to model precipitation data (e.g. Ropelewski et al. 1985; Wilks 1990) because it will allow for a wide range of degrees of asymmetry for different values of the shape parameter, α. (It includes the exponential distribution for $\alpha = 1$.) Under this assumption, the variance of a constant rate estimate can be approximated as

$$Var(\hat{m}) = IN_T/T^2. \tag{8}$$

The coefficient of dispersion, or squared coefficient of variation (Cox and Lewis 1966) is I and for a gamma distribution is

$$I = Var(x)/E^2 = 1/\alpha. \tag{9}$$

An estimate of the variance of a kernel estimate (under the assumption of a constant rate) is

$$Var(\hat{m}(t)) = \hat{m}/4\hat{\alpha}h_0^2 \tag{10}$$

where

$$h_0 = (3/7)^{1/2} h \tag{11}$$

(Solow 1991). Note that in the case of the Poisson distribution ($\alpha = 1$) the relationship is the same as that given by Solow. Confidence intervals can be obtained by using the normal approximation and the fact that the rate estimates are asymptotically unbiased.

The basic statistic used to measure the degee of association between two point processes will be the closest analog to a correlation for point processes, the cross intensity function (Cox and Lewis 1966). This functon measures the conditional probability of an event occurring in one series, given that an event has occurred in the other series. In can be easily estimated by dividing the number of matches (events occurring in simultaneously in series A and B) by the number of events occurring in series A. A straightforward test of independence can be obtained by noting that under the assumption of independence the conditional probability is equal to the unconditional probability. In this case the number of matches is a binomial variate with a probability equal to the unconditional probability of an event occurring in series B.

Result

Calibration

Correlations between the proxy data and the instrument records (Table 17.1) show that the tree-ring index is significantly correlated with all the instrument records. It explains about 30% to 35% of the variance in the ENSO records. The $\delta^{18}O$ record is also significantly correlated with the instrument records at the .01 level, while the total particle correlations are significant at the 0.05 level. Significance levels are based on a full 71 degrees of freedom. A more conservative approach would be to assume that the filtering retains about one-half to two-thirds of the original degrees of freedom. Calculations based on 35 degrees of freedom indicate that the tree-ring and $\delta^{18}O$ correlations are still significant at the 0.01 level while the total particle correlations are no longer significant.

Table 17.1 *Correlations between proxy records and instrument records, 1894–1964*

	Rainfall	SST	SLP
Tree-rings	0.597**	0.529**	0.529**
Ice cores			
Accumulation	−0.186	−0.135	−0.141
All particles	0.258*	0.261*	0.212*
Large particles	0.168	0.189	0.138
Small particles	0.192	0.211	0.144
Oxygen	0.479**	0.462**	0.441**
Conductivity	−0.007	0.003	−0.085

A single asterisk (*) indicates significance at the 0.05 level, and a double asterisk (**) indicates significance at the 0.01 level.

Due to the intercorrelation between the $\delta^{18}O$ and total particle records, a multiple regression using both does not perform significantly better than one using $\delta^{18}O$ alone. As a result, only the $\delta^{18}O$ data was used in further analyses. It explains about 20 to 25% of the variance in the ENSO records. Reconstructions based on the tree-ring and $\delta^{18}O$ records are shown in Figure 17.1. Combining the tree-ring and $\delta^{18}O$ data produces a regession equation which explains up to 40% of the variance in the ENSO records.

It should be noted that the ice-core records are values based on the July-June period, while the instrument records are calendar year averages. Therefore, correlations are based on 6 mo of overlap (January-June) and 6 mo (July-December) where the instrument records lag the ice-core records. Correlations

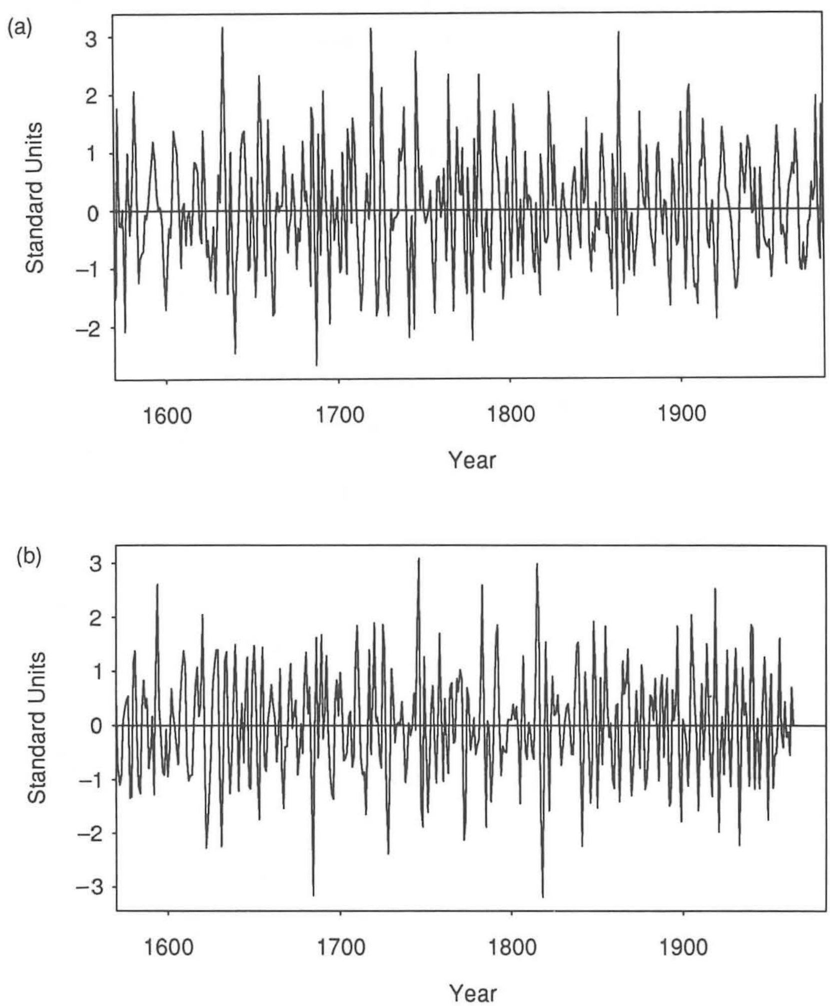

Fig. 17.1 Reconstructions of sea surface temperatures based on (a) the $\delta^{18}O$ record, and (b) the tree-ring record. Units in standard deviations.

between July–June instrument record averages and the ice-core records did not show any appreciable improvement. Comparisons of seasonally averaged instrument records show that the highest correlations with the $\delta^{18}O$ record occur during the January–June overlapping period and remain high through the rest of the year.

The sliding correlation plots (Fig. 17.2) for both proxy records show some evidence of temporal variations in the strengths of the relationships with the ENSO records. Both proxy records have peak correlations with all three instrument records in the first 30 yr of the 20th century, with the tree-ring/instrument record correlations reaching values of 0.65 to 0.70 in the 1920s and the ice-core/instrument record correlations reaching 0.60 around 1910. Both proxy records also show declining correlations with the instrument records in the 1950s, but the ice-core record, which extends into the 1980s, shows some evidence of increasing correlations with three instrument records in the 1970s.

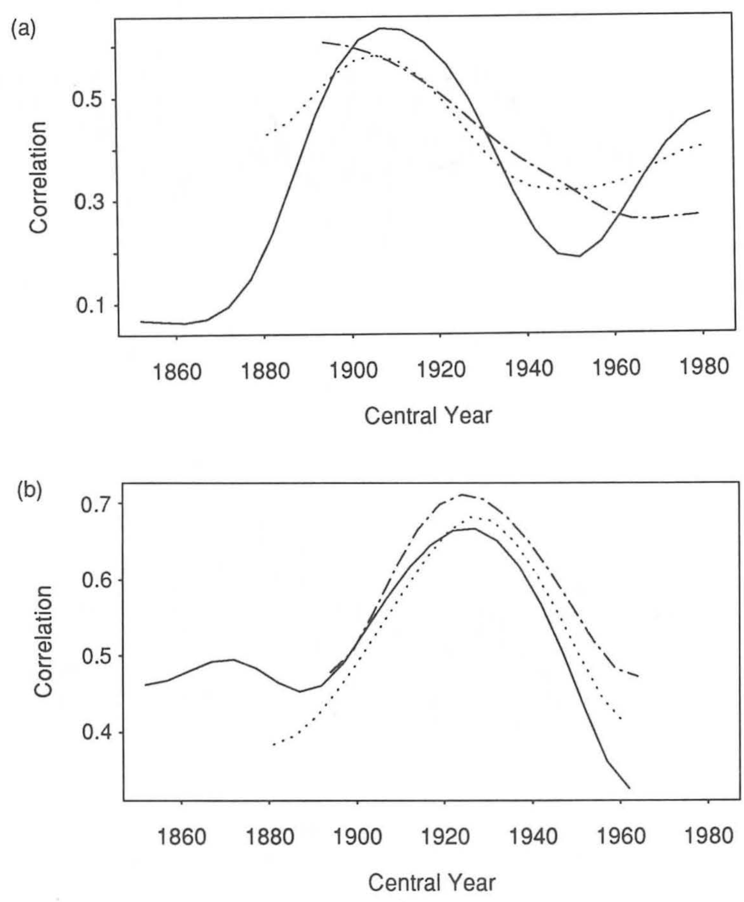

Fig. 17.2 Sliding correlation plots between the pressure record (solid), the SST record (dotted), and the rainfall record (dash-dotted), and (a) the $\delta^{18}O$ record, and (b) the tree-ring record. Window width is 40 yr.

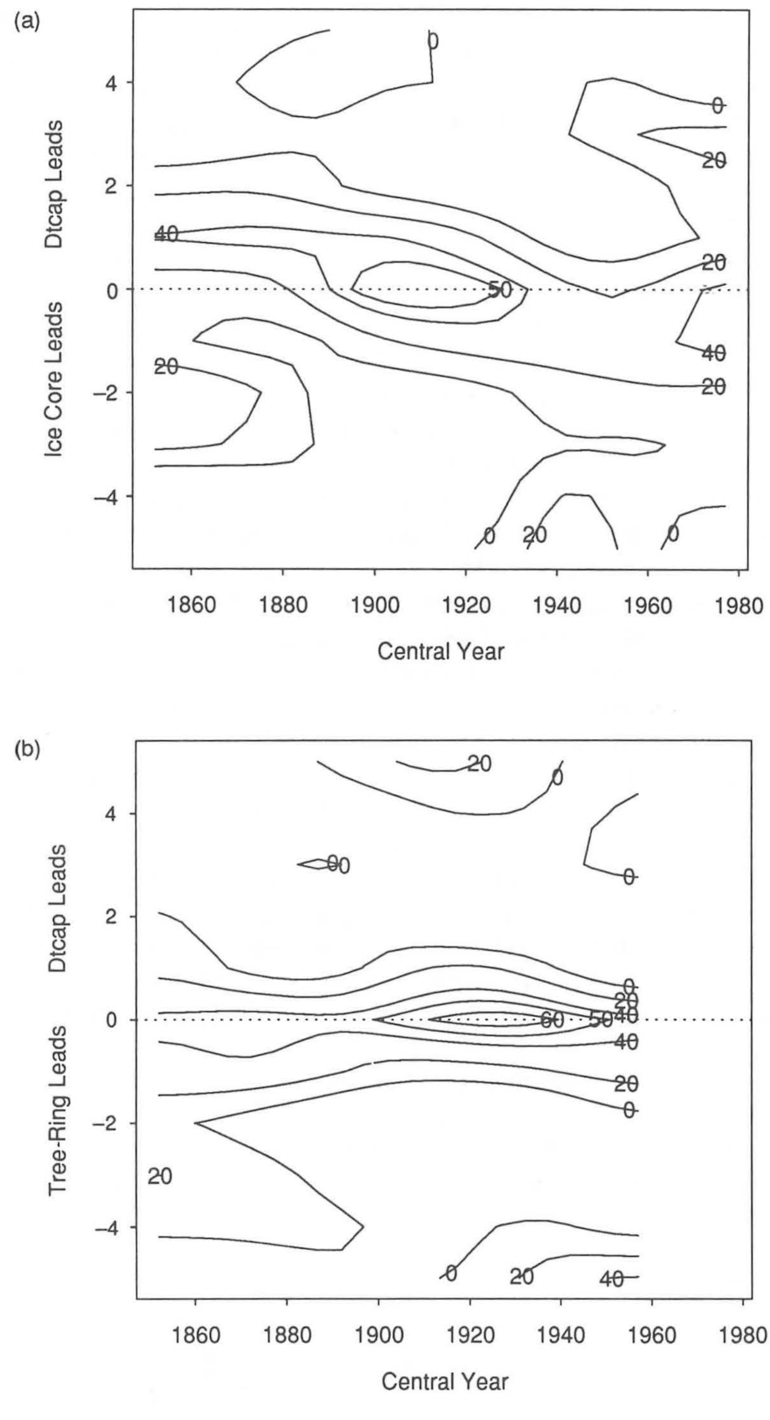

Fig. 17.3 Sliding lag correlations ×100 between the pressure record and (a) the $\delta^{18}O$ record, and (b) the tree-ring record. Leads and lags are given in years, and the window width is 40 yr.

Perhaps the most striking aspect of the correlations is the decline in correlation between the ice-core and SLP records prior to about 1880. This decline reduces the overall correlation for the period 1852–1984 to 0.34, compared to 0.45 for the period 1894–1984. The correlation between the tree-ring and SLP records shows a similar, but less pronounced, pattern. Examination of the sliding lag correlations (Fig. 17.3a) suggests that the decline may be partially caused by a shift in the ice-core record relative to the SLP record so that it lags by one year prior to about 1880. It appears possible that a year was missed in the ice-core record. When a year is added between 1880 and 1881 by inserting the mean, the overall correlation for 1852–1984 increases to 0.46. The sliding lag correlations for the tree-ring record (Fig. 3b) give no indications of any similar shifts.

The $\delta^{18}O$ record for core 1 is highly correlated with the summit core record during this period and shows the same shift relative to the SLP record. Both ice-core records are in phase with the SLP back through the 1880s, showing warm events in 1888 and 1881, but the major 1877 warm event in the SLP record appears in 1878 in the ice-core records. Similarly, the SLP record shows weak-to-moderate warm events in 1855, 1864, and 1868 and cold events in 1863 and 1870, all of which match with events dated 1 yr later in both ice-core records.

Table 17.2 gives the number of matching events for the thresholded instrument records and proxy records. The probability of an event in any year in one record is 0.17 (12/71), so under the independence hypothesis, the probability of events occurring simultaneously in two records is $0.029 = 0.17^2$. Thus, in 71 yr the expected number of matches is two; five or more matches are required to reject the independence hypothesis at the 0.05 level and six or more to reject at the 0.01 level.

All three of the proxy records have enough matches with each of the instrument records to reject the hypothesis of independence at the 0.05 level. The tree-ring record has six matches with each of the instrument records. The $\delta^{18}O$ does slightly better with seven matches with the SST and SLP records, while the documentary record does slightly worse with five matches with the SST and SLP

Table 17.2 *Number of co-occurrences of strong and very strong ENSO events, 1894–1964*

	Rainfall	SST	SLP	Doc.	Trees	Oxygen
Rainfall	–	9	9	6	6	6
SST	0.0000	–	9	5	6	7
SLP	0.0000	0.0000	–	5	6	7
Doc.	0.0085	0.0384	0.0384	–	4	6
Trees	0.0085	0.0085	0.0085	0.1302	–	8
Oxygen	0.0085	0.0014	0.0014	0.0085	0.0002	–

Values below the diagonal are probabilities of at least that number of matches for independent records. (12 events).

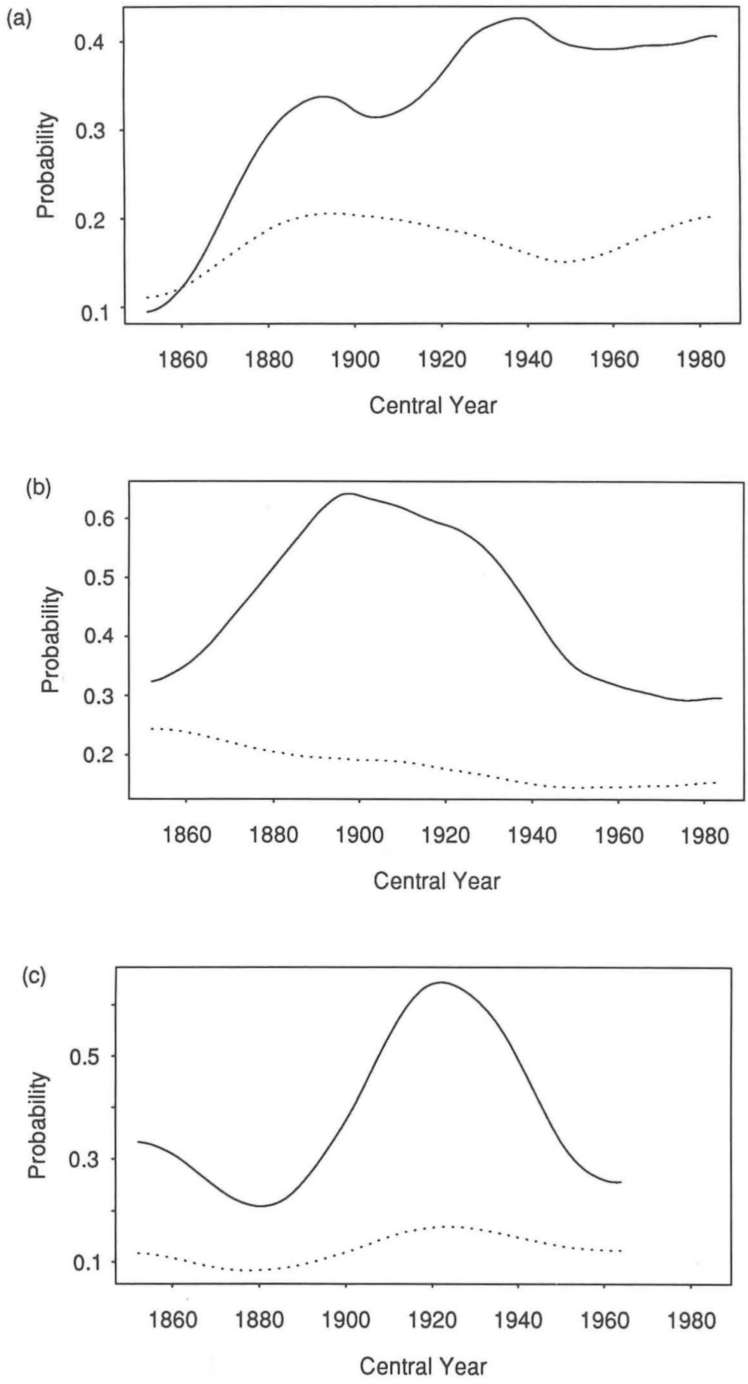

Fig. 17.4 Kernel estimates of the conditional probabilities of a warm ENSO year given an warm ENSO year in the pressure record (solid lines) and unconditional rate estimates (dashed lines) for (a) the documentary record, (b) the $\delta^{18}O$ record, and (c) the tree-ring record. Kernel width is 40 yr.

records. Not surprisingly, the three instrument records are highly related to each other, with nine matches in all cases. The tree-ring and $\delta^{18}O$ records are also highly related by this criterion with eight matches. The $\delta^{18}O$ record also shows a significant number of matches with the documentary record. Only the documentary and tree-ring records are not significantly related, with four matches.

The three proxy records were compared with the longer SLP record to identify any changes in the strength of the correspondence over time. The kernel method described in the previous section was used to estimate time-varying rates of warm ENSO event occurrence for each proxy record and rates of co-occurrence of warm events in the SLP record and the proxy records. The results are displayed in Figure 17.4. In each plot the solid line is the conditional probability of having an ENSO event in the proxy record, given an ENSO event the SLP index, while the dashed line is the unconditional probability of an ENSO event occurring in the proxy record. If the two series were independent the two probabilities would be equal. (Note that the $\delta^{18}O$ record was adjust for a probable missing year as described above.)

In all cases the conditional probabilities vary by at least a factor of two. In general, the conditional probabilities are low prior to 1880 and rise to relative high values by 1900. The documentary record, in particular, has a low correspondence with the SLP index at the beginning of the record, with conditional probabilities as low as the unconditional probabilities. The conditional probabilities rise above 0.30 by 1900 and level off at around 0.40 by 1920. The $\delta^{18}O$ and tree-ring records have higher peaks of about 0.60 around 1900 and 1920 but then decline by 1950 to values around 0.30.

Proxy record comparisons

The tree-ring and $\delta^{18}O$ records were compared for the full period of overlap, 1570–1964, by calculating cross-correlations for sliding windows (Fig. 17.5). Three more instances where the two series became offset by one year were identified. Correlations between the tree-ring and core 1 $\delta^{18}O$ records (not shown) exhibit a very similar pattern, with one exception. Between about 1760 and 1800 core 1 lags the tree-ring record by only 1 yr while the summit core lags by 2 yr. This discrepancy results from the fact that during this period the two $\delta^{18}O$ records are, themselves, offset by 1 yr, as is evident in Figure 17.6. These results are consistent with those reported by Thompson et al. (1986: 363), indicating that the Quelccaya cores have been dated back to A.D. 1500, with an estimated uncertainty of $\pm$ 2 yr and an absolute date of A.D. 1600, defined by the identification of the Huaynaputina ash in both Quelccaya ice cores.

Although is not possible to be certain which series should be shifted, it seems likely that the $\delta^{18}O$ records are responsible, considering the fact that a missing year was located in the comparison with the SLP index and that the tree-ring index is composed of seven different chronologies, each constructed from a number of individual samples. (In a certain sense it is unfair to compare a record

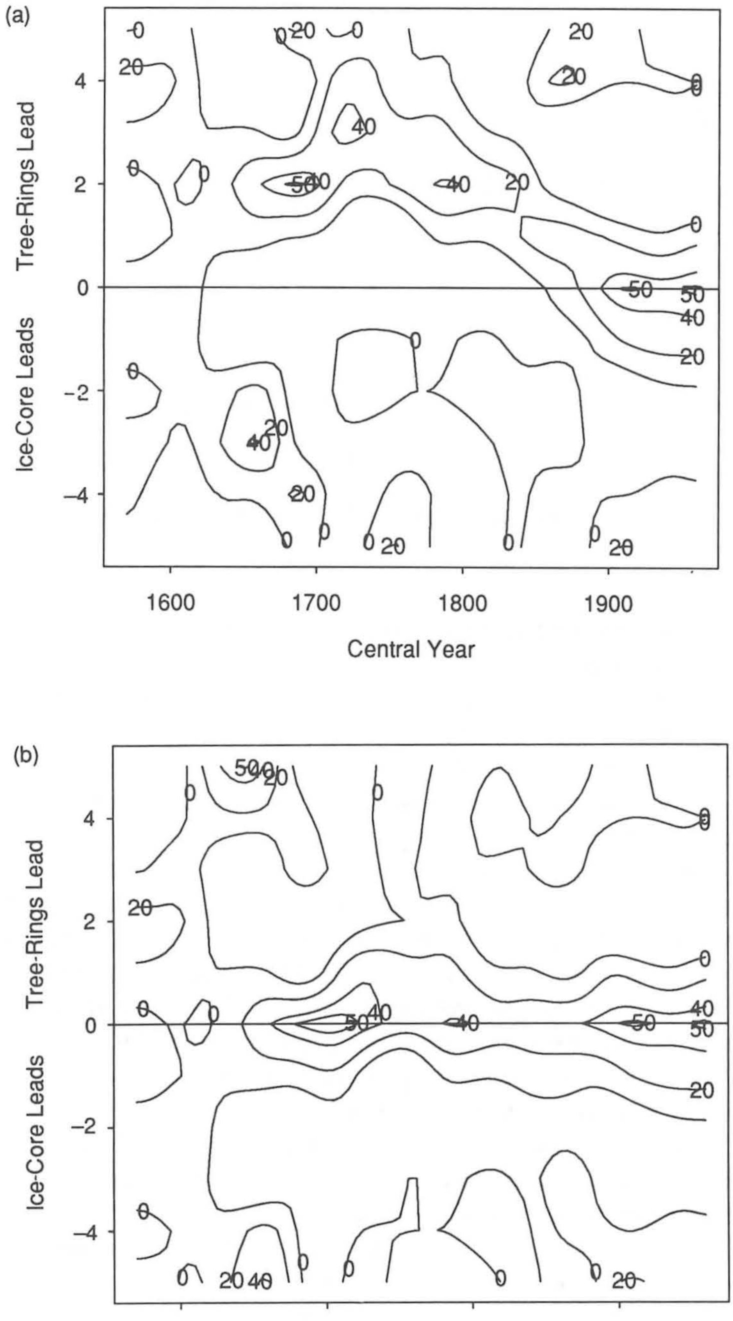

Fig. 17.5 Sliding lag correlations ×100 between tree-ring record and (a) the uncorrected and (b) the corrected $\delta^{18}O$ record. Leads and lags are given in years, and the window width is 50 yr.

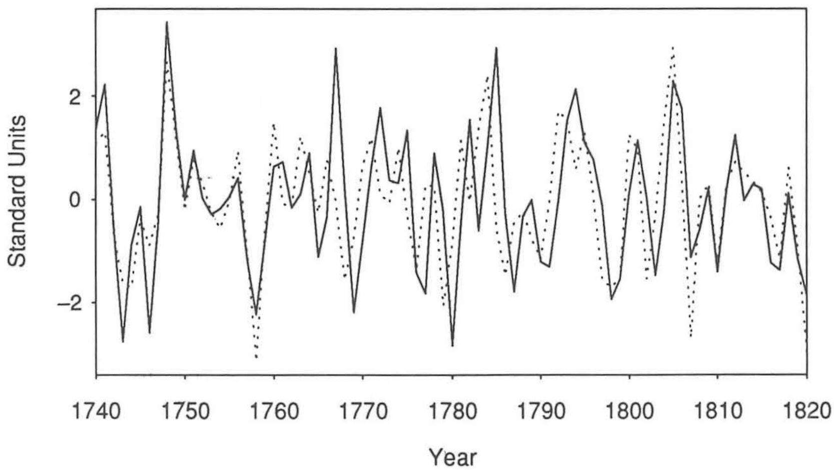

Fig. 17.6 Partial time-series plots of the $\delta^{18}O$ records from the summit core (solid) and core 1 (dotted).

produced from many different trees spread over a region with a single core from a single ice cap.) Consequently, the summit core $\delta^{18}O$ record was adjusted by adding two missing years (1840 and 1731) and deleting one extra year (1692). After adjustment the correlation for the period 1570–1964 with the tree-ring record is 0.351. The cross-correlation analysis also indicates, however, that the relationship between the two records disappears completely prior to 1630. The correlation for the period 1630–1964 increases to 0.426.

The two continuous records were converted to categorical records using the same thresholds as in the calibration study. While this approach fixes the same number of events during the 1894–1964 calibration period, there were substantial differences in the number of events for the full period of overlap, 1570–1964. By this definition, the number of events ranges from 77 (one out of every 5.1 yr is an warm event year) for the ice core record, to 62 (one out of every 6.4 yr) for the tree-ring record, and 55 (one out of every 7.2 yr) for the documentary record. As noted above, however, in many cases warm events persist over more than one year, so there were not as many separate warm events in the records. If the alternative warm event definition is used, and multi-year events are treated as a single event, the discrepancies are not nearly as great. The $\delta^{18}O$ record has 51 events (warm event every 7.7 yr), the tree-ring record has 47 (8.4 yr), and the documentary record still has the least with 40 events (9.9 yr).

The reason for the differences in overall occurrence rates is evident in Figure 17.7. All three records naturally have comparable rates for the 20th century calibration period, but precalibration rates are substantially higher for the $\delta^{18}O$ record, lower for the documentary record, and somewhere in between for the tree-ring record. There are some indications of more frequent ENSOs at around 1650–1700, particularly in the $\delta^{18}O$ and tree-ring records, and frequencies are generally low around 1800. The correspondence between the fluctuations in the three records is not very striking, however, and none of the fluctuations is large enough to reject the hypothesis of a process with a constant rate. The difference in constant rate estimates between the $\delta^{18}O$ and documentary records is significant at the 0.01 level, so combining the decrease in event frequencies in the documentary record with the increase in the $\delta^{18}O$ record does produce significantly different rate estimates, even if the variations within each record do not.

As noted above the disparity in rate estimates is reduced somewhat by treating a multiyear warm event as a single event. Comparison of the warm year rates in Figure 17.7 with the onset occurrence rates in Figure 17.8 suggest that a major reason for this is that the $\delta^{18}O$ warm year rate is much higher than the onset

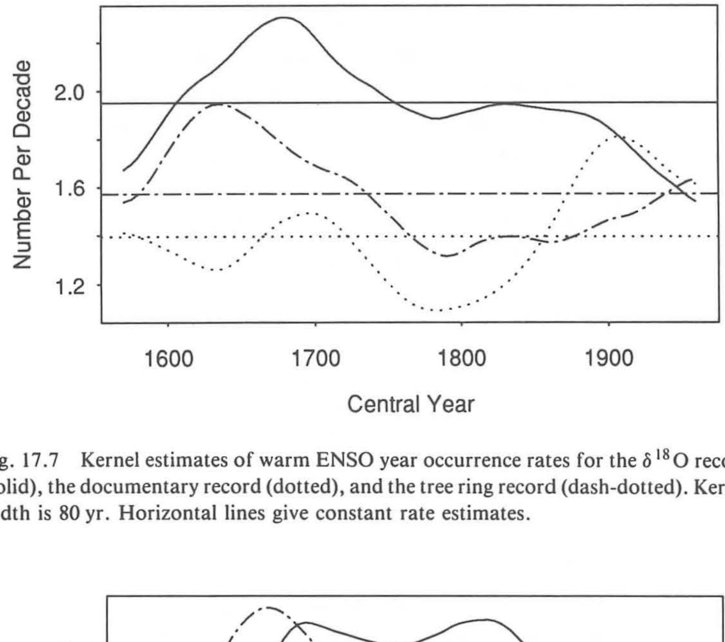

Fig. 17.7 Kernel estimates of warm ENSO year occurrence rates for the $\delta^{18}O$ record (solid), the documentary record (dotted), and the tree ring record (dash-dotted). Kernel width is 80 yr. Horizontal lines give constant rate estimates.

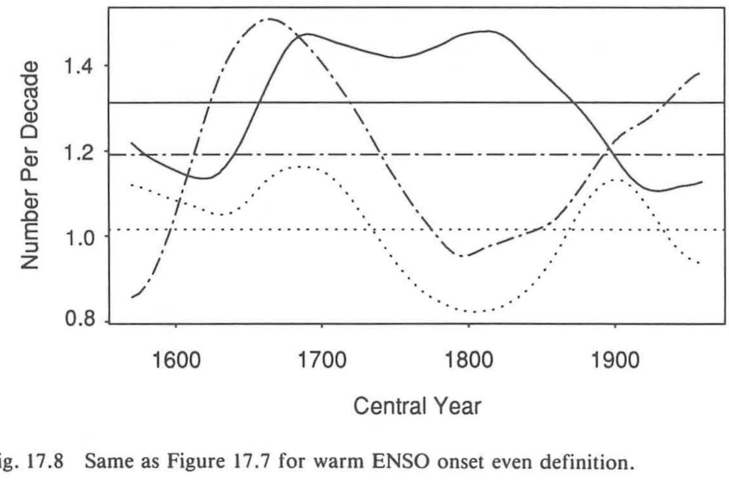

Fig. 17.8 Same as Figure 17.7 for warm ENSO onset even definition.

year rate in the early 1700s (2.3 events/decade compared to 1.5 events/decade). The tree-ring and $\delta^{18}O$ records now show comparable rates during this period. The documentary record onset rate is still substantially lower, but the 20th century peak is not nearly so far out of line with the rest of the record, and its rate fluctuations closely resemble those in the tree-ring record. The main reason the $\delta^{18}O$ rate is still higher than the rates for the other two records is that it does not share in the low onset rates around 1800. As was the case for the ENSO year rate fluctuations, none of the variations in the individual records is large enough to reject the null hypothesis of a constant rate, but the difference between the $\delta^{18}O$ and documentary constant rate estimates is significant.

Tables 17.3 and 17.4 give statistics on the number of matches between the proxy records for the full period, 1570–1964, and for the precalibration period, 1570–1893. The tree-ring and $\delta^{18}O$ records show a high degree of correspondence during both periods, with at least twice the number of matches expected by chance. The tree-ring and documentary records, on the other hand, have no more matches than would be expected by chance. The $\delta^{18}O$ and documentary records have a significant number of matches for the full period, but the correspondence is considerably worse when the modern calibration period is excluded.

The time-varying conditional probabilities are shown in Figure 17.9. The correspondence between all three records is greatest during the calibration period.

Table 17.3 *Number of matches for strong/very strong ENSO events, 1570–1964*

	Doc	Trees	Oxygen
Doc.	–	8(8.6)	19(10.7)
Trees	0.5862	–	27(12.1)
Oxygen	0.0052	0.0000	–

Expected number of matches are given in parentheses, and values below the diagonal are probabilities of getting as many or more matches if the series are independent (based on the normal approximation to the binomial distribution).

Table 17.4 *Number of matches for strong/very strong ENSO events, 1570–1893*

	Doc	Trees	Oxygen
Doc.	–	4(6.6)	12(8.6)
Trees	0.8495	–	20(10.0)
Oxygen	0.1222	0.0007	–

Expected number of matches are given in parentheses, and values below the diagonal are probabilities of getting that number of matches if the series are independent.

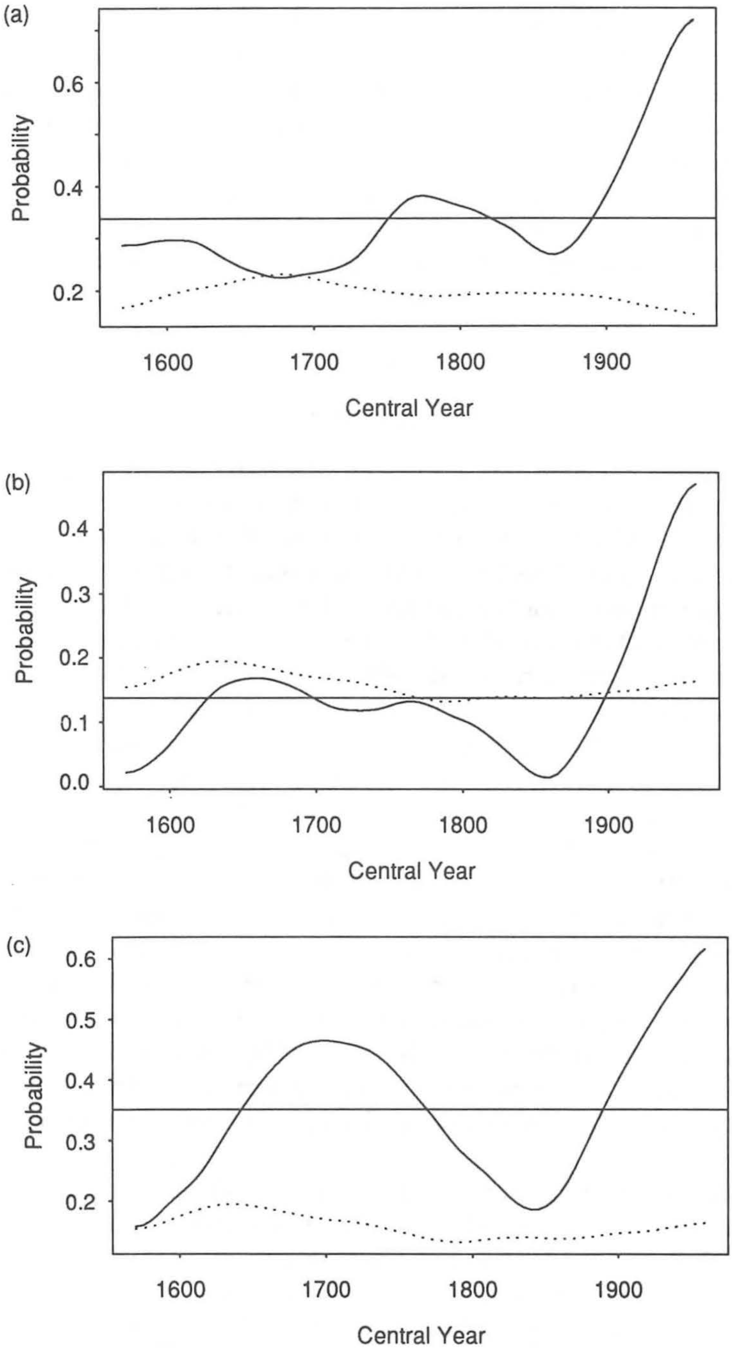

Fig. 17.9 Kernel estimates of conditional probabilities of a warm ENSO event (solid lines) and unconditional probabilities (dashed lines) for (a) $\delta^{18}O$ events conditioned on documentary events; (b) tree-ring events conditioned on documentary events; and (c) tree-ring events conditioned on $\delta^{18}O$ events. Kernel width is 80 yr. Horizontal line gives constant rate estimates.

The tree-ring and $\delta^{18}O$ records are also closely related through much of the 1600s and 1700s. The documentary record does not match well with either of the other records in the precalibration period, apart from a moderate peak with the ice core record in the late 1700s. It is also noteworthy that none of the records match well during the mid-1800s. The small numbers of events in the matching series and the fact that the conditional probabilities are ratios of two rates make it difficult to determine confidence intervals, but it is interesting that the conditional rates fluctuate by a factor of three or four, a level of variability much greater than for the unconditional rates.

Discussion

Calibration

The most important point to note is that all three proxy records do appear to contain some information on ENSO variability. All of the skill measures do show a significant level of correspondence. It seems likely that the relationships between the proxy and ENSO instrument records are not a great deal weaker than would be the relationships between actual climatic data and the ENSO records. For example, Kiladis and Diaz (1989) note that precipitation anomalies at Abilene, Texas, were positive during 70% of warm ENSO winters. The tree-ring record has positive values during 85% of the warm ENSO years in the SST record. Similarly, Manaus, Brazil, temperature anomalies were positive during 95% of warm ENSO winters and 76% of warm ENSO springs, while the comparable figure for the $\delta^{18}O$ record was 75%. Recent work has shown that even El Niño variability in the coastal South American regions covered by the documentary records are not as closely linked to basinwide ENSO variability as was previously thought (Deser and Wallace 1987, 1990). Apparently, the proxy records are doing a satisfactory job of capturing the component of regional variability which is related to large-scale ENSO variability, and the main source of error in the ENSO reconstructions is produced by the lack of correspondence between regional conditions and ENSO variability. In other words, the proxy records, while not perfect recorders of regional conditions, do seem to respond well to that portion of regional variability which is related to large-scale ENSO features.

This conclusion strengthens the argument for combining records from different regions to filter out regional variability not related to ENSO. As noted above, combining the $\delta^{18}O$ and tree-ring records does increase the explained variance by around 10%. The same pattern can also been seen with the categorical records. If a warm ENSO year is identified in any one of the proxy records there is at best a 50 to 55% chance it will also be identified as a warm ENSO year in any of the instrument records. For a year classified as a warm ENSO year in at least two of the proxy records, however, the chance of it being in the warm ENSO class in any of the instrument records increases to 70% (seven out of ten).

The identification of an apparent missing year in the sliding correlation between the SLP and $\delta^{18}O$ records presents a clear lesson of the utility of examining time-varying relationships in calibration studies. This gap produces a substantial decrease in the overall correlation, and if left unadjusted, could lead to the conclusion that the relationship is too weak to be of use. The other fluctuations in the strength of the correlations are probably within the expected level of sampling variability, indicating that the relationships are reasonably consistent over the calibration period. They are large enough, however, to potentially produce misleading results if the common technique of splitting the calibration period into training and verification samples was employed. A full cross-validation (e.g. Michaelsen, 1987) would generally produce more stable skill estimates.

Interpretation of variations in the probabilities of proxy record warm events conditioned on instrument record warm events is complicated somewhat by the need to classify events. As can be seen in Table 17.5, there are a number of instrument warm ENSO years when the proxy records show some indications of warm event activity (weak or moderate class for the documentary record or moderate positive values for the tree-ring and $\delta^{18}O$ record). There do appear to be some common features, however, which are worth noting. Most striking is the lack of correspondence between the SLP record and any of the proxy records prior to about 1880. For example, of the five SLP ENSO years before 1877, none are identified in the documentary record and only one in the $\delta^{18}O$ record. There are a couple of possible explanations for this lack of correspondence. First, the SLP record, itself, is likely to be somewhat shaky for the early period. In may not be coincidence that the correspondence starts to increase about 1880, the same time that the Darwin pressure record begins. Second, as noted in the intercomparisons between the proxy records, for much of the 1800s none of the proxy records show good correspondence among themselves. Furthermore, both the documentary and tree-ring records have low ENSO frequencies during the this period. This raises the possibility that the lack of correspondence among the various proxy records and between the proxy records and the SLP record may be in part caused by a period of weak, infrequent ENSOs which did not have a strong impact on regional conditions in the various different areas.

A marked contrast is seen during the first part of the 1900s. For example, the $\delta^{18}O$ record matches five and the tree-ring record six of the seven SLP warm event years between 1905 and 1941. During this period, warm events were relatively frequent (particularly 1900–1920) and strong. As a result, ENSO variability was a significant factor affecting regional conditions. It is also true, of course, that the SLP and the other instrument records become more reliable after 1900. After 1941, however, only the strong warm events of 1957/58 and 1982/83 are clearly identified in the proxy records, suggesting that improved quality of the instrument records is not solely responsible for the improved correspondence during the early 20th century. Instead, it appears that the variations in the correspondence between the proxy and instrument records is more directly

Table 17.5 *Years classified strong/very strong ENSO events in at least one instrument record, 1853–1983. Years classified as ENSOs are show in bold face type*

Year	Rainfall	SST	SLP	Doc	Trees	Oxygen
1853			0.88	–	−0.72	−0.36
1855			1.40	–	1.84	1.31
1856			0.70	–	0.36	0.56
1868			1.92	W/M	1.41	0.62
1869			0.78	–	−0.09	−0.03
1877			3.14	VS	0.69	1.69
1881		0.09	1.23	–	0.57	1.10
1885		0.19	0.90	S	0.00	−0.98
1888		1.45	1.08	W/M	0.94	1.15
1896	0.36	1.44	0.55	M+	0.42	0.87
1900	0.55	1.69	0.88	S	0.12	0.93
1902	1.31	1.97	1.03	M+	−0.31	0.40
1905	1.91	2.16	1.65	W/M	2.04	2.02
1911	1.03	0.61	0.53	S	0.77	−0.04
1912	1.14	0.52	0.55	S	−0.62	0.83
1914	2.37	2.23	2.15	M+	1.52	1.55
1919	2.14	1.38	0.88	W/M	2.53	0.15
1926	0.68	0.49	0.93	VS	1.39	1.07
1930	1.54	1.23	0.85	W/M	0.65	−0.24
1940	2.14	2.01	1.77	S	1.87	1.27
1941	2.16	2.08	2.32	S	1.81	1.07
1946	0.48	−0.41	0.70	–	−0.40	0.85
1951	0.58	0.86	0.50	W/M	0.20	−0.66
1953	1.10	0.81	1.35	M+	−1.15	−1.17
1957	1.22	1.21	0.58	S	1.61	1.44
1958	0.99	1.07	0.75	S	−0.12	0.92
1965	1.48	1.31	1.47	M		0.56
1966	0.19	0.37	0.80	–		0.79
1969	0.30	1.37	1.13	–		0.86
1972	1.79	1.78	0.98	VS		−0.58
1976	1.07	0.21	−0.42	W/M		−0.18
1977	1.27	0.70	1.55	–		0.46
1978	−0.32	−0.12	0.80	–		0.15
1979	1.00	0.68	0.15	–		0.36
1980	1.12	0.52	0.73	–		1.96
1982	2.00	1.86	1.72	VS		−0.86
1983		1.81	2.17	VS		1.81

related to the magnitude and frequency of ENSO events. Not surprisingly, the proxy records match well during periods when warm events are strong and frequent and considerably less well during periods when when warm events are less frequent and/or generally weaker.

Proxy record comparisons

Probably the most striking result of this research is the relatively stable, significant relationship between the $\delta^{18}O$ and tree-ring records extending back to 1630 (after adjusting the $\delta^{18}O$ record). It is very difficult to conceive of any hypothesis to explain this other than that they are both responding to large-scale ENSO variability. This leads to two conclusions. First, there is strong evidence that ENSO variability quite similar to that in the modern period has existed for at least 350 yr. Since this includes the major cold period of the Little Ice Age, which is also evident in the ice core record (Thompson et al. 1986), it appears that the ENSO phenomenon is fairly robust to large-scale climate changes. Second, the two proxy records recorded this variability with reasonable fidelity throughout the period. Clearly, this correspondence provides a level of verification of the proxy records and of the persistence of ENSO variability far beyond what could be obtained from working with a single proxy record.

It should be noted that the correspondence between the two records depends on the validity of the adjustments applied to the $\delta^{18}O$ record. The statistical evidence for the offsets in the $\delta^{18}O$ record is fairly solid, but the physical mechanisms which might introduce errors in dating the ice-core record are not clear. Furthermore, the Huaynaputina ash layer is accurately dated in A.D. 1600 (Thompson et al. 1986), so any missing years would have to be compensated for by an equal number of false years. There are two possible sources of errors in dating. First, cores were extracted in discrete 1- to 1.5-m segments, and some material could be lost between segments. The fact that the $\delta^{18}O$ records from both cores match, with the minor exception of the 1 yr offset between 1760 and 1800, argues against this possibility. Second, the natural record itself might not always faithfully record the annual cycle. While the $\delta^{18}O$ ratios, microparticle concentrations, and conductivities all show clear annual cycles, there are also short-term intra-annual variations which make it difficult to identify annual cycles from any single record. Ambiguities were resolved by integrating the records (Thompson et al. 1986). It is possible that environmental variations could affect all of these measures in a similar way in both cores, either depressing an annual cycle or producing a intra-annual variation which would be indistinguishable from a second annual cycle. If the statistical evidence is to be believed, this is probably the most likely explanation. Further comparisons with other ENSO proxy records will be needed to resolve the issue.

The reason for the lack of correlation prior to 1630 is not clear at present. It is possible that it signals a decline in ENSO variability, but defects in one or both of the proxy records is a more likely explanation. For example, the tree-ring chronologies are based on successively fewer samples going back in time, so their reliability probably decreases accordingly.

A comparison of the ENSO onset rates with the ENSO year rates indicates that some of the more subtle features of the curves may be primarily artifacts of the way an event is defined. A number of alternative event definitions and thresholds were tried, but the major features of the rate curves did not change appreciably.

In particular the $\delta^{18}O$ record has more warm events prior to 1900, and the documentary record has fewer events. All three records show increased event frequencies in the late 1600s and early 1700s. All three records also show reduced frequencies around 1800, although the evidence in the $\delta^{18}O$ record is admittedly less clear. Given the modest degree of correspondence between the rate fluctuations in the different records, along with the fact that none of the fluctuations are statistically significant, it is probably best to conclude that the evidence does not contradict the hypothesis that ENSO variability has been reasonably consistent over the last 350 yr.

One of the more puzzling results of the study is the lack of correspondence prior to the modern period between the documentary record and the other two records, particularly the tree-ring record. This may reflect some combination of changes in the reliability of the documentary record and a lack of correspondence between local El Niño conditions along the coast of Peru and large-scale ENSO variability. The fact that the correspondence with the proximate $\delta^{18}O$ record is somewhat higher could lend support to the latter possibility. In addition, there are a number of instances in the calibration period when ENSOs identified in the other instrument and proxy records are present in the documentary record as weak or moderate events, suggesting part of the problem may again be related to the difficulties in categorizing a continuously varying phenomenon. The reliability of a documentary record over time is very difficult to assess. Clearly decreases in the quality and quantity of documentary evidence will make interpretation more difficult for earlier periods, as will other factors such as the evolution of meaning and usage in languages. As a result, it may be more difficult and challenging to maintain a constant level of reliability in documentary proxy records than in natural proxy records because there is often less change in the structure of natural recording systems than there has been in human recording systems. Clearly, however, the lack of correspondence with the tree-ring record and weak correspondence with the $\delta^{18}O$ record do not convincingly invalidate the documentary record. It is also clear that neither the documentary record nor any other single proxy record can be considered the base against which to test the validity of new proxy records.

Summary

All three proxy records have significant levels of correspondence with the instrument records during the modern calibration period. After adjusting the $\delta^{18}O$ record for apparent missing years, the correspondence between it and the tree-ring record remains consistent back to about 1630. In addition to providing verification of the reliability of the records, this correspondence suggests strongly that ENSO variability persisted without major changes through a period of significantly different large-scale climatic conditions. This robustness of the ENSO phenomenon to past climatic changes suggests that there is a good possibility that it may continue essentially unchanged through the sorts of climatic changes that are likely to occur during the next century or two. Nevertheless, it should be kept in mind that both the ice cores and the tree-ring record describe variations within the generally colder climate of the so-called Little Ice Age. There is ice-core and archaeological evidence for 'Mega El Niño' events in A.D. 600 and 1100, times that were isotopically warmer than present (see Nials et al. 1979; Shimala et al. 1991).

There is some evidence, albeit less convincing, that there were periods of strong ENSO activity during the early 1700s and the early 1900s and a period of low activity during the early 1800s. Furthermore, there are indications that the level of correspondences between the proxy and instrument records and between the different proxy records are considerably better during periods of high activity. On a methodological note, there are many examples in the study of the utility of examining time-varying statistics in paleoclimatic calibration and reconstruction studies. Finally, the results of this study show very convincingly the importance of comparing different high resolution proxy records. It is hoped that this is just a first step, and as the quality and quantity of ENSO proxy records increases, further studies can remove some of the uncertainties and refine the results presented here.

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