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How unusual was late 20th century El Niño-Southern Oscillation (ENSO)? Assessing evidence from tree-ring, coral, ice-core and documentary palaeoarchives, A.D. 1525–2002

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Abstract. Multiple proxy records (tree-ring, coral, ice and documentary) were examined to isolate ENSO signals associated with both phases of the phenomenon for the period A.D. 1525–2002. To avoid making large-scale inferences from single proxy analysis, regional signals were aggregated into a network of high-resolution records, revealing large-scale trends in the frequency, magnitude and duration of pre-instrumental ENSO using novel applications of percentile analysis. Here we use the newly introduced coupled ocean-atmosphere ENSO index (CEI) as a baseline for the calibration of proxy records. The reconstruction revealed 83 extreme or very strong ENSO episodes since A.D. 1525, expanding considerably on existing ENSO event chronologies. Significantly, excerpts of the most comprehensive list of La Niña events complied to date are presented, indicating peak activity during the 16th to mid 17th and 20th centuries. Although extreme events are seen throughout the 478-year reconstruction, 43% of the extreme ENSO events noted since A.D. 1525 occur during the 20th century, with an obvious bias towards enhanced El Niño conditions in recent decades. Of the total number of extreme event years reconstructed, 30% of all reconstructed ENSO event years occur post-1940 alone suggesting that recent ENSO variability appears anomalous in the context of the past five centuries.

1 Introduction

El Niño-Southern Oscillation (ENSO) is associated with extreme weather events that influence climatic extremes such as drought, flooding, bushfires and tropical cyclone activity across vast areas of the Earth, often associated with large-scale socio-economic adversity. Despite impressive advances in the reconstruction of mean hemispheric and global temperatures of the past five centuries, relatively little attention has been devoted to assessing the long-term context of apparently anomalous ENSO behaviour witnessed in recent decades (Stahle et al., 1998; Crowley, 2000; Folland et al., 2001; Mann, 2003; D'Arrigo et al., 2005).

It is widely understood that instrumental time series (<150 years) are not long enough to ascertain if decadal-scale variability observed during the 20th century is atypical (Trenberth and Hoar, 1997; Allan and D'Arrigo, 1999; Dunbar and Cole, 1999; Fedorov and Philander, 2000). Consequently, multi-century palaeoclimate reconstructions derived from long proxy records, such as seasonally-annually resolved tree-ring, coral, ice or documentary records are sought to examine pre-instrumental patterns of ENSO variability (Jones and Mann, 2004).

Clarification of the definition of ENSO has long been recognised as an issue of practical relevance by CLIVAR (Climate Variability and Predictability), the largest initiative of the World Climate Research Programme (Trenberth, 1997). It is proposed here that an index of only component of ENSO is not ideal as it is only indicative of one physical aspect of the phenomenon, and, as such, is likely to incompletely resolve the wider interactions experienced in the coupled ocean-atmospheric system.

In an attempt describe more of the nature and evolution of ENSO conditions, Gergis and Fowler (2005a) devised the Coupled ENSO Index (CEI) to register synchronous oceanic (Niño 3.4 SST) and atmospheric (Southern Oscillation Index) anomalies for the instrumental period (1871–2003). 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. Where previous studies have chosen to reconstruct the SOI or Niño region SSTs indices alone, here we use the newly introduced coupled ocean-atmosphere ENSO index as a baseline for the calibration of proxy records (Gergis and Fowler, 2005a).

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Table 1. Proxy data information of records used in this study. [a] Berlage (1931), Murphy and Whetton (1989), Whetton and Rutherfurd (1994), Whetton et al. (1996); [b] D'Arrigo et al. (1994), IGBP Pages/WDC-A for Paleoclimatology Contribution Series 1999-063; [c] Fowler et al. (2000, 2004), Gergis et al. (2005b, 2005c); [d] Fenwick (2003); [e] Cleaveland et al. (2003), Stahle and Cleaveland (2002), IGBP Pages/WDC-A for Paleoclimatology Contribution Series 2002-004., Greybill (1994) IGBP Pages/WDC-A for Paleoclimatology Contribution Series 1994-003, Grissino-Mayer and Swetnam (1992) IGBP Pages/WDC-A for Paleoclimatology Contribution Series 1992-012, Dean (1993) IGBP Pages/WDC-A for Paleoclimatology Contribution Series 1993-021, Grow (2000) IGBP Pages/WDC-A for Paleoclimatology Contribution Series 2003-094; [f] Stahle et al. (1998), IGBP Pages/WDC-A for Paleoclimatology Contribution Series 2002-004; [g] Hendy et al. (1998), IGBP Pages/WDC-A for Paleoclimatology Contribution Series 2002-009; [h] Quinn et al. (1998), IGBP Pages/WDC-A for Paleoclimatology Contribution Series 1999-003; [i] Dunbar et al. (1994), IGBP Pages/WDC-A for Paleoclimatology Contribution Series 1994-013; [j] Linsley et al. (2000), IGBP Pages/WDC-A for Paleoclimatology Contribution Series 2000-065; [k] Thompson et al. (1992) IGBP Pages/WDC-A for Paleoclimatology Contribution Series 1992-008; [l] Quinn and Neal (1992), Ortlieb (2000); [m] Hassan (1981), Whetton and Rutherfurd (1994), Whetton et al. (1996); [n] Whetton and Rutherfurd (1994), Whetton et al. (1996); [o] Wang and Zhao (1981), Whetton and Rutherfurd (1994), Whetton et al. (1996).

Proxy Record	Dates (A.D.)	Data filter	ENSO Zone	Season	Climate Variable
Tree-rings					
Berlage Indonesian Teak [a*]	1525-1929	10-year Gaussian	West Pacific	SON	Total Ring Widths
D'Arrigo Indonesian Teak [b*]	1841-1995	20-year Spline	West Pacific	SON	Total Ring Widths
New Zealand Kauri [c]	1525-2002	20-year Spline	West Pacific	SON	Total Ring Widths
New Zealand Pink Pine [d]	1525-1998	20-year Spline	West Pacific	JJA	Total Ring Widths
Mexican Douglas Fir [e]	1525-1998	20-year Spline	East Pacific	DJF	Total Ring Widths
SW USA Pinyon Pine [f]	1525-2000	20-year Spline	East Pacific	DJF	Total Ring Widths
Coral					
Great Barrier Reef [g]	1612-1985	3-year Gaussian	South-west Pacific	DJF	Luminescence SSS
New Caledonia [h]	1658-1992	3-year Gaussian	South-west Pacific	SON	δO^{18} SST
Galapagos Islands [i]	1607-1982	3-year Gaussian	East Pacific	DJF	δO^{18} SST
Rarotonga [j]	1726-1997	3-year Gaussian	Central Pacific	DJF	Sr/Ca SST
Ice					
Quelccaya Ice Core [k]	1525-1984	3-year Gaussian	East Pacific	DJF	Net accumulation
Historical Records					
Quinn/Ortlieb [l]	1525-1987	N/A	East Pacific	JJA	Rainfall
Nile [m]	1587-1984	10-year Gaussian	North Africa Teleconnection	MAM	Rainfall
India Drought [n]	1525-1984	N/A	South Asia Teleconnection	SON	Rainfall
China [o]	1525-1979	10-year Gaussian	North Asia Teleconnection	DJF	Rainfall

The CEI is of practical relevance to the ENSO community as it provides an amplitude preserving, composite index for the calibration of proxy records to simultaneously reconstruct both components of the ENSO system (Gergis and Fowler, 2005a). By maintaining both atmospheric and oceanic components of ENSO represented in the calibration process, it has been possible to resolve seasonal and spatial (teleconnection) characteristics of both decoupled and coupled ENSO episodes using existing palaeoarchives (Gergis, 2006; Braganza et al., 2006[1]; Gergis and Fowler, 2006[2]).

This study reports the results derived from the integration of various regional signals from a variety of ENSO affected locations, to providing insight into the wider, global signature of ENSO events. The primary intention of this paper is to provide a list of very strong to extreme ENSO events observed since A.D. 1525. To verify the occurrence of reconstructed existing ENSO event chronologies were consulted. Importantly, this paper introduces an excerpt of the most comprehensive listing of pre-instrumental La Niña events compiled to date which incorporates data from east and western Pacific centres-of-action (Gergis, 2006; Gergis and Fowler, 2006[2]).

2 Data and methodology

2.1 Proxy selection and calibration with instrumental ENSO

An ENSO event is defined in the CEI as at least six months of simultaneous oceanic (Niño 3.4 SSTs) and atmospheric anomalies (SOI), with no more than two consecutive neutral months interrupting ENSO conditions. The seasonal CEI classifications, which maintain information about individual SST and SOI trends, were used to identify the presence and nature of any ENSO signal recorded within each proxy (Gergis and Fowler, 2005a). Proxy records used in this

[1]Braganza, K., Gergis, J., Risbey, J., and Fowler, A.: El Niño-Southern Oscillation (ENSO) since A.D. 1525; evidence from tree-ring, coral and ice-core records, in preparation, 2006.

[2]Gergis, J. and Fowler, A.: A history of ENSO events since A.D. 1525; implications for future climate change, in preparation, 2006.

Table 2. Reconstructed El Niño events since A.D. 1525. Percentile analysis was used to classify the magnitude of events into extreme (>90th percentile) and very strong (70th–90th percentile). Excerpt taken from (Gergis, 2006; Gergis and Fowler, 2006[2]).

Reconstructed Instrumental El Niño Events	***Reconstructed Event Magnitude***	***Reconstructed Pre-Instrumental El Niño Events***	***Reconstructed Event Magnitude***
1871-2002		***1870-1525***	
2002	E	1868	VS
1991-92	VS	1866	VS
1987	VS	1853	VS
1982-83	E	1845	VS
1941-42	E	1806	VS
1940	VS	1791	VS
1926	E	1770	VS
1918	VS	1737	E
1912-15	VS	1723	E
1905	E	1718	E
1902	VS	1687	VS
1900	VS	1660	VS
1891	VS	1650	E
1888	VS	1618	VS
1877	VS	1607-08	VS
		1585	VS
		1574	VS
		1565	VS
		1559	VS
		1556	VS
		1544	VS
		1525-26	VS

study (Table 1) are largely based on published records from core ENSO and key teleconnection areas to ensure the use of high quality data (Allan et al., 1996). Attention was given to preserving geographical representation of signals from both eastern and western Pacific sites back to A.D. 1525. Note that in this paper, the season of proxy response listed in Table 1 relates to the strongest relationship *identified with the CEI* (Gergis and Fowler, 2005a) and does not assume any a priori seasonal response window based on previous analyses undertaken using other indices of ENSO.

Instead of calibrating proxies using commonly applied regression approaches, a percentile analysis was employed (Gergis, 2006; Gergis and Fowler, 2006[2]). Since the technique is based upon the hierarchical ranking of all anomalies, there is no truncation of statistical outliers or loss of variance in subsequent applications. This is of significance as previous reconstructions have been known to underestimate the amplitude of ENSO events (Folland et al., 2001). Consequently, the novel application of this technique to ENSO analysis may have considerable implications for accurately deciphering the wealth of information contained within proxy archives (Gergis, 2006; Gergis and Fowler, 2006[2]).

2.2 ENSO event magnitude

Following extensive verification related to signal replication and comparison with existing chronologies of historical ENSO events (Gergis, 2006), a three (four) proxy threshold was used to define an El Niño (La Niña) event in a multiple proxy environment. To allow the skill of the proxy to be incorporated into the quantification of event magnitude, a quality adjusted magnitude (MQ) time series was devised (Gergis, 2006; Gergis and Fowler, 2006[2]).

Essentially, to define the intensity and quality of reconstructed events, a percentile analysis was performed on the MQ time series to isolate (>90th percentile) very strong (70th–90th percentile), strong (50th–70th), moderate (50th–30th) and weak events (<30th) ENSO conditions. These percentile thresholds were determined by calibrating the multiproxy reconstructions to match conventional wisdom

Table 3. Reconstructed La Niña events since A.D. 1525. Percentile analysis was used to classify the magnitude of events into extreme (>90th percentile) and very strong (70th–90th percentile). Excerpt taken from (Gergis, 2006; Gergis and Fowler, 2006[2]).

Reconstructed Instrumental La Niña Events	*Reconstructed Event Magnitude*	*Reconstructed Pre-Instrumental La Niña Events*	*Reconstructed Event Magnitude*
1871-2002		***1870-1525***	
1998	E	1863	VS
1989-90	VS	1860-61	VS
1974	E	1808	VS
1971	VS	1805	VS
1956	VS	1801-02	VS
1953	E	1788	VS
1950	E	1752	VS
1917	VS	1743	VS
1909-10	VS	1742	E
1894	E	1739-40	VS
1893	VS	1733	VS
1887	VS	1696	VS
1880	VS	1663	VS
1879	E	1654	VS
1873	VS	1645	E
1870-71	VS	1641	VS
		1632	E
		1631	VS
		1626	VS
		1623-24	VS
		1600	VS
		1592-93	VS
		1584	VS
		1572-73	E
		1560	VS
		1548	VS
		1541	VS
		1533	E
		1531-32	VS
		1528	E

as to what has historically been considered strong-extreme events in the instrumental period (post-1870) using previous research by Trenberth (1997) and the CEI (Gergis and Fowler, 2005a). These classes were then applied to the quality adjusted magnitude time series back to A.D. 1525. Here, only extreme and very strong ENSO events are selected for presentation from the entire ENSO event chronology (Gergis, 2006; Gergis and Fowler, 2006[2]).

2.3 Event verification

To assist the selection of thresholds for the multiproxy event definition, the three and four proxy-threshold events were compared to past ENSO event lists published for the instrumental period (Rasmusson and Carpenter, 1983; Kiladis and Diaz, 1989; Quinn and Neal, 1992; Whetton and Rutherfurd, 1994; Mullan, 1995; Trenberth, 1997; Ortlieb, 2000; Allan et al., 2003). For the pre-instrumental period, two lists provided by the "Quinn record" (Ortlieb (2000) pre-1901 and Quinn and Neal (1992) for the post-1900 period) and Whetton and

Table 4. Verification of reconstructed ENSO event frequency with existing long-term chronologies (Quinn and Neal, 1992; Whetton and Rutherfurd, 1994; Ortlieb, 2000). Here, El Niño (La Niña) event definition represents at least three (four) proxies replicating a single, regional ENSO signal. Note that total events for each sub-period includes all weak, moderate, strong, very strong and extreme magnitude events presented by Gergis (2006) and Gergis and Fowler (2006)[2], rather than the limited very-strong to extreme events presented in Tables 2 and 3.

ENSO Event Lists	Instrumental Event Capture (1871-2002)	Pre-Instrumental Event Capture (1525-1870)	Total Event Capture (1525-2002)
El Niño			
3+ proxy replication	27	65	92
Quinn & Ortlieb	29	80	109
Whetton and Rutherfurd	16	23	39
La Niña			
4+ proxy replication	21	61	82
Quinn and Ortlieb	-	-	-
Whetton and Rutherfurd	4	6	10

Rutherford (1994) were used. Only comparisons with the long-term ENSO chronologies are presented to avoid covering material beyond the scope of this summary paper.

3 Results

From Table 2, a total of 37 very-strong to extreme El Niño were reconstructed since A.D. 1525. Nine events were classifies as extreme, including four well known events of the 20th century (2002, 1982–83, 1941–42, 1926, 1905). The 18th century contained a further three events (1737, 1723, 1718) while only one extreme El Niño event of A.D. 1650 was recorded during the 16th and 17th centuries. The 20th century represents the peak of El Niño activity, when twelve events were classed as either very strong or extreme (Table 2).

Table 3 presents the results for the La Niña phase reconstruction. A total of 46 events were reconstructed, twelve of these classified as extreme. Four extreme La Niña events (1998, 1974, 1953, 1950) were reconstructed during the 20th century. The pre-instrumental period indicates relatively more La Niña activity with 6(24) extreme (very strong) events compared to 4(18) extreme (very strong) events from the El Niño reconstruction. Considerable La Niña activity is indicated during the 16th to mid 17th centuries when five extreme events are reconstructed. The obvious trend towards increased La Niña activity over the 20th century is also evident from Table 3.

Table 4 shows the event frequency characterisitcs of the two primary long-term ENSO event lists of "Quinn" (Quinn and Neal, 1992; Ortlieb, 2000) and Whetton and Rutherfurd (1994) and the multiproxy event lists presented here. There is a high degree of similarity between the Quinn and Ortlieb chronologies and the use of three proxies for El Niño event definition. The additional 16 events not included in the multiproxy event lists may indicate El Niño conditions that may have only been regional in nature. Events from the multiproxy reconstructions have a longer duration than a number of the events indicated in the Quinn records (not shown), which may reflect the impact of calibrating proxies using the CEI which allowed lead/lag signatures associated with decoupled events to be resolved. Consequently, the results may be a sign of larger-scale patterns of ENSO events, rather than the response of one (East Pacific) teleconnection region.

Verification of La Niña events was substantially more difficult due to the lack of coverage in the Quinn records and a total of ten events noted by Whetton and Rutherfurd (1994). The year A.D. 1906 is the only La Niña event not present in the four proxy La Niña chronologies, however, the 1826 La Niña noted by Whetton and Rutherfurd (1994) is only detectable using a three-proxy threshold (not shown). Since there were minor differences in the event capture characteristics of the three and four-proxy event lists, a four proxy threshold for La Niña event definition was considered to be slightly more conservative.

4 Discussion

Verification revealed that a three (four) proxy minimum for El Niño (La Niña) event definition compared well with the two primary long-term ENSO event list of "Quinn" (Quinn and Neal, 1992; Ortlieb, 2000) and Whetton and Rutherfurd (1994). This study provides substantial replication and extension of the events reported by previous research. In particular, the results of Table 3 represent excerpts of the most comprehensive list of La Niña events complied to date (Gergis, 2006; Gergis and Fowler, 2006[2]).

Here, a total of 37 (46) extreme or very strong El Niño (La Niña) episodes since A.D. 1525. Enhanced ENSO activity of the 19th and 20th century is apparent from the ENSO events presented in Tables 2 and 3. From the reconstruction introduced in this paper, it is apparent that La Niña activity has fluctuated considerably through time, with peaks in the 16th to mid 17th and 20th centuries. The 20th century stands out as the peak period of El Niño activity. In total, 43% of the extreme events noted since A.D. 1525 occur during the 20th century, with a bias towards enhanced El Niño conditions (Table 2). Strikingly, the post-1940 period alone accounts for 30% of the total extreme ENSO event years reconstructed over the past five centuries.

5 Conclusions

This paper identified a total of 83 extreme and very strong ENSO events since A.D. 1525, many of which were verified using available long-term ENSO event chronologies. In total, 43% of the extreme events noted since A.D. 1525 occur during the 20th century, with an obvious bias towards enhanced El Niño conditions. 30% of all extreme ENSO years occur post-1940 suggesting that recent ENSO variability may be anomalous in the context of the past five centuries.

An considerably expanded analysis of the nature, magnitude and frequency of pre-observational ENSO events is currently underway to further clarify changes in past ENSO behaviour (Gergis, 2006; Braganza et al., 2006[1]; Gergis and Fowler, 2006[2]). Given the large-scale socio-economic impacts of ENSO events, future investigation into the possible impact an increasingly anthropogenically-warmed world will have on ENSO behaviour is vital.

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