# 'Persistent' ENSO sequences: how unusual was the 1990–1995 El Niño?

Robert J. Allan[1] and Rosanne D. D'Arrigo[2]

*([1]Climate Impact Group, CSIRO Division of Atmospheric Research, Melbourne, Australia; [2]Tree-Ring Laboratory, Lamont-Doherty Earth Observatory, Palisades, New York, USA)*

Received 1 April 1998; revised manuscript accepted 29 June 1998

A HOLOCENE FORUM ARTICLE

**Abstract:** A pronounced climatic pattern, synonymous with protracted El Niño activity, persisted during much of the first half of the 1990s. The impact of this anomaly was primarily a consequence of its duration, which was much longer than the life cycles that have marked a number of the well-documented major El Niño events over the last 30-odd years. Depending on which oceanic or atmospheric parameters or which regions of the Indo-Pacific basin are examined, this recent pattern has been described as either a 'sequence of' El Niño events or a 'persistent' El Niño episode. Such an occurrence has been attributed to a variety of causes, ranging from an enhanced greenhouse effect to volcanic dust to a major change in the earth's climate system. Much of the above conjecture has occurred because the recent El Niño sequence/climatic anomaly has been considered with regard to only contemporary data and events. This study first expands this perspective by examining evidence for both protracted El Niño and La Niña phases of the El Niño Southern Oscillation (ENSO) in historical instrumental data. However, since the presence of such signals in records of relatively short length is of limited statistical significance, recourse to reconstructions based on longer proxy records is necessary. A reconstruction of the Southern Oscillation Index (SOI) derived using a multiple regression model incorporates tree-ring records from ENSO-sensitive regions of the Pacific, including the southwestern USA, Mexico and Indonesia. This reconstruction shows a number of 'persistent' El Niño and La Niña event sequences through time. Due to their generally lower and differing temporal and spatial resolution, the length and amplitude of palaeo-events cannot always be compared directly among different proxies or with events in the various instrumentally based records. Nevertheless, the reconstruction demonstrates that features indicative of 'persistent' event sequences have occurred prior to the period of instrumentally based indices. This finding is supported by documentary evidence from other ENSO-sensitive regions across the Indo-Pacific basin.

**Key words:** ENSO, El Niño, La Niña, Southern Oscillation Index, persistence, instrumental records, historical records, Indo-Pacific basin, Pacific Ocean.

## Introduction

During much of the first half of the 1990s, the global climate system was affected by a climatic anomaly that could be interpreted as suggestive of an unusual El Niño phase of the broader El Niño Southern Oscillation (ENSO) phenomenon (Goddard and Graham, 1997). Apart from the odd month or two, the Tahiti-Darwin Southern Oscillation Index (SOI) was consistently negative from August 1990 until June 1995 (Allan *et al.*, 1996a). However, during this time the SOI fluctuated in intensity to the extent that one could argue that three closely following El Niño episodes occurred, or equally that the climate system has been in a 'persistent' El Niño state (Liu *et al.*, 1995). Several questions have emerged. Is such a sequence unique in the climatic record (Gage *et al.*, 1996; Trenberth and Hoar, 1996; 1997; Harrison and Larkin, 1997; Rajagopalan *et al.*, 1997)? Can it be taken as a possible manifestation of enhanced greenhouse conditions, or even as signifying a regime change in the climatic system (Graham, 1994; Kerr, 1994; Miller *et al.*, 1994a; 1994b; Latif *et al.*, 1995; 1996; 1997; Wang, 1995; Kleeman *et al.*, 1996; Webster and Palmer, 1997)? Alternatively, was Mount Pinatubo haze or some combination of the above factors a possible cause (Kerr, 1993; Latif and Barnett 1994a; 1994b; Trenberth and Hurrell, 1994; Gu and Philander, 1995; Jiang *et al.*, 1995; Wang and Ropelewski, 1995; Self *et al.*, 1997)? Complicating such conjecture is the fact that most stages of the recent event were poorly predicted by numerical models of ENSO, indicating that these models do not include all that is needed to forecast the phenomenon (Kerr, 1993). This is not surprising, given that aspects of the ENSO structure encapsulated in such models have evolved from considerations of the canonical life cycle observed during many major events during the late 1950s to early 1970s through to the different spatio-temporal structure of the events of the 1980s (Allan *et al.*, 1996b).

Other evidence points to the presence of natural fluctuations in

 0959-6836(99)HL294FA

the climate system and ENSO on decadal to multidecadal timescales (Allan *et al.*, 1996b; Brassington, 1997), and the need to resolve the nature and impacts of such variability on climatic patterns. Most recently, Wang and Wang (1996), Torrence and Webster (1998) and Torrence and Compo (1998) have used waveform and wavelet analyses of oceanic and atmospheric data to reveal a varying nature for ENSO phases over various parts of the historical record. Not only has the amplitude/variance of ENSO fluctuated between periods of more robust signal in the 1870–1910s and 1970–90s and less energetic signal in the 1920–30s and 1960s (Allan *et al.*, 1996b), but ENSO has also varied in periodicity. From 1870 to 1910 the SOI had a dominant period of 3–4 years, from 1910 to 1920 and again from 1930 to 1960 it was 5–7 years, and from 1970 to 1990 it was 5 years (Wang and Wang, 1996). Such broad characteristics are also evident in a comparison of various wave analyses of ENSO signatures in Kestin *et al.* (1998), and with particular reference to Indian summer monsoon rainfall and Niño 3 region SSTs in Torrence and Webster (1998). In fact, Torrence and Webster (1998) indicate that interdecadal fluctuations in ENSO are linked to similar variations in Indian summer monsoon rainfall. They further suggest that differences in ENSO characteristics between the 1960–79 and 1980–95 epochs are due to fluctuations in its phase locking with the annual cycle which, in turn, affects the strength of the ENSO 'predictability barrier' (the period when predictability is weakest) in the boreal spring (austral autumn). Thus, there is a growing need to resolve the full nature of ENSO fluctuations in the context of natural and anthropogenic influences on the climate system.

In this paper, an evaluation is made of the degree to which the most recent El Niño sequence is unusual relative to prior long events using historical, instrumentally based, documentary and palaeoclimatic records. To place the sequence in perspective, schematic maps of the global rainfall signatures of the long event from 1990 to 1995 are compared and contrasted with the average El Niño pattern derived from a composite of contemporary events (Allan, 1993; Whetton and Rutherfurd, 1994; Allan *et al.*, 1996b). Instrumentally based indices calculated from various oceanic and atmospheric parameters are then examined and decomposed into their dominant spectral components. Such data are analysed for periods of what have been termed 'persistent' El Niño and, to encompass the whole phenomenon, La Niña conditions in the historical instrumental period. Overall, these records provide a depiction of major fluctuations in ENSO variables over the past 120 years. Yet, even this time interval cannot reflect the full range of spatial and temporal variability of the phenomenon. In order to expand an evaluation of the nature of the most recent event, documentary evidence and several well-dated high-resolution proxy records are explored in order to place recent events into a better context with regard to past situations and the longer term natural (i.e., non-anthropogenic) variability of the climate system. The prime focus of this analysis is a new experimental SOI reconstruction by Stahle *et al.* (1998), using tree-ring data from the Pacific Basin. Such high-resolution proxy data sequences are being encouraged and expanded with the implementation of the PAGES/CLIVAR initiative of the Annual Records of Tropical Systems (ARTS) (Cole, 1997). The above report shows a reasonable distribution of sites across the tropical-subtropical Indo-Pacific region, a situation which is improving rapidly (Figure 1 in Cole, 1997), and indicates the potential for the construction of spatial fields of proxy climatic indicators in the near future.

## Data sources and methods

Various data sets examined in this study were drawn, where possible, from research papers in the literature and climatic summaries. Authors who provided additional material or raw data from their published studies are cited in the Acknowledgements.

The most widely used long-term signatures of the ENSO phenomenon have been indices of the Southern Oscillation (Allan *et al.*, 1996a; 1996b). Of those that have been derived, the most commonly used is the Tahiti-Darwin SOI (anomalies of monthly Tahiti minus Darwin MSLP differences are standardized by the standard deviation of the Tahiti minus Darwin series) often attributed to Troup (1965), but first detailed in raw tabulated form by Pittock (1974). Historical mean sea-level pressure (MSLP) records for Darwin (since 1874) and Tahiti (since 1876) were obtained from the sources referenced in Allan *et al.* (1991). The full historical SOI series, and those portions relating to extended El Niño and La Niña phases, were constructed in the manner detailed in Allan *et al.* (1991). Periods of missing MSLP data at either Tahiti or Darwin were filled with values from the Young (1993) reconstruction, and the entire historical SOI series back to 1876 was then recalculated. This infilled SOI is shown to be extremely highly correlated ($r = +0.99$) with the only other available monthly gap-filled SOI (Jones, 1988; Kelly and Jones, 1996) in Allan *et al.* (1996a). The SOI was not reconstructed before 1876 due to concerns about the reduction in variance in the Tahiti MSLP record.

Historical sea-surface temperatures (SSTs) for the central-eastern equatorial Pacific (CEP-EEP) Niño 3 and Niño 4 regions were obtained from the Hadley Centre for Climatic Prediction and Research, United Kingdom Meteorological Office (UKMO) (Rayner, 1996, personal communication). Details of the Global sea-Ice and Sea Surface Temperature (GISST) data set from which the Niño 3 and Niño 4 region SST anomalies were derived are provided in Parker *et al.* (1995) and Rayner *et al.* (1995).

The studies by Allan (1993) and Allan *et al.* (1996b) detail a number of recent papers that resolve significant spectral signals in oceanic and atmospheric variables indicative of ENSO phases in the Indo-Pacific region. The two most dominant signals are a quasibiennial (QB) frequency of around 18 to 35 months, and a lower frequency (LF) of around 32 to 88 months. As the interaction between these frequency bands is seen to dictate a great deal of ENSO nature, all of the instrumentally based indices detailed above are filtered in the QB and LF ranges by a recursive Butterworth (bandpass) filter (Stearns and Hush, 1990) after having had their linear trends removed.

The longitude-time diagram of recent SST anomalies across the tropical Pacific was redrawn from TAO Project Office/PMEL/NOAA sections available on their World Wide Web (www) site. Precipitation anomalies during 1990, 1991, 1992, 1993, 1994 and 1995 were redrawn from impact maps and descriptions in various issues of the *Climate System Monitoring Monthly Bulletin* listed in the references. The 1994 and 1995 maps were drawn from data on the World Meteorological Organization (WMO) www site.

A number of research papers have described proxy and historical data series which relate to ENSO (e.g., Lough and Fritts, 1985; Stewart *et al.*, 1989; Lindesay and Vogel, 1990; Cleaveland *et al.*, 1992; Stahle and Cleaveland, 1993; Cole *et al.*, 1993; Jacoby and D'Arrigo, 1990; D'Arrigo *et al.*, 1994; Druffel and Griffin, 1993; Dunbar *et al.*, 1994; Quinn, 1993; Quinn *et al.*, 1993; 1996; Whetton and Rutherfurd, 1994; Cook, 1995; Tudhope *et al.*, 1995; Charles *et al.*, 1997; Moore *et al.*, 1998). The locations of these proxy records across the Indo-Pacific basin are shown in Figure 1. The geographical positions of the proxy data sources match regions where contemporary ENSO rainfall anomalies occur (Figure 2). However, as noted in the following section, only the tree-ring proxy records were able to be used in this paper.

The SOI reconstruction used in this study is for the boreal winter (DJF) and is detailed in Stahle *et al.* (1998) and evolved in the following manner. Various combinations of proxies related to

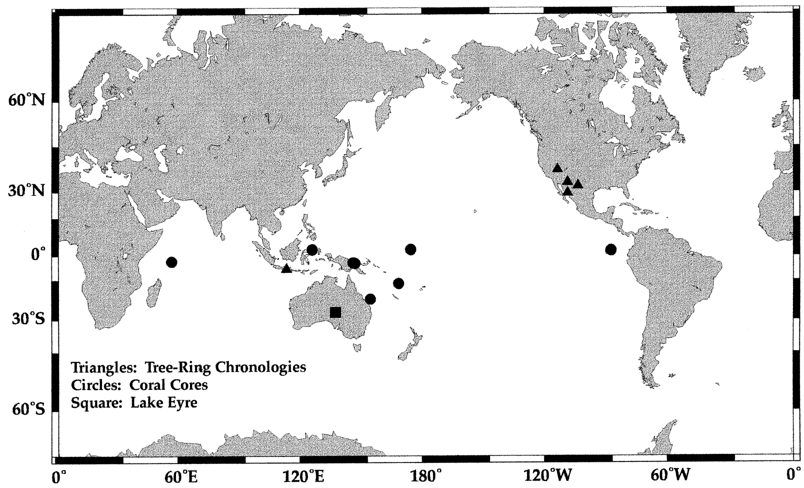


**Figure 1** Location of proxy data types over the Indo-Pacific region discussed in this paper.

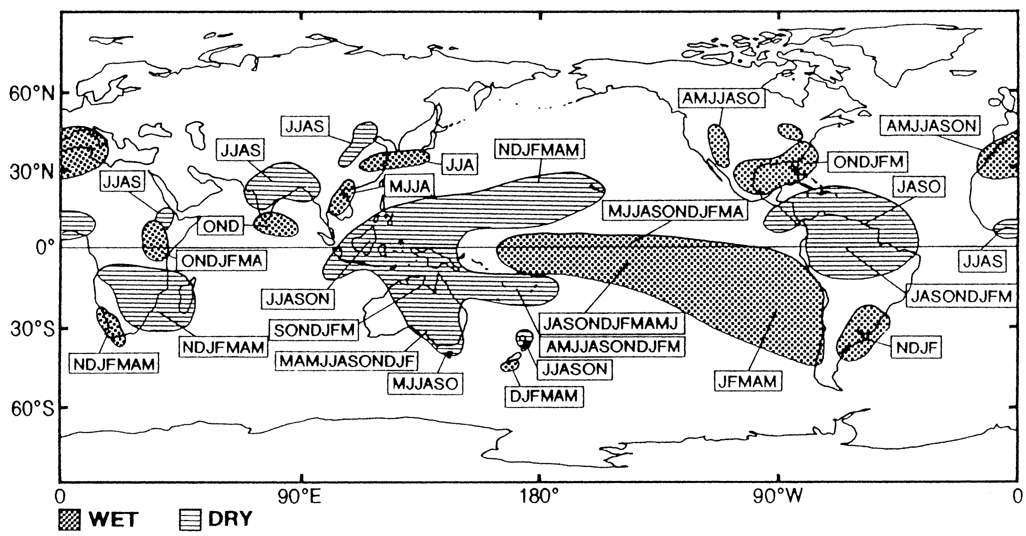


**Figure 2** Schematic diagram showing a composite of global El Niño precipitation anomalies derived from contemporary and some historical records. Average monthly durations of the anomalies are shown by boxed letter sequences. Anomaly shading signatures are given in the key.

ENSO-type variables were evaluated for inclusion in experimental versions of the SOI reconstruction. The final reconstruction is based only on the tree-ring data from Java, Indonesia and the southwestern USA and Mexico. Other series were omitted from the final reconstruction for various reasons. Some of these series lacked a temporal length extending well beyond the historical instrumental record, did not possess stable variance over time or did not display a significant correlation with the historical Tahiti-Darwin SOI. Others were omitted on the grounds that they showed most response on longer decadal-multidecadal timescales, and little consistent relationship with interannual or low-frequency fluctuations in ENSO. The development of an SOI reconstruction reflecting the boreal winter situation is particularly advantageous, in that it encompasses the season of strongest ENSO influence in contemporary and historical data series. The reconstruction covers the period from 1706 to 1977, and explains some 53% of the observed SOI variance for the period 1877–1977 (Stahle *et al.*, 1998).

As teleconnections to higher latitudes can vary between ENSO phases (Allan *et al.*, 1996b), efforts have been made to focus on more tropical-subtropical proxies. This is particularly true of the Pacific-North America (PNA) teleconnection which has been shown to be linked more closely to interdecadal patterns than to interannual ENSO fluctuations (Glantz *et al.*, 1991).

It should also be noted, that focusing on the distribution of precipitation anomalies to define ENSO influence does not produce a pattern that is very different from that defined by air temperature relationships (see Halpert and Ropelewski, 1992; Allan *et al.*, 1996b). The only major exceptions are in Alaska/northwestern Canada and the southwestern Pacific, although some of the timing of rainfall and temperature responses in overlapping regions does differ slightly.

## Instrumental record

### Description of 1990–1995 El Niño sequence

As the ENSO phenomenon involves an aperiodic, large-scale ocean-atmosphere interaction centred in the Indo-Pacific basin that generates atmospheric perturbations which carry its influence to higher latitudes in both hemispheres, its physical manifestations take on near-global dimensions. Papers by Ropelewski and Halpert (1987; 1989), Kiladis and Diaz (1989) and Halpert and Ropelewski (1992) and the atlas/book of Allan *et al.* (1996b) detail schematic maps showing the spatial and temporal patterns and evolution of global precipitation and temperature impacts generated by both ENSO phases (El Niño and La Niña). Such diagrams encapsulate the most coherent signals evident from composites of the more pronounced events, and have a tendency to reinforce the canonical pattern associated with the phenomenon.

Nevertheless, they are important visual impressions of some of the physical manifestations that occur during major ENSO phases.

Patterns of near-global precipitation derived from such composites for the El Niño or warm phase are shown in Figure 2, and are contrasted with the precipitation response during each year of the recent 'persistent' event in Figure 3, a-f. As can be seen in Figure 2, the regions of precipitation anomalies vary in the timing of their response to El Niño episodes. However, there is a tendency for the regions of major spatial extent to show peak response in the boreal summer to winter period. Other hydrological, climatological and environmental responses over the globe during both phases of ENSO can be found in Halpert and Ropelewski (1992), Allan (1993), Whetton and Rutherfurd (1994) and Allan *et al.* (1996b). Detailed descriptions of climatic patterns during the recent El Niño sequence are given in the *Climate System Monitoring Monthly Bulletins* and in articles on the global climate and seasonal climate summaries in the *Journal of Climate* and the *Australian Meteorological Magazine*, respectively.

Major precipitation anomalies in 1990 (Figure 3a) show minimal coherence with those associated with average El Niño conditions (Figure 2). However, there are indications that a warm event was evolving (*Climate System Monitoring Monthly Bulletin*, 1990). The Southern Oscillation Index (SOI) provides further support for such evidence, with a period of low values in the first third of the year, a return to positive values during the mid-seasons, and a fall in the index in the last third of 1990 (see Figure 5).

By 1991 (Figure 3b), indications of an El Niño event were much more prominent and widespread in the global precipitation anomalies. Major and widespread drought conditions are evident in Indonesia, New Guinea and eastern Australia during the austral winter and spring seasons. The SOI was negative with an increasing downward trend during 1991 signifying the development of a mature event (Figure 5).

During 1992 (Figure 3c), oceanic and atmospheric variables suggest that warm event conditions, evident during the first third of the year, appear to be diminishing by the middle seasons. The SOI reflected these conditions, with a jump back to positive values in May, and again between August and September (perhaps suggesting a breakdown in the event), giving way to negative values for the remainder of the year (Figure 5).

The redevelopment of the El Niño in late 1992 continued throughout most of 1993, until a return to a weak positive SOI in November and December (Figure 5). Precipitation anomalies in 1993 (Figure 3d) showed patterns that were less suggestive of El Niño responses as the year progressed.

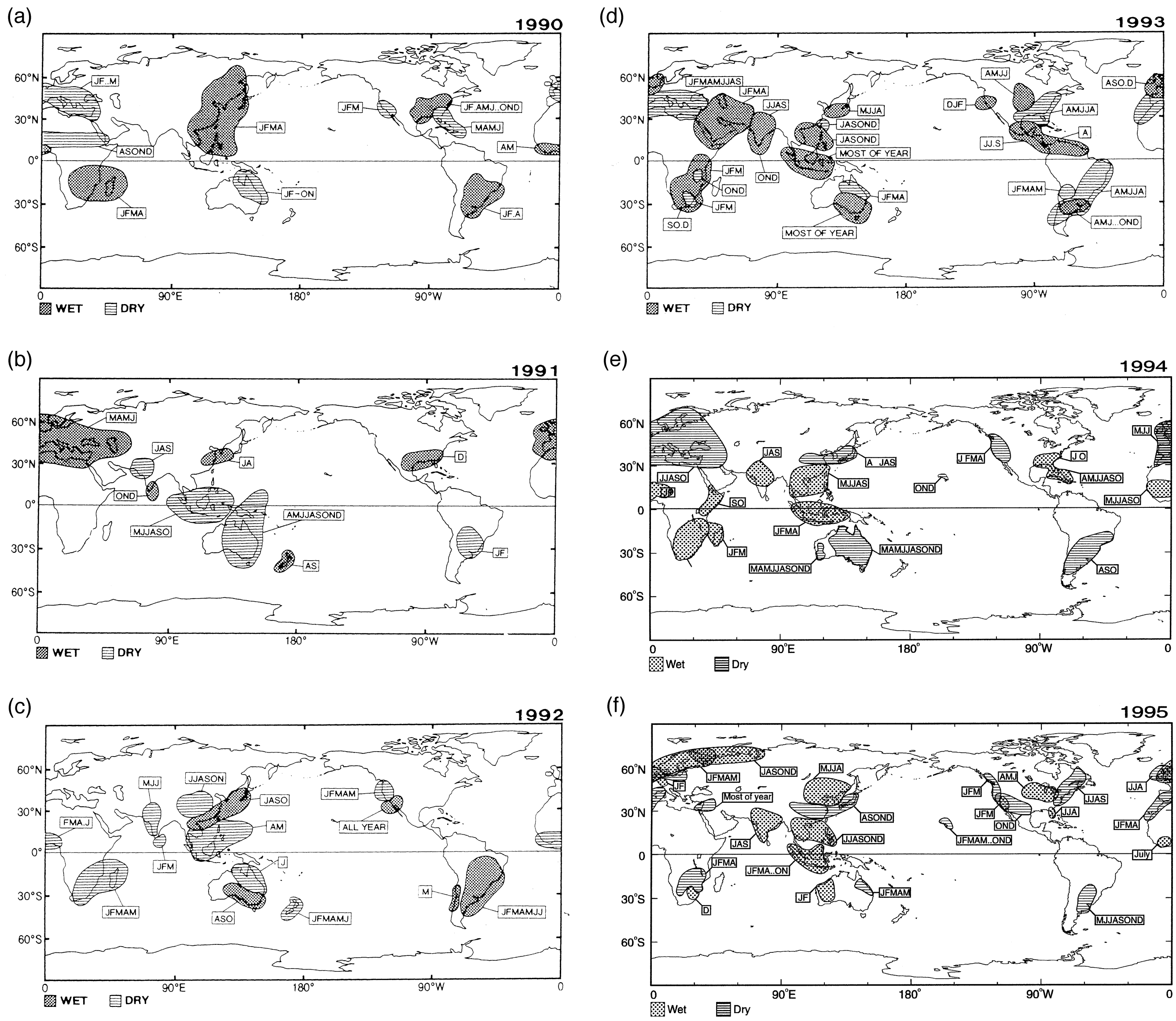


**Figure 3** Schematic diagrams showing global precipitation anomalies for the years (a) 1990, (b) 1991, (c) 1992, (d) 1993, (e) 1994 and (f) 1995. Average monthly durations of the anomalies are shown by boxed letter sequences. Anomaly shading signatures are given in the key.

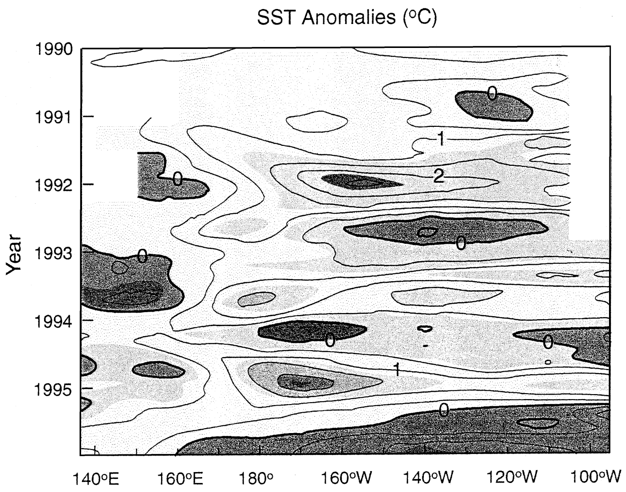


**Figure 4** Longitude-time plot of the SST anomalies across the Pacific averaged for the band 2°N–2°S from 1990 to 1996. Negative (positive) SST anomalies are shown by darker (lighter) shading. Line (shading) contour interval is 0.5°C (0.25°C).

The SOI trace (Figure 5) indicated a return from persistently negative values during the austral summer of 1994, with strong suggestions of the cessation of the event. However, as in 1992 and 1993, signs of the event weakening were short-lived, and by the austral autumn of 1994 El Niño conditions were once again evident (Figure 3e). This pattern continued, with a moderate-strong event throughout the austral winter to summer of 1994 (Figure 3e). As in 1992, 1993 and 1994, the SOI showed a return to near-zero values in the first few months of 1995. However, by the middle of 1995, oceanic and atmospheric circulation patterns and precipitation anomalies had returned to near-average distributions and indicated an end to the El Niño sequence (Figure 3f). Positive SOI values during the three-month period from July to September 1995 supported the cessation of 'persistent' El Niño conditions and even became indicative of the La Niña event that occurred in late 1995 and matured in 1996.

The course of the recent protracted El Niño can be traced through various oceanic and atmospheric variables in the Indo-Pacific region (McPhaden, 1993; TAO www site). Perhaps the most revealing aspects of this episode can be charted by the oceanic temperature profile across the equatorial Pacific. Figure 4 shows a longitude-time series plot of SST anomalies in the equatorial band 2°N–2°S since 1990. This analysis suggests that a warm event had begun to develop steadily during 1991, had reached a peak in the austral summer of 1991/1992 when a broad positive SST anomaly dominated the CEP but then weakened in the latter part of 1992. El Niño conditions were re-established by early 1993, particularly in the western equatorial Pacific (WEP). As in 1992, the event appeared to have terminated following a return to negative SST anomalies during much of 1994. However, this situation soon gave way to El Niño conditions again during the later 1994 to early 1995. The eventual cessation of this recent El Niño sequence occurred during mid- to late 1995. From the longitudinal distribution of SST anomalies during the event sequence in Figure 4, it is evident that warm SST anomalies, associated with El Niño conditions, tended to show more persistence in the WEP-CEP region than in the eastern equatorial Pacific (EEP). It appears to depend on which regions of the Pacific Ocean are examined as to whether the recent episode is considered to be an extensive event or a sequence of events. This El Niño pattern does not follow either the general or canonical structure exhibited

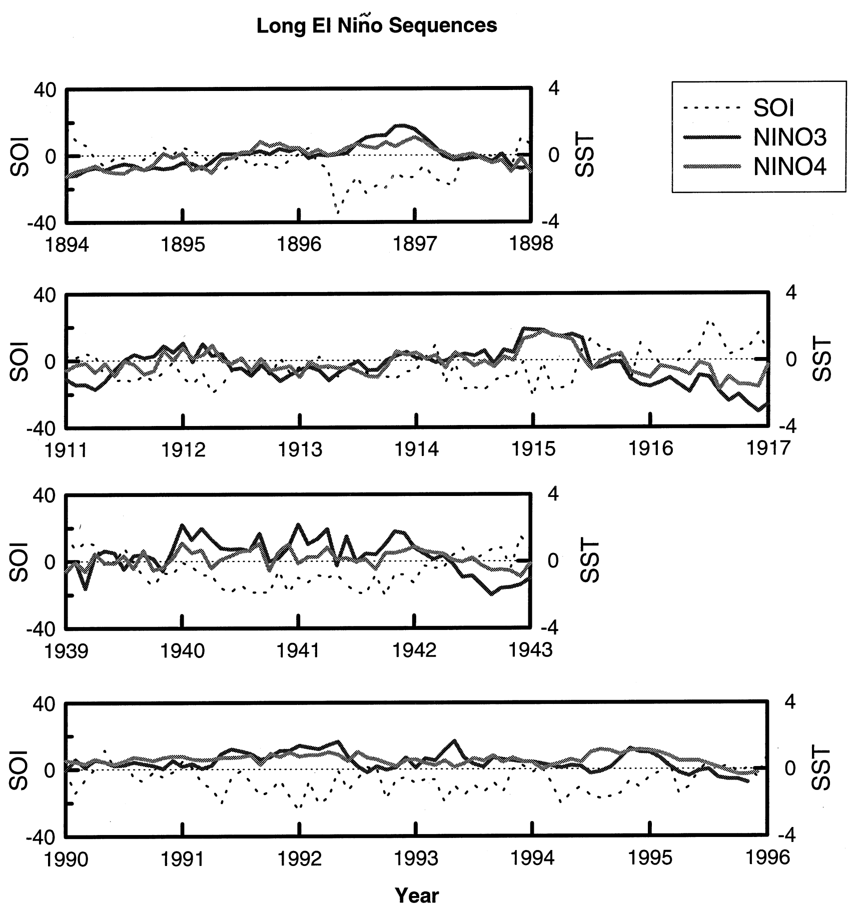


**Figure 5** 'Persistent' El Niño events defined from raw Southern Oscillation Index (SOI) values (solid lines) and sea-surface temperature (SST) anomalies (dashed lines) since 1876.

by El Niño phases in the last 30 years. Consequently, this type of event has been termed a 'persistent' sequence in this study.

However, to begin to evaluate past El Niño events with characteristics similar to 1990–95, it is necessary to look at longer-term parameters and evidence from the regions of prominent ENSO impact. To complete the picture, it is also vital to examine periods of 'persistent' La Niña conditions. In the next section, both ENSO phases are sought in records of historical SOI and SST data.

## Comparable events in the Instrumental Record: El Niños and La Niñas

Attempting to deduce periods likely to have experienced 'persistent' ENSO phases requires a judgement of the characteristics that define such episodes. After examining the available data, and the familiar canonical events, it was decided to designate periods of 24 months or more when the SOI and the Niño 3 and 4 CEP-EEP SST indices were of persistently negative or positive sign, or of the opposite sign in a maximum of only two consecutive months during the period, as 'persistent' episodes.

Applying the above criteria, the gap-filled SOI series and the Niño 3 and 4 SST indices from 1876 to 1996 were found to contain four 'persistent' El Niño and six 'persistent' La Niña event sequences (Figures 5 and 6). In Figure 5, it can be seen that the 1990–95 'persistent' El Niño event has a comparable structure to the 1911–15 sequence, but is the longest historical occurrence observed in the instrumental record. An equally interesting aspect of this analysis is the resolution of 'persistent' La Niña episodes in the sequence. As can be seen in Figure 6, the 'persistent' cold phases of ENSO are of similar magnitude and length to 'persistent' warm phases. All of the event sequences resolved by this approach show a tendency for short, but marked fluctuations back towards zero or values of opposite sign during the course of their life history. Such behaviour can be expected when dealing with the amount of climatic noise inherent in raw monthly values of the SOI or SST, but it may also reflect the season cycle dynamics in ENSO as it attempts to recover from an event.

Noise in the raw SOI is reduced when filtering the data in the QB and LF intervals. This technique is also applied to Niño 3

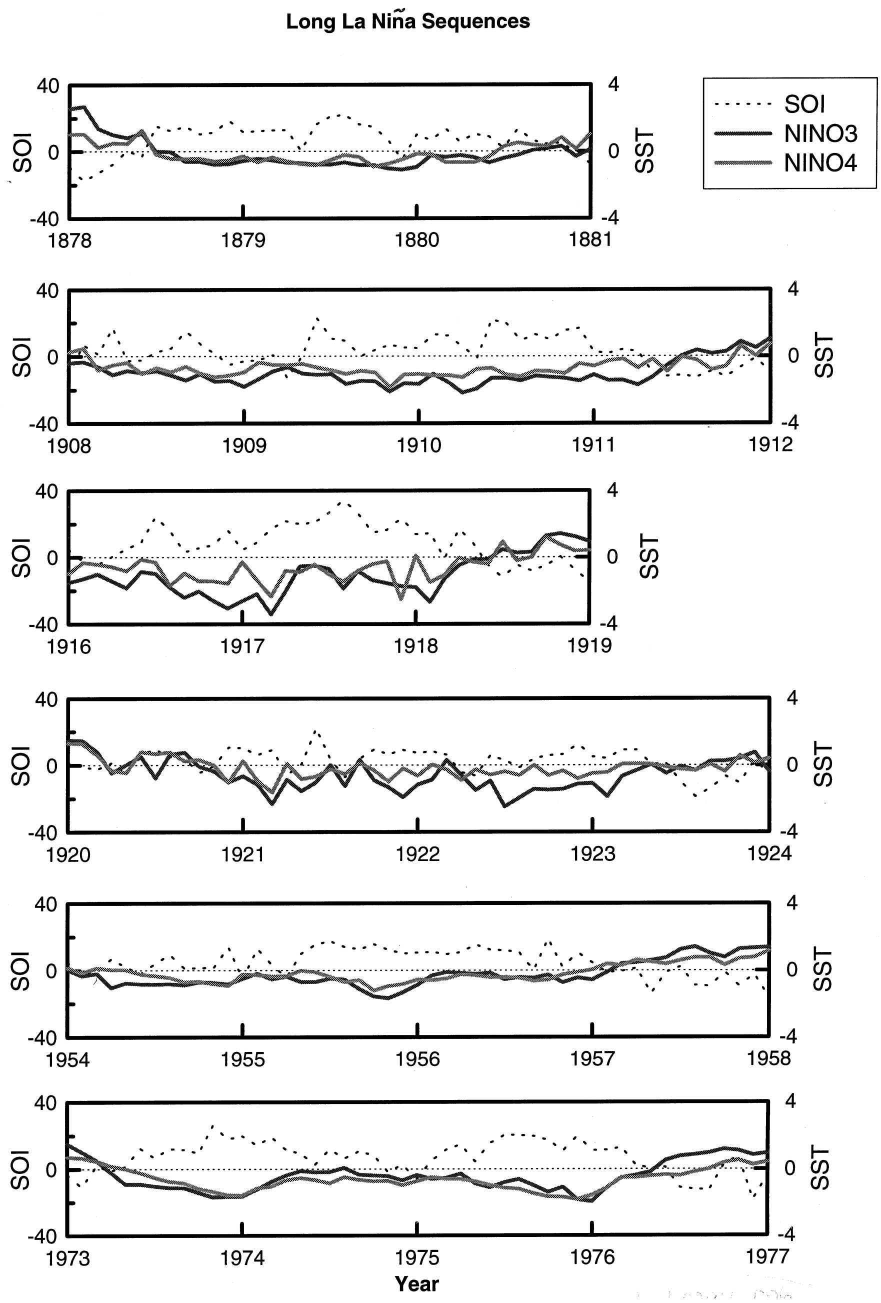


**Figure 6** 'Persistent' La Niña events defined from raw Southern Oscillation Index (SOI) values (solid lines) and sea-surface temperature (SST) anomalies (dashed lines) since 1876.

and 4 CEP-EEP SST anomalies, in order to produce a suite of independent indicators of ENSO from the Pacific basin. The superposition of the QB and LF components of the ENSO signal in the three time series is most revealing, and highlights the very strong coherence in the signatures of the bulk of the various types of El Niño and La Niña phases across this region. Figure 7 indicates that the interaction of the QB and LF signals is basically responsible for much of the magnitude and duration of both ENSO phases. Some of the major historical and contemporary ENSO phases with more canonical structure (El Niños in 1877–78, 1888–89, 1904–05, 1972–73 and 1982–83 and La Niñas 1890, 1903, 1939, 1950–51 and 1970–71) show a particularly close phasing of the QB and LF components, especially in the SOI series. It is the LF signal that reveals modulations of ENSO phases that lead to 'persistent' sequences, even at times when the QB component shows signals of the opposite sign. As shown by the studies of Wang and Wang (1996), Torrence and Webster (1998) and Torrence and Compo (1998), there are also longer period decadal-multidecadal fluctuations in ENSO characteristics, with periods of enhanced ENSO activity from the beginning of these series up until the 1910s and again since the 1940s–50s. During the intervening epoch, ENSO activity is markedly less. These broad regimes are most readily apparent in the LF component of ENSO, although QB frequencies also show similar features. It is well known that the number of major ENSO phases in the 1920s–30s epoch was reduced (Allan *et al.*, 1996b), but Figure 7 reveals that this can be attributed principally to the suppression of the LF component of ENSO. However, recent studies by Mann and Park (1996; 1998) indicate the presence of distinct quasidecadal and interdecadal signals in the climate system. The interaction of these low frequency modes with ENSO QB and LF components may provide additional reinforcement of protracted El Niño and La Niña phases, as suggested by Allan (1998) and Allan *et al.* (1998).

In order to obtain a longer-term perspective and statistical sampling of the incidence of the above characteristics of ENSO phases, an investigation of documentary records and proxy data is needed. From such analyses, ENSO-related proxies were evaluated for possible inclusion in the experimental reconstructions of

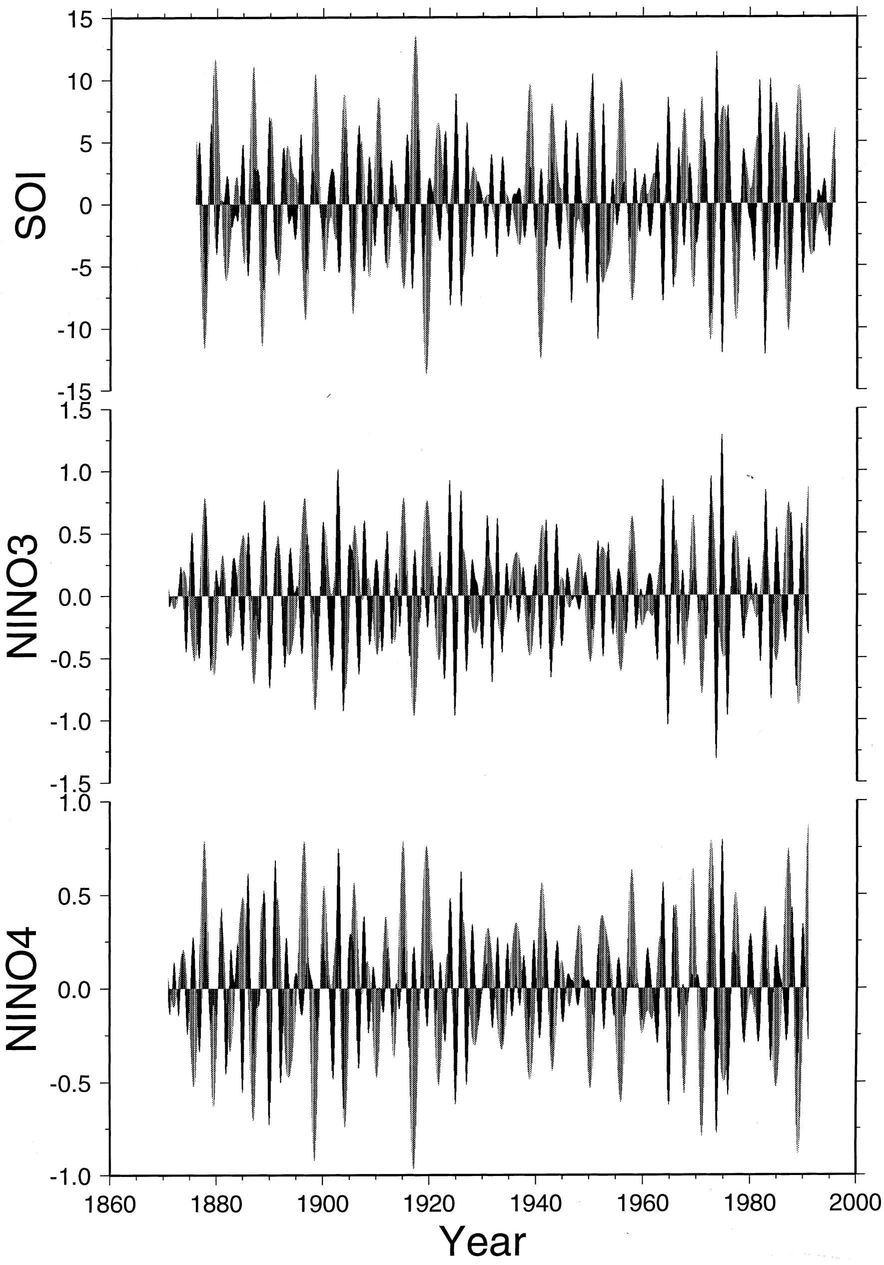


**Figure 7** 18–35 (QB) and 32–88 (LF) month bandpass filtered series of (a) the Southern Oscillation Index (SOI) and (b) GISST-based Niño 3 and 4 region sea-surface temperatures (SSTs) in the central to eastern equatorial Pacific Ocean (CEP-EEP) since 1871. All anomalies and normalizations are with respect to the 1961–90 period. 18–35 (32–88) month filtered series are shown by light (heavy) lines.

the SOI (Stahle *et al.*, 1998). As mentioned, the best of these was considered to be the version of the reconstruction based only on tree-ring data from Indonesia, the southwestern USA and Mexico (Stahle *et al.*, 1998), used in the present analyses below. Documentary evidence provides an independent source of information for comparison with this reconstruction.

## Proxy and documentary records of ENSO

### SOI reconstruction using proxy records of ENSO

In this section the tree-ring-based SOI reconstruction (Figure 8) is used to evaluate the frequency, severity and length of 'persistent' events prior to the period of instrumental record using only DJF data. For the overlapping instrumental period, this expands the number of 'persistent' El Niños discerned by the monthly instrumental data from 4 to 11 in DJF alone (Table 1a), and shifts the period of some sequences in both ENSO phases. However, the strongest protracted events tend to be retained. Future SOI reconstructions will need to resolve more of the ENSO life cycle if greater precision is to be achieved. Given these constraints, Table 1 shows the 'persistent' events (defined as continuous values of the same sign for three or more years) identified in both the DJF instrumental SOI (Table 1a) and in the reconstruction (Table 1b) for the period of overlap from 1877 to 1977 (the observed and reconstructed DJF SOI have a +0.74 correlation in Figure 9). This is reinforced by correlations of −0.68 and −0.67 between DJF Niño 3 and 4 SST series and the reconstructed DJF SOI in the historical instrumental period (not shown). The proxy reconstruction captures the sign and length, and approximate magnitude of the 1912–15, 1916–18, 1921–23, 1940–42 and 1947–49 events, and partially captures the 1893–95, 1931–33 and 1955–57 events. However, it misses those in 1927–30, 1935–37, 1952–54, 1960–63 and 1964–66. The best correspondence is generally found for episodes with the most extreme negative or positive average SOI values. 'Persistent' episodes identified in the reconstruction but not in the instrumental record generally represent relatively minor events, with low average values.

Examination of the pre-instrumental period in Table 1c reveals one seven-year La Niña event (1752–58) and one six-year La Niña event (1859–64). These are approximately equal in length to the 'persistent' El Niño of 1990–95. The next longest phenomena are two five-year episodes (El Niño 1710–14 and La Niña 1764–68). There is generally a marked increase in the number of events of both phases as the length of event decreases, so that there are four four-year El Niño and two four-year La Niña episodes, and eight three-year El Niño and four three-year La Niña events. It is evident that both 'persistent' El Niño and La Niña events have occurred previously and are not unique to the recent period. However, additional verification of these long sequences is desirable and is sought in the following section.

### Historical documentary support

Probably the best known and used historical documentations of El Niño and ENSO-related events for the past several centuries are those of the late William Quinn (most recent examples are in Quinn, 1992; 1993).[1] These listings vary in their degree of spatial representation: one is a regional record for coastal western South America (El Niño),[2] another includes the wider Pacific region (focusing on El Niño or warm phases of ENSO only), and others list the occurrence of Nile River floods associated with both ENSO phases (Quinn, 1992; 1993). Quinn (1993) also attempts to detail the links to northeastern Brazil drought, anomalously heavy rainfall in subtropical Chile and across the equatorial Pacific Ocean, drought associated with Indonesian east monsoon failure, eastern/northern Australian drought, and deficient summer mon-

[1] The bulk of Quinn's papers on the ENSO phenomenon have dealt with evidence for historical El Niño events in the South American region (Quinn *et al.*, 1978; 1987; Quinn and Neal, 1983; 1995). However, as research has shown, these events need not always be representative of the wider ENSO phenomenon across the Indo-Pacific basin. The Quinn (1992; 1993) papers attempt to look at evidence for large-scale ENSO responses. Nevertheless, they deal with only the warm phases of the phenomenon when referring to ENSO and no similar length compilation of cold phases is available. Whetton *et al.* (1996) provide the most complete attempt to document both phases of ENSO since 1700.

[2] Recent papers by Hocquenghem and Ortlieb (1992), Mabres *et al.* (1993), Ortlieb and Machare (1993), Ortlieb (1994) and Whetton *et al.* (1996) have questioned aspects of the South American regional El Niño indices given in Quinn (1992; 1993). These latest Quinn sequences are shown to be influenced by wider global indications of ENSO warm phases. Most affected are some of the dates, magnitudes and reliability of events in the earliest centuries of the Quinn (1992) regional series. Hocquenghem and Ortlieb (1992), Ortlieb and Machare (1993) and Ortlieb (1994) indicate that they are undertaking revisions of the Quinn regional El Niño series.

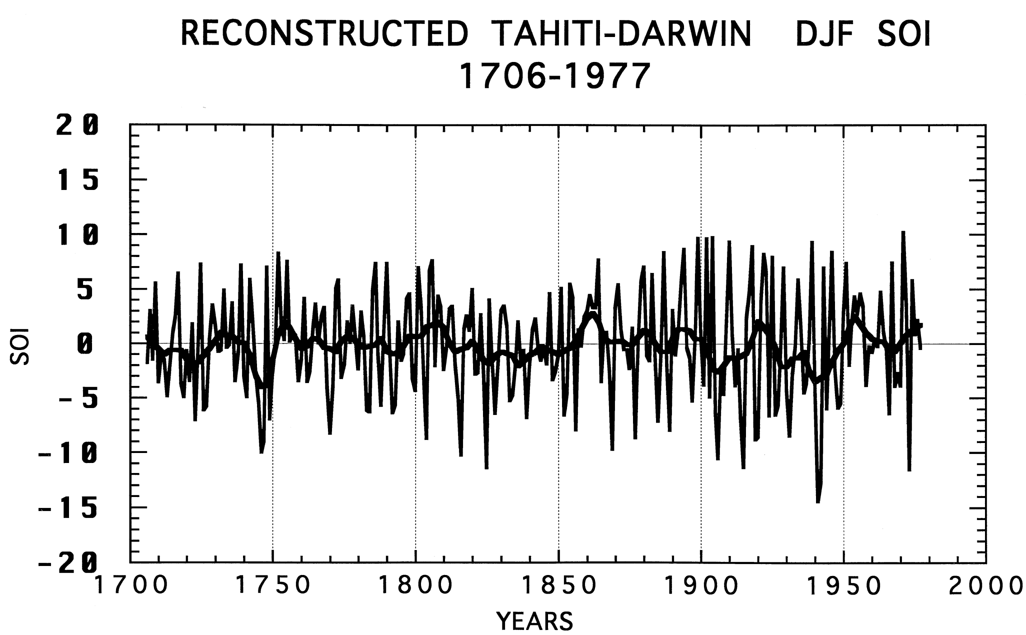


**Figure 8** Reconstructed DJF SOI from 1706 to 1977 based on Java, Indonesia; southwestern USA and Mexico tree-ring data (Stahle *et al.*, 1998). The solid line is the trace of a smoothing spline run through the data to emphasize decadal variability.

**Table 1**

| Period | Sign | Length | Value |
|---|---|---|---|
| **(a) Longest sequences (3+yr) in Tahiti-Darwin SOI (Dec–Feb) 1877–1964** | | | |
| 1893–95 | + | 3 | 5.20 |
| 1912–15 | – | 4 | –8.58 |
| 1916–18 | + | 3 | 9.43 |
| 1921–23 | + | 3 | 6.93 |
| 1927–30 | + | 4 | 6.35 |
| 1931–33 | – | 3 | –2.80 |
| 1935–37 | – | 3 | –1.90 |
| 1940–42 | – | 3 | –11.20 |
| 1947–49 | – | 3 | –4.60 |
| 1952–54 | – | 3 | –6.47 |
| 1955–57 | + | 3 | 6.30 |
| 1960–63 | + | 4 | 3.50 |
| 1964–66 | – | 3 | –5.70 |
| 1979–81 | – | 3 | –1.97 |
| 1985–88 | – | 4 | –4.88 |
| 1990–95 | – | 6 | –6.20 |
| **(b) Longest sequences (3+yr) in SOI reconstruction 1877–1977** | | | |
| 1878–80 | + | 3 | 4.25 |
| 1884–86 | – | 3 | –3.09 |
| 1892–94 | + | 3 | 5.18 |
| 1895–97 | – | 3 | –2.31 |
| 1898–00 | + | 3 | 3.48 |
| 1905–08 | – | 4 | –6.01 |
| 1909–11 | + | 3 | 4.08 |
| 1912–15 | – | 4 | –5.64 |
| 1916–18 | + | 3 | 5.34 |
| 1921–23 | + | 3 | 6.18 |
| 1926–28 | – | 3 | –4.15 |
| 1930–33 | – | 4 | –3.94 |
| 1940–42 | – | 3 | –10.63 |
| 1947–49 | – | 3 | –4.59 |
| 1953–57 | + | 5 | 3.42 |
| 1958–60 | – | 3 | –1.63 |
| 1968–70 | – | 3 | –3.52 |
| 1974–76 | + | 3 | 2.91 |
| **(c) Longest sequences (3+yr) in SOI reconstruction 1706–1876** | | | |
| 1710–14 | – | 5 | –2.53 |
| 1715–17 | + | 3 | 3.28 |
| 1718–21 | – | 4 | –3.18 |
| 1728–30 | + | 3 | 1.82 |
| 1744–47 | – | 4 | 6.76 |
| 1749–51 | – | 3 | –3.30 |
| 1752–58 | + | 7 | 2.82 |
| 1764–68 | + | 5 | 2.11 |
| 1769–71 | – | 3 | –5.43 |
| 1776–79 | + | 4 | 1.49 |
| 1791–93 | – | 3 | –4.07 |
| 1814–16 | – | 3 | –5.66 |
| 1817–20 | + | 4 | 2.49 |
| 1827–29 | – | 3 | –3.23 |
| 1830–32 | + | 3 | 2.64 |
| 1833–35 | – | 3 | –4.07 |
| 1837–40 | – | 4 | –2.82 |
| 1843–46 | – | 4 | –1.05 |
| 1848–50 | – | 3 | –2.32 |
| 1859–64 | + | 6 | 4.00 |
| 1870–72 | + | 3 | 3.28 |
| 1873–75 | – | 3 | –1.12 |

Four protracted ENSO sequence periods, lengths and values in Table 1(a) are deduced from the DJF SOI values relative to the 1877–1977 base period. This provides a time series that can be related to the proxy SOI reconstruction, as in Figure 9. If the DJF SOI values are evaluated relative to the full base period of instrumental data since 1877, then the 1931–33, 1935–37 and 1979–81 sequences are not resolved as lasting three years or more. However, the 1974–76 sequence is then resolved and others are modified to the extent that the 1985–88 and 1990–95 episodes are reduced in length to the years 1986–88 and 1991–95.

soon rainfall over India since the mid-1700s.[3] The most recent, wider Pacific version of Quinn's ENSO events (Table 4 of Quinn, 1993) is used in this study in order to focus on Pacific-wide manifestations of 'persistent' events. Quinn's rankings for relative intensity of ENSO events are: VS = very strong, S = strong and M = moderate; confidence ratings range between 1 = minimal and 5 = complete. 'Persistent' warm event sequences in this listing are considered to be those lasting three or more years, a definition which appears to best match the identification of events in instrumentally based indices.

Recently, Diaz and Pulwarty (1994) used spectral methods to investigate various scales of variability among long documentary and proxy records in ENSO-sensitive regions of the Americas, east Africa and China. Their study suggested that ENSO characteristics on the 2–10-year timescale have been quite consistent over the last millennia. This is a period of time that some sources suggest includes epochs of significantly warmer and colder conditions (e.g., the so-called 'Medieval Optimum' and the 'Little Ice Age') (Lamb, 1982). However, recent reviews by Hughes and Diaz (1994) and Bradley and Jones (1995) have questioned this assertion. They suggest that in fact evidence is poor for both the 'Medieval Optimum' and the 'Little Ice Age', particularly in the tropics and across the Southern Hemisphere. As a result, there is now much uncertainty about the spatio-temporal extent, magnitude and causes of these epochs. Such inferences are supported by a recent 500-year general circulation model (GCM) simulation of the climate system (Hunt, 1998).

Using a number of documentary and proxy data records from Africa, northern China and India, Whetton and Rutherfurd (1994) investigated the occurrence of ENSO phases over the last 500 years. The ENSO relationships described in their paper can be traced back to the mid-1700s, but data problems seem to affect resolution prior to that time. However, some improvement in early ENSO signatures is found in the reanalysis of Whetton *et al.* (1996). Nevertheless, the number of signatures available decreases with time and thus tends to limit their usefulness to the height of the colonial periods in regions across the Indo-Pacific domain.

Table 2 shows an intercomparison between periods of Quinn ENSO (QU), Nile Flood (NI), Indian Monsoon Rainfall Failure (IRF), North China Rainfall (NCR), NE Brazil Drought (BD), Southern Chile Rainfall (SCR), Indonesian East Monsoon Drought (IMD), Australian Drought (AD), from Quinn (1993) and Whetton and Rutherfurd (1994) and South African summer rainfall (SASR) from Lindesay and Vogel (1990), and sequences of three years' duration and more of protracted El Niño and La Niña episodes as defined by the SOI tree-ring-based reconstruction of Stahle *et al.* (1998) from 1706 to 1876. Recent re-evaluations of regional South American Quinn El Niño dates by Hocquenghem and Ortlieb (1992) and/or Ortlieb (1994) are also included after the year designation in Table 2.

Several factors play significant roles in dictating the viability of this type of intercomparison. As noted earlier, the availability of important documentary evidence from countries across the Indo-Pacific basin is generally dictated by the extent of colonial presence. To be of use to this project, these data need to be recorded in ENSO-sensitive regions. In addition, the records/observations need not only to be drawn from the most reliable sources but also to be interpreted correctly. As detailed in Note 2, several South American researchers have questioned some of the earlier dates given by various Quinn evaluations of regional El Niño conditions. This has come about through a reassessment

[3] Caviedes (1991) has examined links between ENSO phases and Caribbean hurricanes using historical data sources covering the last 500 years. However, there are considerable changes in data type and quality with regard to hurricane statistics over time, so that inferences of longer-term patterns and trends that may shed light on ENSO characteristics must be seen as very speculative.

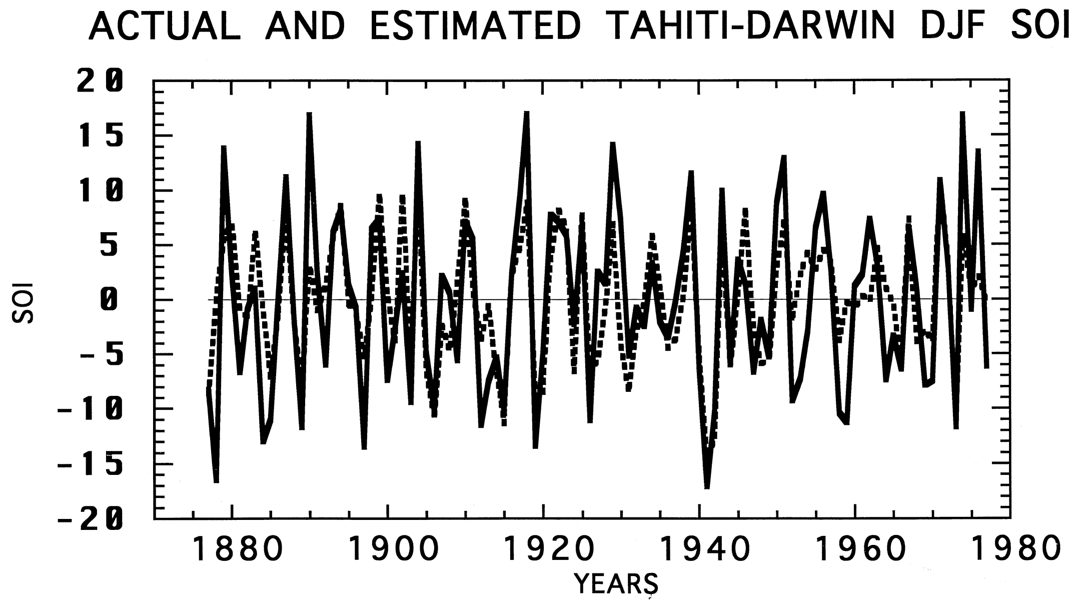


**Figure 9** Observed (solid line) Tahiti-Darwin DJF SOI and estimated (dashed line) DJF SOI for the period of overlap from 1877 to 1977 (r = +0.74).

of the recorded incidence of rainy years in both central Chile and Peru. As a consequence, Ortlieb (1994) suggests that a reasonable convergence of Quinn's regional El Niño dates and Chilean rainfall events occurs only after about 1817. Such findings are clearly evident in Table 2 in Ortlieb (1994), and are supported by increased coherency among El Niño signatures after the above date in Table 2 of this paper. Working on a wider variety of data sets, Whetton and Rutherfurd (1994) and Whetton *et al.* (1996) see more of a 1770s time before which existing historical records of El Niño and La Niña episodes become questionable. Together, these findings indicate a need to be wary of making too much of early documentary evidence for ENSO phases, especially in isolation or where supporting material is sparse or marginal.

The reliability of the tree-ring chronologies used in the SOI reconstruction is discussed in detail in Stahle *et al.* (1998). Basically the southwestern USA and Mexican trees, with considerable replication of data across the region, respond significantly and most strongly to ENSO phases around the boreal (austral) winter (summer) season. The single chronology from Java is still significantly correlated at this time, but explains less SOI variance than the southwestern USA and Mexican trees. The strongest Javan tree-ring response to modern ENSO indices is in the boreal (austral) summer (winter) period. Thus, the Eastern Hemisphere proxy response is technically the weaker component in the SOI reconstruction based on individual correlation relationships with ENSO phases. However, in examinations of the SOI reconstruction itself, Stahle *et al.* (1998) provide strong evidence from cross-validation statistics (split period calibration and verification tests on the reconstructed time series) and correlations with independent ENSO indicators for a particularly robust reconstructed series. At this stage the early historical documentary evidence appears to be of most concern, and problems with it seem to impinge on this study. Nevertheless, further use and analysis of the proxy SOI reconstruction employed here may provide grounds for improvements or modifications to it that will establish more clearly its veracity.

Perhaps the most complicating aspect in assessments of various ENSO evidence is the impact that decadal to multidecadal fluctuations in the climate system have on the phenomenon (Allan, 1998; Allan *et al.* 1998). These low frequency variations lead to not only waxing and waning of El Niño and La Niña event amplitude, frequency and duration, but also the spatial extent of teleconnection patterns and signatures. The result is that there are periods of decades when documentary and proxy evidence is likely to be more or less viable. As shown in Stahle *et al.* (1998), singular spectrum analyses (SSA) of the reconstructed SOI used here reveal weak ENSO signal variance at both the 3.53 and 4.07 year bands in the mid-eighteenth, nineteenth and at the turn of the twentieth centuries. In between these times, and during this century, these ENSO bands display generally robust signals with high variance structure, and thus ENSO's climatic influences are more likely to be present and recorded in historical and proxy sources. The period of weak ENSO variance in the instrumental 1920s–30s period is just discernible in the Stahle *et al.* (1998) SSA series, and in relation to the above fluctuations in the proxy-based SOI is quite small.

Considering all of the above aspects, Table 2 provides varying support for reconstructed SOI phases of El Niño and La Niña. In finding confirmation of event sequences in the historical data, consideration was given as to whether to include the weakest or most marginal teleconnection linking ENSO to northern Chinese rainfall. When it was this one variable dictating whether a year was said to be of one ENSO phase or the other, its omission led to the confirmation of 11 more El Niño and two more La Niña events. Treatment of this evidence in the above manner is justified by the variable phasing of northern Chinese rainfall with the sequence of the 1990–95 'persistent' El Niño event in Figure 3, a–f, and with other historical ENSO phases during the instrumental period in Allan *et al.* (1996b).

Taking all of the above into account, the two longest sequences in the reconstruction, a seven-year and a six-year La Niña in 1752–58 and 1859–64, do not show coherent support in the historical data. The period 1754–56 is not documented as experiencing any El Niño events in Hocquenghem and Ortlieb (1992) or Ortlieb (1994), and only 1757 appears to be justified as a La Niña year, while the long sequence of Australian droughts from 1861–64 seems incongruent with a 'persistent' La Niña period. The next longest sequences are five-year El Niño and La Niña episodes in 1710–14 and 1764–68 respectively. Of these, there is compelling evidence that at least a good part of the former 'persistent' sequence occurred, although Hocquenghem and Ortlieb (1992) and Ortlieb (1994) fail to identify regional El Niño conditions during this time. However, apart from a La Niña in 1767 there is

**Table 2** Periods of Quinn ENSO (QU), Nile Flood (NI), Indian Monsoon Rainfall (IR), North China Rainfall (NCR), NE Brazil Drought (BD), Southern Chile Rainfall (SCR), Indonesian East Monsoon Drought (IMD), Australian Drought (AD), South African Summer Rainfall (SASR) from Lindesay and Vogel (1990) from Quinn (1993) and Whetton and Rutherfurd (1994), and their relationship to El Niño and La Niña sequences defined by the SOI reconstruction from 1706 to 1875. Recent re-evaluations of regional South American Quinn El Niño dates by Hocquenghem and Ortlieb (1992) and/or Ortlieb (1994) are shown by the symbol # after the year designation

Large blocks of light (dark) shading links evidence suggesting protracted El Niño (La Niña) conditions.

❊ = El Niño
☼ = La Niña
✚ = Rainfall/flood occurrence
■ = Drought/rainfall deficiency
⊕ / Θ = Category ignored in persistence consideration

‖ = Extended periods of rainfall deficiency or drought
| = Extended periods of rainfall excess or flooding

| YEAR | QU | NI | IR | NCR | BD | SCR | IMD | AD | SASR | SOI REC EL NIÑO | SOI REC LA NIÑA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1706 | | | | | | | | | | ❊ | |
| 1707 | ❊ | ✚ | | | | | | | | | ☼ |
| 1708 | ❊ | | | ■ | | | | | | ❊ | |
| 1709 | ❊ | ■ | ■ | ✚ | | | ■ | | | | ☼ |
| 1710 | | ✚ | | | | | | | | ❊ | |
| 1711 | | | | ■ | | | | | | ❊ | |
| 1712 | | | | | | | | | | ❊ | |
| 1713 | ❊ | ■ | ‖ | ⊕ | | | | | | ❊ | |
| 1714 | ❊ | ■ | ‖ | ■ | | | | | | ❊ | |
| 1715 | ❊ | ■ | ‖ | ✚ | | | | | | | ☼ |
| 1716 | ❊ | ■ | ‖ | ✚ | | | | | | | ☼ |
| 1717 | | | | | | | | | | | ☼ |
| 1718 | ❊ | | ■ | | | | | | | ❊ | |
| 1719 | | | | ⊕ | | | | | | ❊ | |
| 1720# | ❊ | ■ | | | | | | | | ❊ | |
| 1721 | | | | ■ | | | | | | ❊ | |
| 1722 | | ✚ | | Θ | | | | | | | ☼ |
| 1723# | ❊ | ■ | | | | | | | | ❊ | |
| 1724 | | ✚ | | | | | | | | ❊ | |
| 1725 | | ■ | | ✚ | | | | | | | ☼ |
| 1726 | | | | | | | | | | ❊ | |
| 1727 | | ✚ | | | | | | | | ❊ | |
| 1728# | ❊ | | | | | | | | | | ☼ |
| 1729 | | | | Θ | | | | | | | ☼ |
| 1730 | | | | ✚ | | | | | | | ☼ |
| 1731 | ❊ | ■ | | ■ | | | | | | ❊ | |
| 1732 | | ✚ | | ■ | | | | | | ❊ | |
| 1733 | | | ■ | ✚ | | | | | | | ☼ |
| 1734 | ❊ | ■ | | | | | | | | ❊ | |
| 1735 | | | | ■ | | | | | | ❊ | |
| 1736 | ❊ | ✚ | | ✚ | | | | | | | ☼ |

**Table 2** Continued

| YEAR | QU | NI | IR | NCR | BD | SCR | IMD | AD | SASR | SOI REC EL NIÑO | SOI REC LA NIÑA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1737 | ✲ | ■ | ■ | ⊕ | | | | | | ✲ | |
| 1738 | | + | | ■ | | | | | | ✲ | |
| 1739 | | | ■ | + | | | | | | | ☼ |
| 1740 | ✲ | | | | | | | | | ✲ | |
| 1741 | | | | | | | | | | ✲ | |
| 1742 | | | | + | | | | | | | ☼ |
| 1743 | | ■ | | ■ | | | | | | | ☼ |
| 1744# | ✲ | ■ | ■ | | | | | | | ✲ | |
| 1745 | | | | | | | | | | ✲ | |
| 1746# | | | ■ | ⊕ | | | | | | ✲ | |
| 1747# | ✲ | + | ■ | | | | | | | ✲ | |
| 1748# | ✲ | ■ | | ■ | | | | | | | ☼ |
| 1749 | | | | ⊕ | | | | | | ✲ | |
| 1750 | ✲ | | | | | | | | | ✲ | |
| 1751# | ✲ | + | | + | | | | | | ✲ | |
| 1752 | | ■ | ■ | ■ | | | | | | | ☼ |
| 1753 | | ■ | | | | | | | | | ☼ |
| 1754 | ✲ | ■ | | | | | | | | | ☼ |
| 1755 | ✲ | | | + | | | | | | | ☼ |
| 1756 | ✲ | | | | | | | | | | ☼ |
| 1757 | | + | | + | | | | | | | ☼ |
| 1758 | ✲ | ■ | | ■ | | | | | | | ☼ |
| 1759 | | ■ | | ■ | | | | | | ✲ | |
| 1760 | | + | | | | | | | | ✲ | |
| 1761 | ✲ | | | + | | | | | | | ☼ |
| 1762 | ✲ | ■ | | | | | | | | ✲ | |
| 1763 | | + | | ■ | | | | | | ✲ | |
| 1764# | ✲ | + | | | | | | | | | ☼ |
| 1765 | ✲ | ■ | | ■ | | | | | | | ☼ |
| 1766 | ✲ | ■ | | | | | | | | | ☼ |
| 1767 | | + | | + | | | | | | | ☼ |
| 1768# | ✲ | + | | ■ | | + | | | | | ☼ |
| 1769 | ✲ | ■ | ■ | ■ | | | | | | ✲ | |
| 1770 | | + | ■ | | | | | | | ✲ | |
| 1771 | | + | | + | | | | | | ✲ | |
| 1772 | ✲ | ■ | | | ■ | | | | | | ☼ |
| 1773 | ✲ | ■ | | | | | | | | | ☼ |
| 1774 | | | | ■ | | | | | | ✲ | |
| 1775 | | + | | + | | | | | | ✲ | |
| 1776 | ✲ | ■ | | + | | | | | | | ☼ |

**Table 2** Continued

| YEAR | QU | NI | IR | NCR | BD | SCR | IMD | AD | SASR | SOI REC EL NIÑO | SOI REC LA NIÑA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1777 | ✽ | | | | ■ | | | | | | ☼ |
| 1778 | ✽ | | | ■ | ■ | | | | | | ☼ |
| 1779 | | ✚ | | ✚ | | | | | | | ☼ |
| 1780 | | ✚ | | ✚ | | | | | | ✽ | |
| 1781 | | ✚ | | ✚ | | | | | | | ☼ |
| 1782 | ✽ | ■ | ■ | ✚ | | | | | | | ☼ |
| 1783# | ✽ | ■ | ■ | | | ✚ | | | | ✽ | |
| 1784 | ✽ | ■ | ■ | ■ | ■ | | | | | ✽ | |
| 1785 | ✽ | ■ | | ■ | | | | | | | ☼ |
| 1786 | ✽ | ✚ | | | ■ | | | | | | ☼ |
| 1787 | | ✚ | | | | | | | | ✽ | |
| 1788 | | | | | | | | | | ✽ | |
| 1789 | | | | ✚ | | | | | | | ☼ |
| 1790 | ✽ | ■ | ■ | ✚ | ■ | | | ■ | | | ☼ |
| 1791# | ✽ | ■ | ■ | | ■ | | | ■ | | ✽ | |
| 1792 | ✽ | ■ | ■ | ■ | ■ | | | | | ✽ | |
| 1793 | ✽ | ■ | | ⊕ | ■ | | | | | ✽ | |
| 1794 | ✽ | ■ | | ✚ | | | | ■ | | | ☼ |
| 1795 | ✽ | ■ | | | | | | ■ | | ✽ | |
| 1796 | ✽ | ■ | | | | | | ■ | | ✽ | |
| 1797 | ✽ | ■ | | | | | | ■ | | | ☼ |
| 1798 | | ✚ | | | | | | ■ | | | ☼ |
| 1799 | ✽ | ■ | ■ | | | | | ■ | | ✽ | |
| 1800 | | ✚ | | | | | | | | ✽ | |
| 1801 | | | | | | | | | | | ☼ |
| 1802 | ✽ | | ■ | | | | | | | | ☼ |
| 1803# | ✽ | ■ | ■ | | | | | ■ | | ✽ | |
| 1804# | ✽ | | ■ | | ■ | | | ■ | | ✽ | |
| 1805 | | | | Θ | | | | | | | ☼ |
| 1806 | ✽ | ■ | ■ | ✚ | | | | | | | ☼ |
| 1807 | ✽ | ■ | ■ | | | | | | | ✽ | |
| 1808 | | | | ✚ | | | | | | | ☼ |
| 1809 | | | | | ■ | | | | | | ☼ |
| 1810 | ✽ | | | | ■ | | | ■ | | ✽ | |
| 1811 | | | | | | | | | | ✽ | |
| 1812 | ✽ | ■ | ■ | | | | | | | | ☼ |
| 1813 | | | ■ | ■ | | | | | | | ☼ |
| 1814# | ✽ | ■ | | ■ | ■ | | | ■ | | ✽ | |
| 1815 | | | | ⊕ | | | | | | ✽ | |
| 1816 | | | | ⊕ | ■ | | | | | ✽ | |

**Table 2** Continued

| YEAR | QU | NI | IR | NCR | BD | SCR | IMD | AD | SASR | SOI REC EL NIÑO | SOI REC LA NIÑA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1817# | ✼ | | | ■ | ■ | ✚ | | ■ | | | ☼ |
| 1818 | | | | ■ | | | | | | | ☼ |
| 1819# | ✼ | | ■ | ⊕ | | ✚ | | ■ | | | ☼ |
| 1820# | | | ■ | ■ | | ✚ | | | | | ☼ |
| 1821 | ✼ | | | | | ✚ | | ■ | | ✼ | |
| 1822 | | | | ✚ | | | | | | ✼ | |
| 1823 | | | ■ | ✚ | | | | | ✚ | | ☼ |
| 1824# | ✼ | ■ | ■ | ■ | ■ | | | ■ | | ✼ | |
| 1825 | | ■ | ■ | ■ | ■ | | | | ■ | ✼ | |
| 1826 | | ✚ | | ✚ | | | | | | | ☼ |
| 1827# | ✼ | ✚ | ■ | | ■ | ✚ | | | ■ | ✼ | |
| 1828# | ✼ | ■ | ■ | | | ✚ | | ■ | ■ | ✼ | |
| 1829# | | ✚ | | | | ✚ | | | ■ | ✼ | |
| 1830 | ✼ | ■ | | | | | | | ■ | | ☼ |
| 1831 | | | | ✚ | | | | | ✚ | | ☼ |
| 1832# | ✼ | ■ | ■ | | | | | ■ | ✚ | | ☼ |
| 1833# | ✼ | ■ | ■ | ⊕ | ■ | ✚ | ■ | | ■ | ✼ | |
| 1834 | | ✚ | | | | | | | ■ | ✼ | |
| 1835 | ✼ | ■ | | ■ | | | ■ | | | ✼ | |
| 1836 | ✼ | ■ | | ■ | | | | | | | ☼ |
| 1837# | ✼ | ■ | ■ | ■ | ■ | ✚ | | ■ | ■ | ✼ | |
| 1838 | ✼ | ■ | ■ | | | | | | ■ | ✼ | |
| 1839 | ✼ | ■ | | ⊕ | | | | | ■ | ✼ | |
| 1840 | | ✚ | | | | | | | ✚ | ✼ | |
| 1841# | | ✚ | | | | | | | ■ | | ☼ |
| 1842 | | | | ■ | | | | | ■ | | ☼ |
| 1843# | | | | ⊕ | | ✚ | | | | ✼ | |
| 1844# | ✼ | ■ | ■ | ⊕ | ■ | | ■ | | ✚ | ✼ | |
| 1845# | ✼ | ■ | | | ■ | ✚ | ■ | ■ | ✚ | ✼ | |
| 1846 | ✼ | ✚ | | ■ | | | | | ■ | ✼ | |
| 1847 | | | | ■ | | | | | ✚ | | ☼ |
| 1848 | | ✚ | | ✚ | | | | | ✚ | ✼ | |
| 1849 | | ✚ | | ✚ | | | | | ■ | ✼ | |
| 1850# | ✼ | ■ | ■ | ■ | ■ | ✚ | ■ | ■ | | ✼ | |
| 1851# | | ✚ | | | | ✚ | | | ■ | | ☼ |
| 1852 | ✼ | ■ | | | | | | | ✚ | ✼ | |
| 1853 | ✼ | ✚ | ■ | ✚ | | | ■ | ■ | ✚ | ✼ | |
| 1854# | ✼ | ✚ | | | | | | ■ | | | ☼ |
| 1855# | ✼ | ■ | ■ | ✚ | | ✚ | ■ | | | | ☼ |
| 1856# | | ✚ | | ■ | | ✚ | | | ✚ | ✼ | |

**Table 2** Continued

| YEAR | QU | NI | IR | NCR | BD | SCR | IMD | AD | SASR | SOI REC EL NIÑO | SOI REC LA NIÑA |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1857# | ❊ | ■ ‖ | | ■ | | | ■ | ■ | ✚ | | ☀ |
| 1858# | ❊ | ■ ‖ | | | | ✚ | | | ■ | ❊ | |
| 1859 | ❊ | ■ ‖ | | | | | | | ■ | | ☀ |
| 1860# | ❊ | ✚ | ■ | ✚ | | ✚ | | | | | ☀ |
| 1861 | | ✚ | | | | | | ■ ‖ | ■ | | ☀ |
| 1862# | ❊ | | | ■ | | | | ■ ‖ | ■ | | ☀ |
| 1863 | | ✚ | | ✚ | | | | ■ ‖ | ✚ | | ☀ |
| 1864# | ❊ | ■ | ■ ‖ | | | ✚ | ■ | ■ ‖ | ✚ | | ☀ |
| 1865 | ❊ | | ■ ‖ | | | | | | ■ | ❊ | |
| 1866# | ❊ | ✚ | ■ ‖ | ✚ | | | ■ | ■ | ■ | | ☀ |
| 1867 | ❊ | ■ | | ■ | ■ | | | | ✚ | | ☀ |
| 1868# | ❊ | ■ | ■ | ⊕ | | ✚ | ■ | ■ | | ❊ | |
| 1869 | ❊ | ✚ | ■ | | | | | | ■ | ❊ | |
| 1870 | | ✚ | | ⊖ | | | | | ✚ | | ☀ |
| 1871# | ❊ | | ■ | ✚ | | | | ■ | | | ☀ |
| 1872 | | ✚ | | | | | | | | | ☀ |
| 1873 | ❊ | ■ | ■ | ⊕ | | | | | ■ | ❊ | |
| 1874 | ❊ | ✚ | | ⊕ | | | | ■ | | ❊ | |
| 1875 | | | | | | | | | ✚ | ❊ | |

no documentary support for 1764–68 being part of a 'persistent' episode. There is generally strong evidence that four-year 'persistent' El Niño phases in 1718–21, 1744–47, 1837–40 and 1843–46 have validity. However, none of the four-year La Niñas (1776–79 and 1817–20) are verifiable by the documentary evidence. The remaining three-year reconstructed ENSO phases show very contrasting relationships with the various historical data. Of these, the most supported are the El Niños of 1749–51, 1791–93, 1814–16 and 1833–35 and the La Niñas of 1728–30 and 1870–72. The remaining 'persistent' events of either phase show usually some year with documentary elements that relate to the correct ENSO episode, but not the full sequence. Interestingly, of the sequences with poor support in the historical records there is perhaps some clustering around the mid-eighteenth and nineteenth epochs of weak variance in the 3.53 and 4.07 year SSA bands of the reconstructed SOI.

Despite caveats about the quality of the early documentary evidence discussed above, it would seem that long El Niño sequences are better supported than are the 'persistent' La Niña phases. The result is that there remain about four or five 'persistent' El Niño sequences occurring in each of the eighteenth and nineteenth centuries.

## Conclusions

Evaluation of the instrumental record of the SOI, and Niño 3 and 4 CEP-EEP SST series has revealed that 'persistent' event sequences (as defined here) have occurred previously over the past 100 to 120 odd years. Over this time, monthly instrumental data indicates that there have been four 'persistent' El Niño and six 'persistent' La Niña episodes. Although the most recent event is the longest in duration, it shows similar temporal behaviour to the 1911–15 and 1939–42 sequences. There are also other ENSO episodes which show 'persistent' features. Interestingly, both 'persistent' warm and cold event sequences have occurred with similar frequency and magnitude in the observed record. Analyses of filtered series reveal that the bulk of the ENSO signal is contained in QB and LF components. Superposition of these components results in enhancement and annulment of the overall signal, and so modulates the magnitude and frequency of El Niño and La Niña events. 'Persistent' ENSO phases reflect the dominance of a pronounced LF signal in the climate system, but may also be modulated by distinct quasidecadal and interdecadal modes of variability.

An examination of historical documentary and selected palaeoclimatic records of ENSO suggests that 'persistent' event sequences of three years' duration and longer are not rare or unusual, and have occurred with around the same range of event length during the past. It is estimated that El Niño events of this nature have occurred with a frequency of around four or five times per century when matched against available historical documentary evidence (Table 2). This estimate compares favourably with the instrumentally based data which indicates a frequency of around six times per century. However, La Niña events tend to be poorly resolved in the longer historical documentary records.

No evidence for an enhanced greenhouse influence on the frequency or duration of 'persistent' ENSO event sequences was found among the ensemble of instrumentally based, documentary and proxy data. However, analyses of both instrumental and proxy data show that decadal-multidecadal signals are present in the ENSO record. In general, such low frequency fluctuations are poorly understood and may explain recent difficulties in forecasting ENSO and, as noted above, have an influence on the occurrence of protracted ENSO phases. It is probable that they are linked to other features of the global climate system and require further investigation.

Recent recovery of pressure data for Jakarta (Konnen *et al*., 1997) and Madras (Carroll, 1997, personal communication) has extended the MSLP time series at these stations back to 1841 (1829 using June–November raindays) and 1796 respectively. Together with MSLP series from stations across the Indo-Australasian region that extend back to the 1840s–50s, such as Trivandrum (India), Colombo (Sri Lanka) and Singapore, the above provides a longer measure of the Southern Oscillation, or at least one dipole of it. This may be further enhanced if it were possible to piece together the Sydney (Australia) MSLP record back to the start of Australian colonization by Europeans in 1788 (Chenoweth, 1996). Apart from the documentary evidence described in this paper, these MSLP series constitute the only observational MSLP database with which the proxy-based SOI reconstruction can be assessed. A future paper examining such relationships is envisaged.

## Acknowledgements

The participation of one of us (RJA) in this study was made possible under the CSIRO Climate Change Research Program, funded in part by the Australian Federal Government's Commonwealth Department of Environment, Sport and Territories, and the State Governments of the Northern Territory, Queensland and Western Australia. This research was also funded for one of us (RDD) under the NOAA Grant No. NA56GP0217. Raw data series from coral cores were kindly provided by Dr Julia Cole, INSTAAR, University of Colorado, Boulder, Colorado, USA (Tarawa, Kiribarti), Dr Ellen Druffel, Department of Geosciences, University of California-Irvine, California, USA (Abraham Reef, Great Barrier Reef), Dr Rob Dunbar, Department of Geology, Rice University, Houston, Texas, USA (Galapagos Island) and Dr Janice Lough, AIMS, Townsville, Queensland, Australia (Pandora Reef, Great Barrier Reef). Raw data series from tree-rings were kindly provided by Drs David Stahle and Malcolm Cleaveland, Department of Geography, University of Arkansas, Fayetteville, Arkansas, USA. This paper is Lamont-Doherty Earth Observatory Contribution No. 5887. The manuscript and tables were typed and prepared by Gail Willetts.

## References

**Allan, R.J.** 1993: Historical fluctuations in ENSO and teleconnection structure since 1879: near-global patterns. *Quaternary Australasia*, 11, 17–27.

—— 1998: ENSO variability in the last 150 years. In Diaz, H.F. and Markgraf, V., editors, El Niño and the Southern Oscillation: multiscale variability and its impacts on natural ecosystems and society. Cambridge: Cambridge University Press, in press.

**Allan, R.J., Beard, G., Close, A., Herczeg, A.L., Jones, P.D.** and **Simpson, H.J.** 1996a: Mean sea level pressure indices of the El Niño-Southern Oscillation: Relevance to stream discharge in southeastern Australia. *CSIRO Division of Water Resources Report* 96/1.

**Allan, R.J., Folland, C.K., Parker, D.E., Mann, M.E., Smith, I.N., Basnett, T.A.** and **Rayner, N.A.** 1998: ENSO and large-scale modes of climatic variability in global instrumental data. *Science*, in press.

**Allan, R.J., Lindesay, J.A.** and **Parker, D.E.** 1996b: *El Niño Southern Oscillation and Climatic Variability*. Melbourne: CSIRO Publishing, 405 pp.

**Allan, R.J., Nicholls, N., Jones, P.D.** and **Butterworth, I.J.** 1991: A further extension of the Tahiti-Darwin SOI, early ENSO events and Darwin pressure. *J. Climate* 4, 743–49.

**Bradley, R.S.** and **Jones, P.D.** 1995: *Climate since* AD *1500*. London: Routledge, 706 pp.

**Brassington, G.B.** 1997: The modal evolution of the Southern Oscillation. *J. Climate* 10, 1021–34.

**Caviedes, C.N.** 1991: Five hundred years of hurricanes in the Caribbean: their relationship to global climate variabilities. *GeoJournal* 23, 301–10.

**Charles, C.D., Hunter, D.E.** and **Fairbanks, R.G.** 1997: Interaction between the ENSO and the Asian Monsoon in a coral record of tropical climate. *Science* 277, 925–28.

**Chenoweth, M.** 1996: Ship's logbooks and 'The year without a summer'. *Bull. Amer. Meteor. Soc.* 77, 2077–93.

**Cleaveland, M.K., Cook, E.R.** and **Stahle, D.W.** 1992: Secular variability of the Southern Oscillation detected in tree-ring data from Mexico and the southern United States. In Diaz, H.F. and Markgraf, V., editors, *El Niño: historical and paleoclimatic aspects of the Southern Oscillation*, Cambridge: CUP, 271–91.

***Climate System Monitoring Monthly Bulletin***, 1990: Issue No. 12, WCDMP, UNEP, WMO.

—— 1992: Issue No. 1, WCDMP, UNEP, WMO.

—— 1993a: Issue No. 1, WCDMP, UNEP, WMO.

—— 1993b: Issue No. 12, WCDMP, UNEP, WMO.

**Cole, J.E.** 1997: ARTS: annual records of tropical systems – a PAGES/CLIVAR initiative. *CLIVAR-Exchanges* 2, 6–9.

**Cole, J.E., Fairbanks, R.G.** and **Shen, G.T.** 1993: Recent variability in the Southern Oscillation: isotopic results from a Tarawa atoll coral. *Science* 260, 1790–93.

**Cook, E.R.** 1995: Temperature histories from tree rings and corals. *Clim. Dyn*. 11, 211–22.

**D'Arrigo, R.D., Jacoby, G.C.** and **Krusic, P.J.** 1994: Progress in Dendroclimatic Studies in Indonesia. *TAO* 5, 349–63.

**Diaz, H.F.** and **Pulwarty, R.S.** 1994: An analysis of the time scales of variability in centuries-long ENSO-sensitive records in the last 1000 years. *Climatic Change* 26, 317–42.

**Druffel, E.R.M.** and **Griffin, S.** 1993: Large variations of surface ocean radiocarbon: evidence of circulation changes in the southwestern Pacific. *J. Geophys. Res.* 98, 20, 249–59.

**Dunbar, R.B, Wellington, G.M., Colgan, M.W.** and **Glynn, P.W.** 1994: Eastern Pacific sea surface temperature since 1600 AD: the $^{18}$O record of climate variability in Galapagos corals. *Paleoceanography* 9, 291–315.

**Gage, K.S., McAfee, J.R.** and **Williams, C.R.** 1996: Recent changes in tropospheric circulation over the central equatorial Pacific. *Geophys. Res. Lett.* 23, 2149–52.

**Glantz, M.H., Katz, R.W.** and **Nicholls, N.** 1991: Teleconnections linking worldwide climate anomalies. New York: Cambridge University Press, 535pp.

**Goddard, L.** and **Graham, N.E.** 1997: El Niño in the 1990s. *J. Geophys. Res.* 102, 10,423–36.

**Graham, N.E.** 1994: Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: observations and model results. *Clim. Dyn.* 10, 135–62.

**Gu, D.** and **Philander, S.G.H.** 1995: Secular changes of annual and interannual variability in the tropics during the past century. *J. Climate* 8, 864–76.

**Halpert, M.S.** and **Ropelewski, C.F.** 1992: Surface temperature patterns associated with the Southern Oscillation. *J. Climate* 5, 577–93.

**Harrison, D.E.** and **Larkin, N.K.** 1997: Darwin sea level pressure, 1876–1996: evidence for climate change? *Geophys. Res. Lett.* 24, 1779–82.

**Hocquenghem, A.M.** and **Ortlieb, L.** 1992: Eventos El Niño y Iluvias anormales en la costa del Peru: siglos XVI–XIX. *Bull. Inst. Fr. Etud. Andines, Lima* 21(1), 197–278.

**Hughes, M.K.** and **Diaz, H.F.** 1994: Was there a 'Medieval Warm Period', and if so, where and when? *Climatic Change* 26, 109–42.

**Hunt, B.G.** 1998: Natural climatic variability as an explanation for historical climatic fluctuations. *Climatic Change* 38, 133–57.

**Isdale, P.** and **Kotwicki, V.** 1987: Lake Eyre and the Great Barrier Reef: a palaeohydrological ENSO connection. *J. Roy. Geogr. Soc. Austr. S. Aust. Branch* 87, 44–55.

**Jacoby, G.C.** and **D'Arrigo, R.D.** 1990: Teak (*Tectona grandis* L.F.): a tropical species of large-scale dendroclimatic potential. *Dendrocronologia* 8, 83–98.

**Jiang, F.-F., Neelin, J.D.** and **Ghil, M.** 1995: Quasi-quadrennial and quasi-biennial variability in the equatorial Pacific. *Clim. Dyn.* 12, 101–12.
**Jones, P.D.** 1988: The influence of ENSO on global temperatures. *Climate Monitor* 17, 80–89.
**Kelly, P.M.** and **Jones, P.D.** 1996: Removal of the El Niño-Southern Oscillation signal from the gridded surface air temperature data set. *J. Geophys. Res.* 101, 19,013–22.
**Kerr, R.A.** 1993: El Niño metamorphosis throws forecasters. *Science* 262, 656–57.
—— 1994: Did the tropical Pacific drive the world's warming? *Science* 266, 544–45.
**Kestin, T.S., Karoly, D.J., Yano, J.-I.** and **Rayner, N.A.** 1998: Time-frequency variability of ENSO and stochastic simulations. *J. Climate* 11, 2258–72.
**Kiladis, G.N.** and **Diaz, H.F.** 1989: Global climatic anomalies associated with extremes in the Southern Oscillation. *J. Climate* 2, 1069–90.
**Kleeman, R., Colman, R.A., Smith, N.R.** and **Power, S.B.** 1996: A recent change in the mean state of the Pacific basin: observational evidence and atmospheric and oceanic responses. *J. Geophys. Res.* 101, 20,483–99.
**Konnen, G.P., Jones, P.D., Kaltofen, M.H.** and **Allan, R.J.** 1997: Pre-1866 extensions of the Southern Oscillation Index using early Indonesian and Tahitian meteorological readings. *J. Climate* 11, 2325–39.
**Kotwicki, V.** and **Isdale, P.** 1991: Hydrology of Lake Eyre, Australia: El Niño link. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 84, 87–98.
**Lamb, H.H.** 1982: *Climate, history and the modern world.* London: Methuen, 387 pp.
**Latif, M.** and **Barnett, T.P.** 1994a: Causes of decadal climate variability over the North Pacific and North America. *Max-Planck-Institut fur Meteorologie,* Report No. 141, 17 pp.
—— 1994b: Causes of decadal climate variability over the North Pacific and North America. *Science* 266, 634–37.
**Latif, M., Groetzner, A., Munnich, M., Maier-Reimer, E., Venzke, S.** and **Barnett, T.P.** 1996: A mechanism of decadal climate variability. *Max-Planck-Institut fur Meteorologie*, Report No. 187, 43 pp.
**Latif, M., Kleeman, R. and Eckert, C.** 1995: Greenhouse warming, decadal variability, or El Niño? An attempt to understand the anomalous 1990s. *Max-Planck-Institut fur Meteorologie*, Report No. 175, 51 pp.
—— 1997: Greenhouse warming, decadal variability, or El Niño? An attempt to understand the anomalous 1990s. *J. Climate 10, 2221–39.*
**Lindesay, J.A.** and **Vogel, C.H.** 1990: Historical evidence for Southern Oscillation-southern African rainfall relationships. *Int. J. Climatol*. 10, 679–89.
**Liu, W.T., Tang, W.** and **Fu, L.-L.** 1995: Recent warming event in the Pacific may be an El Niño. *EOS Trans. AGU* 76, 429 and 437.
**Lough, J.M. and Fritts, H.C.** 1985: The Southern Oscillation and tree rings: 1600–1961. *J. Clim. Appl. Meteor.* 24, 952–66.
**Mabres, A., Woodman R. and Zeta R.,** 1993: Some additional historical notes on the chronology of the El Niño. *Bull. Inst. Fr. Etud. Andines, Lima* 22(1), 395–406.
**Mann, M.E.** and **Park, J.** 1996: Joint spatiotemporal modes of surface temperature and sea level pressure variability in the Northern Hemisphere during the last century. *J. Climate* 9, 2137–62.
—— 1998: Oscillatory spatiotemporal signal detection in climate studies. *Adv. Geophys.*, in press.
**McPhaden, M.J.,** 1993: TOGA-TAO and the 1991–93 El Niño-Southern Oscillation Event. *Oceanography* 6 (2), 36–44.
**Miller, A.J., Cayan, D.R., Barnett, T.P., Graham, N.E.** and **Oberhuber, J.M.** 1994a: Interdecadal variability of the Pacific Ocean: model response to observed heat flux and wind stress anomalies. *Clim. Dyn.* 9, 287–302.
—— 1994b: The 1976–77 climate shift of the Pacific Ocean. *Oceanography* 7, 21–26.
**Moore, M.D., Charles, C.** and **Wells, L.** 1998: A Coral Index of ENSO and Lower Frequency Climate Variability in the Equatorial west Pacific. *J. Geog. Res. Oceans*, in press.
**Ortlieb, L.** 1994: Major historical rainfalls in central Chile and the chronology of ENSO events during the XVth–XIXth centuries. *Revista Chilena Historia Natural* 67, 463–85.
**Ortlieb, L.** and **Machare, J.** 1993: Former El Niño Events: records from western South America. *Global Planetary Change* 7, 181–202.
**Parker, D.E., Jackson, M.** and **Horton, E.B.** 1995: The GISST2.2 sea surface temperature and sea-ice climatology. *Climate Research Tech. Note CRTN* No 63, Hadley Centre for Climate Prediction and Research, Meteorological Office, Bracknell, Berkshire, UK, 35 pp.
**Pittock, A.B.** 1974: Global interactions in stratosphere and troposphere. Proc. Int. Conf. Structure, Composition and Geberal Circulation of the Upper and Lower Atmospheres and Possible Anthropogenic Perturbations, Vol. II, IUGG, IAMAP, The Australian Academy of Science, US Dept of Transportation, 716–26.
**Quinn, W.H.** 1992: A study of Southern Oscillation-related climatic activity for AD 622–1900 incorporating Nile River flood data. In Diaz, H.F. and Markgraf, V., editors, *El Niño: historical and paleoclimatic aspects of the Southern Oscillation*, Cambridge: CUP, 119–49.
—— 1993: The large-scale ENSO event, the El Niño and other important regional features. In Machare, J. and Ortlieb, L., editors, Records of El Niño phenomena and ENSO events in South America, *Bulletin de l'Instîtut Français d'Etudes Andines* 22(1), 13–34.
**Quinn, W.H.** and **Neal, V.T.** 1983: Long-term variations in the Southern Oscillation, El Niño and Chilean subtropical rainfall. *Fish. Bull.* 81, 363–74.
—— 1995: The historical record of El Niño events. In Bradley, R.S. and Jones, P.D., editors, *Climate since AD 1500, London: Routledge, 623–48.*
**Quinn, T.M., Crowley, T.J.** and **Taylor, F.W.** 1996: New stable isotope results from a 173-year coral from Espiritu Santo, Vanuatu. *Geophys. Res. Lett.* 23, 3413–16.
**Quinn, W.H., Neal, V.T.** and **Antunez de Mayolo, S.E.** 1987: El Niño occurrences over the past four and a half centuries. *J. Geophys. Res.* 92, 14,449–61.
**Quinn, T.M., Taylor, F.W.** and **Crowley, T.J.** 1993: A 173-year stable isotope record from a tropical South Pacific coral. *Quat. Sci. Rev.* 12, 407–18.
**Quinn, W.H., Zopf, D.O., Short, K.S.** and **Kuo Yang, R.T.W.** 1978: Historical trends and statistics of the Southern Oscillation, El Niño and Indonesian droughts. *Fish. Bull.* 76, 663–78.
**Rajagopalan, B., Lall, U.** and **Cane, M.A.** 1997: Anomalous ENSO occurrences: an alternative view. *J. Climate* 10, 2351–57.
**Rayner, N.A., Folland, C.K., Parker, D.E.** and **Horton, E.B.** 1995: A new global sea-ice and sea surface temperature (GISST) data set for 1903–1994 for forcing climate models. *Climate Research Tech. Note CRTN* No 69, Hadley Centre for Climate Prediction and Research, Meteorological Office, Bracknell, Berkshire, UK, 14 pp.
**Ropelewski, C.F.** and **Halpert, M.S.** 1987: Global and regional scale precipitation patterns associated with the El Niño/Southern Oscillation. *Mon. Wea. Rev.* 115, 1606–26.
—— 1989: Precipitation patterns associated with the high index phase of Southern Oscillation. *J. Climate* 2, 268–84.
**Self, S., Rampino, M.R., Zhao, J.** and **Katz, M.G.** 1997: Volcanic aerosol perturbations and strong El Niño events: No general correlation. *Geophys. Res. Lett.* 24, 1247–50.
**Stahle, D.W.** and **Cleaveland, M.K.** 1993: Southern Oscillation extremes reconstructed from tree-rings of the Sierra Madre Occidental and Southern Great Plains. *J. Climate* 6, 129–40.
**Stahle, D.W., D'Arrigo, R.D., Cleaveland, M.K., Krusic, P.J., Allan, R.J., Cook, E.R., Cole, J.E., Dunbar, R.B., Therrell, M.D., Gay, D.A., Moore, M., Stokes, M.A., Burns, B.T.** and **Thompson, L.G.** 1998: Experimental multiproxy reconstructions of the Southern Oscillation. *Bull. Amer. Meteor. Soc.* 79, 2137–52.
**Stearns, S.D.** and **Hush, D.R.** 1990: *Digital signal analysis* (second edition). New Jersey: Prentice-Hall, 440 pp.
**Stewart, B.J., Tickle, K.S.,** and **Isdale, P.J.** 1989: Reconstruction of past hydrological data in the Burdekin Basin. *Hydrology and Water Resources Symposium*, Christchurch, New Zealand, 28–30 November.
**Torrence, C.** and **Compo, G.P.** 1998: A practical guide to wavelet analysis. *Bull. Amer. Meteor. Soc.* 79, 61–78.
**Torrence, C.** and **Webster, P.J.** 1998: The annual cycle of persistence in the El Niño/Southern Oscillation. *Quart. J. Roy. Meteor. Soc.* 124, 1985–2004.
**Trenberth, K.E.** and **Hoar, T.J.** 1996: The 1990–1995 El Niño Southern Oscillation event. *Geophys. Res. Lett.* 23, 57–60.
—— 1997: El Niño and climate change. *Geophys. Res. Lett.* 24, 3057–60.
**Trenberth, K.E.** and **Hurrell, J.W.** 1994: Decadal atmosphere-ocean variations in the Pacific. *Clim. Dyn.* 9, 303–19.
**Troup, A.J.** 1965: The Southern Oscillation. *Quart. J. Roy. Meteor. Soc.* 91, 490–506.
**Tudhope, A.W., Shimmield, G.B., Chilcott, C.P., Jebb, M., Fallick,**

**A.E.** and **Dalgleish, A.N.** 1995: Recent changes in the far western equatorial Pacific and their relationship to the Southern Oscillation; oxygen isotope records from massive corals, Papua New Guinea. *Earth Planetary Sci. Lett.* 136, 575–90.

**Wang, B.,** 1995: Interdecadal changes in El Niño onset in the last four decades. *J. Climate* 8, 267–85.

**Wang, B.** and Wang, Y. 1996: Temporal structure of the Southern Oscillation as revealed by waveform and wavelet analysis. *J. Climate* 9, 1586–98.

**Wang, X.L.** and **Ropelewski, C.F.** 1995: An assessment of ENSO-scale secular variability. *J. Climate* 8, 1584–99.

**Webster, P.J.** and **Palmer, T.N.** 1997: The past and the future of El Niño. *Nature* 390, 562–64.

**Whetton, P.H.** and **Rutherfurd, I.** 1994: El Niño-Southern Oscillation teleconnections in the Eastern Hemisphere over the last 500 years. *Climatic Change* 28, 221–53.

**Whetton, P.H., Allan, R.J.** and **Rutherfurd, I.** 1996: Historical ENSO teleconnections in the Eastern Hemisphere: comparison with latest El Niño series of Quinn. *Climatic Change* 32, 103–109.

**Young, K.C.** 1993: Detecting and removing inhomogeneities from long-term monthly sea level pressure time series. *J. Climate* 6, 1205–20.