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Reconstructing El Niño–Southern Oscillation (ENSO) from high-resolution palaeoarchives

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ABSTRACT: El Niño–Southern Oscillation (ENSO) is one of the most important coupled ocean–atmospheric phenomena to cause global climate variability on interannual timescales. Efforts to understand recent, apparently anomalous ENSO behaviour are hampered by the phenomenon's unstable (non-stationary) nature and the limitations inherent in palaeoclimate records. In this paper, the complexities associated with isolating ENSO signals in observational and palaeoclimate records are reviewed. The utility and limitations of high-resolution (tree-ring, coral, speleothems, ice and documentary) proxy data for ENSO reconstruction are discussed. To overcome the regional biases contained within each palaeoclimatic source, it is necessary to compare complementary signals derived from multiple proxy climate records. To date, there have been limited attempts to reconstruct large-scale ENSO using these 'multiproxy' methodologies. A critique of the complexities associated with previous approaches of reconstructing discrete ENSO events and atmospheric/oceanic indices is provided. Abundant potential remains to better characterise teleconnection patterns, propagation signatures and non-stationary features of large-scale ENSO behaviour. If key uncertainties in ENSO dynamics (such as the response of extreme events to natural/human forcing) are to be adequately assessed, then complementary attempts must be made to model the historic synoptic conditions with apparent changes in reconstructed indices. Copyright © 2006 John Wiley & Sons, Ltd.

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KEYWORDS: El Niño–Southern Oscillation; ENSO; palaeoclimatology; high-resolution; climate reconstruction

Introduction

El Niño–Southern Oscillation (ENSO) is a complex interaction of oceanic and atmospheric processes that dominates changes in interannual global circulation. Initially generated in the equatorial Pacific, ENSO events create a far-reaching system of climate anomalies that operate on a range of timescales important to society (Glantz *et al.*, 1991; Grove and Chappell, 2000; Glantz, 2005). This is experienced through the modulation of climatic extremes including drought, flooding, bushfires and tropical cyclone activity across vast areas of the Earth. These episodes are commonly associated with large-scale socio-economic adversity for the millions of people living in areas where agricultural productivity is influenced by the Australasian, African and American monsoon systems (Bouma *et al.*, 1997; Dunbar and Cole, 1999; Caviedes, 2001; Chen *et al.*, 2001; Goddard and Dilley, 2005; Patz *et al.*, 2005).

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Extra-tropical climate variability associated with ENSO episodes, referred to as 'teleconnections', are known to have varied through time (Gagan *et al.*, 2000; Hendy *et al.*, 2003; Linsley *et al.*, 2004; Lough, 2004). During the instrumental (observational) period, the strength and stability of ENSO teleconnection patterns have responded to fluctuations in mean state characteristics such as changes in 'epicentre' locations, seasonal timing, and the intensity of atmospheric and oceanic anomalies (Troup, 1965; Chen, 1982; Allan *et al.*, 1996; Allan, 2000; Mann *et al.*, 2000a). The irregular quality of a process in which the statistical parameters (e.g. mean and standard deviation) changes with time is commonly referred to as 'non-stationarity'. Increasingly, the importance of characterising the frequency and strength shifts associated with this non-stationary behaviour of ENSO prior to the instrumental period has been recognised in light of the considerable implications for the accurate modelling of future climate change scenarios and their regional socio-economic impacts (Hoerling *et al.*, 1997; Karl and Easterling, 1999; Chen *et al.*, 2001; Folland *et al.*, 2001).

Despite being the dominant source of global interannual climate variability, the manner in which the frequency, duration and magnitude of ENSO events has varied through time is still poorly understood (Crowley, 2000; Grove and Chappell, 2000). Since the mid-1970s, ENSO has apparently changed in character to a dominance of El Niño conditions. For example, it has been observed that the two most intense El Niños (1982–83 and 1997–98) and La Niñas (1988–89, 1973–74) and the longest event in the instrumental record (1990–1995) have occurred over the past three decades (Trenberth and Hoar, 1996; Allan and D'Arrigo, 1999; Folland *et al.*, 2001; Allan *et al.*, 2003; Gergis and Fowler, 2005).

Nevertheless, the long-term context of these apparently anomalous events is still being debated (Latif *et al.*, 1997; Crowley, 2000; Folland *et al.*, 2001; Mann, 2003). In particular, recent research has sought to further clarify whether the modern behaviour of ENSO is a manifestation of human-induced global warming (Trenberth and Hoar, 1997; Folland *et al.*, 2001; Timmermann, 2001; Tsonis *et al.*, 2003; Collins, 2005), or simply an expression of natural decadal or multi-centennial climate variability (Mantua and Hare, 2002; Mantua *et al.*, 1997; Zhang *et al.*, 1998; Power *et al.*, 1999, 2006; Salinger *et al.*, 2001; Trenberth and Stepaniak, 2001; Mendelssohn *et al.*, 2005).

For example, using observational ENSO indices available from 1882, Mendelssohn *et al.* (2005) used state-space analysis to decompose atmospheric and oceanic indices into a variety of independent frequency components to investigate the role of low-frequency ENSO trends. They propose that since the long-term sea-surface temperature trend in the eastern equatorial Pacific is currently more than 0.5°C warmer than for events prior to 1950, there is no clear evidence that the *frequency* of ENSO events has changed over the 20th century (Mendelssohn *et al.*, 2005). They suggest that recent ENSO events are likely to have a stronger tropical Pacific signal as they are beginning from a warmer background state, reflected in an apparent increase in the *magnitude* (rather than overall frequency) of recent ENSO events by up to 50% of their estimated annual cycle (Mendelssohn *et al.*, 2005).

It is, however, widely recognised that instrumental time series (less than 150 years) are too short to assess whether 20th century ENSO behaviour was atypical (Allan and D'Arrigo, 1999; Dunbar and Cole, 1999; Fedorov and Philander, 2000; Folland *et al.*, 2001). Consequently, multi-century palaeoclimate reconstructions derived from proxy records such as annually resolved tree-ring, coral, ice, speleothem, sedimentary and documentary records are sought to provide the long-term background against which recent ENSO variability can be assessed (Jones and Mann, 2004). Although significant advances in the reconstruction of mean hemispheric and global temperatures of the past millennium have been made (Mann *et al.*, 1998; Crowley, 2000; Folland *et al.*, 2001; Jones and Mann, 2004; Moberg *et al.*, 2005; Oerlemans, 2005; D'Arrigo *et al.*, 2006; Osborn and Briffa, 2006), relatively little attention has focused on the long-term context of the apparently anomalous ENSO behaviour witnessed in recent decades (Trenberth and Hoar, 1996, 1997; Crowley, 2000; Folland *et al.*, 2001; Mann, 2003; Gergis and Fowler, 2005).

The dynamic (non-stationary) nature of ENSO makes any reconstruction using palaeoarchives problematic. Although ENSO is phase-locked to the annual cycle, with peaks in the amplitude of the Southern Oscillation Index (SOI) generally observed during the austral summer (December–February), associated rainfall, sea-surface temperature (SST) and wind field anomalies differ considerably from event to event (Rasmusson and Carpenter, 1982; Allan *et al.*, 1996; Fedorov and Philander, 2000; Trenberth and Stepaniak, 2001; Lyon and Barnston, 2005). Additionally, extra-tropical teleconnections of ENSO will often lag equatorial perturbations by months (Allan *et al.*, 1996; Kumar and Hoerling, 1997), with the regional response to different phases of ENSO forcing often displaying nonlinear characteristics (Ropelewski and Halpert, 1987; Kiladis and Diaz, 1989; Hoerling *et al.*, 1997, 2001; Mann *et al.*, 2000a; Diaz *et al.*, 2001; Power *et al.*, 2006).

The lack of climate-sensitive proxies for key ENSO locations of the Southern Hemisphere and differences in regional teleconnection signatures make it necessary to include proxy indicators from a variety of regions to adequately capture the spatial variability of ENSO through time. Data used for previous ENSO reconstructions have predominately come from eastern or central Pacific teleconnection regions (Stahle *et al.*, 1998; D'Arrigo *et al.*, 2005), with little representation of sites influenced by the west Pacific warm pool, a key area of ENSO influence (Allan *et al.*, 1996). However, it is recognised that reconstructions of ENSO derived from both east and west Pacific poles are more likely to be representative of basin-wide ocean–atmosphere processes than any of the geographically restricted single proxy climate records (Stahle *et al.*, 1998; Baumgartner *et al.*, 1989; D'Arrigo *et al.*, 1994; Diaz and Pulwarty, 1994; Gedalof and Mantua, 2002).

Further hampering efforts aimed at reconstructing past ENSO behaviour from palaeoclimate archives is the fact that palaeo-ENSO research rarely incorporates instrumental indices from both components of ENSO into proxy calibration (Gergis and Fowler, 2005). To date, reconstructive efforts have tended to focus on only one aspect of the ENSO phenomenon, commonly the SOI (Stahle *et al.*, 1998) or oceanic Niño 3 SST region (Mann *et al.*, 1998, 2000a; D'Arrigo *et al.*, 2005). However, it is not clear whether reconstructions based on calibrating proxy indicators based on a single component of ENSO are sufficient to fully characterise the magnitude and timing of ENSO perturbations contained within palaeoclimate records (Gergis and Fowler, 2005). Depending on the proxy, the signal of ENSO is generally recorded as function of variability in rainfall, sea-surface temperature, near-surface air temperature or some combination of climate parameters. Given that discrete event capture has been shown to be index-dependent (Hanley *et al.*, 2003; Gergis and Fowler, 2005) and that atmosphere and ocean perturbations may evolve differently, calibration to SOI or SST alone may fail to represent large-scale dynamics of the coupled ocean–atmosphere system.

In this paper, the complexities associated with isolating ENSO signals in observational and palaeoclimate records are reviewed. Observational records of oceanic and atmospheric components of the ENSO system are summarised with regard to their role in the calibration of proxy climate records. Next, an overview of the role of palaeoclimatic archives and their utility for ENSO reconstruction is presented. The issues associated with isolating ENSO signals in individual proxy records are highlighted in the context of large-scale reconstructions of ENSO using multiple proxy climate records. Finally, a discussion of the complexities associated with previous methodologies and interpretations of past ENSO reconstruction is provided.

Instrumental records of ENSO

What is ENSO?

The El Niño–Southern Oscillation (ENSO) is recognised as the strongest natural interannual climate fluctuation operating on the planet aside from the seasonal cycle and monsoon systems (Allan *et al.*, 1996; Wang *et al.*, 1999). Consequently, studies on

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the ENSO cycle and related climate variability are considered to rank among the most important frontiers in the atmospheric and oceanic sciences (Wang *et al.*, 1999).

The ENSO phenomenon is a coupled cycle in the atmosphere–oceanic system (Bjerknes, 1966, 1969). It is an irregular phenomenon that tends to reoccur every 2–7 years and alternates between its two phases or extremes, termed El Niño and La Niña events (Allan *et al.*, 1996; Markgraf and Diaz, 2000). Generally, during an El Niño (La Niña) event, warming (cooling) of tropical regions of the Pacific and Indian Oceans leads to massive redistributions of major rainfall-producing systems (Rasmusson and Carpenter, 1983; Allan, 2000). During an El Niño event rainfall is greatly suppressed (enhanced) in western (eastern) Pacific regions (Allan *et al.*, 1996). Essentially the opposite occurs under La Niña conditions when rainfall is greatly enhanced (suppressed) in western (eastern) Pacific locations (Allan *et al.*, 1996). A 'typical' ENSO event tends to last for 18–24 months with peaks in amplitude generally occurring in the austral summer (December–February) (Rasmusson and Carpenter, 1983; Allan, 2000; Horii and Hanawa, 2004).

Although ENSO is phase-locked to the annual cycle, episodes can differ in terms of their relative strengths, season of onset and maturity, overall duration, and the spatial extent of maximum sea-surface temperature (SST) anomalies in the tropical Pacific (Rasmusson and Carpenter, 1982; Allan *et al.*, 1996; Trenberth, 1997; Trenberth and Stepaniak, 2001; Horii and Hanawa, 2004; Lyon and Barnston, 2005). Along with SSTs, rainfall and wind field anomalies associated with ENSO events differ considerably from event to event, as these tropical 'centres of action' shift (Ropelewski and Halpert, 1987, 1989; Allan *et al.*, 1996; Fedorov and Philander, 2000).

As tropical regions are linked to higher latitudes in both hemispheres, for example through the Hadley cell circulation, any major variations in mass, energy and momentum due to redistributed equatorial rainfall are communicated to more temperate regions of the globe (Allan, 2000). This effect extends ENSO's influence beyond the tropics and causes near-global modulations of climate. It is likely that many large-scale components of intrinsic climate variability, such as the North Atlantic Oscillation (NAO), the North Pacific Oscillation (NPO) and the Southern Annular Mode (SAM), have some relationship to ENSO variability (Allan, 2000; Cook *et al.*, 2002a; Keskin and Olmez, 2004; Turner, 2004). A better understanding of the dynamical links between these features would provide much insight into the evolution of ENSO events and associated teleconnections.

The strength of ENSO teleconnection patterns over the 20th century have responded to fluctuations in mean state characteristics such as changes in 'centre of action' locations, seasonal timing, and intensity of anomalies (Troup, 1965; Chen, 1982; Allan *et al.*, 1996; Allan, 2000; Mann *et al.*, 2000a). For example, ENSO appears to have weakened during the 1920s–1950s and existed in a more amplified state from the 1970s onwards (Allan *et al.*, 1996; Allan, 2000). Clearly, characterising any frequency and strength shifts associated with the non-stationarity of ENSO has considerable implications for the accurate modelling of future climate change scenarios and their regional socio-economic impacts (Hoerling *et al.*, 1997; Karl and Easterling, 1999; Easterling *et al.*, 2000; Chen *et al.*, 2001; Folland *et al.*, 2001).

Oceanic component of ENSO; El Niño

Observations of equatorial Pacific SST signatures of ENSO events have provided the basis for simple indices of the phenomenon (Allan *et al.*, 1996). The temperature-based indices are defined with a mean SST from different regions of the equatorial Pacific (Allan *et al.*, 1996; Hanley *et al.*, 2003). The most widely used ENSO indices of Pacific SST fluctuations are characterised by the Niño SST anomaly regions, shown in Fig. 1. The Niño 1 region is located off the coast of Peru and Ecuador, while the Niño 2 region is located near the Galapagos Islands (Hanley *et al.*, 2003). SST in the combined Niño 1+2 region is highly responsive to the anomalous warming (the classical 'El Niño') experienced off the South American coastline around Christmas time, traditionally associated with collapses in fisheries and marine bird populations in coastal Peru and Ecuador (Quinn *et al.*, 1978; Trenberth, 1997; Caviedes, 2001).

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

The location of the Niño 3 region straddles two distinct ENSO-affected regions (Allan *et al.*, 1996; Hanley *et al.*, 2003). The beginning of an ENSO warm event has commonly been defined by SST warming in the eastern part of the Niño 3 region, adjacent to South America (Allan *et al.*, 1996; Hanley *et al.*, 2003). The mature phase of ENSO, several months later, brings

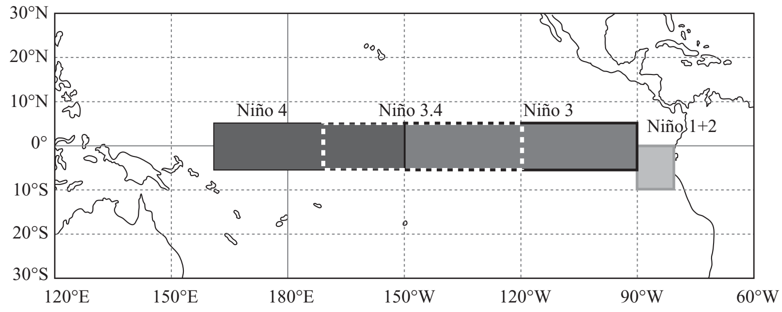

Figure 1 The Niño sea-surface temperature (SST) regions used to characterise ENSO conditions in the Pacific Ocean. Niño 1+2 (0°–10° S, 90° W–80° W), Niño 3 (5° N–5° S, 150° W–90° W) Niño 4 (5° N–5° S, 160° E–150° W) and (dotted) Niño 3.4 region (5° N–5° S, 170°–120° W) discussed in the text are shown. Source: Adapted from National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre (http://www.cpc.ncep.noaa.gov/)

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maximum SST anomalies to the western portion of the region (Cane, 1983; Fairbanks *et al.*, 1997). Consequently, a considerable focus of ENSO research is based on the Niño 3 SST region (Mann *et al.*, 1998; Evans *et al.*, 2002; D'Arrigo *et al.*, 2005), and it remains the primary area for climate model prediction of ENSO (Trenberth, 1997; Timmermann *et al.*, 1999; Latif *et al.*, 2001; Cane, 2004; Collins, 2005; Mann *et al.*, 2005).

The Niño 4 region encompasses part of the western equatorial Pacific where the sea-surface temperatures are typically warmest during ENSO events (Hanley *et al.*, 2003). Changes in SSTs in this region are related to longitudinal shifts of the strong east–west temperature gradients along the equator (Hanley *et al.*, 2003). The Niño 4 region has a deeper mixed layer compared to the other ENSO regions, which suppresses the amount of warming recorded in the sea-surface temperatures (Fig. 2) (Hanley *et al.*, 2003). Hanley *et al.* (2003) noted that the Niño 4 index responds weakly to warm phase events and downgrades the magnitude of moderate–strong events, when compared to the Southern Oscillation Index (SOI). Like Niño 3, the Niño 4 index is commonly used in model simulations of past ENSO behaviour (Latif *et al.*, 2001).

From the 1990s, it has become apparent that the key region for coupled atmospheric–ocean interactions involved in ENSO is located further west than traditionally defined by the eastern Pacific ENSO zones (Wang, 1995; Trenberth and Hoar, 1996, 1997; Trenberth, 1997). SST anomalies have fluctuated in the traditional Niño 1+2 region along the South American coastline in contrast to the central equatorial Pacific where a greater stability of oceanic anomalies have been noted (Trenberth, 1997). The understanding of the importance of SST variability in this area lead to the introduction of the Niño 3.4 region in 1996, combining the overlapping portions of the Niño 3 and Niño 4 regions covering an area from 5° N–5° S to 120°–170° W (Trenberth and Hoar, 1996; Trenberth, 1997) (see Fig. 1).

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). Thus, Niño 3.4 SST anomalies may be thought of as departures from average equatorial SST conditions across the Pacific from the western to central Pacific, that have a more robust correlation with the SOI than the Niño 3 index (Trenberth and Stepaniak, 2001; Hanley *et al.*, 2003). Most recently, the significance of this SST region was acknowledged by its selection as the geographical basis for the USA's National Oceanic and Atmospheric Administration's operational Oceanic Niño Index (ONI) (Elsey, 2004; McPhaden, 2004). In fact, the recent successful prediction of all prominent ENSO events since 1857 reported by Chen *et al.* (2004) made use of SST data from the Niño 3.4 region, highlighting the improved accuracy attainable through the careful use of SST indices of ENSO.

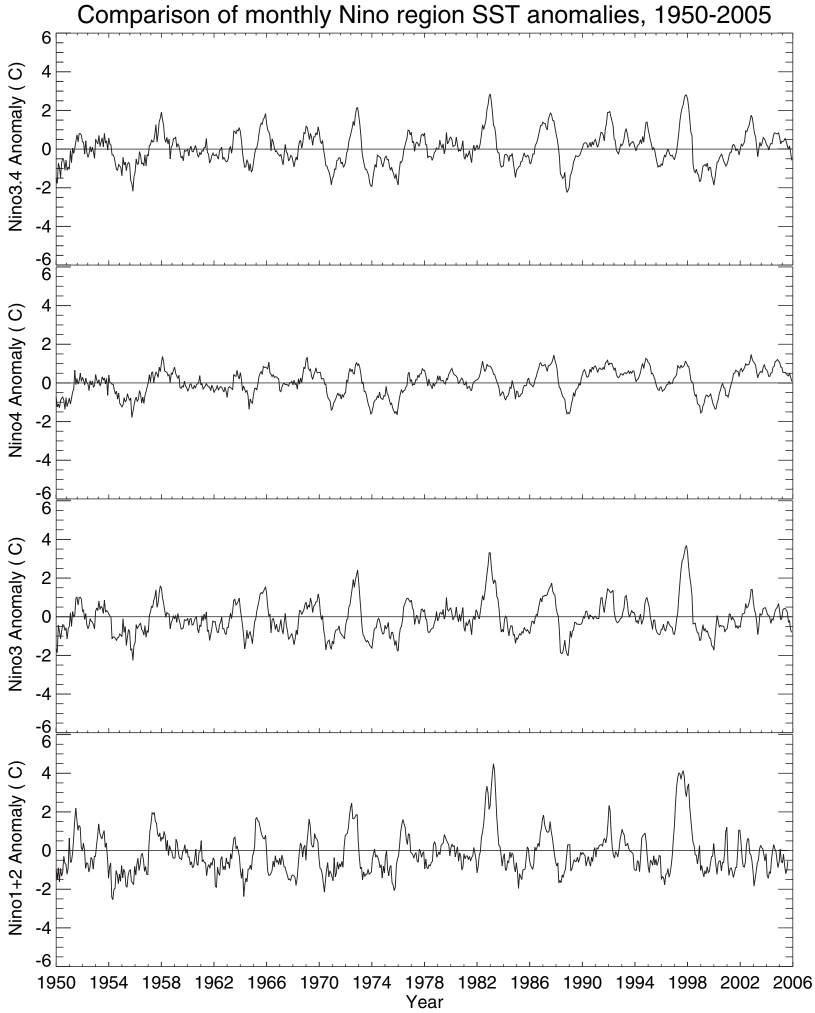

Figure 2 Monthly Niño region sea-surface temperature (SST) anomalies, 1950–2005. A base period of 1971–2000 used to calculate the mean and standard deviations of anomalies. Vertical scale indicates SST anomalies in °C. The Niño 1+2 region represents SST anomalies from the far eastern Pacific near South America spanning to the far western Pacific represented by Niño 4 adjacent to the Papua New Guinean coast. Note the considerable differences in the amplitude of SST anomalies for each region during the 1997–98 El Niño event. Source: Adapted from National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Centre (http://www.cpc.ncep.noaa.gov/data/indices)

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A number of caveats should be borne in mind during any subsequent palaeoclimatological use of SST data. The historic distribution of *in situ* SST data from ships has varied with time due to a variety of economic and political changes such as the opening of the Panama Canal, world wars, and improvements in technology and communication (Smith and Reynolds, 2004). As a result, the number of SST observations in the tropical Pacific drops greatly prior to about 1950, the quality of the analyses is not as good as in recent years and structures of SST anomalies are partially imposed by the method of analysis (e.g. empirical orthogonal functions as a means of spatial interpolation) and bias correction techniques (Smith and Reynolds, 2004; Trenberth and Stepaniak, 2001). However, comparing the similarity of Trenberth and Stepaniak's (2001) SST interpolation-based reconstruction of the Niño 3.4 SST zone with high-quality observational SST, Gergis and Fowler (2005) found a striking similarity of the ENSO event capture capabilities of both datasets. This suggests that reliable, albeit imperfect, records of early oceanic ENSO conditions are available, but must be interpreted with some degree of caution.

Atmospheric component of ENSO; Southern Oscillation

The atmospheric component of ENSO, first termed the Southern Oscillation (SO) by Sir Gilbert Walker, represents a seesaw in atmospheric mass between the Indonesian equatorial low and the South Pacific subtropical high (Rasmusson and Wallace, 1983; Allan *et al.*, 1996; Trenberth, 1997). It is a measure of the atmospheric surface pressure difference between eastern and western hemispheres (Troup, 1965; Bjerknes, 1966; Chen, 1982; Trenberth and Caron, 2000). Meteorological and oceanographic variables such as the equatorial zonal Walker circulation, rainfall, sea-surface temperatures, air temperature, winds and sea level in the equatorial Pacific are closely related fluctuations in the SO (Bjerknes, 1966; Chen, 1982; Rasmusson and Carpenter, 1982).

Following Chen (1982), the Southern Oscillation Index (SOI) is defined as the mean sea-level pressure (MSLP) difference between Tahiti and Darwin and is the standard atmospheric metric for diagnostic studies of the SO. The SOI is calculated using monthly average pressure anomalies at each station, normalised by the respective standard deviation, and provides a homogeneous index of the atmospheric pressure gradient between the eastern and western Pacific (Allan *et al.*, 1996). The SOI is a dimensionless parameter since the anomaly of each factor is divided by its standard deviation (Troup, 1965). A number of studies have examined the reliability of the data and the properties of the SOI (Allan *et al.*, 1991, 1996; Können *et al.*, 1998; Trenberth and Caron, 2000). For example, a strong annual MSLP cycle at Darwin and Tahiti makes interannual and lower frequency variability a small fraction of explained variance (Trenberth and Caron, 2000). As the SOI is based on just two stations, high-frequency phenomena such as the Madden–Julian Oscillation may obscure oscillations attributed to the Southern Oscillation (Trenberth, 1997).

Troup (1965) noted that the centres of action involved in the SO vary in position and activity. Prior to 1935, Tahiti has a number of missing values and periods when the correlation between Tahiti–Darwin atmospheric pressure was low despite evidence that the SO was present from other stations (Trenberth and Hoar, 1996). Recently, Mendelssohn *et al.* (2005) revealed that the long-term trend in the SOI is due solely to changes at Darwin, as Tahiti exhibits a consistent (i.e. stationary) low-frequency trend. Furthermore, they noted that the contribution of Darwin and Tahiti to negative SOI values is not equal, and that in fact, for the majority of ENSO events, most of the cyclic variability in the SOI is explained by Darwin MSLP (Mendelssohn *et al.*, 2005). Such factors highlight the need for high-quality, homogeneous climate series (Allen *et al.*, 1991), the potential for misinterpreting past climate variability based on an uncritical use of a sole index of this complex phenomenon. Nevertheless, the SOI is generally considered a good representative of the Southern Oscillation, with the advantage of a relatively long and homogeneous record length when compared with oceanic records (Brassington, 1997).

Monitoring ENSO from single indices

Observations of the appropriate resolution and quality for monitoring climate in the tropical Pacific span only the past few decades, with only a handful of isolated records pre-dating the early 1900s (Dunbar and Cole, 1999; Gagan *et al.*, 2000). Consequently, state-of-the-art predictive models can only be verified from the limited information available from such observational records (Dunbar and Cole, 1999). Recently, interpretational issues associated with simple instrumental indices of ENSO have been revisited (Trenberth and Stepaniak, 2001; Hanley *et al.*, 2003; Gergis and Fowler, 2005). For example, during the mid-1970s, it was observed that ENSO events tended to develop first along the coast of South America and then spread westward (Wang, 1995; Fedorov and Philander, 2000), as was found in the composites of Rasmusson and Carpenter (1982) based on six warm ENSO events from 1951 to 1972. Beginning from the 1982–83 El Niño, however, it was shown that on average El Niño events originated in the far western equatorial Pacific and propagated eastward to the central equatorial Pacific (Clarke and Van Gorder, 2001).

Furthermore, it is well known that atmospheric and oceanic components of ENSO can be out of phase with one another (Hanley *et al.*, 2003; Gergis and Fowler, 2005; Lyon and Barnston, 2005) (Fig. 3). The 2004–05 El Niño was an example of a 'decoupled' ENSO event. SST anomalies exceeded 0.5°C in the western-central Pacific (Niño 4, Niño 3.4 and Niño 3 regions), while warming exceeding 1°C did not expanded eastward of 140° W, resulting in near-zero anomalies along the 'classical' El Niño region off the west coast of South America (Niño 1+2 SST region) (Lyon and Barnston, 2005). The atmosphere failed to reflect SST conditions registered by SST indices until late in the austral summer when in February 2005, the SOI reached its lowest level since the 1982–83 event (Lyon and Barnston, 2005). Interestingly, this weak El Niño was detected by the Niño 3.4 SST index for at least 6 months, while the Niño 3 SST index (commonly used to calibrate ENSO proxy records) only indicated anomalous conditions for one to two months (Lyon and Barnston, 2005).

This lack of agreement between ENSO indices suggests that, for example, an index of average SST taken from one region, such as the traditionally defined 'El Niño' region of South America, may not adequately characterise the Pacific basin-wide occurrence of an event (Lyon and Barnston, 2005). To many people in ENSO-impacted regions, ENSO historically refers to their local El Niño/La Niña-associated climate condition rather than the physical conditions governed by the tropical Pacific. As such, the choice of an appropriate definition may depend on which aspects of ENSO create climate responses in the country or region in question (Glantz, 2005; Lyon and Barnston, 2005).

The implications of differences in local/regional and global-scale signatures of historical ENSO events were first recognised by Quinn (1992), detailed further in the subsection 'Historical

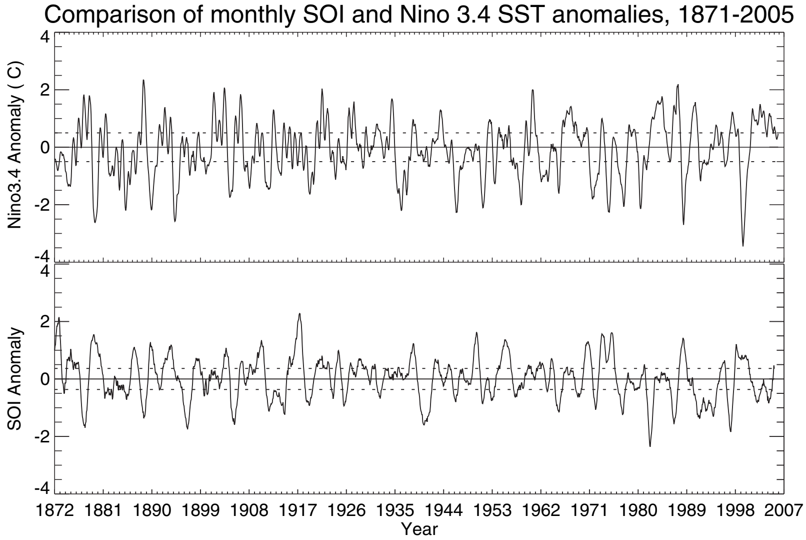

Figure 3 Monthly SOI smoothed with an 11-month running mean (below) and 5-month running mean of instrumental Niño 3.4 region SSTs (above) for the 1871–2005 period. Note that the Niño 3.4 region SSTs reconstruction of Trenberth and Stepaniak (2001) was used for the 1871–1949 period and post-1950 instrumental data sourced from NOAA's Climate Prediction Center (http://www.cpc.ncep.noaa.gov/). SSTs have been inverted to show El Niño SSTs as negative departures to facilitate comparison with the SOI. Decoupled and out-of-phase behaviour of atmospheric and oceanic components of ENSO are apparent for example, centred on the years 1880, 1900, 1930, 1990

records of El Niño events'. In a recent attempt to provide some clarity to this issue of ENSO classification, it was proposed that El Niño forecasts should be labelled as 'basin-wide El Niño', 'coastal El Niño', or a 'dateline El Niño' to account for the spatial differences of each episode (Glantz, 2005). Clearly, ENSO experiences significant variation from current simplistic definitions and may indeed suffer from attempts to reduce such a complex phenomenon into a single, universally accepted definition (Glantz, 2005; Lyon and Barnston, 2005). This remains a fundamental challenge of all contemporary and palaeoclimatic ENSO research and requires a direct effort to address these uncertainties.

Defining ENSO for palaeoclimatic applications

Clarification of the definition of ENSO has long been recognised as an issue of practical relevance (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 for palaeoclimatic applications (Trenberth, 1997; Hanley *et al.*, 2003; Elsey, 2004; Gergis and Fowler, 2005; Lyon and Barnston, 2005). From a palaeoclimatologist's perspective, the common approach to reconstructing ENSO from palaeoclimate records is to use statistical regression to establish a connection between instrumental records and the variability of the proxy over the period of overlap (Jones *et al.*, 2001; Mann, 2002; Jones and Mann, 2004). This calibration process provides a transfer function that enables the proxy record to be used as a surrogate of past climate. Thus, it is important to select a calibration index on the basis of the direct physical process influenced by ENSO conditions in a given area (e.g. temperature or precipitation) that an individual palaeoclimate is primarily registering. Subsequently, a broader network made up of these regional proxy-climate records can be used to reconstruct, large-scale (atmospheric, oceanic or coupled) components of the ENSO system.

In an attempt to represent both atmospheric and oceanic conditions of the ENSO system, Gergis and Fowler (2005) devised the Coupled ENSO Index (CEI) to register synchronous oceanic (Niño 3.4 SST) and atmospheric (SOI) anomalies for the instrumental period. Anomalies expressed in either Niño 3.4 SST or SOI indices (and therefore perhaps indicative of decoupled or out-of-phase behaviour) are maintained in the CEI, while fully coupled ocean–atmospheric anomalies result in an amplification of the index (Fig. 4). Where previous

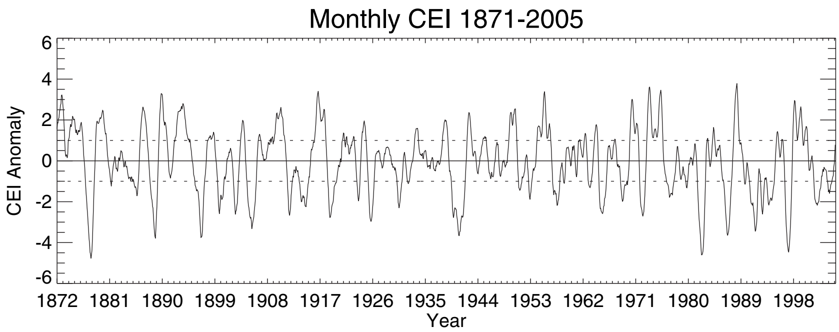

Figure 4 Coupled ENSO Index (CEI) developed by Gergis and Fowler (2005) registers synchronous oceanic (Niño 3.4 SST) and atmospheric (SOI) anomalies for the instrumental period (1871–2005). The CEI time series was developed by simply adding monthly SOI values to monthly Niño 3.4 SST anomalies (multiplied by −1 to allow warm SST values to directionally correspond to low SOI values, indicative of El Niño conditions). Anomalies expressed in either Niño 3.4 SST or SOI indices (and therefore perhaps indicative of decoupled or out-of-phase behaviour) are maintained in the CEI, while fully coupled ocean–atmospheric anomalies result in an amplification of the index

studies have chosen to examine the SOI or Niño region SSTs indices alone, a coupled ocean–atmosphere ENSO index is now being used as a baseline for the definition of ENSO conditions (Gergis and Fowler, 2006; Kane, 2006). Maintaining both atmospheric and oceanic components of ENSO represented in the calibration process has been found to help resolve seasonal and spatial (teleconnection) characteristics of both decoupled and coupled ENSO episodes using existing palaeoarchives (Gergis, 2006; Gergis and Fowler, 2006).

Reconstructing ENSO using high-resolution palaeoclimate data

Rationale

To determine whether the characteristics of ENSO during the late 20th century were unusual, it is essential to place them in the context of longer-term climate variability. Reconstructions of past climate are unique in their ability to provide a long-term, historical context for evaluating the nature of 20th century climate change. High-resolution records derived from corals, tree-rings, speleothems, varved sediments and ice cores have the advantage of registering discrete seasonal to annual environmental signals that may be attributed to single ENSO events (Markgraf and Diaz, 2000). Characteristic ENSO signals include drought, fires, floods, temperature and precipitation fluctuations, SST anomalies and changes in ocean salinity (Markgraf and Diaz, 2000).

There is, however, danger in assuming a simple (linear) relationship between a given proxy-climate record and its relationship to ENSO forcing. Although there is some early historical evidence of a long-term association of regional drought conditions with ENSO (Hamilton and Garcia, 1986; Nicholls, 1988), there evidence of the nonlinearity of regional ENSO teleconnections (Ropelewski and Halpert, 1987; Kiladis and Diaz, 1989; Hoerling *et al.*, 1997, 2001; Mann *et al.*, 2000a; Diaz *et al.*, 2001; Power *et al.*, 2006). For example, recent work by Power *et al.* (2006) found the relationship between ENSO the Australian rainfall to be nonlinear. Large SST anomalies associated with La Niña conditions were closely linked to a large Australian rainfall response (mostly becomes much wetter), whereas the magnitude of an El Niño SST anomaly is less closely linked to the degree of drying. The asymmetry of Australia's regional response to ENSO has considerable implications for palaeoclimatic reconstructions. Rather than assuming simple linear relationships with ENSO variables, it may be more useful to assess ENSO-proxies independently based on phase sensitivity to address such complexities (Gergis and Fowler, 2006). Similarly, the occurrence of drought in various parts of Asia is not always related to ENSO (Whetton and Rutherfurd, 1994; Kane, 1999, 2006).

Nevertheless, studies of high-resolution palaeoarchives provide considerable potential for documenting various aspects of the ENSO phenomenon. When considered together, ENSO-sensitive proxy records can reveal how individual events vary spatially across the equatorial Pacific and over areas of ENSO teleconnection influence (Baumgartner *et al.*, 1989; Allan and D'Arrigo, 1999; Mann *et al.*, 2000a), as seen in Fig. 5. Estimates of seasonal, annual or decadal climate variations must be derived from sources that are capable of resolving annual or seasonal climatic variations. Continuously recording, high-resolution systems all generate distinct layering as a response to climatic variation from one season to the next (Baumgartner *et al.*, 1989). High-resolution records generally result from the growth of living organisms that produce structures such as tree-rings and coral banding, or from complex depositional processes producing for example, dust layers within glacial ice, or the lamina couplets in varved sediments (Fisher, 2002). Proxy variables include width and density measurements from tree-rings, layer thickness from laminated sediments, and accumulation/isotopic indicators from annually resolved ice, speleothem and coral records.

These kinds of proxy climate data provide records of climate variations several centuries into the past, with the potential to resolve large-scale patterns of climate change prior to the instrumental period, albeit with important limitations and uncertainties (Jones and Mann, 2004). In recent years, the latest studies based on 'multiproxy' data have proved particularly useful for describing global or hemispheric patterns of climate variability in past centuries (Mann *et al.*, 1998, 2000a; Esper *et al.*, 2002; Fisher, 2002; Gedalof and Mantua, 2002; Bradley *et al.*, 2003; Linsley *et al.*, 2004; Moberg *et al.*, 2005; Oerlemans, 2005). Such estimates allow the observed trends of the 20th century to be

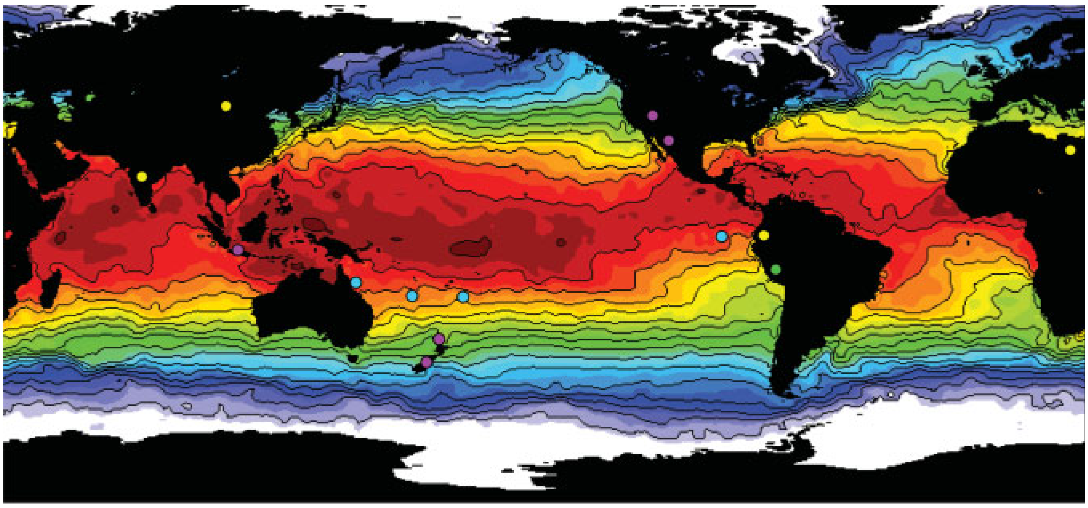

Figure 5 Location of selected tree-ring (purple), coral (blue), historical (yellow) and ice (green) ENSO-sensitive palaeoclimate records. Regional differences associated with absolute SSTs of the 1997–98 El Niño event are clearly seen, emphasising the merits of using a multiproxy approach to ENSO reconstruction. Source: Modified from Bureau of Meteorology Research Centre's NCEP SST analysis (http://www.bom.gov.au/bmrc/ocean/results/pastanal.htm)

put into a longer-term perspective, allowing improved comparisons with simulated climates driven by different forcing mechanisms (Mann *et al.*, 2005).

Palaeoclimate data quality issues

There are, however, a number of limitations associated with high temporal resolution palaeoclimatic reconstructions. Unfortunately, high-resolution records are difficult to obtain and often have restricted geographic availability (Markgraf and Diaz, 2000). Constraints may include a lack of tree species with annual growth rings in low–mid-latitude areas of the Southern Hemisphere and the restriction of coral records to tropical warm-water regions of the equatorial Pacific. Such spatial limitations on the location of study sites dictate the type of climatic and oceanic influences that can be resolved (Harrison and Dodson, 1993; Allan and Lindsay, 1998). As a result, regions in which data is sparse or absent present major problems in achieving a spatially balanced understanding of important components of the global climatic system such as ENSO (Allan and Lindsay, 1998).

A major challenge of palaeoclimatic studies is to integrate findings derived from numerous palaeoenvironmental sources analysed at fine scale (i.e. seasonal–annual) resolution (Cronin, 1999). Markgraf and Diaz (2000) emphasised the importance of comparing a variety of proxy indicators that represent regional responses to different aspects of the ENSO phenomenon. In doing so, multiproxy investigations taken from spatially distributed locations dramatically reduce the possibility that non-ENSO environmental factors are responsible for observed proxy variability, allowing the effective study of past ENSO behaviour (Markgraf and Diaz, 2000).

The limitations and potential biases that are specific to each individual type of palaeoclimate proxy are well understood (Jones and Mann, 2004). For example, differences in temporal resolution (seasonal versus annual), or inherent limitations in temporal coverage varies from a few centuries using corals and historical documentary sources, to thousands of years in the case of tree-ring, sedimentary and ice-core sequences (Jones and Mann, 2004). Commonly, a proxy record is specific to one particular season, rarely captures more than 50% of instrumental variance, and is often unable to register variance equally well across a number of frequency domains (Bradley, 1996). Thus, each proxy represents a unique signal from different regions of the globe (tropics versus extra tropics, terrestrial versus marine environments) allowing complementary information on the widespread nature of ENSO event signatures to be investigated (Jones and Mann, 2004).

The consequences of the unstable or non-stationary behaviour of ENSO have profound implications for the reconstruction of past ENSO event signatures. Proxies derived from a number of ENSO-influenced locations have considerable differences in the seasonality of their response signatures. As a result, a variety of regions are needed to adequately capture the spatial variability of ENSO through time (Fairbanks *et al.*, 1997). Accordingly, representation of ENSO signals from a number of widely spaced regional proxies (Fig. 5) is more likely to be representative of large-scale ocean–atmosphere processes than is possible from single proxy analysis (Baumgartner *et al.*, 1989; D'Arrigo *et al.*, 1994; Diaz and Pulwarty, 1994; Gedalof and Mantua, 2002).

There are a number of issues that arise from the use of multiple proxy sources (Mann *et al.*, 1998; Fisher, 2002). Potential limitations specific to each type of proxy data series (e.g. limitations to record length or the maximum frequency resolvable) must be carefully taken into account while structuring a multiproxy network for climatic assessment (Mann *et al.*, 1998). Most importantly, dating errors in a given record, such as incorrectly assigned annual layers or rings, are particularly detrimental if synchronous information is sought to describe climate patterns on a year-by-year basis, as is the case for ENSO which is characterised by discrete events operating on interannual timescales (Mann *et al.*, 1998; Markgraf and Diaz, 2000).

Palaeoclimate data filtering

Conservative standardisation procedures are applied to remove biological influences, such as competitive/injury/growth trends from proxy records. For tree-ring analyses, the standardisation process involves fitting a curve to the ring-width series (detrending) and then dividing or subtracting each ring-width value by the corresponding detrended curve values (Fritts, 1976, 1991; Cook and Kairiukstis, 1990). Importantly, however, the constituent segment lengths can restrict the maximum timescale of climate variability that is recorded in a proxy-climate record (Esper *et al.*, 2002). For example, millennia-long tree-ring chronologies are constructed by averages of many tree-ring sequences from living and subfossil trees (Cook *et al.*, 1992, 2002b; Boswijk *et al.*, 2006). The segment lengths of these series are typically several centuries long with the overlapping individual series exactly aligned by calendar year and connected in time using cross-dating techniques (Fritts, 1976, 1991; Cook and Kairiukstis, 1990). When the segment lengths are substantially shorter than the length of the overall chronology being developed, it is difficult to preserve multi-centennial variation in tree-ring series (Cook *et al.*, 1995; Esper *et al.*, 2002). This results from the need to remove age-related biological growth trends that represent noise for the purpose of climate reconstruction (Esper *et al.*, 2002).

Dendrochronologists usually eliminate growth trends by detrending each tree-ring width series with a fitted mathematical growth function (Cook and Peters, 1981; Holmes *et al.*, 1986; Esper *et al.*, 2002). As a result, the maximum wavelength of recoverable climatic information is fundamentally limited by the segment lengths of the individual detrended series (Cook *et al.*, 1995; Esper *et al.*, 2002). Thus, a 100-year-long tree-ring sequence will not contain any climatic variance at periods longer then 100 years if it is explicitly detrended by a fitted growth curve (Esper *et al.*, 2002). Consequently, it is possible to miss long-term trends in millennia-length tree-ring chronologies by using detrended series that are short relative to the multi-centennial fluctuations due to climate (Cook *et al.*, 1995; Esper *et al.*, 2002).

Fisher (2002) identified further problems associated with heterogeneous data compilations. It is often necessary to include records with imperfect transfer functions, the statistical relationship between proxy climate records and direct meteorological variables, which may limit the accuracy of any climatic information gained. Differing seasonal sensitivities, resolutions/spectral sensitivities, high local noise levels and inconsistent resolution of some records are also accredited as posing potential obstacles to palaeoclimatic reconstructions (Fisher, 2002). The reconstruction of tropical ENSO variability and the associated extra-tropical climate impact is further complicated by the fact that climate proxies are not consistently accurate in recording their local climate or oceanographic environment in both time and space (Stahle *et al.*, 1998) for reasons discussed previously. Furthermore, the sometimes narrow seasonal response of even the most climate-sensitive proxies may not perfectly coincide with the seasonality of the local ENSO teleconnection (Stahle *et al.*, 1998).

Despite such considerations, Mann *et al.* (1998) noted that with appropriate data treatment, the common signal recorded by a diverse and widely distributed set of independent climate indicators more accurately captures any consistent climate signal present than single proxy analysis. Importantly, this reduces the compromising effects of the biases and weaknesses inherent to individual proxy records (Mann *et al.*, 1998).

Previous approaches to 'multiproxy' ENSO reconstruction

As noted, the dynamic nature of ENSO makes any reconstruction using proxy archives problematic. ENSO episodes are known to differ in terms of their relative strengths, season of onset and maturity and of the location of maximum SST anomalies in the tropical Pacific (Rasmusson and Carpenter, 1982; Allan *et al.*, 1996; Lyon and Barnston, 2005). Consequently, 'multiproxy' approaches have been employed to take advantage of the complementary strengths of a selected number of ENSO-sensitive data sources, allowing event signatures in core and key teleconnection areas to be investigated (Stahle *et al.*, 1998; Mann *et al.*, 2000a; D'Arrigo *et al.*, 2005). Here, previous approaches to multiproxy ENSO reconstruction are reviewed for the benefit of the non-specialist reader.

Discrete ENSO event chronologies

Historical records of El Niño events

To date, there have been limited attempts to develop chronologies of individual ENSO events for the pre-instrumental period using palaeoclimatic records (Quinn and Neal, 1992; Whetton and Rutherfurd, 1994; Allan and D'Arrigo, 1999; Ortlieb, 2000; Gergis, 2006; Gergis and Fowler, 2006). These records provide a year-by-year chronology of unusual meteorological and hydrological phenomena characteristic of discrete ENSO episodes such as extreme flooding or drought conditions (Quinn *et al.*, 1987; Whetton and Rutherfurd, 1994).

To determine the intensity of events, years are classified from very strong to weak based on the apparent extent of destruction and societal cost detailed in these historical documents or through simple statistical definitions (Quinn *et al.*, 1987; Quinn and Neal, 1992; Whetton and Rutherfurd, 1994; Gergis, 2006). Importantly, these records can provide an independent means of verifying model simulations and continuous proxy reconstructions of ENSO indices (Stahle *et al.*, 1998; Rodbell *et al.*, 1999; Mann *et al.*, 2000a; Gergis, 2006), and are of use to archaeologists and social scientists interested in human responses to climatic events (Bouma *et al.*, 1997; Grove and Chappell, 2000; Kuhnel and Coates, 2000; *et al.*, 2001; Kovats *et al.*, 2003; Goddard and Dilley, 2005; Patz *et al.*, 2005).

A key paper for the historical chronology of El Niño events was that of Quinn *et al.* (1987). Following on from exploratory work on the association between ENSO and Indonesian droughts (Quinn *et al.*, 1978), Quinn *et al.* (1987) established the magnitude scale of the El Niño events that has been generally adopted by the scientific community working on ENSO (Ortlieb, 2000). Quinn's list of past El Niño events recorded in the eastern Pacific during the past four and a half centuries has long been viewed as the major reference for any long-term analysis of ENSO (Ortlieb, 2000). An ordinal scale of the intensity of events (ranging from weak to moderate, strong and very strong) was established using published documentary data dealing with reports of anomalous rainfall and storm events on the coast of Peru, travel time of ships in the eastern Pacific, or anomalous SST and air-temperature episodes in western South America (Quinn *et al.*, 1987). Importantly, however, the record only provides a history of El Niño events in the eastern Pacific teleconnection region, and significantly excludes the occurrence of La Niña conditions. This is a likely consequence of the stronger mean seasonal signal exhibited during extreme El Niño conditions (Hoerling *et al.*, 2001).

In the early 1990s, Quinn and Neal (1992) refined this chronology by including additional documentary data, mainly from the countries adjacent to Peru including Chile, Bolivia and Brazil. This then became the major reference for proxy calibrations and for most studies on climate variability related to ENSO during observational and pre-instrumental times (Ortlieb, 2000). In fact, Ortlieb (2000) noted that practically all the decadal–centennial ENSO studies during the 1990s that used dendroclimatology, coral records, tropical ice cores or other proxy climate sequences were compared to and calibrated with Quinn's El Niño chronologies (Stahle *et al.*, 1998; Rodbell *et al.*, 1999; Diaz and Markgraf, 2000; Mann *et al.*, 2000a). In an attempt to document a record of El Niño events beyond the South American region, Quinn (1992) incorporated Nile flood height data and historical records of drought in India in the pre-AD 1824 period to develop a more 'global' El Niño chronology. This led to revisions in the occurrence, timing, duration and apparent magnitude of the El Niño events identified by Quinn and Neal (1992), again highlighting the biases associated with a purely regional analysis of ENSO conditions.

Historical records of ENSO events

Using data covering the AD1525–1994 period, an attempt was made by Whetton and Rutherfurd (1994) to extend the record of climatic extremes related to ENSO affecting the eastern hemisphere. Following on from Quinn (1992), Whetton and Rutherford (1994) used annual time series of flood height of the Nile in Egypt, an index of rainfall in northern China based on historical records and tree-ring widths based on teak growing in Java, Indonesia. In addition, two historical records of drought and famine from India, and the El Niño chronology assembled by Quinn and Neal (1992) were also analysed. Following a further update of the historical record to include data from Egypt (Quinn, 1992), slight analytical revisions were made by Whetton *et al.* (1996).

Unlike earlier works by Quinn and his colleagues, Whetton and Rutherfurd (1994) were the first to attempt to document both phases of the ENSO phenomenon (Whetton and Rutherfurd, 1994; Allan and D'Arrigo, 1999; Ortlieb, 2000). In fact, the ENSO chronology of eastern hemisphere teleconnections complied by Whetton and Rutherfurd (1994) has been considered to be the most complete attempt to document both phases of ENSO for pre-instrumental times (Allan and D'Arrigo, 1999; Ortlieb, 2000). However, owing to inadequate long-term data coverage, the ENSO chronology and analysis of teleconnection stability analysis were restricted to AD1701–1979 period (Whetton and Rutherfurd, 1994). It is important to note that the study only provided a list of the occurrence of standard deviation defined extreme ENSO events, rather than the range of magnitude classes detailed by the 'Quinn' chronologies. Furthermore, the La Niña aspect of the chronology is only based on three records (Java, Nile and China), two of which originate from more peripheral teleconnection zones. Nonetheless, the chronology remains an important source for determining the presence of ENSO conditions during pre-instrumental times.

Most recently, Gergis (2006) examined a number of ENSO-sensitive proxy records (tree-ring, coral, ice and documentary) and isolated ENSO signals associated with both phases of the phenomenon. Using novel applications of percentile analysis (Gergis, 2006), an extensive 478-year chronology of ENSO events using a variety of regional ENSO signals spanning the both the east and west Pacific was developed back to AD 1525. Significantly, for the first time, there was a considerable improvement in proxy representation from western Pacific locations, allowing both key ENSO 'centres of action' to be adequately assessed over the past five centuries. The chronology allowed large-scale trends in the frequency, magnitude and duration of pre-instrumental ENSO (Gergis, 2006). In addition, methods for the quantification of event magnitude and reconstruction uncertainty were provided for both ENSO phases, and the most comprehensive La Niña event chronology complied to date was developed for the AD 1525–2002 period (Gergis, 2006; Gergis and Fowler, 2006).

The chronology of Gergis and Fowler (2006) expands upon the discrete ENSO event chronologies such as those provided by previous researchers (e.g. Quinn and Neal (1992), Ortlieb (2000) and Whetton and Rutherfurd (1994)), providing an expanded alternative to the 'Quinn records' commonly used by palaeoclimatologists for the calibration and verification of past ENSO conditions from palaeoarchives (Gergis, 2006). Importantly, the chronology provides an expansive listing of historical ENSO events for a range of percentile-defined magnitude classes using data from both eastern and western Pacific locations back to AD 1525 (Gergis and Fowler, 2006).

Protracted ENSO event chronology

Using the proxy data set of Stahle *et al.* (1998) detailed in the subsection 'Southern Oscillation Index' below, Allan and D'Arrigo (1999) derived a multiple regression reconstruction of the SOI for the AD 1706–1875 period. Allan and D'Arrigo (1999) discussed how recent ENSO sequences, such as the protracted El Niño event of 1990–1995, have only been considered with regard to contemporary data and events (Trenberth and Hoar, 1996, 1997). Since the presence of such signals in records of relatively short length may be of limited statistical significance, other instrumental, documentary and palaeoclimatic data is critical to investigate longer-term, natural (non-anthropogenic) variability of the ENSO system (Allan and D'Arrigo, 1999).

Allan and D'Arrigo (1999) demonstrated that features indicative of protracted event sequences have occurred prior to the period of instrumentally based indices. They concluded that that ENSO sequences of 3 years' duration or longer are not rare or unusual, and estimated that El Niño events of this nature have occurred around four or five times per century when matched against the historical documentary evidence of Whetton *et al.* (1996). This estimate compared favourably with the instrumentally based data which revealed a frequency of about six protracted events per century, supporting evidence that pervasive decadal signals are represented in the ENSO record (Allan and D'Arrigo, 1999). Once again, the merits of integrating complementary and well-dated, high-resolution records into multiproxy reconstructions for comparison with instrumental trends was clearly demonstrated (Allan and D'Arrigo, 1999).

Reconstructing ENSO indices

The most common approach to the reconstruction of ENSO involves the use of multiproxy networks of annually resolved palaeoclimate indicators. Statistical techniques are employed to extract the dominant modes of covariability from palaeonetworks. These techniques are most often some form of empirical orthogonal function (EOF) technique or principal component analysis (PCA) (Jolliffe, 2002; Von Storch and Zwiers, 1999). Such techniques makes it possible to represent very large fields of data with just a few dominant modes of variability (most often represented as spatial patterns for geophysical data) and their time-varying amplitudes. The spatial and temporal signature of such modes of covariability can be related physical processes such as those associated with ENSO.

Effectively, the use of PCA reduces the noise associated with differences in the seasonal climate responses of each proxy, minimising differences associated with the seasonality and duration of regional ENSO teleconnection signatures (Stahle *et al.*, 1998; Mann *et al.*, 2000a). Variables used to reconstruct ENSO are produced from the multiproxy data by first decomposing the data into principal components (PCs). The associated time series (PC scores) is used in a simple, least-squares, multiple linear regression model that relates variability in the palaeoclimate data with instrumental ENSO indices (Von Storch and Zwiers, 1999). To date, reconstructive efforts have tended to focus on only one aspect of the ENSO phenomenon, commonly the SOI (Stahle *et al.*, 1998) or oceanic Niño 3 SST region (Mann *et al.*, 1998, 2000; D'Arrigo *et al.*, 2005) (Fig. 6).

Southern Oscillation Index

Expanding on early studies demonstrating the potential of tree-rings for resolving ENSO (Lough and Fritts, 1985; D'Arrigo and Jacoby, 1991; Cleaveland *et al.*, 1992; D'Arrigo *et al.*, 1994), Stahle *et al.* (1998) were the first to use extensive tree-ring data from southwestern USA, Mexico and Indonesia to experimentally reconstruct the Southern Oscillation. Currently, these exactly dated tree-ring chronologies from ENSO-sensitive regions in subtropical North America and Indonesia are considered to collectively register the strongest ENSO signal yet detected in tree-ring data worldwide (Stahle *et al.*, 1998).

Selected annual-resolution coral and ice-core records available from the equatorial Pacific were also used to develop reconstructions of the December-February SOI (Stahle *et al.*, 1998). However, the coral and ice-core data available for the analysis were found to be either relatively short (<130 years) or were not well correlated with the particular seasonal index of the SO that was most consistent with the tree-ring data (Stahle *et al.*, 1998). As a result, Stahle *et al.* (1998) based their experimental reconstruction of December-January-February (DJF) SOI from AD 1706 to 1977, hereafter referred to as the 'ST98' reconstruction, solely on the tree-ring data and reserved the coral and ice-core proxies for comparison with the tree-ring estimates of past ENSO variability.

Seasonalised DJF SOI data was chosen to represent the season in which ENSO events are typically mature in the equatorial Pacific (Rasmusson and Carpenter, 1982; Kiladis and

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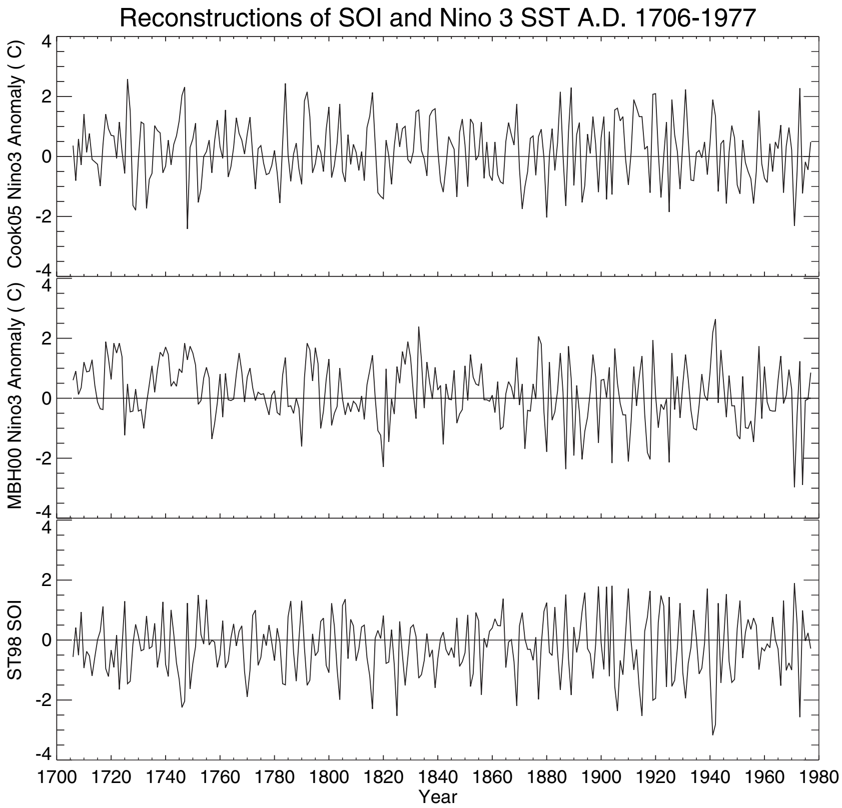

Figure 6 Palaeoclimate reconstructions of ENSO indices, AD 1704–1977. The December–February Niño 3 SST Cook05 reconstruction of D'Arrigo *et al.* (2005) (top), October–March mean Niño 3 SST index of Mann *et al.* (2000a) (middle), and the December–February SOI index of Stahle *et al.* (1998) (bottom). Note that all time series have been normalised (i.e. have unit variance)

Diaz, 1989; Allan *et al.*, 1996; Stahle *et al.*, 1998). The ST98 reconstruction explained 53% of the variance in the instrumental DJF SOI and was verified by comparisons with independent instrumental SOI and SST data (Stahle *et al.*, 1998). The results tentatively suggested that the ENSO variance might have increased from the 19th to 20th century. The analysis also indicated a small increase in the atmospheric pressure gradient across the Pacific during the period AD 1879–1977, suggestive of more positive DJF SOI and more frequent La Niña episodes compared with the AD 1706–1878 time period (Stahle *et al.*, 1998).

Importantly, Stahle *et al.* (1998) highlighted the fact that the network of ENSO-sensitive proxies is indeed still in its infancy, hindering substantial advancements in ENSO reconstruction. For example, they recognised that longer coral records from the tropical Pacific and additional tree-ring chronologies from the western tropical Pacific would substantially improve on tree-ring reconstructions of the SOI (Stahle *et al.*, 1998). They proposed that ideally, exactly dated and climatically sensitive proxies from the equatorial Pacific centres of action of ENSO should be used to reconstruct the characteristics of ENSO, and all remaining annual resolution proxies could then be used to map the spatial anomaly patterns of tropical and extra-tropical climate associated with each reconstructed ENSO events (Stahle *et al.*, 1998).

This ideal approach is hardly possible even for the 20th century owing to the poor spatial coverage of the instrumental data, particularly over the oceans, and the limited network of exactly dated annually resolved palaeoclimate proxies currently available (Stahle *et al.*, 1998). The reconstruction of tropical ENSO variability and the associated extra-tropical climate impact is further complicated by the fact that climate proxies are not uniformly accurate in recording their local climate or oceanographic environment, and the sometimes brief seasonal response of even the most sensitive proxies may not perfectly coincide with the seasonality of the local ENSO teleconnection.

Nevertheless, Stahle *et al.* (1998) stressed that the available tree-ring data from subtropical North America and Java demonstrated a temporal and spatial ENSO signal and strongly justified the further development of annual palaeoclimatic proxies of the ENSO system (Stahle *et al.*, 1998). They concluded that if these reconstructed 19th–20th century changes in reconstructed DJF SOI are substantiated by further studies, they will have important implications to the long-term dynamics of ENSO and its associated climate teleconnections (Stahle *et al.*, 1998).

Niño 3 SSTs

Using a more restricted 'tropical' subset of the Mann *et al.* (1998) multiproxy database used to reconstruct Northern Hemisphere temperature, a reconstruction of October to March Niño 3 SSTs for the period AD 1650–1980 was developed (Mann *et al.*, 2000a, b). Two different sets of calibration experiments were performed; the first used the entire global multiproxy network to reconstruct the 'global ENSO' signal, while a more restricted 'tropical' network of indicators from approximately twenty distinct tropical or subtropical sites were used to reconstruct the specific tropical Pacific El Niño signal (Mann *et al.*, 2000a, b). This study is hereafter referred to as the 'MBH00' reconstruction.

Unlike the ST98 reconstruction, descriptions of low-frequency changes in the mean state were potentially maintained in the MBH00 reconstruction. Additionally, changes in the amplitude of interannual variability, ENSO

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extremes and trends in the global pattern of ENSO variability were reported (Mann *et al*., 2000a, b). Certain ENSO-related patterns such as enhanced interdecadal variance appear to have exhibited significant trends during the 20th century; however, Mann *et al*. (2000a, b) suggest that typical ENSO indices show only modest warming trends in comparison with the dramatic warming trend in hemispheric and global temperature during the past century (Mann *et al*., 2000a). Nonetheless, some indication of a pattern associated with negative tropical feedbacks dampening an El Niño-like warming trend in the tropical Pacific were identified (Mann *et al*., 2000a).

Mann *et al*. (2000a, b) also found evidence of changes in the amplitude of interannual ENSO variability, global teleconnections of ENSO and the amplitude and frequency of extreme events As seen in Fig. 6, the incidence of large warm and cold events appears to have increased during the past century (Mann *et al*., 2000a). The apparent breakdown of interannual ENSO variability during the 19th century appears to have had significant impact on the incidence of extremes and on global teleconnection patterns of ENSO during that period (Mann *et al*., 2000a).

MBH00 propose the hypothesis that this breakdown may have been associated with the same external forcing that led to generally cold global temperatures during the 19th century. This period may thus provide an analogue for the behaviour of ENSO and the possible breakdown of typical mechanisms of ENSO variability under the impacts of external and anthropogenic forcing of climate (Mann *et al*., 2000a). Once again, they recognised that, as increasingly rich networks of high-quality, seasonally resolved proxy data become available, both global temperature and ENSO reconstructions should be possible with considerably reduced uncertainties (Mann *et al*., 2000a). In particular, the increased availability of well-dated coral isotopic indicators in the tropical Pacific were identified as being especially useful for large-scale ENSO reconstruction in the future.

Most recently, using an expanded and updated version of the Stahle *et al*. (1998) data, D'Arrigo *et al*. (2005) reconstructed December to February Niño 3 SSTs (Fig. 7). Following the protocol of D'Arrigo *et al*. (2005), it is hereafter referred to as the 'Cook05' reconstruction. A total of 175 chronologies from the southwestern USA and Mexico were screened as potential predictors (lags $t-1$; $t+1$) of the instrumental Niño 3 data in principal component regression (D'Arrigo *et al*., 2005). Both the tree-ring and instrumental data were prewhitened using autoregressive modelling, with instrumental persistence added back in to the reconstruction.

Prewhitening removes a large portion of annual periodicities (such as biological growth factors) that may otherwise dominate the spectrum and impair its fidelity at other frequencies (Gilman *et al*., 1963). This is by fitting autoregressive–moving average (ARMA) techniques which are mathematical models designed to identify persistence, or lower-order autocorrelation, in a time series (Chatfield, 1975). A subset of ARMA models is the autoregressive or AR models which express a time series as a linear function of its past values plus a noise term (Chatfield, 1975). The order of the AR model indicates how many lagged values are included.

Tree-ring series that were significantly correlated with the instrumental record were then used to reconstruct Niño 3 SSTs using a 'nested' procedure which accounts for the decrease in the number of chronologies back in time (D'Arrigo *et al*., 2005). This procedure involves normalising the tree-ring series to the common period of all series in each nest (beginning in AD 1408, 1507, 1608 and 1709) and then averaging the series together to create a nest mean (D'Arrigo *et al*., 2005, 2006). To generate the longest possible final reconstruction, the mean and variance of each nested reconstructed time series were scaled to that of the most replicated nest (AD 1709–1978) and the relevant sections of each nest spliced together (D'Arrigo *et al*., 2005, 2006). This approach is thought to stabilise the variance of the final time series that is not biased because of varying number of constituent series (D'Arrigo *et al*., 2005, 2006). All chronologies were compiled from indices of tree growth (primarily ring-width) detrended to remove biological trends (Cook and Peters, 1981) to best reflect the high-frequency 2–7 year band of ENSO variability (D'Arrigo *et al*., 2005).

It is important to note that prewhitening of the proxy chronologies removes *all* persistence or lower-frequency signals from the data, including those related to climate processes. Fitting observed autocorrelation structures back into prewhitened regression models makes the assumption that the 20th century period is representative of the entire reconstruction. In short, the lower-frequency amplitude modulation of the reconstructed ENSO indices is extremely uncertain. Caution is also needed in using nested or changing proxy networks for

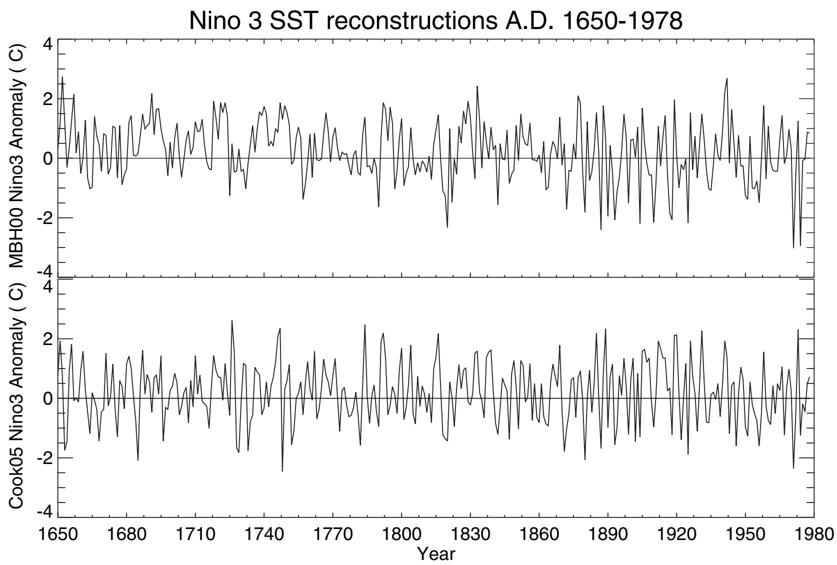

Figure 7 Palaeoclimate reconstructions of Niño 3 SST, AD 1650–1978. October–March mean Niño 3 index of Mann *et al*. (2000) shown in the upper panel and December–February Niño 3 SST Cook05 reconstruction (D'Arrigo *et al*., 2005) in the lower panel. Note all time series have been normalised to have unit variance

ENSO reconstructions. Potential inhomogeneities from a changing proxy network are potentially more pronounced when retrieving signals of ENSO compared with mean surface temperature since different networks may provide variable signals of the same event. For a recent analysis of the effect of prewhitening a time series for the detection of regime shifts in climate analysis, see Rodionov (2006).

D'Arrigo (2005) concluded that ENSO variability appears to be somewhat modulated by external solar forcing. Generally, higher ENSO variability reflected in the Cook05 tree-ring reconstruction coincided with decreased solar variability in line with recent coral and modelling results (Cobb *et al.*, 2003; Mann *et al.*, 2005). However, a notable exception occurs during the Maunder Minimum period of low solar irradiance (ca. AD 1645–1715), when lowest ENSO variability over the past six centuries during the broadly defined 'Little Ice Age' (LIA) (ca. AD 1550–1850).

While it is difficult to determine the accuracy of past changes inferred from palaeo-reconstructions alone, it is unclear what mechanisms may have forced such changes. Dynamical studies have suggested that solar, volcanic and anthropogenic radiative forcing have influenced past ENSO variability, particularly a tendency toward El Niño-like conditions during periods of radiative cooling (Clement *et al.*, 2001; Cane, 2004; Mann *et al.*, 2005), although the complexity of the atmosphere–ocean feedbacks involved and inconsistency in current ENSO models increase the uncertainty of such conclusions (Collins, 2005).

Discussion and future recommendations

Characterisation of ENSO may suffer from attempts to reduce such a complex phenomenon into a single, universally accepted definition. Therefore the choice of an appropriate definition should be based on the intended application with regard to ENSO-local climate responses in question. Furthermore, the unstable (non-stationary) behaviour of ENSO observed from observational records has considerable implications for the reconstruction of past ENSO event signatures. There may be danger in assuming a simple (linear) relationship between a given proxy-climate record and its relationship to ENSO forcing. Rather than assuming simple linear relationships with ENSO variables, it may be more useful to assess ENSO-proxies independently on the basis of phase sensitivity to address such complexities (Fowler, 2005; Gergis and Fowler, 2006). Furthermore, it is important to select a calibration index on the basis of the direct physical process influenced by ENSO conditions in a given area (e.g. temperature or precipitation) that an individual palaeoclimate is primarily registering. Subsequently, a broader network made up of these regional proxy-climate records can be used to reconstruct, large-scale (atmospheric, oceanic or coupled) components of the ENSO system.

By using a variety of regional records, it is possible to capture more of the spatial variability of ENSO more likely to be representative of large-scale ocean–atmosphere processes than is possible from single proxy analysis. Previous studies which have examined long-term trends in the SOI or Niño region SSTs are now being complemented with reconstructions based on a newly developed coupled ocean–atmosphere ENSO index (Gergis and Fowler, 2005). Maintaining both atmospheric and oceanic components of ENSO represented in the proxy calibration process may help resolve more of the seasonal and spatial (teleconnection) characteristics of both decoupled and coupled ENSO episodes using existing palaeoarchives (Gergis and Fowler, 2005, 2006).

It is clear that reconstructions of simple ENSO indices or event signatures are insufficient to clearly characterise past ENSO behaviour. If low-frequency (decadal and greater) intrinsic variability of ENSO and the response of ENSO to external radiative forcing is to be thoroughly assessed, then complementary attempts must be made to reconstruct ENSO variability across the entire frequency domain and to reconstruct and model the larger historic synoptic conditions with apparent changes in reconstructed indices (e.g. Fowler, 2005). In this manner, proxy reconstructions could be better employed to constrain the variety of numerical experiments that are required to assess uncertainties in ENSO dynamics (e.g. response of extreme events to natural/human forcing). This has excellent potential for resolving the dynamics of past ENSO activity influencing the Australian region.

Significantly, none of the ENSO indices reconstructed to date (Stahle *et al.*, 1998; Mann *et al.*, 2000a; D'Arrigo *et al.*, 2005) are able to completely reproduce the variance exhibited by the instrumental record. This reflects both the truncation of variance due to regression-type approaches to generating transfer functions as well as inherent limitations in the ability of palaeoclimatic proxies to fully resolve the magnitude of associated climate variability. This remains a central challenge to forthcoming reconstructions of past ENSO variability.

Nevertheless, reconstructions of past climate are unique in their ability to provide a long-term, historical context for evaluating the nature of 20th century climate change. Such high-resolution records derived from corals, tree-rings, speleothems, varved sediments and ice-cores have the advantage of registering discrete seasonal to annual environmental signals that may be attributed to single ENSO events. A major challenge of future palaeoclimatic studies will be to integrate findings derived from multiple high-resolution proxies with longer, lower-resolution palaeohydrological records from lakes and swamps. This holds excellent prospects for the groundbreaking description of low-frequency climate variability in the Australian region, comparable to seminal European works (Moberg *et al.*, 2005; Osborn and Briffa, 2006).

Multiproxy ENSO reconstruction is still indeed in its infancy, and abundant potential remains to characterise teleconnection patterns, propagation signatures and non-stationarities of large-scale ENSO behaviour. There is a need for the expansion of high-quality proxies from key ENSO-affected regions, particularly from the western Pacific sites (e.g. Boswijk *et al.*, 2006; Fenwick, 2003; Fowler, 2005; Hendy *et al.*, 2003; McDonald *et al.*, 2004). It is imperative that existing Australasian records be reviewed for their ENSO-sensitivity to allow features of the regional dynamics of the western Pacific to be resolved. In this way, improved reconstructions of ENSO could be used to refine key factors influencing climate variability in the Australian region simulated by climate models.

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