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CLASSIFICATION OF SYNCHRONOUS OCEANIC AND ATMOSPHERIC EL NIÑO-SOUTHERN OSCILLATION (ENSO) EVENTS FOR PALAEOCLIMATE RECONSTRUCTION

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ABSTRACT

Since the mid-1970s, ENSO has changed in character to a predominance of El Niño conditions, the extreme phase of which appears coincidental with increases in global temperature records. Instrumental time series (<150 years) are too short to adequately address the significance of late twentieth-century ENSO variability, thus, multi-century palaeoclimate reconstructions derived from long proxy records are sought. Despite the global influence exerted by ENSO on society, limited consensus exists within the scientific community as to which index best defines the timing, duration and strength of events. Here we address issues associated with the complexity of ENSO characterisation by comparing the 'event capture' ability of two currently used indices of ENSO. It is suggested that the use of a sole ENSO index is undesirable as a given index is only indicative of one physical aspect of the phenomenon, and as such is unlikely to be representative of the wider interactions experienced in the coupled ocean-atmospheric system. In an attempt to describe more of the nature and evolution of ENSO events, the Coupled ENSO Index (CEI) classification scheme was devised to identify synchronous oceanic (Niño 3.4 SST) and atmospheric (Southern Oscillation Index) anomalies associated with ENSO for the instrumental period (1871–2003). The CEI is of practical relevance to the ENSO community as it provides an amplitude preserving instrumental baseline for the calibration of proxy records to reconstruct both components of the ENSO system. Analysis of the nature of instrumental ENSO events from the CEI suggests that the frequency and intensity of post-1970 ENSO events (when 50% of all extreme events identified occur) appears the most anomalous in the context of at least the past century. It is hoped that the CEI will facilitate palaeo-ENSO research to systematically resolve the long-term context of past ENSO behaviour to assess whether the apparently anomalous nature of late twentieth-century variability is unprecedented within existing palaeoclimate archives. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: Niño 3.4 region SSTs; southern oscillation index; discrete event analysis; ENSO classification; El Niño; La Niña; palaeoclimate reconstruction

1. INTRODUCTION

The El Niño-Southern Oscillation (ENSO) phenomenon is a complex interaction of oceanic and atmospheric processes that results in massive redistributions of global weather phenomena. Since the mid-1970s, ENSO has changed in character to a predominance of El Niño conditions, the extreme phase of which appears coincidental with increases in global temperature records (Fedorov and Philander, 2000; Folland *et al.*, 2001; Jones and Mann, 2004; Tsonis *et al.*, 2003). The two most intense El Niño events in more than a century occurred in 1982–1983 and 1997–1998, while the longest event in the instrumental record was experienced between 1990 and 1995 (Allan and D'Arrigo, 1999; Allan *et al.*, 2003; Folland *et al.*, 2001; Trenberth and Hoar, 1996). The long-term context of these apparently anomalous events is still being debated (Crowley, 2000; Folland *et al.*, 2001; Mann, 2003; Soon and Baliunas, 2003). Recent research has sought to further

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clarify whether the modern behaviour of ENSO is indeed a manifestation of human-induced global warming (Folland *et al.*, 2001; Timmermann, 2001; Tsonis *et al.*, 2003), or simply an expression of natural decadal or multi-centennial climate variability (Jones and Mann, 2004).

The phase and strength of ENSO events are typically defined using an index derived from various oceanic and atmospheric records (Allan and D'Arrigo, 1999; Fedorov and Philander, 2000). However, it is recognised that these instrumental time series (<150 years) are too short to adequately address the significance of late twentieth-century and decadal properties of ENSO variability (Allan and D'Arrigo, 1999; Fedorov and Philander, 2000). Thus, multi-century palaeoclimate reconstructions derived from long proxy records, such as annually resolved tree-ring and coral sequences, are required to examine pre-instrumental decadal patterns of climate variability (Jones and Mann, 2004).

The common approach for climate reconstruction from proxies is to use statistical regression to establish a connection between instrumental records and the variability of the proxy over the period of overlap (Jones and Mann, 2004; Jones *et al.*, 2001; Mann, 2002). This calibration process provides a transfer function that enables the proxy to be used as a surrogate of past climate.

Unfortunately, palaeo-ENSO researchers rarely incorporate indices from both components of ENSO into the calibration process, which has resulted in a persistently fragmented description of the coupled ocean–atmosphere system. To date, reconstructive efforts have tended to focus on only one aspect of the ENSO phenomenon, commonly the Southern Oscillation Index (SOI) (Stahle *et al.*, 1998) or oceanic Niño 3 Sea Surface Temperature (SST) region (D'Arrigo *et al.*, 2005; Evans *et al.*, 2002; Mann *et al.*, 1998, 2000), which can only partially characterise ENSO perturbations.

Clarification of the definition of ENSO has long been recognised as an issue of practical relevance by Climate Variability and Predictability (CLIVAR), the largest initiative of the World Climate Research Programme (Trenberth, 1997). Nevertheless, limited consensus exists within the scientific community working on ENSO as to which index best defines ENSO years and the strength, timing and duration of events (Elsey, 2004; Hanley *et al.*, 2003; Trenberth, 1997). ENSO is still inadequately understood because of its complex nature that further complicates efforts to define the morphology of ENSO events (Hanley *et al.*, 2003; Mc Phaden, 2004).

In the absence of a firm consensus, palaeoclimatologists often verify any 'ENSO signal' in a proxy record by comparing it to the suite of historical chronologies of El Niño events first compiled by Quinn *et al.* (1987), most recently revised by Ortlieb (2000). These lists of past El Niño events recorded in South America have been widely viewed as the major reference for any long-term analysis of ENSO. This is despite the fact that the record is only representative of past ENSO conditions experienced in the eastern Pacific teleconnection region, excludes La Niña episodes and is not a direct record of instrumental registration of ENSO conditions.

Furthermore, anomalies in the traditional 'El Niño' region defined by the Niño $1 + 2$ SST zone have long been recognised to fluctuate considerably, relative to the waters further west in the central Pacific or the SOI (e.g. Trenberth and Hoar (1996), and Deser and Wallace (1987)). In fact, using five SST indices and the SOI, Hanley *et al.* (2003) found the east Pacific Niño $1 + 2$ region (i) to be less sensitive to El Niño conditions than the SOI, (ii) to be the least responsive to La Niña conditions and (iii) to include the highest instances of missed events and false positive cases of all the SST indices analysed for El Niño events. This raises serious issues related to the credibility of the uncritical, pervasive use of SSTs from this classically defined 'El Niño' region in any contemporary appraisal of past ENSO behaviour.

Although various lists of instrumental ENSO events are available (e.g. Allan *et al.*, 2003; Kiladis and Diaz, 1989; Trenberth, 1997), there is no established chronology of unambiguous events that combines both oceanic and atmospheric aspects of the coupled phenomenon. This is somewhat surprising considering that the accurate characterisation of past episodes is vital for the ongoing climate prediction efforts related to ENSO (Allan *et al.*, 2003; Folland *et al.*, 2001; Trenberth, 1997). As such, there is a practical need for an index of the synchronous atmosphere–ocean ENSO anomalies that provides a more comprehensive chronology of past ENSO episodes.

This paper addresses the issues associated with the complexity of ENSO characterisation through comparing the 'event capture' ability of two currently used indices of ENSO. Consequently, the Coupled ENSO Index (CEI) is proposed as a composite oceanic (Niño 3.4 SST) and atmospheric (SOI) calibration index for the instrumental period. A list of simultaneous oceanic and atmospheric ENSO anomalies was complied to assist the palaeoenvironmental community in identifying distinct, unambiguous 'ENSO signals' contained within proxy records. This will facilitate the seasonal timing and teleconnection signatures of individual events to be suitably characterised using existing palaeoenvironmental archives and encourage the development of proxy records for use in detecting imprints of past ENSO behaviour.

2. INSTRUMENTAL RECORDS OF ENSO

2.1. Oceanic component of ENSO; El Niño

For the oceanic characterisation of ENSO, we have used the post-1949 SSTs from the Niño 3.4 zone (5 °N–5 °S, 120°–170 °W), representing 40% of the distance between the Niño 3 and Niño 4 SST regions, obtained from the National Oceanic and Atmospheric Administration's (NOAA) Climate Prediction Center (http://www.cpc.ncep.noaa.gov/data/indices/index.html). Higher mean temperatures than the often-quoted Niño 3 zone and its proximity to the west Pacific warm pool and main centres of ocean convection account for the physical importance of the Niño 3.4 region (Trenberth, 1997). Most recently, the significance of this SST region was acknowledged by its selection as the geographical basis for NOAA's operational Oceanic Niño Index (ONI) (Elsey, 2004; Mc Phaden, 2004).

Data from this area represent *in situ* measurements of SST variability, thus are considered to be the best available *direct* record of ENSO conditions. For a detailed analysis of the sensitivity of currently used ENSO SST indices, the reader is referred to the review by Hanley *et al.* (2003).

SSTs were standardised to the 1950–1979 base period and smoothed with a 5-month running mean to minimise intra-seasonal noise (Trenberth, 1997). This 30-year base period avoids the post-1979 bias of El Niño events identified in the literature (Trenberth, 1997; Trenberth and Hoar, 1996). An ENSO event is defined here as a 5-month running mean of SST anomalies from the six consecutive months, with no more than two consecutive neutral months impeding ENSO conditions (Allan and D'Arrigo, 1999; Hanley *et al.*, 2003; Trenberth, 1997). The ±0.5 °C threshold is consistent with the ONI. Following Trenberth (1997), a threshold sensitivity analysis was carried out for the ±0.4 °C ENSO definition given by Trenberth (1997) and Trenberth and Stepaniak (2001) to allow event-capture discrepancies to be investigated.

Pre-1950, we used the Trenberth and Stepaniak (2001) reconstruction of Niño 3.4 SSTs. This was derived from the HadISST (Hadley Centre Sea Ice and Sea Surface Temperature) dataset using $1^\circ \times 1^\circ$ latitude/longitude grids with all area averages and interpolation computations calculated at full resolution (Trenberth and Stepaniak, 2001). The period of overlap between observational and reconstructed SSTs was analysed to assess the ability of the latter to serve as a reliable pre-instrumental surrogate, details of which are found in Section 3.1.

2.2. Atmospheric component of ENSO; Southern Oscillation

For the atmospheric characterisation of ENSO, we used the SOI sourced from the Australian Bureau of Meteorology (http://www.bom.gov.au/climate/current/soihtm1.shtml). On the basis of the Troup (1965) method, this SOI time series (1871–2003) is the standardised anomaly of the mean sea level pressure difference between Tahiti and Darwin relative to the 1933–1992 base period (Allan *et al.*, 1996). The SOI is presented in standard deviation units around a mean of zero, with significant positive/negative departures representing La Niña/El Niño conditions. Following Trenberth and Hoar (1996) and Allan *et al.* (2003), the SOI was smoothed with a 11-month running mean to remove high frequency fluctuations caused by phenomenon such as the Madden–Julian Oscillation.

Unlike Niño 3.4 region SSTs, it was difficult to obtain a firm consensus on the SOI threshold values used to define ENSO events from the literature. To begin, we tested the suitability of using a SOI value of ±0.5 for La Niña/El Niño events for a period of at least 6 months, consistent with the SST methodology. This definition was applied to the post-1949 SOI time series to examine the occurrence of ENSO episodes recorded by the atmosphere, discussed further in Section 3.2.

3. INSTRUMENTAL EVENT CAPTURE COMPARISONS

3.1. Oceanic ENSO event capture

Instrumental and reconstructed Niño 3.4 SST data were compared to assess the reconstruction's suitability for use as a pre-1950 substitute. The post-1949 observational record indicated 15(13) El Niño (La Niña) events compared to 15(9) for the reconstruction (Figure 1). Both SST records capture the same 15 El Niño events; however, the overall onset and duration of events varied slightly. For example, the reconstruction exaggerates the persistence of El Niño conditions by up to 7 months (e.g. 1977/78). Mean El Niño duration from the reconstruction was 13.7 months compared to 13.1 months for observed SSTs. The onset of three El Niños was delayed using the reconstruction by 1 month (1991), 4 months (1968) and 6 months (1979/80). Most conspicuously, the reconstruction overestimates the magnitude of strong El Niño conditions (e.g. 1972, 1982 and 1997).

The undercount of four La Niñas from the SST reconstruction events related to instances where neutral conditions in the observational record punctuated the duration criteria for the classification of an ENSO episode. This resulted in the 1954–1955, 1955–1956, 1970–1971, 1971–1972, 1973–1974, 1975–1976, 1998–1999 and 1999–2000 La Niñas being distinguished as discrete events in the observational SST record, whereas the reconstruction combines them into four longer events spanning 1954–1956, 1970–1972, 1973–1976 and 1998–2000.

An increase in neutral months elevated the mean duration of La Niñas from the reconstruction to 18.6 months, compared to the more frequent, shorter La Niñas averaging 8.4 months from observed SSTs. Furthermore, the reconstruction shows some La Niñas starting 1 (1970, 1973, 1984, 1998) and 2 months (1954, 1964, 1988) earlier, which results in the extension of the length of these five events by two (1996) to 10 months (1956).

The discrepancies between instrumental and reconstructed Niño 3.4 SSTs identified the potential issues of underestimating the number of La Niñas and overestimating the magnitude of El Niño events prior to 1950.

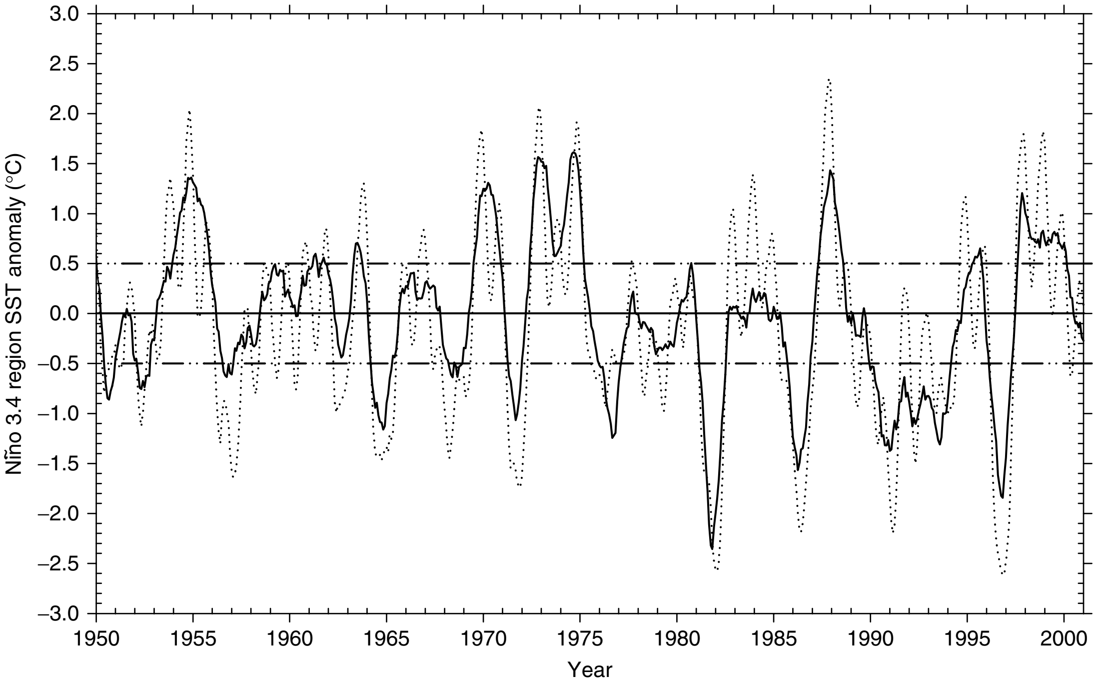

Figure 1. Five-month running mean of instrumental (solid) and reconstructed (dashed) Niño 3.4 Region SSTs (1950–2001). Horizontal lines represent La Niña and El Niño ±0.5 threshold conditions. Note that the reconstruction appears to amplify the magnitude of positive anomalies (El Niño events)

Nevertheless, the striking similarity of the reconstruction shown in Figure 1 confirms that the latter is an acceptable, albeit imperfect, pre-instrumental substitute.

To examine the sensitivity of ENSO event capture relative to a given threshold, a sensitivity analysis was carried out (Table I). Adjusting the threshold mainly impacted the ratio of neutral and La Niña conditions, as implied by the greater variability in La Niña event capture seen in Table I. The peak number of El Niño events was captured using the ±0.3 threshold, while the maximum number of La Niñas was obtained using ±0.1.

Increasing the SST event capture threshold raises the number of neutral conditions, which sometimes leads to a 'splitting' of discrete events, impacting event counts. For example, when using the ±0.3 threshold, the 1979–1980 El Niño is recorded as two discrete episodes in 1979 and 1980. Similarly, the 1984–1986 La Niña given by the ±0.1 threshold is recorded as two separate events (1984–1985, 1985–1986) by all the other thresholds. This accounts for the somewhat counter-intuitive increase in event capture sometimes associated with raising threshold values.

The ±0.4 definition used by Trenberth (1997) agrees well with the ENSO episodes identified by the ±0.5 definition. The main disparity was that the ±0.4 threshold identified four additional La Niña events during 2000–2001, 1985–1986, 1983–1984, 1974–1975 and 1967–1968. In all these instances, the ±0.5 threshold was breached for 5 rather than the 6 months required for ENSO event capture.

3.2. *Atmospheric ENSO event capture*

Applying the ±0.5 threshold defined in Section 2.2 to the post-1949 SOI, time series identified twelve El Niño and nine La Niña episodes. In line with the SST analysis, a sensitivity test was used to examine the threshold-dependent changes in ENSO event capture (Table II). A maximum of 14 El Niño episodes were recorded from the SOI using ±0.1 and ±0.2 thresholds, while ±0.1 yielded a maximum of 13 La Niña events. Threshold manipulation impacted the frequency of La Niña episodes more notably than El Niño event registration, probably caused by the relatively lower magnitude of La Niña events recorded by the SOI.

The threshold-dependent variability in ENSO event capture for the SOI for the upper and lower thresholds used in the sensitivity analysis are shown in Figure 2. The minimum/maximum occurrence of both ENSO phases was registered for the ±0.5/±0.1 definitions, respectively. These differences relate to the registration of an additional four La Niña events (1984–1985, 1981, 1966–1968, 1959–1961) and two weak El Niños (1979–1980, 1963–1964) using ±0.1.

Instead of splitting the events, raising the SOI event-capture threshold increases the number of neutral conditions that reduces event duration. For example, using the ±0.1 definition, the 26-month 1957–1959 El Niño progressively shortens to 17, 11, 8 and 7 months as the threshold is raised. This process accounts for

Table I. 1950–2003 ENSO event capture threshold sensitivity test for Niño 3.4 region SSTs. Positive/negative SST anomalies denote El Niño/La Niña conditions

ENSO phase	±0.1	±0.2	±0.3	±0.4	±0.5
El Niño	17	18	19	16	16
La Niña	19	15	18	17	13

Table II. 1950–2003 threshold sensitivity for ENSO event capture from the Southern Oscillation Index. Negative/positive phase in the SOI refers to El Niño/La Niña conditions

ENSO phase	±0.1	±0.2	±0.3	±0.4	±0.5
El Niño	14	14	13	12	12
La Niña	13	12	10	10	9

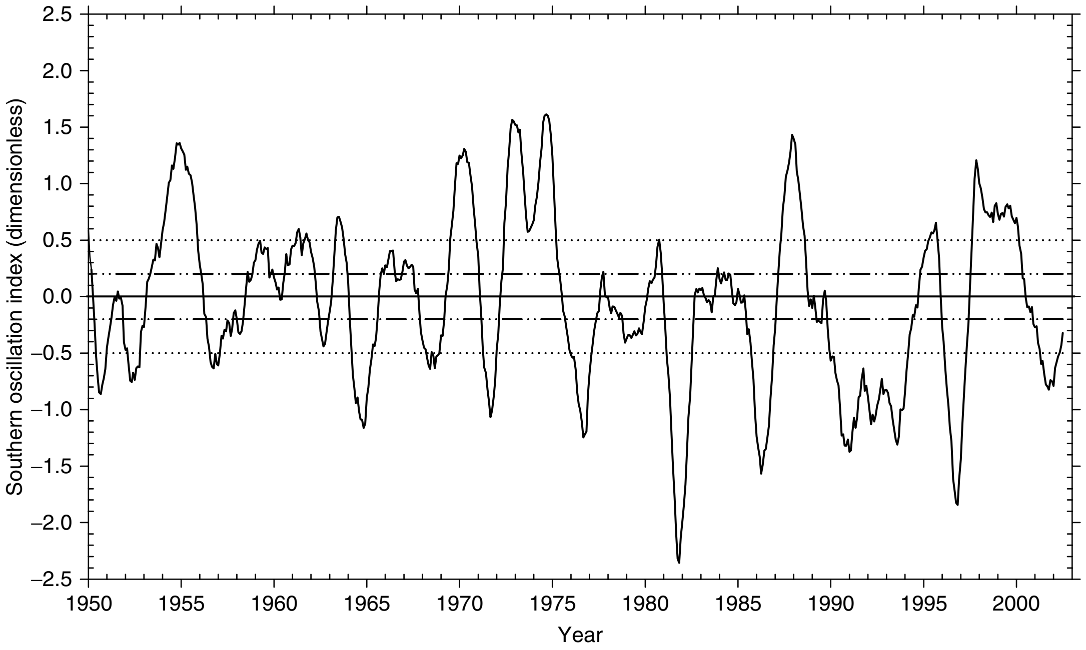

Figure 2. Monthly Southern Oscillation Index (SOI) from 1950 to 2003 smoothed with an 11-month running mean. ENSO event capture comparison using ±0.5 and ±0.2 thresholds to highlight the impact of threshold selection on event capture

changes in the mean duration of El Niño (La Niña) episodes of 20.4 (20.8) months using ±0.1 compared to 14.4 (16.9) months El Niños (La Niñas) produced by using a SOI threshold of ±0.5.

The only instance of event splitting noted using a ±0.1 threshold is the La Niña of 1966–1968, which breaks into two events (1966–1967, 1967–1968) using the ±0.2 threshold. The validity of this is questionable as there is only a 4-month period of neutral conditions in 1967 that impedes the registration of a continuous event. The fact that these events are not recorded at all by the higher thresholds of Table II implies a mild atmospheric response for this moderate La Niña. Similarly, the ±0.1 defined 1959–1961 event is recorded only up to the −0.4 threshold, suggesting that relatively weak La Niña events may not be adequately accounted for using a SOI threshold value of ±0.5. In addition, high SOI thresholds appear insensitive to weaker El Niño events. For example, the 1963–1964 episode is captured using ±0.1 or ±0.2 thresholds, however, drops out using thresholds higher than ±0.3.

Nevertheless, 70% of both La Niña and El Niño events identified by ±0.1 threshold are captured by the ±0.5 definition. Very slight differences are noted dropping the threshold to ±0.3 and ±0.4 (Table II); both record 77% of ±0.1 El Niños, while one extra La Niña event increases event capture from 86% to 93%. There is very little difference between ±0.2 and ±0.1 thresholds; the ±0.2 threshold captures 100% of El Niños and one fewer La Niña resulting in a 92% agreement with ±0.1 events.

3.3. Intercomparison of SST and SOI event analysis

It is evident from comparisons of Tables I and II that event capture varies considerably with each index of ENSO and the threshold imposed. Interestingly, no SOI threshold was able to yield enough events to completely agree with the minimum number of events captured by the SST record. The SST analysis identified a minimum of 16(13) El Niños (La Niñas) in the post-1949 period, compared to a maximum of 12(9) El Niño (La Niña) episodes using the ±0.5 SOI definition (see Section 2.2).

Compared to the SST event capture, four fewer El Niño and four La Niña events were recorded by the ±0.5 SOI threshold. Two of the El Niños seen from SSTs were not present at all in the SOI (1980, 1963–1964). The other two differences in El Niño capture relate to the 1990–1995 SOI, El Niño being recorded as three discrete SST events (1991–1992, 1993 and 1994–1995). Similarly, the 1998–2001 La Niña seen from the SOI is recorded as two separate SST events (1998–1999, 1999–2000). This was also noted for the La Niñas of 1973–1976, 1970–1972 and 1955–1956. The higher number of ENSO episodes noted from SSTs reiterates the event-splitting tendency of the oceanic index, raised in Section 3.1.

There are also considerable differences in the mean duration of ENSO events seen from the SST and SOI records. Notably, the mean duration of La Niña events from SSTs is 8.4 months compared to a maximum of 16.9 months using ±0.5 for the SOI. Differences are not as marked for El Niños, where the average SST event is 13 months compared to 14.4 months observed from the SOI. This may reflect true differences in the duration of ENSO conditions, or may be an artifact of the data smoothing and subsequent threshold selection.

The SST event-splitting trend impacts the examination of relatively lower magnitude, 'protracted' events defined as 24 months or more of ENSO conditions from the SOI (Allan and D'Arrigo, 1999; Allan *et al.*, 2003; Trenberth and Hoar, 1996). Significantly, strictly applying the 24-month definition to the post-1949 SST record identifies no persistent events from the oceanic record. The maximum duration of any ENSO event recorded from instrumental SSTs is a 22-month El Niño event spanning 1986–1988, which falls two months short of the duration criteria (Allan and D'Arrigo, 1999; Allan *et al.*, 2003; Trenberth and Hoar, 1996).

The lack of protracted SST events is inconsistent with up to three protracted El Niños (1990–1995, 1976–1978, 1957–1959) and three extended La Niñas (1998–2001, 1973–1976, 1954–1957) identified using a ±0.1 SOI threshold. For example, the longest SOI El Niño event on record (1990–1995) identified by Trenberth and Hoar (1996), is a 50-month event even using the most conservative −0.5 SOI threshold, compared to a total of 39 anomalous months combined from the three corresponding discrete SST events (1991–1992, 1993, 1994–1995). In addition, there are four weak SOI La Niñas (1959–1961, 1961–1963, 1966–1968 and 1981) that occur independently of a corresponding SST response. There are no El Niños that occur separately of a simultaneous response in both the indices.

To further complicate matters, it is well known that the registration of the timing of atmospheric and oceanic components of ENSO can be out of phase with one another (Deser and Wallace, 1987; Kane, 1999; Trenberth, 1997), seen clearly in Figure 3. For example, seven El Niños (e.g. 1982, 1990, 1997) and seven La Niñas (e.g. 1988, 1979, 1970) from the SOI start earlier than their oceanic counterparts. Atmospheric El Niños were noted between 5 (1954, 1964) and 8 months (1979) in advance of anomalous SST conditions. By contrast, the ocean was found to initiate three El Niños (1957, 1963 and 1986) 1 month earlier than the SOI, and two La Niñas (1984 and 1995) 2 months earlier than atmospheric anomalies.

Likewise, the atmosphere appears to have greater persistence compared to the SST record. The atmosphere was found to lag oceanic ENSO signatures for seven La Niñas (e.g. 1976, 1989, 2001) and seven El Niños (e.g. 1951, 1982, 2003). SOI persistence varied up to 12 months (1977–1978) for El Niños and 14 months (2000-01) for La Niña episodes. By contrast, there are only four instances where the ocean lags the atmosphere (1964, 1970, 1973, 1988 El Niños), and no indication of oceanic lag from the post-1949 La Niñas. As previously noted, there is a possibility that such trends may not represent true features of ENSO dynamics, but rather a construct of the smoothing applied to the time series.

The differences in event-capture characteristics noted above may account for the observed variation in event lists based on SSTs and the SOI. It is essential to keep in mind that a sole ENSO index only has the ability to resolve one physical aspect of the phenomenon, and is likely to contain unique information about the dynamics of ENSO evolution. This signifies considerable implications of using a single ENSO index for subsequent palaeoclimatic calibration applications.

4. COUPLED ENSO INDEX (CEI)

4.1. Rationale

Obviously, the widely used indices of ENSO detailed in Section 3 have notable issues which limit their usefulness for describing past ENSO behaviour. Furthermore, a number of studies have examined issues associated with the quality of the station data and the properties of the SOI (Allan *et al.*, 1996; Trenberth and Caron, 2000). For example, Troup (1965) noted that the centres of action involved in the Southern Oscillation

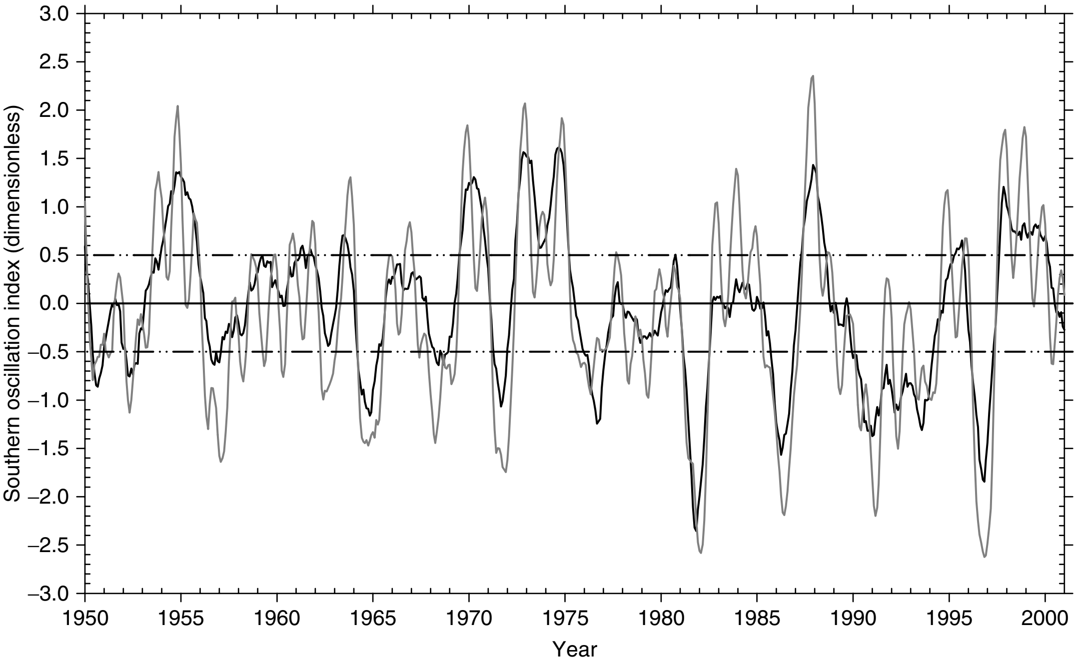

Figure 3. Monthly SOI smoothed with an 11-month running mean (solid black line) superposed on 5-month running mean of instrumental Niño 3.4 region SSTs (solid grey line) for the 1950–2003 period. SSTs have been inverted to show El Niño SSTs as negative departures to facilitate comparison with the SOI

vary in position and activity. Similarly, there are very few continuously recorded measurements of tropical oceans in existence prior to 1950 (Fairbanks *et al*., 1997). Ocean temperature time series that are present may be corrupted by changes in the measurement process, such as the gradual switch from bucket to engine intake water starting around 1940 (Fairbanks *et al*., 1997). Post-1949 SSTs, therefore, may represent the best available, *in situ* measurements of SST variability.

To date, ENSO reconstruction efforts have tended to focus on only one aspect of the ENSO phenomenon, commonly the SOI, which only partially characterises the entirety of ENSO perturbations. Considerable research has also focused on the oceanic Niño 3 region SSTs (D' Arrigo *et al*., 2005; Evans *et al*., 2002; Latif *et al*., 2001; Mann *et al*., 1998; Timmermann, 1999), despite the fact that in recent years it has become apparent that the key region for coupled atmospheric–oceanic interactions involved in ENSO is located further west than traditionally defined by eastern Pacific ENSO zones (Trenberth, 1997; Trenberth and Hoar, 1996; Trenberth and Hoar, 1997; Wang, 1995).

In the context of such issues, the use of a sole ENSO index is considered undesirable, as there is only the potential to describe one aspect of the phenomenon, which is not fully representative of the coupled ocean–atmosphere system. Failing to incorporate appropriate elements of both components of the phenomenon into the calibration process may result in a persistently fragmented description of ENSO, which in turn may hinder efforts to refine our description of the phenomenon's life cycle through proxy archives. Evidently, there is a need for a combined ocean–atmosphere calibration index if an integrated reconstruction of ENSO is desired.

A notable attempt to integrate various variables of ENSO is the Multivariate ENSO Index (MEI) developed by Wolter and Timlin (1993). The MEI is calculated on the basis of six observed variables over the tropical Pacific including sea level pressure, zonal and meridional components of the surface wind, SST, surface air temperature and total cloudiness fraction of the sky from 1950 to the present (Wolter and Timlin, 1993). Values of the MEI are available online from NOAA's Climate Diagnostics Center (http://www.cdc.noaa.gov/ENSO/enso.mei_index.html).

Recently, Hanley *et al.* (2003) commented that the MEI had a higher correlation to the Niño 3 index than the SOI or other SST indices. Their analysis revealed that the Niño 3 SST index is less sensitive in capturing both El Niño and La Niña events than Niño 3.4 SSTs (Hanley *et al.*, 2003), a result also reported by Trenberth (1997). Furthermore, Hanley *et al.* (2003) note issues associated with the index included the relatively short length of the time series, a tendency to 'over-predict' ENSO events, a weaker relationship with SOI than the other SST indices and were unable to completely assess the response and sensitivity of the MEI because of 'data limitations with the MEI' (Hanley *et al.*, 2003). Primarily, insufficient length of the time series required for palaeoclimatic calibration applications resulted in the exclusion of the MEI from the analysis presented here.

4.2. *CEI classification scheme*

A classification scheme incorporating both ocean and atmosphere components of ENSO was devised to accurately distinguish unequivocal ENSO events (Figure 4). The basic inputs were monthly values of Niño 3.4 SSTs and the SOI. These were smoothed using running means of 5 and 11 months, respectively, as detailed in Section 2.

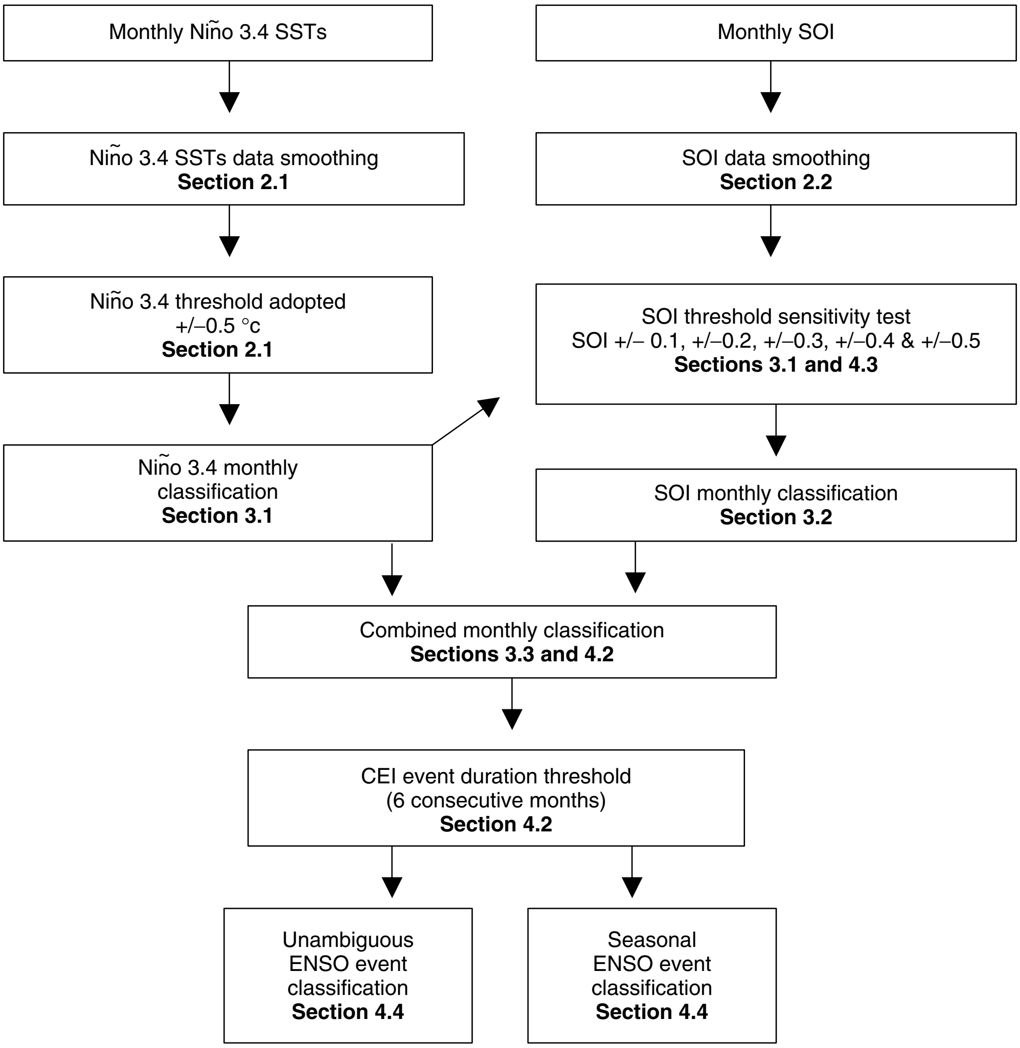

Figure 4. Coupled ENSO Index (CEI) classification flowchart showing in monthly and seasonal ENSO classification processes

On the basis of the arguments presented in Sections 2.1 and 3.1, post-1949 Niño 3.4 SSTs were adopted as an appropriate direct instrumental record of ENSO conditions. We also adopted the ±0.5 threshold recently proposed by NOAA to distinguish El Niño, La Niña and neutral months (Elsey, 2004; Mc Phaden, 2004).

Having established the SST-based monthly ENSO classification, we undertook a SOI-based sensitivity analysis to identify the SOI threshold giving the best agreement with the SST analysis. This was done to ensure near-equal weighting for the oceanic and atmospheric components of ENSO when the two sources were subsequently combined. The results of this sensitivity analysis are presented in Section 4.3.

The SOI-based threshold sensitivity analysis yielded a threshold value, which was used to generate a time series of El Niño, La Niña and neutral months. This was combined with the equivalent analysis undertaken on Niño 3.4 SSTs to produce a composite CEI time series. Where the two series were in agreement, an unambiguous classification for those months resulted. In other cases, an ambiguity was flagged and information about the nature of the ambiguity was retained (see Section 4.6 for details).

Following Trenberth (1997) and Hanley *et al.* (2003), a minimum duration of six consecutive months was adopted as the requirement for confident identification of an ENSO event. However, in line with Allan and D'Arrigo (1999), we allowed a sequence of ENSO event months to be punctuated by a maximum of 2 neutral or ambiguous months. Section 4.6 details the application of the method used to derive unambiguous ENSO episodes.

The final step in our method was to derive a seasonal version of the CEI, to facilitate investigation of proxy–ENSO relationships over various parts of the year. Because of the smoothing inherent to both the SST and SOI data sets, we simply extracted middle month values for the commonly defined seasons of DJF, MAM, JJA and SON (i.e. January, April, July and October). Results are presented in Section 4.5.

4.3. *SOI threshold sensitity analysis*

To produce a combined ocean–atmosphere ENSO index, it was necessary to identify the SOI threshold needed to achieve the best agreement with Niño 3.4 SST event capture. The sensitivity analysis, using 0.1 standard deviation increments ranging from ±/0.1 to ±/0.5 (see Section 3.2), was next compared to the ENSO events captured using the ±0.5 SST definition from the post-1949 event period. These results are presented in Table III as percentage of SOI agreement with SST-determined ENSO months.

The high ±0.5 threshold proposed in Section 2.2 appears to miss the occurrence of lower magnitude episodes such as the 1908–1911 (30 months) and 1949–1954 (17 month) La Niñas. As flagged in Section 3.3, the nature of this omission may have considerable implications for the detection of notable, protracted events such as those experienced during the late twentieth century (Allan and D'Arrigo, 1999; Allan *et al.*, 2003; Trenberth and Hoar, 1996). In light of potential loss of important evolutive information, use of a high SOI threshold (±0.5/0.4) was deemed inappropriate.

Of note is the similarity of agreement between the SOI ±0.1, ±0.2 and ±0.3 thresholds and the SST record. Although ±0.1 yielded the highest percentage agreement for both ENSO phases, it identified one additional La Niña (1981) compared to ±0.2. This episode is not concurrently observed in the SST record; therefore it was considered to be a false positive case (in light of our use of SST anomalies as a basis for defining the presence of ENSO episodes). Similarly, using a ±0.3 SOI threshold does not capture the 1963–1964 El Niño recorded in the SST record. Despite the SST record indicating anomalies reaching 1.0 °C during this 10 month

Table III. Post-1949 sensitivity test for SOI event capture related to threshold adjustment. Values are percentage of agreement with SST-determined ENSO phase months (from Niño 3.4 SSTs for a threshold of ±0.5 for at least 6 consecutive months) using different SOI thresholds. A SOI threshold of ±0.2 shaded yields the most satisfactory agreement with oceanic ENSO events and maintenance of neutral conditions

ENSO phase	SOI ± 0.1 (%)	SOI ± 0.2 (%)	SOI ± 0.3 (%)	SOI ± 0.4 (%)	SOI ± 0.5 (%)
El Niño	91	86	80	69	62
La Niña	90	83	77	70	64
Neutral	19	33	48	57	67

event, this episode is not captured using the upper three thresholds of Table III. As a result, the ±0.3 (±0.1) thresholds were rejected on the grounds of potentially being insensitive (oversensitive) to capturing moderate ENSO events.

Finally, the choice of the most appropriate SOI threshold was based on the highest event capture and an adequate agreement of monthly neutral conditions registered by the ocean index. A SOI threshold of ±0.2 was considered to yield the most optimal event capture with respect to the Niño 3.4 SST record while maintaining a satisfactory 1/3 agreement of neutral conditions.

4.4. Unambiguous ENSO event classification

Achieving unambiguous ENSO event classification involved addressing the uncertainties presented in Table IV. Event counts were impacted when ENSO conditions were disrupted by more than two neutral or ambiguous months from one index. This results in event splitting seen, for example, by examining the La Niñas of 1970–1971 and 1971–1972. In recognition that trends recorded by each sole index may contain meaningful evolutive information, individual classifications were maintained as per Table IV and presented in Section 4.5. Using the CEI scheme, 28 distinct El Niño and 26 La Niña episodes were identified from the post-1870 period (Table V), representing synchronous anomalies common to both components of the ENSO system.

To compare generic ENSO trends from the CEI for the instrumental period, event frequency and duration characteristics for the pre-1950 and post-1949 periods were evaluated against the sole indices of ENSO for the two sub-intervals (Table VI). Using the CEI, there is an apparent switch from a predominance of La Niña conditions in the pre-1950 period, to heightened El Niño activity post-1949. This is reflected in a decrease in the number of La Niña events from 15 to 11, and a corresponding increase in the frequency of El Niños from 12 to 16 in the post-1949 period. This is accompanied by a decline in the mean duration of El Niños (La Niñas) from 15.6 (14.6) to 11.8 (9.2) months.

These results raise the need for caution when investigating ENSO based on a sole index. For example, using the SST record alone, the trend towards more frequent El Niños is not as marked. This contrasts greatly to the SOI results, which show a notable decline in the frequency of La Niñas from a pre-1950 peak of 21 events, to 12 observed post-1949. Furthermore, atmospheric ENSO events appear to last longer than SST anomalies as seen from the maximum duration of El Niño/La Niñas (55/37 months) in the post-1949 period (noted in Section 3.3). Using the CEI, however, it is possible to avoid the ambiguity associated with using a sole record of the SOI or SSTs. This is not to suggest, however, that trends observed in either of the records are not meaningful. The purpose of this study, however, is concerned with focusing on the simultaneous climate signature common to both components of the ENSO system.

4.5. Seasonal ENSO classification

Palaeoclimatologists are often dealing with proxy records of varying resolution such as the monthly scale of many coral sequences or the annual dating of tree-ring chronologies. To facilitate further insight into ENSO evolution from subsequent proxy reconstructions, seasonal ENSO classifications (see Section 4.2) were identified by the process demonstrated in Table IV. The seasonal classification preserves information about the individual SOI and SST conditions of the CEI that may provide important evolutive detail on the nature of ENSO events, such as atmosphere/ocean lead/lag signatures. Thus, event lists based on seasonal conditions were generated for the commonly defined seasons (DJF, MAM, JJA, SON) to assist the identification of characteristics such as the onset or peak ENSO conditions from a given proxy record.

Slight discrepancies between the monthly unambiguous event results presented in Table V and the seasonal compilation of Table VII were observed. These were often reflected through a modification of the duration rather than the occurrence of an event. For example, the 1968–1970 El Niño of Table V is only seen for 1969–1970 using seasonal Table VII. This is likely an artifact of transferring from monthly to seasonal detail

Table IV. Monthly ENSO classification processes for Niño 3.4 SSTs, SOI and CEI where a maximum of two neutral or ambiguous months are allowed to punctuate ENSO conditions (dark shading). (i) Classification of the 17-month 1949–1951 La Niña. (ii) 1970–1971 (6 months) and 1971–1972 (8 months) La Niña event 'splitting' resulting from 4 consecutive months of neutral conditions in SST record. (iii) Potentially useful lead/lag relationships (light shading) classifications are maintained for seasonal ENSO classification presented in Section 4.5 highlighted for the 14 month 1997–1998 El Niño

(i)	M	Niño 3.4 SST	SOI	CEI	(ii)	M	Niño 3.4 SST	SOI	CEI	(iii)	M	Niño 3.4 SST	SOI	CEI
1951	2	NIÑA	NIÑA	NIÑA	1972	1	NIÑA	NIÑA	NIÑA	1998	6	NEUTRAL	NIÑO	SOI NIÑO
1951	1	NIÑA	NIÑA	NIÑA	1971	12	NIÑA	NIÑA	NIÑA	1998	5	NIÑO	NIÑO	NIÑO
1950	12	NIÑA	NIÑA	NIÑA	1971	11	NIÑA	NIÑA	NIÑA	1998	4	NIÑO	NIÑO	NIÑO
1950	11	NIÑA	NIÑA	NIÑA	1971	10	NIÑA	NIÑA	NIÑA	1998	3	NIÑO	NIÑO	NIÑO
1950	10	NIÑA	NIÑA	NIÑA	1971	9	NIÑA	NIÑA	NIÑA	1998	2	NIÑO	NIÑO	NIÑO
1950	9	NIÑA	NIÑA	NIÑA	1971	8	NIÑA	NIÑA	NIÑA	1998	1	NIÑO	NIÑO	NIÑO
1950	8	NIÑA	NIÑA	NIÑA	1971	7	NEUTRAL	NIÑA	SOI NIÑA	1997	12	NIÑO	NIÑO	NIÑO
1950	7	NIÑA	NIÑA	NIÑA	1971	6	NEUTRAL	NIÑA	SOI NIÑA	1997	11	NIÑO	NIÑO	NIÑO
1950	6	NEUTRAL	NIÑA	SOI NIÑA	1971	5	NEUTRAL	NIÑA	SOI NIÑA	1997	10	NIÑO	NIÑO	NIÑO
1950	5	NEUTRAL	NIÑA	SOI NIÑA	1971	4	NEUTRAL	NIÑA	SOI NIÑA	1997	9	NIÑO	NIÑO	NIÑO
1950	4	NIÑA	NIÑA	NIÑA	1971	3	NIÑA	NIÑA	NIÑA	1997	8	NIÑO	NIÑO	NIÑO
1950	3	NIÑA	NIÑA	NIÑA	1971	2	NIÑA	NIÑA	NIÑA	1997	7	NIÑO	NIÑO	NIÑO
1950	2	NIÑA	NIÑA	NIÑA	1971	1	NIÑA	NIÑA	NIÑA	1997	6	NIÑO	NIÑO	NIÑO
1950	1	NIÑA	NIÑA	NIÑA	1970	12	NIÑA	NIÑA	NIÑA	1997	5	NIÑO	NIÑO	NIÑO
1949	12	NIÑA	NIÑA	NIÑA	1970	11	NIÑA	NIÑA	NIÑA	1997	4	NIÑO	NIÑO	NIÑO
1949	11	NIÑA	NIÑA	NIÑA	1970	10	NIÑA	NIÑA	NIÑA	1997	3	NEUTRAL	NIÑO	SOI NIÑO
1949	10	NIÑA	NIÑA	NIÑA	1970	9	NIÑA	NIÑA	NIÑA	1997	2	NEUTRAL	NIÑO	SOI NIÑO
1949	9	NIÑA	NEUTRAL	N3.4 NIÑA	1970	8	NIÑA	NIÑA	NIÑA	1997	1	NEUTRAL	NIÑO	SOI NIÑO

Table V. Unambiguous ENSO events from 1871 to 2003 derived from Coupled ENSO Index (CEI) classification scheme incorporating the atmospheric SOI and oceanic SSTs from the Niño 3.4 region. Unambiguous status indicates ENSO conditions were simultaneously registered in both instrumental indices. When applicable, event duration includes a maximum of two neutral or ambiguous months as defined in Section 4.2. Mean and maximum event magnitude CEI values (detailed in Section 4.7) are shown alongside event duration. Extreme events (CEI values exceeding ±3) referred to in Section 4.7 are in bold. An asterisk (*) indicates that although ±3 threshold was achieved, this event is not considered extreme as a minimum 50% duration was not observed independently from the SOI in order to reduce the uncertainty associated with the Niño 3.4 SST reconstruction's propensity to slightly overestimate the magnitude of anomalies (see Section 4.7 for details)

El Niño start	El Niño end	Duration (months)	Mean CEI magnitude	Maximum CEI value	La Niña start	La Niña end	Duration (months)	Mean CEI magnitude	Maximum CEI value
March 2002	June 2003	16	−1.74	−2.18	July 1999	March 2000	9	2.06	2.65
April 1997	**May 1998**	14	−3.32	**−4.47**	August 1998	March 1999	8	2.35	2.96
April 1994	May 1995	14	−1.77	−2.17	**June 1988**	**March 1989**	10	2.87	**3.79**
February 1993	August 1993	7	−2.07	−2.61	**July 1975**	**March 1976**	9	2.75	**3.47**
March 1991	**July 1992**	17	−2.44	**−3.45**	**July 1973**	**March 1974**	9	2.89	**3.62**
July 1986	**January 1988**	19	−2.31	**−3.65**	August 1971	January 1972	6	1.59	1.85
March 1982	**July 1983**	17	−3.23	**−4.60**	**August 1970**	**March 1971**	8	2.48	**3.02**
February 1980	July 1980	6	−1.10	−1.32	July 1964	December 1964	6	1.57	1.78
October 1976	July 1977	10	−1.33	−1.79	**July 1955**	**February 1956**	8	2.74	**3.39**
April 1972	February 1973	11	−2.23	−2.71	August 1954	March 1955	8	1.55	1.71
December 1968	March 1970	16	−1.38	−1.99	October 1949	February 1951	17	2.01	2.54
April 1965	July 1966	16	−2.04	−2.58	February 1945	November 1945	10	1.04	1.20
July 1963	December 1963	6	−1.18	−1.31	July 1942	April 1943	10	1.81	2.36
June 1957	July 1958	14	−1.66	−2.19	June 1938	March 1939	10	1.75	2.01
March 1953	August 1953	6	−1.57	−1.89	July 1933	February 1934	8	1.44	1.59
May 1951	October 1951	6	−1.28	−1.45	June 1924	March 1925	10	1.51	1.96
November 1939	**March 1942**	29	−2.60	**−3.67**	**May 1916**	**March 1917**	11	2.54	**3.41**
August 1925	July 1926	12	−2.30	−2.97	September 1908	February 1911	30	1.71	2.62
August 1923	January 1924	6	−1.59	−1.97	September 1903	March 1904	7	1.71	1.98
August 1918	February 1920	19	−1.82	−2.77	December 1897	June 1898	7	1.13	1.24
October 1913	February 1915	17	−1.82	−2.25	March 1892	June 1894	28	2.03	2.81
October 1911	May 1912	8	−2.16	−2.67	August 1889	November 1890	16	2.33	3.30*
October 1904	**April 1906**	19	−2.43	**−3.33**	May 1886	July 1887	15	2.01	2.64
September 1889	September 1900	13	−1.89	−2.59	May 1879	May 1880	13	2.03	2.47
June 1896	**April 1897**	11	−2.89	**−3.75**	April 1874	June 1876	27	1.66	2.19
January 1888	**April 1889**	16	−2.43	**−3.79**	**December 1871**	**May 1873**	18	2.24	**3.22**
May 1884	December 1885	20	−1.10	−1.72					
December 1876	**April 1878**	17	−3.29	**−4.77**					

Table VI. 1871–2003 comparison of pre- and post-1949 ENSO event characteristics using various indices: the CEI (this study); SST (±0.5 from the Niño 3.4 region) and SOI (threshold of ±0.2). Note that the CEI produces a higher number of post-1949 CEI El Niños than the SOI due to the event splitting tendency noted for the SST record (see Section 3.1). The discrepancy relates to the 1991–1992, 1993, and 1994–1995 SST El Niños being recorded as one continuous event spanning 1990–1995 in the SOI. This leads to an additional two events in the CEI (highlighting our SST basis), rather than the 'lowest common denominator' value of 14 expected to be determined from the SOI

ENSO phase & index	Post-1949 frequency (total)	Post-1949 mean duration (months)	Pre-1950 frequency (total)	Pre-1950 mean duration (months)	Post-1949 maximum duration (months)	Post-1949 minimum duration (months)	Pre-1950 maximum duration (months)	Pre-1950 minimum duration (months)
El Niño								
CEI	16	11.8	12	15.6	19	6	29	6
SST	16	13.1	14	18.8	22	6	29	7
SOI	14	18.4	15	19.3	55	6	46	6
La Niña								
CEI	11	9.2	15	14.6	17	6	28	7
SST	13	8.4	15	16.3	14	6	35	7
SOI	12	18.7	21	19.3	37	8	36	6

and a reflection of the weak nature of this event (see Table V). The complex issues of seasonal lead/lag relationships were not pursued beyond preserving the ENSO classification generated for the SOI and SST indices. These elements are flagged in Table VII, and not addressed further in this study to avoid detracting from the primary scope of this paper which is concerned with the establishment of a list of unequivocal ENSO events for the instrumental era. Nevertheless, this information is intended to encourage the investigation of the subtleties of discrete ENSO evolution from subsequent proxy reconstruction.

4.6. Verification of the CEI classification scheme

To verify the credibility of the CEI events, Table V was compared to eight published lists of past ENSO events available in the literature (Allan *et al*., 2003; Kiladis and Diaz, 1989; Mullan, 1995; Ortlieb, 2000; Quinn and Neal, 1992; Rasmusson and Carpenter, 1983; Trenberth, 1997; Whetton and Rutherford, 1994). Of the five published event lists that extend prior to 1950, three are instrument based (Allan *et al*., 2001; Kiladis and Diaz, 1989; Rasmusson and Carpenter, 1983), while the remaining three are historical lists provided by Ortlieb (2000) (pre-1901), Quinn and Neal (1992) (post-1900) and Whetton and Rutherford (1994). The latter three are proxy assemblages rather than direct instrumental records, so should be interpreted with a degree of caution.

Differences in temporal coverage make a quantitative comparison between various ENSO event lists problematic. Furthermore, converting a monthly classification into a yearly event list resulted in the need to introduce a 'BOTH' status to the CEI list to accommodate 'phase-flipping'. Nevertheless, the results presented in Tables VIII and IX indicate the CEI's significant agreement with other lists. During the post-1949 period (Table VIII), every ENSO episode identified by the CEI was verified by at least one other independent list, with the exception of the most recent 2002/03 warm event, not yet incorporated into the event literature, but documented by recent works such as Mc Phaden (2004) and Vecchi and Harrison (2003).

For the pre-1950 period (Table IX), the CEI was found to have the closest agreement to the list developed initially by Reason *et al*. (2000) and subsequently updated to 2001 by Allan *et al*. (2003). This is probably because a composite approach was employed. Reason *et al*. (2000, p. 1287) refers to using the 'magnitude of the SOI and SST in the Niño 3 and Niño 4 regions to identify ENSO events'; however, precise details of this methodology are not detailed. Discrepancies observed with the other lists shown in Tables V and VI are often associated with phase-flipping ('BOTH') cases such as 1911, 1925, and 1951 where other event lists have tended to exclude the occurrence of La Niña conditions.

Table VII. CEI seasonal classification, 1872–2002. 'NIÑO' (light shading) and 'NIÑA' (dark shading) represent synchronous ENSO conditions, a '?' indicates disagreement, and 'Neutral' no ENSO. 'N 3.4' or 'SOI' preceding 'NIÑO' or 'NIÑA' indicates an event independently flagged in the Niño 3.4 SST or SOI record

YEAR	DJF	MAM	JJA	SON	YEAR	DJF	MAM	JJA	SON	YEAR	DJF	MAM	JJA	SON
2002	SOI NIÑO	NIÑO	NIÑO	NIÑO	1951	NIÑA	Neutral	NIÑO	NIÑO	1900	NIÑO	NIÑO	NIÑO	N3.4 NIÑO
2001	NIÑA	SOI NIÑA	Neutral	Neutral	1950	NIÑA	NIÑA	NIÑA	NIÑA	1899	NIÑA	Neutral	N3.4 NIÑO	NIÑO
2000	NIÑA	SOI NIÑA	SOI NIÑA	NIÑA	1949	SOI NIÑO	Neutral	Neutral	NIÑA	1898	NIÑA	NIÑA	SOI NIÑA	NIÑA
1999	NIÑA	SOI NIÑA	NIÑA	NIÑA	1948	SOI NIÑA	N3.4 NIÑO	Neutral	Neutral	1897	NIÑO	NIÑO	SOI NIÑO	Neutral
1998	NIÑO	NIÑO	Neutral	NIÑA	1947	SOI NIÑO	Neutral	SOI NIÑA	N3.4 NIÑA	1896	NIÑO	SOI NIÑO	NIÑO	NIÑO
1997	SOI NIÑO	NIÑO	NIÑO	NIÑO	1946	Neutral	SOI NIÑO	SOI NIÑO	SOI NIÑO	1895	N3.4 NIÑA	Neutral	SOI NIÑO	NIÑO
1996	NIÑA	SOI NIÑA	SOI NIÑA	NIÑA	1945	Neutral	NIÑA	NIÑA	NIÑA	1894	NIÑA	NIÑA	N3.4 NIÑA	N3.4 NIÑA
1995	NIÑO	NIÑO	Neutral	N3.4 NIÑA	1944	Neutral	Neutral	Neutral	Neutral	1893	NIÑA	NIÑA	NIÑA	NIÑA
1994	SOI NIÑO	NIÑO	NIÑO	NIÑO	1943	NIÑA	NIÑA	SOI NIÑA	Neutral	1892	Neutral	NIÑA	NIÑA	NIÑA
1993	SOI NIÑO	NIÑO	NIÑO	SOI NIÑO	1942	NIÑO	Neutral	NIÑA	NIÑA	1891	N3.4 NIÑA	Neutral	SOI NIÑO	SOI NIÑO
1992	NIÑO	NIÑO	NIÑO	SOI NIÑO	1941	NIÑO	NIÑO	NIÑO	NIÑO	1890	NIÑA	NIÑA	NIÑA	NIÑA
1991	SOI NIÑO	NIÑO	NIÑO	NIÑO	1940	NIÑO	NIÑO	NIÑO	NIÑO	1889	NIÑO	NIÑO	SOI NIÑA	NIÑA
1990	Neutral	NIÑO	NIÑO	Neutral	1939	NIÑA	SOI NIÑA	Neutral	SOI NIÑO	1888	NIÑO	NIÑO	NIÑO	NIÑO
1989	NIÑA	SOI NIÑA	SOI NIÑA	N3.4 NIÑA	1938	SOI NIÑA	SOI NIÑA	NIÑA	NIÑA	1887	NIÑA	NIÑA	NIÑA	Neutral
1988	NIÑO	SOI NIÑA	NIÑA	NIÑA	1937	Neutral	Neutral	Neutral	Neutral	1886	N3.4 NIÑO	SOI NIÑA	NIÑA	NIÑA
1987	NIÑO	NIÑO	NIÑO	NIÑO	1936	?	SOI NIÑA	Neutral	Neutral	1885	NIÑO	NIÑO	NIÑO	NIÑO
1986	N3.4 NIÑA	Neutral	NIÑO	NIÑO	1935	Neutral	SOI NIÑA	Neutral	Neutral	1884	SOI NIÑO	SOI NIÑO	NIÑO	NIÑO
1985	N3.4 NIÑA	SOI NIÑA	SOI NIÑA	N3.4 NIÑA	1934	NIÑA	N3.4 NIÑA	Neutral	Neutral	1883	N3.4 NIÑA	Neutral	Neutral	Neutral
1984	N3.4 NIÑA	Neutral	Neutral	N3.4 NIÑA	1933	SOI NIÑO		NIÑA	NIÑA	1882	?	SOI NIÑO	SOI NIÑO	?
1983	NIÑO	NIÑO	NIÑO	N3.4 NIÑA	1932	SOI NIÑO	NIÑO	SOI NIÑO	SOI NIÑO	1881	N3.4 NIÑO	NIÑO	SOI NIÑO	SOI NIÑO
1982	Neutral	NIÑO	NIÑO	NIÑO	1931	?	?	?	SOI NIÑA	1880	NIÑA	NIÑA	SOI NIÑA	SOI NIÑA
1981	Neutral	Neutral	Neutral	SOI NIÑA	1930	?	N3.4 NIÑO	N3.4 NIÑO	N3.4 NIÑO	1879	NIÑA	SOI NIÑA	NIÑA	NIÑA
1980	SOI NIÑO	NIÑO	NIÑO	SOI NIÑO	1929	SOI NIÑA	SOI NIÑA	SOI NIÑA	?	1878	NIÑO	NIÑO	?	NIÑA
1979	Neutral	N3.4 NIÑO	N3.4 NIÑO	Neutral	1928	Neutral	SOI NIÑA	SOI NIÑA	SOI NIÑA	1877	NIÑO	NIÑO	NIÑO	NIÑO
1978	SOI NIÑO	SOI NIÑO	Neutral	SOI NIÑA	1927	SOI NIÑA	SOI NIÑA	SOI NIÑA	Neutral	1876	NIÑA	NIÑA	SOI NIÑA	Neutral

(*continued overleaf*)

Table VII. (*Continued*)

YEAR	DJF	MAM	JJA	SON	YEAR	DJF	MAM	JJA	SON	YEAR	DJF	MAM	JJA	SON
1977	NIÑO	NIÑO	NIÑO	SOI NIÑO	1926	NIÑO	NIÑO	NIÑO	Neutral	1875	NIÑA	NIÑA	NIÑA	NIÑA
1976	NIÑA	SOI NIÑA	Neutral	NIÑO	1925	NIÑA	SOI NIÑA	N3.4 NIÑO	NIÑO	1874	N3.4 NIÑA	NIÑA	NIÑA	NIÑA
1975	NIÑA	SOI NIÑA	NIÑA	NIÑA	1924	NIÑO	Neutral	NIÑA	NIÑA	1873	NIÑA	NIÑA	Neutral	?
1974	NIÑA	SOI NIÑA	SOI NIÑA	NIÑA	1923	NIÑA	Neutral	SOI NIÑO	NIÑO	1872	NIÑA	NIÑA	NIÑA	NIÑA
1973	NIÑO	N3.4 NIÑO	NIÑA	NIÑA	1922	SOI NIÑA	SOI NIÑA	SOI NIÑA	SOI NIÑA					
1972	NIÑA	NIÑO	NIÑO	NIÑO	1921	SOI NIÑA	NIÑA	SOI NIÑA	SOI NIÑA					
1971	NIÑA	SOI NIÑA	SOI NIÑA	NIÑA	1920	NIÑO	N3.4 NIÑO	SOI NIÑA	SOI NIÑA					
1970	NIÑO	N3.4 NIÑO	SOI NIÑA	NIÑA	1919	NIÑO	NIÑO	NIÑO	NIÑO					
1969	NIÑO	NIÑO	NIÑO	NIÑO	1918	NIÑA	SOI NIÑA	N3.4 NIÑO	NIÑO					
1968	NIÑA	SOI NIÑA	SOI NIÑA	Neutral	1917	NIÑA	SOI NIÑA	SOI NIÑA	SOI NIÑA					
1967	SOI NIÑA	SOI NIÑA	SOI NIÑA	N3.4 NIÑA	1916	SOI NIÑA	SOI NIÑA	NIÑA	NIÑA					
1966	NIÑO	NIÑO	NIÑO	Neutral	1915	NIÑO	N3.4 NIÑO	?	SOI NIÑA					
1965	N3.4 NIÑA	NIÑO	NIÑO	NIÑO	1914	NIÑO	NIÑO	NIÑO	NIÑO					
1964	N3.4 NIÑO	SOI NIÑA	NIÑA	NIÑA	1913	SOI NIÑO	SOI NIÑO	SOI NIÑO	NIÑO					
1963	NIÑA	Neutral	NIÑO	NIÑO	1912	NIÑO	NIÑO	SOI NIÑO	SOI NIÑO					
1962	SOI NIÑA	SOI NIÑA	SOI NIÑA	NIÑA	1911	NIÑA	N3.4 NIÑA	SOI NIÑO	NIÑO					
1961	Neutral	N3.4 NIÑO	Neutral	NIÑA	1910	NIÑA	NIÑA	NIÑA	NIÑA					
1960	SOI NIÑA	SOI NIÑA	SOI NIÑA	Neutral	1909	NIÑA	NIÑA	NIÑA	NIÑA					
1959	SOI NIÑO	NIÑO	Neutral	Neutral	1908	Neutral	SOI NIÑA	SOI NIÑA	NIÑA					
1958	NIÑO	NIÑO	NIÑO	SOI NIÑO	1907	SOI NIÑA	Neutral	Neutral	Neutral					
1957	SOI NIÑA	N3.4 NIÑO	NIÑO	NIÑO	1906	NIÑO	NIÑO	SOI NIÑA	NIÑA					
1956	NIÑA	SOI NIÑA	SOI NIÑA	NIÑA	1905	NIÑO	NIÑO	NIÑO	NIÑO					
1955	NIÑA	SOI NIÑA	NIÑA	NIÑA	1904	NIÑA	SOI NIÑA	?	NIÑO					
1954	SOI NIÑO	Neutral	SOI NIÑA	NIÑA	1903	N3.4 NIÑO	?	SOI NIÑA	NIÑA					
1953	SOI NIÑO	NIÑO	NIÑO	SOI NIÑO	1902	Neutral	N3.4 NIÑO	N3.4 NIÑO	NIÑO					
1952	SOI NIÑO	N3.4 NIÑO	Neutral	Neutral	1901	N3.4 NIÑO	SOI NIÑA	Neutral	SOI NIÑA					

Table VIII. Post–1949 comparison of Coupled ENSO Index and 7 published event lists. An asterisk (*) denotes no temporal coverage, while a dash (–) indicates the absence of ENSO conditions. 'BOTH' denotes phase-flipping

Year	Coupled ENSO index	Allan *et al.* (2003)	Trenberth (1997)	Kiladis and Diaz (1989)	Quinn and Neal (1992)	Whetton and Rutherfurd (1994)	Rasmusson and Carpenter (1983)	Mullan (1995)
2003	NIÑO	*	*	*	*	*	*	*
2002	NIÑO	*	*	*	*	*	*	*
2001	–	NIÑA	*	*	*	*	*	*
2000	NIÑA	NIÑA	*	*	*	*	*	*
1999	NIÑA	NIÑA	*	*	*	*	*	*
1998	BOTH	NIÑA	*	*	*	*	*	*
1997	NIÑO	–	*	*	*	*	*	*
1996	–	–	NIÑA	*	*	*	*	*
1995	NIÑO	–	BOTH	*	*	*	*	*
1994	NIÑO	–	NIÑO	*	*	*	*	*
1993	NIÑO	NIÑO	NIÑO	*	*	*	*	*
1992	NIÑO	NIÑO	NIÑO	*	*	*	*	*
1991	NIÑO	NIÑO	NIÑO	*	*	*	*	*
1990	–	NIÑO	–	*	*	*	*	*
1989	NIÑA	NIÑA	NIÑA	*	*	*	*	NIÑA
1988	NIÑA	NIÑA	BOTH	NIÑA	*	*	*	NIÑA
1987	NIÑO	NIÑO	NIÑO	–	*	*	*	–
1986	NIÑO	NIÑO	NIÑO	NIÑO	*	*	*	–
1985	–	–	NIÑA	–	*	*	*	–
1984	–	–	NIÑA	–	*	*	*	–
1983	NIÑO	NIÑO	NIÑO	–	*	*	NIÑO	NIÑO
1982	NIÑO	NIÑO	NIÑO	NIÑO	*	*	–	NIÑO
1981	–	–	–	–	*	*	–	NIÑO
1980	NIÑO	–	NIÑO	–	*	*	–	NIÑO
1979	–	–	NIÑO	–	*	*	–	–
1978	–	–	NIÑO	–	*	*	–	NIÑO
1977	NIÑO	–	NIÑO	–	*	*	–	NIÑO
1976	BOTH	–	BOTH	NIÑO	NIÑO	–	NIÑO	NIÑO
1975	NIÑA	NIÑA	NIÑA	NIÑA	–	–	–	NIÑA
1974	NIÑA	NIÑA	NIÑA	–	–	–	–	NIÑA
1973	BOTH	BOTH	BOTH	NIÑA	NIÑO	–	–	BOTH
1972	BOTH	NIÑO	BOTH	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO
1971	NIÑA	NIÑA	NIÑA	–	–	–	–	NIÑA
1970	BOTH	NIÑA	BOTH	NIÑA	NIÑO	–	–	NIÑA
1969	NIÑO	–	NIÑO	NIÑO	–	–	NIÑO	NIÑO
1968	NIÑO	–	NIÑO		–	–	–	NIÑA
1967	–	–	–	–	–	–	–	NIÑA
1966	NIÑO	NIÑO	NIÑO	–	NIÑO	NIÑO		NIÑO
1965	NIÑO	NIÑO	BOTH	NIÑO	–	NIÑO	NIÑO	NIÑO
1964	BOTH	NIÑO	BOTH	NIÑA	–	–	–	BOTH
1963	NIÑO	NIÑO	NIÑO	NIÑO	–	–	NIÑO	NIÑA
1962	–	–	–	–	–	–	–	NIÑA
1961	–	–	–	–	–	–	–	–
1960	–	–	–	–	–	–	–	–
1959	–	–	–	–	–	–	–	NIÑO
1958	NIÑO	NIÑO	NIÑO		NIÑO		–	NIÑO

(*continued overleaf*)

Table VIII. (*Continued*)

Year	Coupled ENSO index	Allan *et al.* (2003)	Trenberth (1997)	Kiladis and Diaz (1989)	Quinn and Neal (1992)	Whetton and Rutherfurd (1994)	Rasmusson and Carpenter (1983)	Mullan (1995)
1957	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO
1956	NIÑA	NIÑA	NIÑA	–	–	–	–	NIÑA
1955	NIÑA	NIÑA	NIÑA	–	–	–	–	NIÑA
1954	NIÑA	NIÑA	NIÑA	NIÑA	–	–	–	–
1953	NIÑO	–	NIÑO	NIÑO	NIÑO	–	NIÑO	NIÑO
1952	–	–	NIÑO	–	–	NIÑO		NIÑO
1951	BOTH	–	BOTH	NIÑO	NIÑO	NIÑO	NIÑO	BOTH
1950	NIÑA	NIÑA	NIÑA	–	–	–	–	NIÑA

Table IX. 1871–1949 ENSO event comparison of coupled ENSO index and five published event lists. An asterisk (*) denotes end of temporal coverage, and a dash (–), the absence of ENSO conditions. The lists of Ortlieb (2000), Quinn and Neal (1992) and Whetton and Rutherfurd (1994) lists are proxy based. The other three are derived from instrumental records. 'BOTH' denotes phase-flipping

Year	Coupled ENSO Index	Allan *et al.* (2003)	Kiladis and Diaz (1989)	Quinn and Neal (1992) Ortlieb (2000)	Whetton and Rutherfurd (1994)	Rasmusson and Carpenter (1983)
1949	NIÑA	NIÑA	NIÑA	–	–	–
1948	–	–	–	–	–	–
1947	–	–	–	–	–	–
1946	–	–	–	–	–	–
1945	NIÑA	–	–	–	–	–
1944	–	–	–	–	–	–
1943	NIÑA	NIÑA		NIÑO	–	–
1942	BOTH	BOTH	NIÑA	–	–	–
1941	NIÑO	NIÑO	–	NIÑO	NIÑO	NIÑO
1940	NIÑO	NIÑO	–	NIÑO	–	–
1939	NIÑO	NIÑA	NIÑO	NIÑO	NIÑO	NIÑO
1938	–	NIÑA	NIÑA	–	–	–
1937	–	–	–	–	–	–
1936	–	–	–	–	–	–
1935	–	–	–	–	–	–
1934	NIÑA	NIÑA	–	–	–	–
1933	NIÑA	NIÑA	–	–	–	–
1932	–	–	NIÑO	NIÑO	–	NIÑO
1931	–	NIÑO	NIÑA		–	
1930	–	NIÑO	–	NIÑO	–	NIÑO
1929	–	–	–	–	–	–
1928	–	–	NIÑA	–	–	–
1927	–	–	–		–	–
1926	NIÑO	NIÑO	–	NIÑO	–	–
1925	BOTH	BOTH	NIÑO	NIÑO	NIÑO	NIÑO
1924	BOTH	NIÑA	NIÑA	–	–	–
1923	NIÑO		NIÑO	NIÑO		NIÑO
1922	–	–	–	–	–	–
1921	–	–	–	–	–	–
1920	NIÑO	–	NIÑA	–	–	–

Table IX. (*Continued*)

Year	Coupled ENSO Index	Allan *et al.* (2003)	Kiladis and Diaz (1989)	Quinn and Neal (1992) Ortlieb (2000)	Whetton and Rutherfurd (1994)	Rasmusson and Carpenter (1983)
1919	NIÑO	NIÑO	–	NIÑO		
1918	NIÑO	BOTH	NIÑO	NIÑO	NIÑO	NIÑO
1917	NIÑA	NIÑA	–	NIÑO	–	–
1916	NIÑA	NIÑA	NIÑA	–	–	–
1915	NIÑO	NIÑO	–	NIÑO	NIÑO	NIÑO
1914	NIÑO	NIÑO	–	NIÑO	–	–
1913	NIÑO	NIÑO	NIÑO	–	NIÑO	–
1912	NIÑO	NIÑO		NIÑO	–	–
1911	BOTH	NIÑO	NIÑO	NIÑO	–	NIÑO
1910	NIÑA	NIÑA	–	NIÑO		–
1909	NIÑA	NIÑA	–	–	–	–
1908	–	–	NIÑA	–	–	–
1907	–	–	–	NIÑO	NIÑO	–
1906	NIÑO	NIÑO	NIÑA		NIÑA	–
1905	NIÑO	NIÑO	–	NIÑO	NIÑO	NIÑO
1904	BOTH	–	NIÑO	NIÑO	NIÑO	–
1903	BOTH	NIÑO	NIÑA	–	–	–
1902	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO
1901	–	–	–	–	–	–
1900	NIÑO	NIÑO	–	NIÑO	–	–
1899	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO
1898	NIÑA	–	NIÑA	–	–	–
1897	BOTH	NIÑO		NIÑO		–
1896	NIÑO	NIÑO	NIÑO	–	–	NIÑO
1895	–	–	–	–	–	–
1894	NIÑA	–	–	–	NIÑA	–
1893	NIÑA	NIÑA	–	–	–	–
1892	NIÑA	NIÑA	NIÑA	–	–	–
1891	–	–	NIÑO	NIÑO	NIÑO	NIÑO
1890	NIÑA	NIÑA	–	–	–	–
1889	BOTH	BOTH	NIÑA	NIÑO	–	–
1888	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO	–
1887	NIÑA	NIÑA	–	NIÑO	–	NIÑO
1886	NIÑA	NIÑA	NIÑA	–	–	–
1885	NIÑO	–			–	–
1884	NIÑO	–	NIÑO	NIÑO	–	NIÑO
1883	–	–	–	–	–	–
1882	–	–	–	–	–	–
1881	–	–	–	–	–	–
1880	NIÑA	NIÑA	NIÑO	NIÑO	–	NIÑO
1879	NIÑA	NIÑA		–	NIÑA	–
1878	NIÑO	NIÑO	–	NIÑO	–	–
1877	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO	NIÑO
1876	BOTH	*	*	–	–	*
1875	NIÑA	*	*	–	–	*
1874	NIÑA	*	*	NIÑO	NIÑA	*
1873	NIÑA	*	*	–	–	*
1872	NIÑA	*	*	–	–	*
1871	NIÑA	*	*	–	–	*

Notably, the historical El Niño event list of Quinn and Neal (1992) and Ortlieb (2000) appears to 'mislabel' the years 1874, 1910, 1917 and 1943 as El Niños, while the available instrumental records have indicated La Niñas. Only 32 of the 46 CEI El Niño years for their period of overlap (1976–1871) are found in these South American historical chronologies, representing a 70% agreement to the instrumentally based CEI. Furthermore, there are an additional four El Niños (1932, 1930, 1907, and 1891) identified by Quinn and Neal (1992) and Ortlieb (2000) that are not found using the CEI. This highlights the issue of referring to ENSO events as simply 'El Niños', and the important implications for palaeo–ENSO reconstructions of the uncritical use of historical records such as the frequently cited 'Quinn' records for proxy calibration or verification purposes.

Defining an ENSO event based just on SSTs or the SOI also has the potential to introduce similar classification ambiguities. For example, Trenberth's (1997) Niño 3.4 index indicates oceanic La Niña conditions during 1984–1985 and 1997, and El Niño conditions during 1952 and 1978–1979. These 'events' are absent in the CEI, representing the absence of a simultaneous atmospheric response in the SOI, again emphasising the value of a coupled ENSO classification system for palaeoclimate reconstruction.

4.7. *CEI extreme event analysis*

Having verified the accuracy of the CEI, we now examine changes in the frequency and strength of extreme ENSO events for the instrumental era. So far this study has focused on ENSO phase classification and duration, which does not provide any quantification of event magnitude. The need to identify event magnitude from the instrumental record is considered important so that information on event amplitude is preserved in the analysis and interpretation of subsequent proxy reconstructions. Accurately accounting for the strength of past ENSO episodes from proxy archives is imperative to providing a long-term context for extreme ENSO events noted for the late twentieth century.

To quantify the magnitude of ENSO events indicated by the CEI, monthly Niño 3.4 SST anomalies were multiplied by -1 to allow warm SST values to directionally correspond to low SOI values (indicative of El Niño conditions). These monthly SSTs were then added to the corresponding monthly SOI value to produce a numeric value for the CEI. This ranged from a minimum of -4.77 in November 1878 to a maximum of 3.79 recorded in December 1988. Magnitude characteristics for all CEI-identified ENSO events are detailed in Table V.

To examine the suitability of combining the SOI and SST records, we analysed the respective variances of the records. Negative CEI values produced a standard deviation of 0.51 from the SOI compared to 0.66 from SSTs, while positive CEI values corresponded to a standard deviation value of 0.48 for the SOI and 0.65 for SSTs. This is further reflected in the slightly higher correlation between the CEI and the SST ($r = 0.955$) than with the SOI ($r = 0.922$). This indicates that there is probably a greater weighting of SSTs than the SOI in the combined index.

To investigate extreme events, we isolated the upper 1/3 of the 28 El Niños and 26 La Niñas identified from the CEI (Table V). This definition corresponded to a CEI value of ± 3. Examination of Table V and Figure 5 indicates that El Niño events tend to attain greater magnitudes than La Niña episodes. This is exemplified by the 1876–1878, 1982–1983, and 1997–1998 El Niños, which exceeded a CEI value of -4 represented the upper 1% of all ENSO cases. To address the uncertainty introduced by the use of the reconstructed Niño 3.4 dataset pre-1950 period, the SOI response was independently examined in terms of standard deviation departures relative to the 1933–1992 base period (see Sections 2.1 and Figure 2). To qualify as an extreme event during the 1871–1949 interval, the SOI was independently required to display a minimum of ± 1.5 standard deviation anomalies consecutively for a minimum of 50% of the overall duration of each event defined in Table V.

Examining Table V, extreme El Niños events all exceeded a minimum duration of 11 months (1896–1897), lasting up to 29 months (1939–1942). In contrast, the most extreme La Niñas were experienced in 1988–1989, followed by 1973–1974 and 1975–1976. These La Niñas were on average 9 months long, and did not exceed a CEI value of 3.79 (1988–1989). The maximum duration of an extreme La Niña event was 18 months during 1871–1873, achieving a maximum CEI value of 3.22.

Of the 16 extreme ENSO episodes indicated in Table V, nine occur post-1949. In fact, eight of these extreme events (four El Niños and four La Niñas) are observed since 1970. The reader is reminded that the

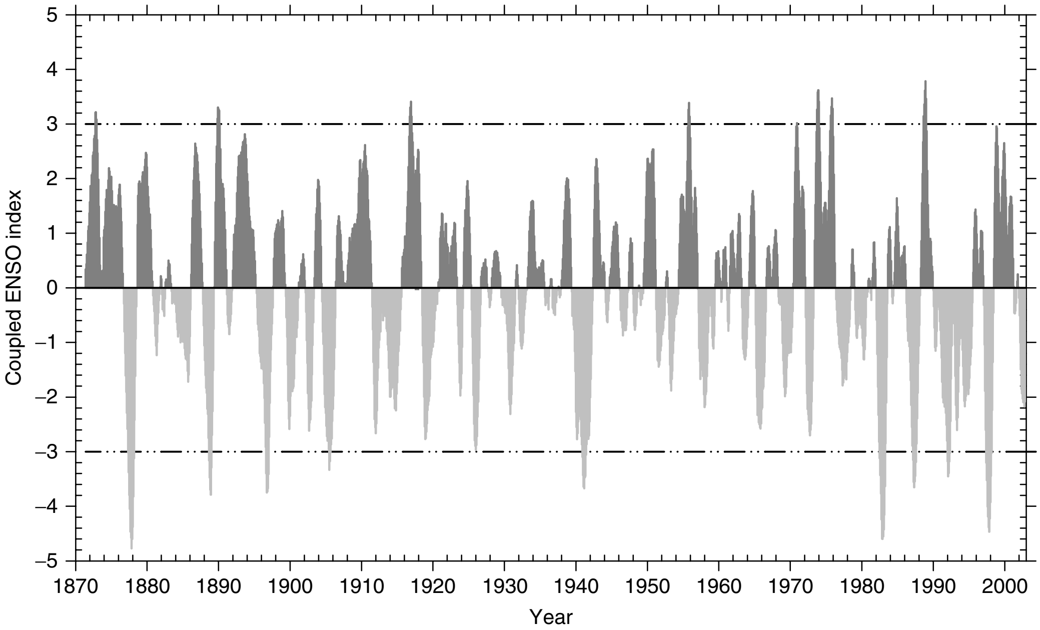

Figure 5. CEI event magnitude for 1872–2003 (start and end years omitted due to incomplete seasonal coverage). Extreme ENSO events are defined as a CEI index of ±3

CEI comprised observed, rather than reconstructed Niño 3.4 SST anomalies and the SOI for this post-1949 period, suggesting the absence of the amplitude enhancing affects of the reconstructed SST data noted in Section 3.1. The most comparable period of heightened ENSO activity is seen between 1871 and 1917 when four extreme El Niños (1876–1878, 1888–1889, 1896–1897, 1904–1906) and two La Niñas (1871–1873 and 1916–1917) are observed.

The most extreme El Niño of the entire time series is a 17-month event spanning 1876–1878, including seven months when the SOI exceeded two standard deviations (not shown). An event of a similar magnitude does not reoccur in the record until the two extreme El Niños of 1982–1983 and 1997–1998 (exceeding two standard deviations in the SOI for 9 and 6 months, respectively). During the 1982–1983 El Niño, the SOI independently exceeded three standard deviations for 3 months from October to December 1982, representing the highest observed SOI anomaly for the instrumental period (3.35 standard deviations in November 1982). Overall, there appears to be a shift in the frequency of extreme ENSO events from 1 in 11.3 years prior to 1950, to 1 in 6.0 years in the post-1949 period.

The examination of protracted events ($\geq$24 months) from the CEI revealed three La Niñas (1908–1911, 1892–1894, 1874–1876) and one El Niño (1939–1942) episode. With the exception of the 1939–1942 El Niño, these events are not extreme in terms of magnitude, they are however, considered extreme in terms of their duration (Table V). For example, the longest La Niña (El Niño) event is a 30(29)-month episode spanning 1908–1911(1939–1942) with an average magnitude of 1.71(−2.6), and a peak CEI value of 2.62 (−3.67). This suggests that persistent El Niño events identified from the CEI attain higher magnitudes than their La Niña counterparts.

5. DISCUSSION

In an attempt to describe more of the nature and evolution of ENSO events, a classification scheme that captured the synchronous dynamics of the coupled ocean–atmosphere system was devised. The dangers of using a sole index were highlighted through the analyses presented in Sections 3 and 4. For example, the SOI has a tendency of extending event duration (relative to SSTs) and the Niño 3.4 SST reconstruction has a propensity to over-estimate the magnitude of El Niño events. It should also be acknowledged that proxy reconstructions that only incorporate one component of the ocean–atmosphere system into the calibration process may be producing a somewhat incomplete characterisation of past ENSO behaviour, and thus should be interpreted as such.

This study addressed the complexities associated with generating a combined ENSO index for the instrumental era. To do so, it was necessary to investigate the threshold-dependent event capture characteristics of the atmosphere (SOI) and oceanic (Niño 3.4 SSTs) components for both ENSO phases. Comparing features such as event capture and duration allowed us to identify a SOI threshold of ±0.2, which gave the most suitable agreement with NOAA's recently proposed ONI definition of ±0.5 from the Niño 3.4 SST region.

Lack of direct pre-1950 instrumental SST measurements required reliance on a SST reconstruction from the Niño 3.4 SST zone. Section 3.1 raised the issues of slightly undercounting low magnitude La Niñas and overestimating the magnitude of El Niño events. This may influence, for example, the slightly longer event duration of pre-1950 SSTs (noted in Table VI) compared to the instrumental SST record. This bias may also be reflected in the slightly unequal weighting observed when generating the combined ENSO index (see Section 4.7). Nevertheless, with the above-mentioned provisos in mind, the striking similarity of instrumental and reconstructed SSTs suggests that the latter is a reliable record of oceanic ENSO conditions.

Imposing the fairly strict criteria of SOI and SST synchronous agreement for ENSO classification resulted in the exclusion of potentially important lead/lag relationships that are likely to provide additional information on ENSO event evolution. Recognition of this issue resulted in the generation of the seasonal classification scheme that preserved ENSO classifications for the individual SOI and SST components of the CEI (presented in Section 4.5). This provided the CEI with the flexibility to reintroduce this level of sophistication, as warranted, without detracting from the paper's primary objective of identifying distinct ENSO event classification.

The CEI also maintains information relating to various seasonal windows in an attempt to encourage the palaeo–ENSO community to reinvestigate proxies for important evolutive detail. To date, ENSO reconstructions such as the tree-ring SOI reconstruction of Stahle *et al.* (1998) have focused on only one seasonal window, typically the boreal winter/austral summer months of DJF, as this is when ENSO conditions are generally at their peak maturity (Rasmusson and Carpenter, 1982).

Recent work by Horii and Hanawa (2004), however, reported that the evolution of ENSO events from the Niño 3.4 region differs considerably depending on the timing of onset. For example, they found that El Niños that begin in April–June tend to develop into high magnitude events that peak during the boreal winter/austral summer, while events developing from July to October are relatively weaker in magnitude and have more irregular decay dynamics. Reporting seasonal ENSO conditions from the CEI (see Section 4.5) may assist the recovery of important evolutive information from proxy reconstructions based on calibrating to one season. As Allan *et al.* (2003) recently emphasised, resolving more of the ENSO life cycle is critical if greater modelling precision is be achieved.

From the perspective of a palaeoclimatologist, the CEI has the flexibility to allow the investigation of ENSO on monthly, seasonal and yearly timescales. This is of practical relevance as the community is often dealing with proxy records of varying resolution such as the monthly scale of many coral sequences or the annual dating of tree-ring chronologies. However, it is recognised that transferring from monthly to seasonal resolution involves issues associated with the arbitrary construct of selecting the middle month of the commonly defined seasonal windows. To avoid further smoothing of the data, ENSO classification for the middle month was presented as a partial representation of the entire seasonal conditions, as necessitated by the methodology adopted here.

This study importantly raised the issues associated with calibrating proxies to the coarser resolution, non-instrumentally based historical chronologies such as the widespread use of Quinn and Neal (1992). The potential danger of uncritical use of these major references for the long-term analysis of ENSO (examined in Section 4.6) was highlighted from the somewhat low 70% agreement of the South American El Niño record with the list of CEI events. Failing to incorporate advances in the description of the ENSO system into the analytical treatment of records may detrimentally impact efforts to accurately decipher the wealth of information contained within proxy archives.

As evident through even a basic extreme event analysis for the instrumental period, the magnitude of ENSO events has varied considerably though time. An apparent switch from a predominance of La Niña conditions in the pre-1950 period, to heightened El Niño activity post-1949 was noted in Section 4.4. Notably, the discernible increase in the frequency and magnitude of ENSO events since the mid-1970s identified in the literature (Fedorov and Philander, 2000; Folland *et al.*, 2001; Philander and Fedorov, 2003; Wang, 1995; Wang and Soon-II, 2001) was also confirmed from the CEI (Section 4.7). The frequency and intensity of post-1970 ENSO events appear the most anomalous in the context of at least the past century, with 50% of all extreme events noted from the CEI occurring in this period. This finding underscores the need to further investigate the long-term context and nature of recently anomalous ENSO sequences from appropriately calibrated proxy archives.

This study highlighted the significant implications of appropriate threshold selection on ENSO event sensitivity for subsequent palaeoclimate applications. There is a vital need to ensure that ENSO reconstructions attempt to maintain magnitude resolution through the appropriate application of thresholds to instrumental record if an assessment of late twentieth-century ENSO variability from a multi-centennial context is to be accurately achieved. This reinforces the need for 'amplitude preservation' in proxy calibration to assist refine the details essential for subsequent applications such as the validation of palaeoclimate model variability (Hegerl *et al.*, 2004).

The need for palaeoclimatic disciplines to work more closely together to establish standard protocols, such as the consistent statistical treatment of proxy records suggested by Lough (2004) to facilitate ready intercomparison of proxy records, is advocated by this study. The CEI classification scheme presented may contribute an instrumental benchmark to facilitate the calibration of proxy records for analysing ENSO in the pre-observational era (Gergis *et al.*, 2004).

From a broader perspective, climate dynamists may also benefit from an integrated description of the ENSO system. Cane (2004, p. 10) recently concluded 'if we are to trust a model to predict ENSO in the greenhouse world, it is necessary that it reproduces the changes in prior centuries'. Currently, climate models have great difficulty in realistically simulating ENSO as they often fail to adequately integrate both oceanic and atmospheric aspects of the phenomenon (Cane, 2004; Latif *et al.*, 2001). Often the primary variables analysed for ENSO are SSTs, which are often biased towards the eastern Pacific, despite the obvious predictive success recently attained by Chen *et al.* (2004) using SSTs from the Niño 3.4 region. Indeed, the development of a coupled ENSO classification based on this region appears well justified, and indeed timely, for incorporation into the palaeo-ENSO community.

As the spatial and temporal details of ENSO dynamics are increasingly resolved, high resolution reconstructions of the recent past may be readily used as quality templates for calibrating networks of longer, lower resolution proxies (Jones and Mann, 2004). It is hoped that the CEI will contribute to the systematic description of archives of past climate change that will continue to refine the details required for improving our description and simulation of the ENSO system well into the twenty-first century.

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