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Reconstructing ENSO: the influence of method, proxy data, climate forcing and teleconnections

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ABSTRACT: In this study we compare three newly developed independent NINO3.4 sea surface temperature (SST) reconstructions using data from (1) the central Pacific (corals), (2) the TexMex region of the USA (tree rings) and (3) other regions in the Tropics (corals and an ice core) which are teleconnected with central Pacific SSTs in the 20th century. Although these three reconstructions are strongly calibrated and well verified, inter-proxy comparison shows a significant weakening in inter-proxy coherence in the 19th century. This breakdown in common signal could be related to insufficient data, dating errors in some of the proxy records or a breakdown in El Niño–Southern Oscillation's (ENSO's) influence on other regions. However, spectral analysis indicates that each reconstruction portrays ENSO-like spectral properties. Superposed epoch analysis also shows that each reconstruction shows a generally consistent 'El Niño-like' response to major volcanic events in the following year, while during years $T+4$ to $T+7$ 'La Niña-like' conditions prevail. These results suggest that each of the series expresses ENSO-like 'behaviour', but this 'behaviour' does not appear to be spatially or temporally consistent. This result may reflect published observations that there appear to be distinct 'types' of ENSO variability depending on location within the tropical Pacific. Future work must address potential dating issues within some proxies (i.e. sampling of multiple coral heads for one location) as well as assessing the time stability of local climate relationships with central Pacific SSTs. More emphasis is needed on sampling new and extending old coral proxy records from the crucial central and eastern tropical Pacific region. Copyright © 2009 John Wiley & Sons, Ltd. and © Crown Copyright 2009.

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KEYWORDS: ENSO; reconstruction; corals; tree rings; teleconnection.

Introduction

Despite the global importance of the El Niño–Southern Oscillation (ENSO) for influencing weather and climate at interannual timescales (Broennimann *et al.*, 2007), only a small section of the recent 2007 IPCC report (Solomon *et al.*, 2007) was dedicated to ENSO variability over recent centuries. This is somewhat surprising, as this phenomenon is often linked with extreme weather events such as flooding and drought and associated socio-economic problems (Allan *et al.*, 1996; Glantz, 2000; Gergis and Fowler, 2006). There are also considerable uncertainties that need to be resolved in both climate models and instrumental data regarding how the tropical Pacific and the ENSO system will respond to global warming (Vecchi *et al.*, 2008). Although numerical model experiments may help in understanding the changing dynamics of ENSO variability under different forcing scenarios, these models differ in their projections about ENSO under global warming – for example, whether or not the tropical Pacific will move to a more 'El Niño-like' or 'La Niña-like' state or whether the climate system can be locked into such distinct states (Clement *et al.*, 1996; Cane *et al.*, 1997; Vecchi *et al.*, 2008). The instrumental record is also not long enough to assess whether recent changes in ENSO variability (particularly at lower frequencies, e.g. Allan and D'Arrigo, 1999; Allan, 2000; Ault *et al.*, 2009) are unique in a longer-term context. However,

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it should be noted that ongoing data recovery activities led by the international Atmospheric Circulation Reconstructions over the Earth (ACRE) initiative (http://www.met-acre.org/) will markedly improve late 18th to early 19th-century instrumental records in the coming years.

Thus, currently, a true understanding of the variability of the tropical Pacific over recent centuries must rely upon palaeoclimate reconstructions to provide information on changes in mean state and variability prior to measured observations. Over the last decade, there have been several attempts to reconstruct continuous time series of ENSO variability: Stahle *et al*. (1998) utilised tree ring data from the southwestern USA and Java to produce a December–February record of the Southern Oscillation Index (SOI) from 1706 to 1977. Mann *et al*. (2000) derived a multi-proxy reconstruction of October–March NINO3 sea surface temperatures (SSTs) from 1650 to 1980. Evans *et al*. (2002) developed a coral-based reconstruction from two leading Pacific SST patterns, while a more recent coral-based reconstruction of tropically averaged annual SSTs (Wilson *et al*., 2006) also showed that the high-frequency component was strongly related to ENSO. The longest published reconstruction to date (D'Arrigo *et al*., 2005a – the so called 'Cook' reconstruction) calibrated tree ring records from the American southwest to reconstruct December–February NINO3 SSTs back to AD 1408. Recently, Braganza *et al*. (2009) detailed a new multi-proxy reconstruction (1525–1982) of ENSO variability using tree ring data from New Zealand, Australia and southwestern USA, coral data from the southwestern Pacific and ice core data from the South American Andes. All of these studies, except Braganza *et al*. (2009), are consistent in that they are well calibrated (explaining more than $\sim$50% of the target instrumental data variance) and verified (i.e. reconstructed values correlate significantly when compared to independent climate data).

One of the key issues with regard to ENSO is how much of this phenomenon's variability may be a response to radiative forcing (anthropogenic or natural) or a product of internal forcing within the ocean–atmospheric system itself. Adams *et al*. (2003) and Mann *et al*. (2005a) have shown that there may be an increased probability of warm El Niños after major volcanic events, as well as 'El Niño-like' states during periods of low solar irradiance (see also Waple *et al*., 2002; D'Arrigo *et al*., 2005a). However, Chen *et al*. (2004) also showed that it was possible to predict El Niño events without knowledge of volcanic forcing for the last 148a, although it could be argued that over this period there had been no volcanic events of sufficient strength to set up conditions favourable for El Niños (Emile-Geay *et al*., 2008). D'Arrigo *et al*. (2009) also showed that there appeared to be little impact of volcanic events on tropical SSTs through the 20th century.

Although ENSO has a global impact, it is likely that its spatial influence changes over time, which will complicate not only predictions but also palaeoclimatic reconstructions – especially those that rely on proxy data located in regions that are teleconnected with the central Pacific. Cole and Cook (1998) showed a significant relationship between ENSO and drought across the North American continent over the 20th century but that its influence varied spatially over time – likely partly modulated by the Pacific Decadal Oscillation (PDO) – and that the only time-stable relationship was found in the American southwest. Mann *et al*. (2000) and D'Arrigo *et al*. (2005b) also showed evidence for a weakening in the ENSO spatial pattern in the first half of the 19th century which may reflect a weakening of the ENSO influence on other regions during this period. To further complicate the issue, within the tropical Pacific itself Kao and Yu (2009) identify two distinct types of ENSO – an eastern and central Pacific mode – which exhibit different teleconnections with the Indian Ocean and other regions, with resultant implications for proxy data location and relevant predictand ENSO indices for reconstruction. Similar Pacific ENSO modes or phases of the phenomenon have been reported in the literature by Folland *et al*. (1999), Trenberth and Stepaniak (2001) and Trenberth *et al*. (2002). Allan and D'Arrigo (1999) have discussed different patterns of Pacific SSTs during interannual and longer 'protracted' ENSO episodes with 'El Niño-like' and 'La Niña-like' characteristics. Finally, Allan *et al*. (1996) and Allan (2000) have indicated that ENSO has many 'flavours' (from weak, moderate to strong) encompassing quasibiennial, interannual to decadal temporal signatures, and even abortive events.

In this paper, we return to the challenge of reconstructing past ENSO variability, with particular emphasis on examining the time stability of the teleconnected relationships. To do this we introduce an updated and extended version of the D'Arrigo *et al*. (2005a) NINO3 SST reconstruction (Cook *et al*., 2008), as well as derive two new reconstructions of NINO3.4 SSTs – each one using completely independent proxy datasets restricted to the Tropics (30° S to 30° N). One reconstruction relies on coral proxy records located from the central and eastern Pacific (defining this region as the 'centre of action' with respect to ENSO variability in the tropical Pacific), while the other reconstruction uses multi-proxy data sources from locations that are teleconnected with the central Pacific. These three, entirely independent NINO3.4 reconstructions are used to assess the temporal stability of the ENSO fingerprint between these regions and to also examine the apparent post-volcanic response of ENSO. The paper concludes with a series of recommendations that palaeoclimate researchers should consider in the future to allow for better estimates of past ENSO variability.

Proxy data and screening

Figure 1 presents correlations (calculated over 1925–1979 – the period used for calibration) between NINO3.4 SSTs and individual 1×1 degree grid cells using the HADISST dataset (Rayner *et al*., 2003) for the annualised previous December to current November season. The spatial correlation pattern clearly shows the 'classic' ENSO pattern and highlights those regions which are 'linked' to central Pacific climate. This annual season was chosen as it includes the more classic 'cold' season commonly targeted for reconstructions of ENSO variability (Stahle *et al*., 1998; Mann *et al*., 2000; D'Arrigo *et al*., 2005a), while also taking into account that some of the proxy records used in this study have annual (as opposed to monthly) resolution only. Finally, we appreciate that both the ENSO phenomenon and the patterns of impacts and physical manifestations it causes evolve in space and time, and that proxy records may miss parts of this structure.

To realise the main aim of this study, proxy archives were chosen if they were (1) annually resolved, (2) expressed some degree of coherence with ENSO indices and (3) were located in the Tropics (30° S to 30° N). Although the climate of certain extra-tropical regions is also teleconnected with the central Pacific (Allan *et al*., 1996; Gergis and Fowler, 2006; Bronnimann *et al*., 2007; Braganza *et al*., 2009); see also Fig. 1), we hypothesise that the probability that these relationships are temporally stable will decrease the further away from the Tropics. We delineate the Tropics into two regions with respect to the influence of ENSO: the 'centre of action' (COA) region is defined as the region in the central and eastern Pacific where SSTs are positively correlated with NINO3.4 SSTs, while the 'teleconnection' (TEL) region covers

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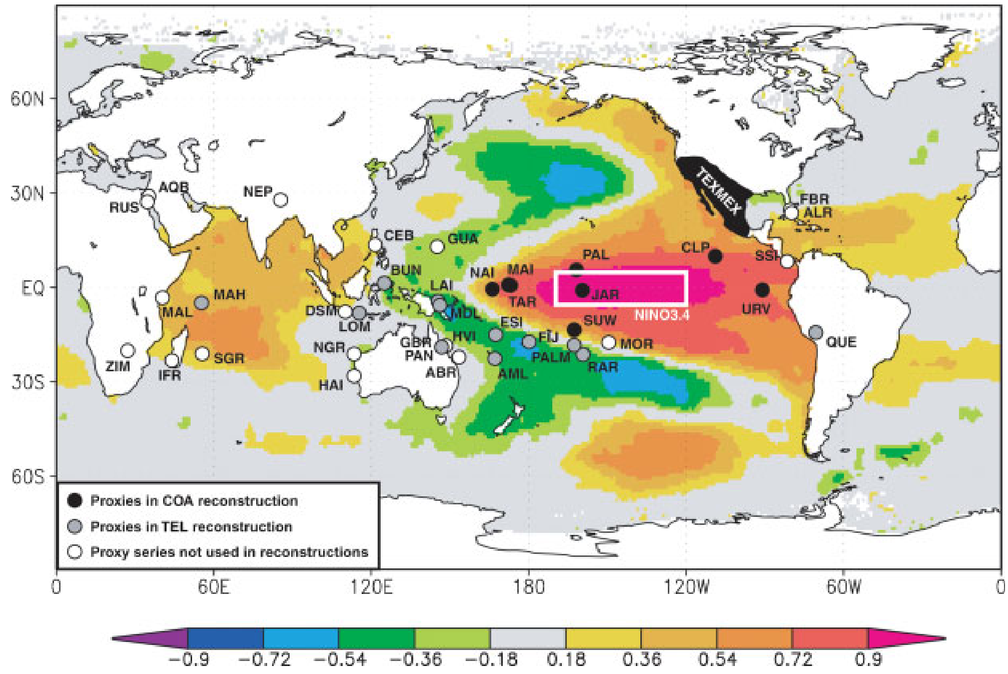

Figure 1 Spatial correlations (1925–1979) between NINO3.4 SSTs and local HADISST 1 × 1 degree grid squares for the annualised (previous December–November) season. Two-tailed significance (95%) is ±0.27. Locations of annually resolved proxy records (see Table 1 for details on each series) utilised in this study are shown. The white box denotes the NINO3.4 region of the central Pacific. The black shaded region of the southwestern USA highlights the region from where tree ring chronologies were used to derive the TEXMEX NINO reconstructions (see main text). The spatial correlation base map was generated using the KNMI Climate Explorer (van Oldenborgh and Burgers, 2005)

all other tropical areas where SSTs are either inversely (e.g. Indonesia to Tonga) or positively (e.g. Indian Ocean) correlated with NINO3.4 SSTs (see Fig. 1).

From NOAA's National Climatic Data Centre (http://www.ncdc.noaa.gov/paleo/) and unpublished sources, we identified 40 candidate annually resolved proxy records (Table 1) from different regions within the Tropics (30° S to 30° N; Fig. 1) that start in the 19th century or earlier, and which have been interpreted to represent different climatic parameters. The bulk of these records are coral δ^{18}O time series, many of which have been utilised in earlier studies to reconstruct tropical SSTs (Mann *et al.*, 2000; Evans *et al.*, 2002; D'Arrigo *et al.*, 2006a; Wilson *et al.*, 2006; D'Arrigo *et al.*, 2009). Non-coral candidate datasets include (1) tree ring data from Indonesia which have been shown to cohere with ENSO variability (Stahle *et al.*, 1998; D'Arrigo *et al.*, 2006b); (2) an averaged pre- and post-monsoon air temperature reconstruction based on tree rings from Nepal (Cook *et al.*, 2003); (3) a tree-ring-based reconstruction of rainfall for Zimbabwe (Therrell *et al.*, 2006); and (4) a δ^{18}O ice core record for Quelccaya, Peru (Thompson *et al.*, 2006).

As many of the coral time series portray long-term trends which are climatologically difficult to interpret (i.e. conflicting temperature and salinity influences), prior to analysis all the proxy time series were detrended with a 150-year cubic smoothing spline (50% frequency cut-off), which allows the retention of potential climatic information at 50a or higher timescales, but removes all longer-term secular trends. This detrending choice still allows any potential multi-decadal variability (outside the classic 2–7 a ENSO bandwidth) to be captured in the reconstructions if it exists (Allan, 2000).

The candidate proxy time series (annualised for those with higher resolution) were screened against NINO3.4 annual SSTs over the 1925–1979 period (Table 1), allowing the pre-1925 data to be retained for independent verification of the reconstructions and recognising the common proxy end date of 1979. Twenty-two series were found to correlate significantly (95% confidence limit) with ENSO variability. Of these, eight were located in the COA region and 14 in the defined TEL areas (see Table 1). We should note that the TEL dataset was reduced to 12 predictor series as the GBRain and GBRiv coral luminescence series (Lough, 2007) are effectively the same data and are highly correlated ($r = 0.94$, 1631–2004). HVI (Isdale *et al.*, 1998), another luminescence series in the GBR region and used to reconstruct river flow, was found to have minor dating issues (Hendy *et al.*, 2003). Therefore, of the three luminescence series, owing to its slightly superior correlations with HADISST NINO3.4 we utilise only the GBRiv series in the following analyses.

Reconstruction methods

Independent reconstructions of annual NINO3.4 SSTs were developed for the COA and TEL regions. However, as there is currently much methodological debate as to what methods are most appropriate to derive robust reconstructions from proxy datasets (von Storch *et al.*, 2004; Esper *et al.*, 2005; Mann *et al.*, 2005b, 2007a,b; Rutherford *et al.*, 2005; Smerdon and Kaplan, 2007; Christiansen *et al.*, 2009; von Storch *et al.*, 2009), and since the final reconstruction outcome could be sensitive to method, we experimented with three approaches: (1) composite plus regression; (2) principal component regression; and (3) regularised expectation maximisation.

Composite plus regression (CPR)

This is the simplest of the three reconstruction methods and essentially relies on simple averaging of the proxy series. This approach has not been previously used to derive estimates of past ENSO variability per se, although Wilson *et al.* (2006) and D'Arrigo *et al.* (2009) used this approach to developed a 250a reconstruction of tropic-wide SSTs. A variation of CPR – composite plus scaling – is often used for the reconstruction of

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Table 1 Summary information of annually resolved proxy archives used in this study

Reconstruction	Name	Code	Reference	Record length	Proxy type	Longitude	Latitude	Correlation screening with HADISST NINO3.4 1925–1979	Correlation with HADISST NINO3.4 1897–1924
COA	Urvina Bay	URV[a]	Dunbar *et al.* (1994); Shen *et al.* (1992)	1607–1981	Coral – ^{18}O	91.14° ° W	0.24° S	**−0.55**	−0.14
	Maiana	MAI	Urban *et al.* (2000)	1840–1994	Coral – ^{18}O	173.00° E	1.00° N	**−0.72**	**−0.82**
	Jarvis	JAR	Tudhope *et al.* (in prep.)	1850–1998	Coral – ^{18}O	159.59° W	0.22° S	**−0.88**	**−0.50**
	Suwarrow Atoll	SUW	Tudhope *et al.* (in prep.)	1881–1998	Coral – ^{18}O	163.06° W	13.15° S	**−0.34**	−0.07
	Palmyra Island	PAL	Cobb *et al.* (2001)	1886–1996	Coral – ^{18}O	162.08° W	5.52° N	**−0.73**	**−0.70**
	Tarawa	TAR	Cole and Fairbanks (1990); Cole *et al.* (1993)	1894–1988	Coral – ^{18}O	172.00° E	1.00° N	**−0.62**	**−0.66**
	Clipperton Atoll	CLP	Linsley *et al.* (2000b)	1894–1993	Coral – ^{18}O	109.13° W	10.18° N	**−0.37**	**−0.77**
	Nauru Island	NAI	Guilderson and Schrag (1999)	1897–1994	Coral – ^{18}O	166.00° E	0.30° S	**−0.60**	**−0.38**
TEL	Quelccaya	QUE	Thompson *et al.* (2006)	1540–2002	Ice Core	70.50° W	13.56° S	**0.45**	0.33
	Great Barrier Reef (river)	GBRiv	Lough (2007)	1629–2005	Coral – luminescence	148.33° E	18.34° S	**−0.30**	**−0.51**
	New Caledonia	AML	Quinn *et al.* (1998); Crowley *et al.* (1997)	1658–1992	Coral – ^{18}O	166.27° E	22.29° S	**0.40**	0.36
	Rarotonga	RAR	Linsley *et al.* (2000a, 2004)	1726–1996	Coral – ^{18}O	159.00° W	21.00° S	**0.57**	**0.62**
	Fiji	FIJ	Bagnato *et al.* (2005)	1776–2001	Coral – ^{18}O	179.14° E	16.49° S	**0.52**	**0.56**
	Lombok Straight	LOM	Moore (1995); Charles *et al.* (2003)	1782–1989	Coral – ^{18}O	115.30° E	8.15° S	**0.53**	0.18
	Espiritu Santo Island	ESI	Quinn *et al.* (1993, 1996)	1806–1979	Coral – ^{18}O	167° E	15° S	**0.28**	**0.62**
	Palmerston	PALM	Tudhope *et al.* (in prep.)	1834–1998	Coral – ^{18}O	163.12° W	18.03° S	**0.35**	0.36
	Mahe, Seychelles	MAH	Charles *et al.* (1997)	1846–1995	Coral – ^{18}O	55.00° E	4.37° S	**−0.29**	**−0.74**
	Bunaken Island	BUN	Charles *et al.* (2003)	1860–1989	Coral – ^{18}O	124.50° E	1.30° N	**0.52**	**0.56**
	Madang Lagoon	MDL	Tudhope *et al.* (2001)	1881–1992	Coral – ^{18}O	145.49° E	5.13° S	**0.39**	0.14
	Laing Island	LAI	Tudhope *et al.* (2001)	1885–1992	Coral – ^{18}O	144.53° E	4.09° S	**0.30**	0.27
Data not included in final reconstructions	Nepal	NEP	Cook *et al.* (2003)	1546–1991	Tree ring	82-88° E	27-30° N	−0.11	−0.11
	Great Barrier Reef (rain)	GBRain	Lough (2007)	1629–2005	Coral – luminescence	148.33° E	18.34° S	**−0.28**	**−0.47**
	Abraham Reef	ABR	Druffel and Griffin (1999)	1638–1983	Coral – ^{18}O	153.0° E	22.06° S	−0.12	0.24
	Havannah Island	HVI	Isdale *et al.* (1998)	1644–1986	Coral – luminescence	146.33° E	18.51° S	**−0.29**	**−0.46**
	Madagascar (Ifaty)	IFR	Zinke *et al.* (2004)	1660–1995	Coral – ^{18}O	43.34° E	23.09° S	−0.08	0.17
	Javan Teak	DSM[b]	D'Arrigo *et al.* (2006a,b)	1689–2004	Tree ring	110-123° E	5.30 - 7.30° S	−0.24	**−0.45**
	Secas Island	SSI	Linsley *et al.* (1994)	1708–1983	Coral – ^{18}O	82.03° W	7.59° N	0.02	−0.03
	Pandora Reef	PAN	Isdale *et al.* (1998)	1737–1980	Coral – luminescence	146.26° E	18.49° S	−0.13	**−0.42**
	Ras Umm Sidd	RUS	Felis *et al.* (2000)	1751–1995	Coral – ^{18}O	34.18° E	27.50° N	−0.20	−0.11
	Alina's Reef (Biscayne NP)	ALR	Swart *et al.* (1996a)	1751–1986	Coral – ^{18}O	80.10° W	24.25° N	0.00	−0.09
	Aqaba	AQB	Heiss (1994)	1788–1992	Coral – ^{18}O	34.58° E	29.26° N	−0.23	0.25
	Guam	GUA	Asami *et al.* (2005)	1790–2000	Coral – ^{18}O	144.50° E	13.36° N	0.17	0.06
	Houtman Abrolhos Islands	HAI	Kuhnert *et al.* (1999)	1794–1994	Coral – ^{18}O	113.46° E	28.28° S	0.04	0.28
	Zimbabwe	ZIM	Therrell *et al.* (2006)	1796–1996	Tree–ring	27.18° E	18.30° S	−0.17	−0.01
	Malindi	MAL	Cole *et al.* (2000)	1801–1992	Coral – ^{18}O	40.00° E	3.00° S	−0.15	**−0.46**
	Florida Bay	FBR	Swart *et al.* (1996b)	1824–1985	Coral – ^{18}O	80.45° W	24.56° N	0.02	−0.21
	St. Gilles, La Réunion	SGR	Pfeiffer *et al.* (2004)	1832–1995	Coral – ^{18}O	55.15° E	21.02° S	−0.19	0.03
	Moorea	MOR	Boiseau *et al.* (1998, 1999)	1852–1990	Coral – ^{18}O	149.50° W	17.30° S	−0.11	−0.26
	Cebu	CEB	Patzold (1986)	1859–1980	Coral – ^{18}O	121° E	14° N	0.18	−0.27
	Ningaloo Reef	NGR	Kuhnert *et al.* (2000)	1879–1994	Coral – ^{18}O	113.58° E	21.54° S	0.15	0.12

Correlations in bold type are significant at the 95% confidence limit. COA represent those series that were included in the central Pacific 'centre of action' reconstruction; TEL represents the proxies included in the 'teleconnected' reconstruction.

[a]URV is a composite of Urvina Bay (1607–1953/1962–1981; Dunbar *et al.*, 1994) and Punta Pitt (1936–1981; Shen *et al.*, 1992). See Wilson *et al.* (2006, Table 1) for details.

[b]DSM is a composite record of three teak ring-width chronologies (Pagerwunung Darupono, Saradan and Muna). See D'Arrigo *et al.* (2006a) for more details.

Northern Hemisphere temperatures (Esper *et al.*, 2002; D'Arrigo *et al.*, 2006c; Wilson *et al.*, 2007).

The 20 records retained for analysis had their sign adjusted so that they correlated positively with NINO3.4 SSTs. To derive the CPR reconstructions, for both the COA and TEL datasets, the proxy time series were normalised over their respective periods common to all series (1897–1981 for COA and 1885–1979 for TEL) and then averaged to formulate a nested composite mean. To extend the composite record as far back in time as possible using proxy series of different length, the shortest proxy series were removed from the data matrix, and the remaining series were again normalised to the extended common period before averaging. This process is undertaken iteratively until the final longest proxy record remains. Nests were also developed for the post-1981 (1979 for TEL) period, as the number of available series also declines forward in time (Table 1), allowing reconstruction extension to 1998 for both regional reconstructions. For each nested series, calibration (using ordinary least squares forward regression) was made over the 1925–1979 screening period, while verification was undertaken over the 1897–1924 period (plus 1871–1896 for longer nests).

To derive the final reconstruction time series, the mean and variance of each nested series were adjusted to that of the shortest (most replicated) nested reconstruction and the relevant sections spliced together. The rescaling of the data removes artificial changes in the variance of the final time series, owing to the weakening in explained variance (related to the decreasing number of proxy series), while retaining potential real changes in variance that may represent a response to actual changes in climatic variability.

Principal component regression (PCR)

PCR has been a staple reconstruction method for producing climate field reconstructions in the Tropics (Mann *et al*., 2000; Evans *et al*., 2002; Ault *et al*., 2009) and elsewhere (Briffa *et al*., 1983, 1986; Cook *et al*., 1994, 1999). Essentially, the PCR approach, as applied in this study, is very similar to the CPR method described above, but rather than simply averaging the relevant proxies for each nest, the input data matrix was reduced to a few component scores (with a minimum eigenvalue of 1.0) using principal component analysis. PC scores were then entered into the calibration regression model using a stepwise procedure. When the number of input proxy series was three or less, a simple mean (i.e. the CPR approach) was used as the predictor variable. The nested reconstruction time series were spliced together and error bars calculated in the same manner as used for CPR, after appropriate scaling. PCR has one potential advantage over the CPR approach as it may help overcome the apparent loss in common signal between the proxy records noted in the TEL dataset (see later), by weighting the proxies in the first PC score to those series which represent a more coherent and consistent signal through time.

Regularised expectation maximisation (RegEM)

RegEM is a covariance-based iterative algorithm, which linearly models the relationship between available and missing values (given plausible ones). The method is based on the expectation maximisation (EM) algorithm, and a regularisation scheme to take into account under-determined settings. The conventional iterative EM algorithm estimates the mean and the covariance matrix of an incomplete data matrix (Schneider, 2001). The EM algorithm is used under the assumption that the predictand and predictor data are Gaussian. In cases where the number of variables exceeds sample size, the EM algorithm has to be regularised. Thus the regularisation scheme truncated total least squares (TTLS) is applied (a departure from the procedure described by Schneider, 2001). In order to regularise the covariance matrix, its principal components are truncated, i.e. only a specific number of principal components are considered, according to the truncation parameter. Optimal truncation parameters are identified based on the criterion proposed by Mann *et al.* (2007a). Here RegEM is used to reconstruct a single series, while usually it is applied to reconstruct climatic fields, but is undertaken using the same nesting approach utilised for the CPR and PCR methods.

Verification statistics

Verification using independent data is a crucial step as it represents a stringent assessment of the derived nested reconstruction independent of the initial screening process. For model validation using CPR, PCR and RegEM, we used the coefficient of determination (r^2), reduction of error (RE) and coefficient of efficiency (CE) statistics. RE and CE values greater than zero denote some statistical skill in that the reconstructed values over the verification periods are better estimates of climate than using either the instrumental mean of the calibration (for RE) or verification (for CE) periods (for detail on these statistics, see Cook *et al*., 1994; Wilson *et al*., 2006). The root mean square error was also calculated over the verification period to derive a 2σ confidence interval for each predicted annual value. The 2σ error bars were also adjusted (inflated), to account for the decrease in explained variance in each nest, using the same scaling function utilised to stabilise the variance of the nested series.

The NINO3.4 SST reconstructions

Between-series coherence assessment

One potential advantage of the CPR approach is that the between-proxy coherence can be assessed using running mean inter-series correlations (RBAR; Wigley *et al*., 1984; Briffa, 1995). Presumably, the input proxy series should show a consistent common signal through time if they portray the same climatic signal. The RBAR time series were derived by calculating running 31-year correlation time series between each bivariate pair of proxy series and calculating a mean of these values. RBAR was calculated separately for the COA and TEL datasets (Fig. 2). Over the 1925–1979 screening period, RBAR is slightly higher ($r = \sim 0.37$) for the COA dataset compared to ~ 0.21 for the TEL data, suggesting a generally stronger between proxy common signal within the central Pacific. Prior to the screening period, however, RBAR values remain at similar levels until they start decreasing in the late 19th century. The decrease is less marked for the COA dataset, again suggesting reasonable between proxy coherence in the central Pacific. However, for the TEL data, mean inter-series correlation values reach zero around the mid 19th century, suggesting a complete loss in common signal between these proxy records in the 19th century. It could be argued that with such a lack of common signal between proxy records a valid reconstruction could not be derived using the CPR approach. However, as this method will be compared to the PCR and RegEM methodologies, the CPR method is used in the knowledge that it will likely not produce robust inter-annual

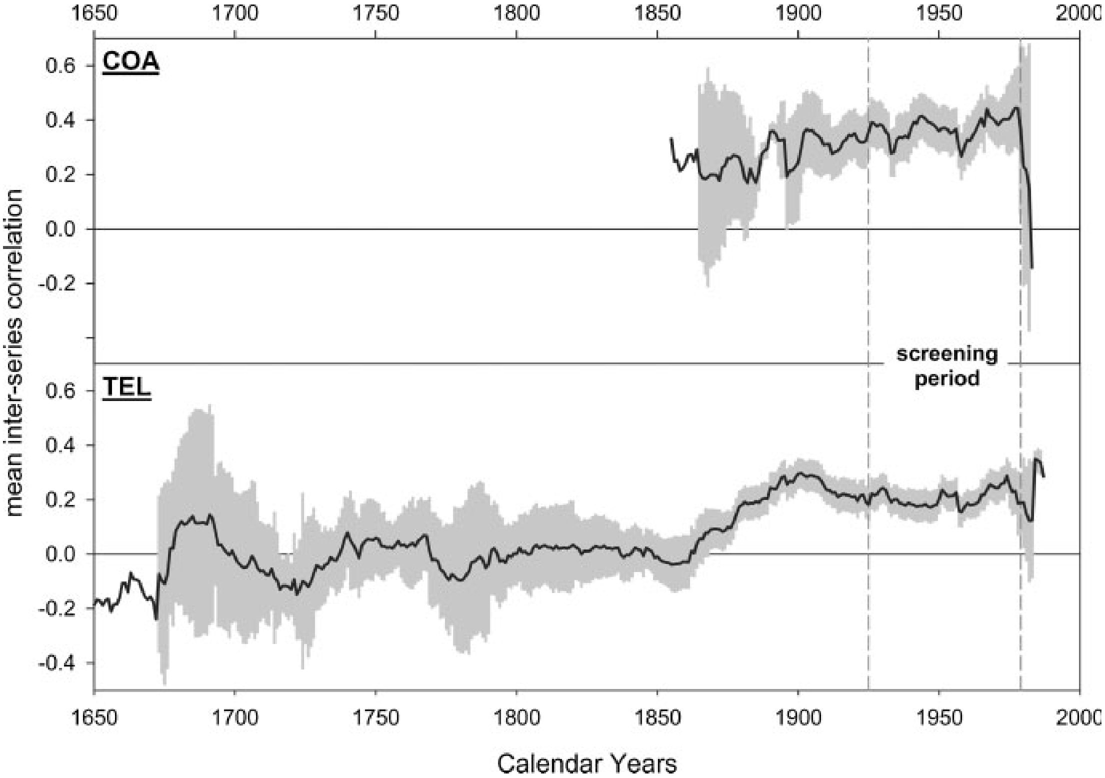

Figure 2 Running 31-year RBAR time-series (with 2σ error envelopes) for both the central Pacific 'centre of action' (COA) and 'teleconnected' (TEL) datasets. The RBAR values are centred on the central year of each 31 a window. Error estimates are only calculated for those periods where replication is greater than three proxy series. See Figs. 3 and 4 for proxy replication for each dataset

results prior to the mid 19th century. The implications of this lack of coherence are discussed further later in the paper.

COA and TEL calibration and verification results

Figures 3 and 4 present associated calibration and verification results, using each reconstruction method, for the COA and TEL datasets respectively. On the whole, the results between the three calibration methods are quite similar. For the COA reconstruction, the calibration model (Fig. 3(B)) explains >80% of the variance over the most replicated nest with associated verification r^2, RE and CE values (Fig. 3(C)–(E)) around ~0.60. Unfortunately, the COA dataset is quite small and the period from 1850 to 1880 is represented by only three proxy series (URV, JAR and MAI). Despite this, calibration is high ($r^2 = 0.76$) and verification still acceptable ($r^2 = 0.52$; RE = 0.34; CE = 0.26). Prior to 1850, however, verification weakens markedly and this period is likely not a robust representation of ENSO variability.

Using the TEL dataset over the most replicated period (1885–1979), the explained variance from the regression calibration is not as strong as the COA dataset, but is still reasonable at 63% (Fig. 4(B)). Verification, however, is robust with r^2, RE and CE values around ~0.60 (Fig. 4(C)–(E)). As would be expected, there is a general weakening in calibration and verification as the number of proxy records drop out from the data matrix. When considering the CPR and PCR results, verification is robust for the whole length of the reconstruction. However, the RegEM results appear worse, with CE values falling below zero prior to 1776. It should be noted, however, that RE and CE do become positive again prior to 1657. On the whole, there is little statistical difference between the CPR and PCR results. The RegEM results, however, are markedly weaker, especially prior to 1727, which appears to be associated with greater variance in the reconstructed time series at this time (Fig. 4(A)). The variance is also slightly higher using the COA dataset (Fig. 3(A)). These slightly weaker results using the RegEM method, which appear related to the adjustment of the truncation parameter, suggest that this method may not work well with relatively sparse datasets.

TEXMEX tree-ring-based reconstruction

The area comprising the American Southwest and Mexico (the so-called 'TEXMEX' region; see Fig. 1 for location) supports some of the most ENSO-sensitive trees on Earth. While this link reflects a statistical climate teleconnection between the tropical Pacific and climate over this region of North America, there is also a dynamical connection that should promote the physical stability of this ENSO teleconnection over time (Cole and Cook, 1998). Utilising a network of 404 tree ring chronologies, Cook *et al.* (2008) derived a reconstruction of gridded fields of tropical Pacific SSTs in the 20° N to 20° S, 150° E to 80° W zone. Calibration was made using reduced-space multivariate regression while using standard verification procedures. From the spatial field reconstruction, separate time series of NINO1.2, NINO3, NINO3.4 and NINO4 ENSO indices were derived back to 1300. Although there is little difference between these ENSO index variants, in this study, for consistencies' sake, we compare only with the NINO3.4 version.

Inter-reconstruction comparison

It is clear from Figs. 3 and 4 for both the COA and TEL NINO3.4 reconstructions that there is statistically little difference between the series generated using either CPR, PCR or RegEM. Although there is some potential variance inflation in the least replicated part of the RegEM versions, it is not possible to state

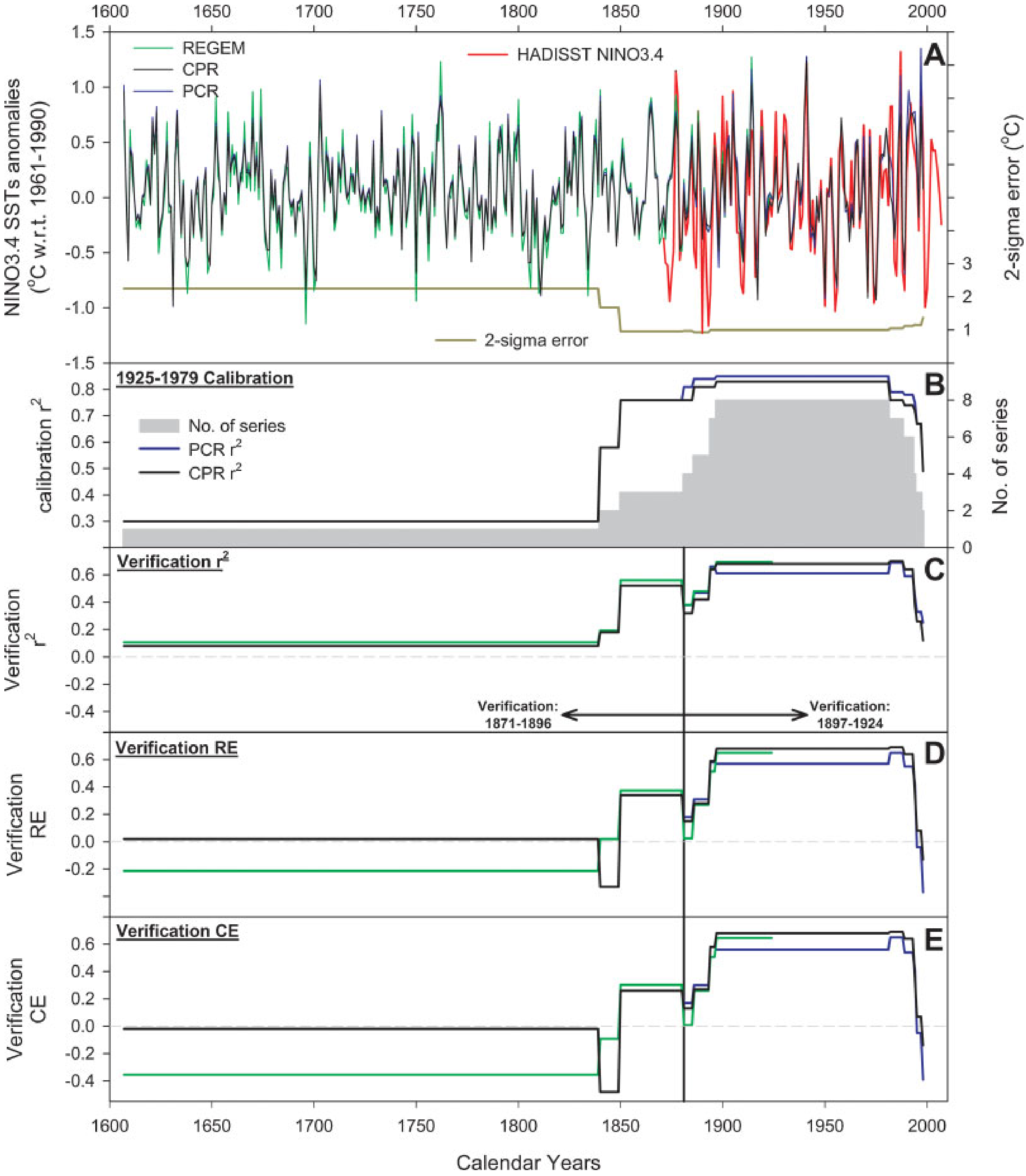

Figure 3 COA reconstruction. (A) Comparison of the CPR, PCR and REGEM time series with maximum 2σ error estimates from the three methods. Legend relevant for all panels. (B) Calibration r^2 results and replication histogram of proxies used. (C) Verification r^2. (D) Verification RE. (E) Verification CE

which is the optimal reconstruction. Therefore, for the remainder of this paper, the three reconstruction 'flavours' were transformed to *z*-scores (same mean and variance over their common period) and their composite average used for further analyses.

In this section we compare the resultant COA and TEL reconstructions with the newly updated Cook *et al*. (2008) TEXMEX NINO3.4 reconstruction (see above) and the Mann *et al*. (2000) NINO3 reconstruction (hereafter referred to as MANN). We do not make any comparison to the Stahle *et al*. (1998) and D'Arrigo *et al*. (2005a) series as the TEXMEX reconstruction utilises an expanded dataset of these earlier studies and supersedes them. It should be noted that the MANN and TEXMEX reconstructions are not entirely independent as they share some input tree ring data. One other caveat worthy of note is that the MANN and TEXMEX series were calibrated against 'cold' season SSTs. The correlation using the HADISST instrumental data between the DJF and annual previous December to November seasons is 0.70 (1871–2007) so it should not be expected that there will be perfect coherence between the proxy reconstructions.

Figure 5 presents time series plots of each ENSO-related reconstruction with associated running 31-year variance plots. D'Arrigo *et al*. (2005a) highlighted a relatively consistent

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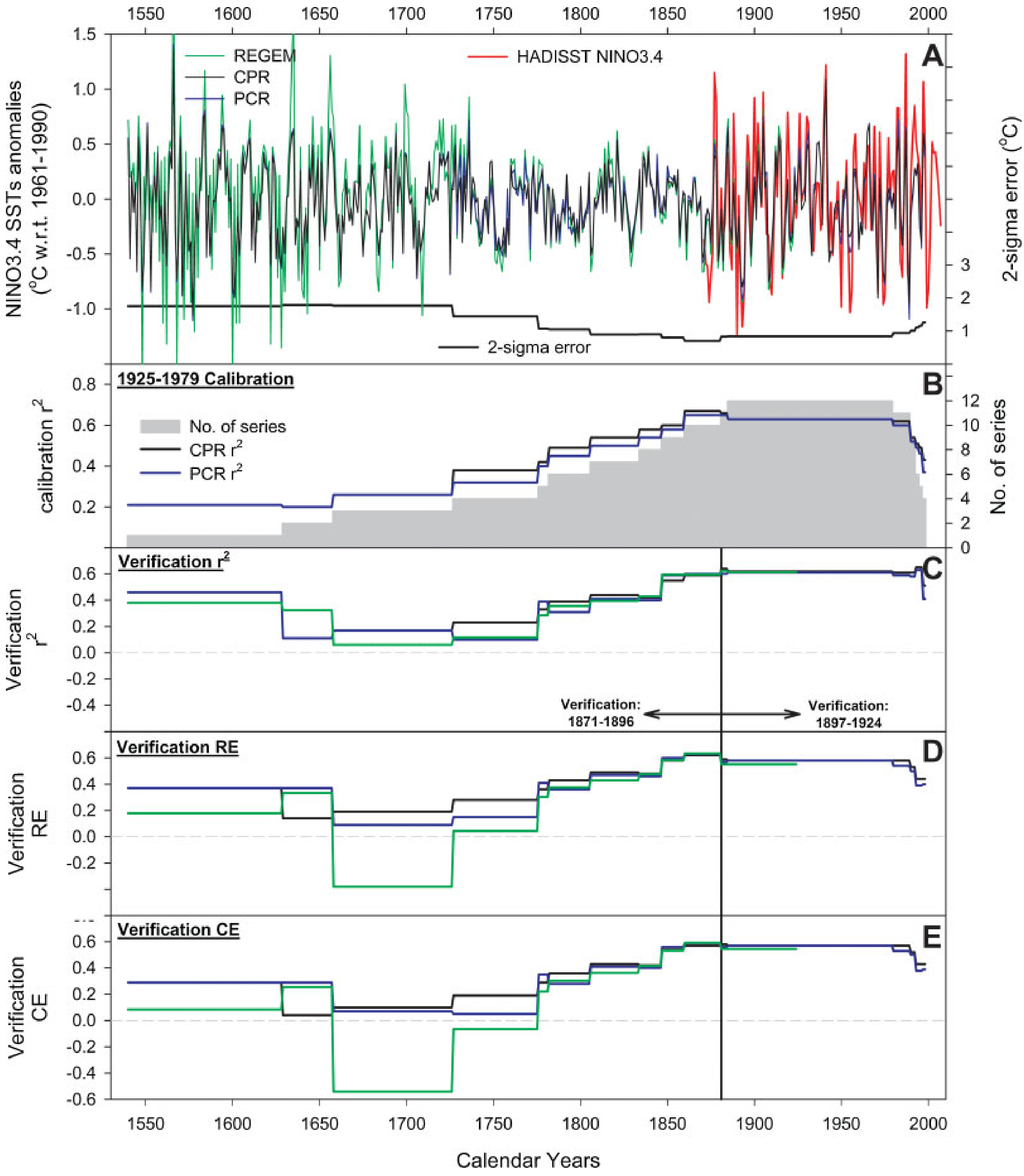

Figure 4 As Fig. 3 but for the TEL reconstruction

change in year-to-year variance between several records that portrayed 'ENSO-like' variability, the Stahle *et al.* (1998), Mann *et al.* (2000) and D'Arrigo *et al.* (2005a) series being included in that comparison. D'Arrigo *et al.* (2005a) showed evidence of increased proxy variance during periods of low solar irradiance (e.g. Dalton (1790–1830) minimum) and a further increase in variance in the recent period. TEL and COA may partly challenge the D'Arrigo *et al.* (2005a) observations, however, with TEL showing generally low year-to-year variance from the mid 18th to late 19th century period and COA expressing a more constant rise in year-to-year variability since the mid 19th century. It should be noted, however, that the decreased variance seen in TEL may partly be an artefact related to the low between proxy coherence noted in Fig. 2, which could decrease variance due to a lack of common signal between records (Frank *et al.*, 2007). Despite these discrepancies between the four ENSO reconstructions, there appears to be an overall pattern of reduced variance during the 19th century compared to the 20th century.

Table 2 presents a correlation matrix between the four ENSO records for 1871–1980 and the pre-calibration/verification 1800–1870 period. The latter period is not ideal for comparative analysis as it incorporates a period (pre-1850) which was defined as non-robust in the COA record (Fig. 3). Despite the different target seasonal windows, coherence is generally good between the four records since 1871. The

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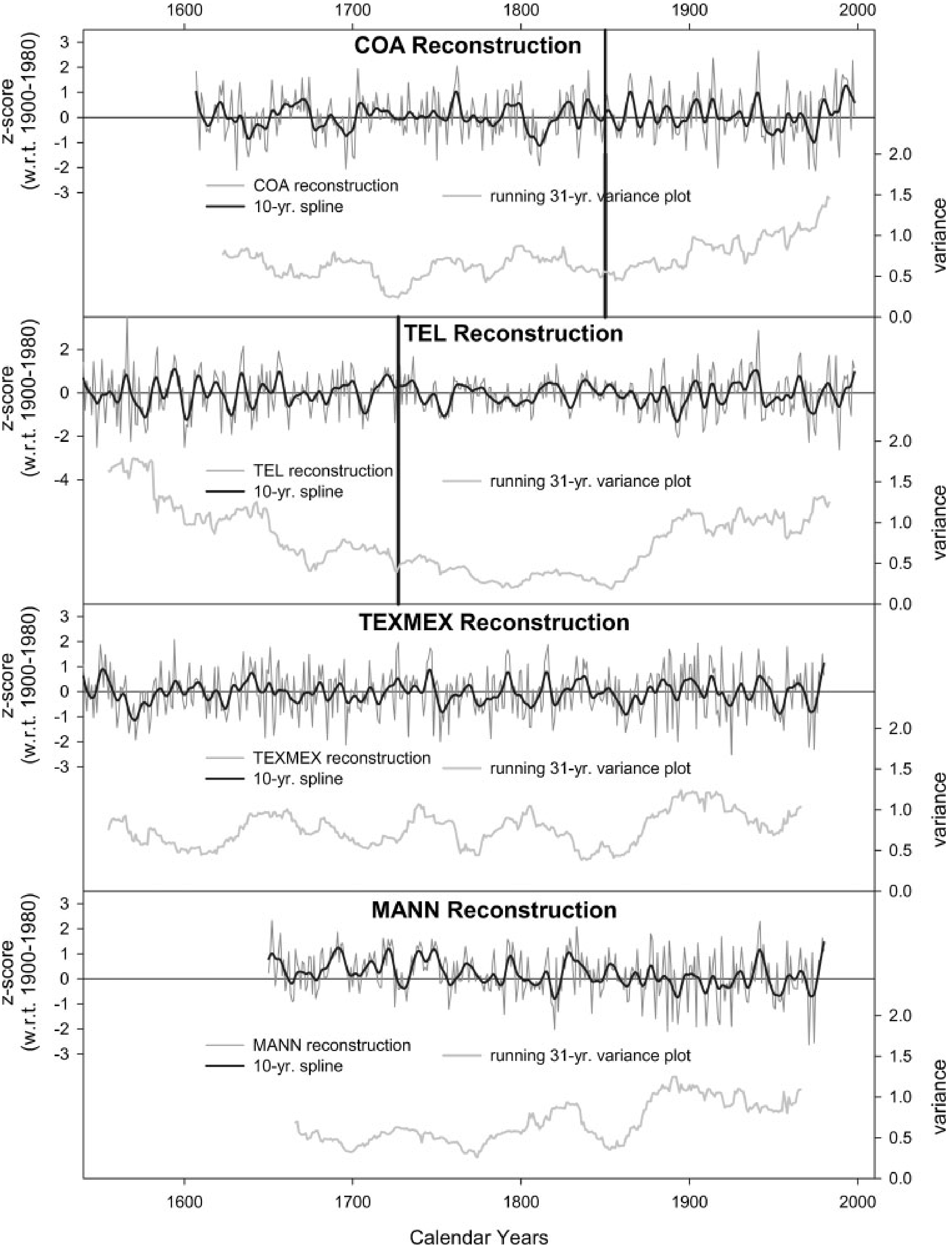

Figure 5 Time series and running 31 a variance plots of each ENSO reconstruction. The data have been normalised to the 1900–1980 period. The vertical lines for COA and TEL delineate the start of the 'robust' period (1850 and 1727, respectively)

strongest correlations ($r = 0.82$) are noted between both COA and TEL and TEXMEX and MANN, while the weakest correlation ($r = 0.50$) is noted between TEL and TEXMEX. Over the earlier 1800–1870 period, however, between-reconstruction coherence weakens markedly. All correlations with COA over this period are close to zero. In fact the only significant (95% confidence limit) correlations are between TEL and TEXMEX ($r = 0.33$) and TEXMEX and MANN ($r = 0.57$). The latter correlation is likely higher due to the shared tree ring data used for both these reconstructions. The TEL/TEXMEX correlation, however, does indicate some degree of coherence between these independent reconstructions. To better explore the between reconstruction coherence, we employ a Kalman filter analysis (Visser and Molenaar, 1988) which allows an assessment of the between-series relationship using regression models with time-varying coefficients. The COA

Table 2 Correlation matrix (calculated over the 1800–1870 and 1871–1980 periods) between the four ENSO reconstructions

	TEL	TEXMEXN3.4	MANN
1871–1980			
COA	0.82	0.59	0.64
TEL		0.50	0.54
TEXMEXN3.4			0.82
1800–1870			
COA	**0.02**	**0.05**	**0.08**
TEL		0.33	**0.22**
TEXMEXN3.4			0.57

Values in bold type are not significant at the 95% confidence limit.

reconstruction shows a consistent decrease in common signal (Fig. 6) with the other ENSO reconstructions from the 20th century into the 19th century. In fact, by the mid 19th century, there is no significant common variance with the other reconstruction at all. This result is entirely consistent with the calibration/verification results (Fig. 3), which indicated that the reconstruction is not robust prior to 1850 simply due to low replication of input proxy series. This is a frustrating result as the COA series, of all the reconstructions, should theoretically best portray past ENSO variability as the original proxy data are located in the central and eastern Pacific (Fig. 1). The relationship of TEL with TEXMEX and MANN again shows high coherence in the 20th century, which weakens back in time. The common signal breaks down during the first half of the 19th century. Intriguingly, there is some significant coherence between TEL and TEXMEX during the ~1570–1650 period, although caution is advised when interpreting this observation as the proxy replication for TEL is only one or two series through this period. As was stated above, the TEXMEX and MANN series are not independent, and coherence is significant between the two series through their period of common overlap, although it also decreases back in time.

Spectral properties of ENSO reconstructions

In the previous section, intercorrelation and Kalman filter analysis indicated a weakening in the common signal expressed by the four ENSO reconstructions in the 19th century compared to the 20th century. There are several reasons why this loss in coherence could be observed:

1. COA is not a robust representation of NINO3.4 SSTs prior to 1850 due to a lack of sufficient input proxy records from the central Pacific.
2. Although minor, the probability of dating errors will likely increase in the coral/ice core records going back in time. Even a dating error of only one year will affect the correlation and Kalman filter analysis substantially.
3. For the TEL, TEXMEX and MANN reconstructions, the teleconnected relationship between the central/eastern Pacific and the regions where the different proxy records are located may not be time stable.
4. The influence of ENSO on different regions around the world may be modulated by other large synoptic-scale phenomena (e.g. the PDO; Cole and Cook, 1998).

Spectral analysis can be employed to ascertain whether the four ENSO reconstructions do portray consistent power within the 'classic' ENSO bandwidth over time. Firstly, to highlight any potential seasonal differences that the reconstructions may show, a multi-taper method (MTM; Mann and Lees, 1996) analysis was first performed on the instrumental data over the 1925–1980 period. Significant peaks were identified at 4.6–6.0a for both the DJF and previous December to November seasons, as well as a further peak at 3.8–3.9a for the annual season, indicating that there are minimal differences in the spectral properties of these two seasonal parameters.

MTM spectral analysis was made for each of the reconstructions over the three independent periods 1925–1980, 1850–1924 and 1650–1849 (Fig. 7). Over the 1925–1980 period, COA, TEL and TEXMEX express similar spectral properties to the instrumental data. Interestingly, however, the MANN series does not show any significant peaks at the 95% confidence limit over this period. Over the 1850–1923 period, the spectra for COA and TEL are again quite similar, with a common peak at 3.5–4.0a (as does MANN). COA also expresses significant power at 9.7–10.3a, which is not quite significant in TEL, possibly reflecting the quasidecadal mode identified by Allan and D'Arrigo (1999). Ault *et al.* (2009) also identified similar decadal variability since 1850 in the first principal component derived from 23 coral oxygen isotope records. The TEXMEX series shows no significant peaks during this period. Over the longer extended 1650–1850 period, the spectral properties of the series generally express much stronger multi-decadal variability. Despite the fact that COA is represented by only one series (URV), it does still portray some 'ENSO-like' variability, with peaks around 4.1–4.8a, which is similar to peaks ranging from 3.9 to 4.8a in the TEXMEX and MANN series. COA also shows a marked multi-decadal peak ca. 32–57a which coincides with similar peaks in TEL (38–49a) and MANN (34–35a). The TEXMEX series does not appear to express any multi-decadal signal over this period, however.

Exploring ENSO's post-volcanic response

Despite a weakening in inter-series coherence during the early/mid 19th century compared to the 20th century (Table 2 and Fig. 6), MTM spectral analyses (Fig. 7) indicate that all four reconstructions express 'ENSO-like' characteristics. Although dating errors could affect the RBAR (Fig. 2) and Kalman filter analyses (Fig. 6), the spectral analysis results do appear to indicate that all the reconstructions portray some aspect of past ENSO variability, but it may be different in each time series related to the locations of the original constituent proxy sources used. This observation also agrees with Kao and Yu (2009), who identified distinct 'types' of ENSO depending on location within the tropical Pacific.

If each of the reconstructions therefore portray slightly different 'flavours' of past ENSO behaviour, what are the implications of this observation on the hypothesis that there is an increased probability of warm El Niños after major volcanic events (Adams *et al.*, 2003; Mann *et al.*, 2005a; Emile-Geay *et al.*, 2008)? To test this, we undertook a superposed epoch analysis (SEA) on each time series after they had been normalised to *z*-scores over the 1800–1980 period. The 10 strongest and most significant tropical volcanic events were identified between 1800 and 1998 (see Table 3) using a variety of volcanic indices (Crowley, 2000; Robertson *et al.*, 2001; Adams *et al.*, 2003; Ammann and Naveau, 2003; Mann *et al.*, 2005a) and relative mean departures for each reconstruction were calculated for the 5 years preceding and 10 years

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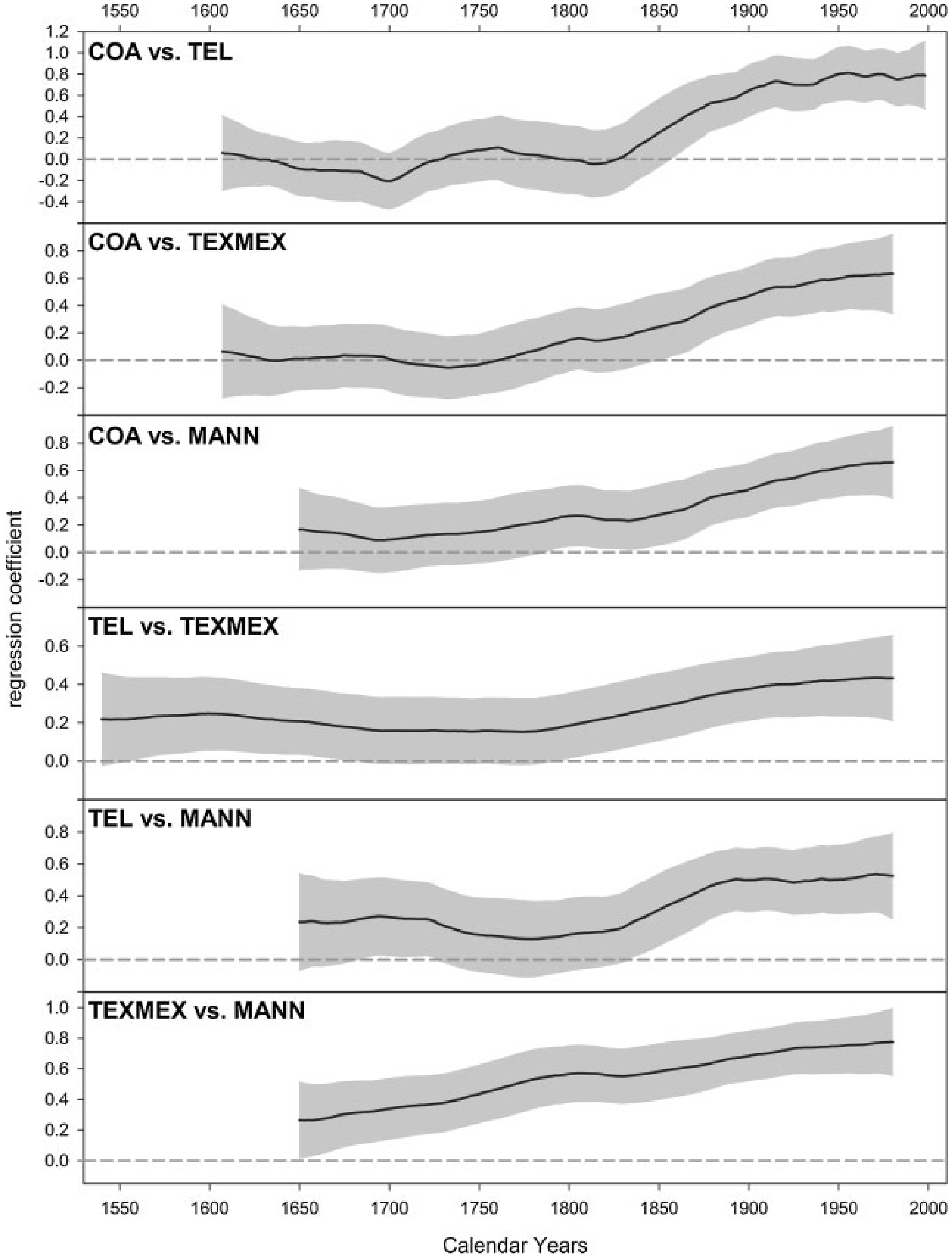

Figure 6 Kalman filter analysis between each ENSO reconstruction. Grey shading denotes 2σ error bars

following an event. As the COA reconstruction is likely not particularly robust prior to 1850 (Fig. 3) and the TEXMEX and MANN records only go to 1980 (so reducing the number of events in the analysis to eight), a reduced SEA analysis was also made targeting the four events (1883, 1902, 1963 and 1968) common to all four records.

The SEA results (Fig. 8) show that neither COA nor MANN show a post-event 'El Niño-like' warming. This is a surprising result with respect to the MANN record as Adams *et al.* (2003) clearly showed, using the same series, an increased probability of warmer SSTs after strong volcanic events. Ultimately, this disparity in results likely reflects the sensitivity of the SEA method to differing periods of analysis and different volcanic events used. For example, the results for the four-event analysis do indicate significant warming in year $T+1$ for both COA and MANN.

For the full SEA analysis both TEL and TEXMEX show significant mean 'El Niño-like' warming for the first and second years after volcanic events. Caution is advised, however, for the TEL results as most of the proxies utilised for this reconstruction are located in regions where local SSTs are inversely correlated with NINO3.4 SSTs (Fig. 1; see also D'Arrigo *et al.*, 2009) and so their time series entered into the regression models with negative weighting (in the CPR approach). Therefore, the reconstructed local cooling after a volcanic event is transformed in the NINO3.4 reconstructions to a warming which in actual fact may not reflect a 'real' warming in the central Pacific, but an overall cooling in the regions where the TEL proxy records came from.

Another interesting observation from the SEA is that there appears to be an apparent shift to negative SST ('La Niña-like') conditions at $T+7$ (COA and TEL) and $T+4$ (TEXMEX and

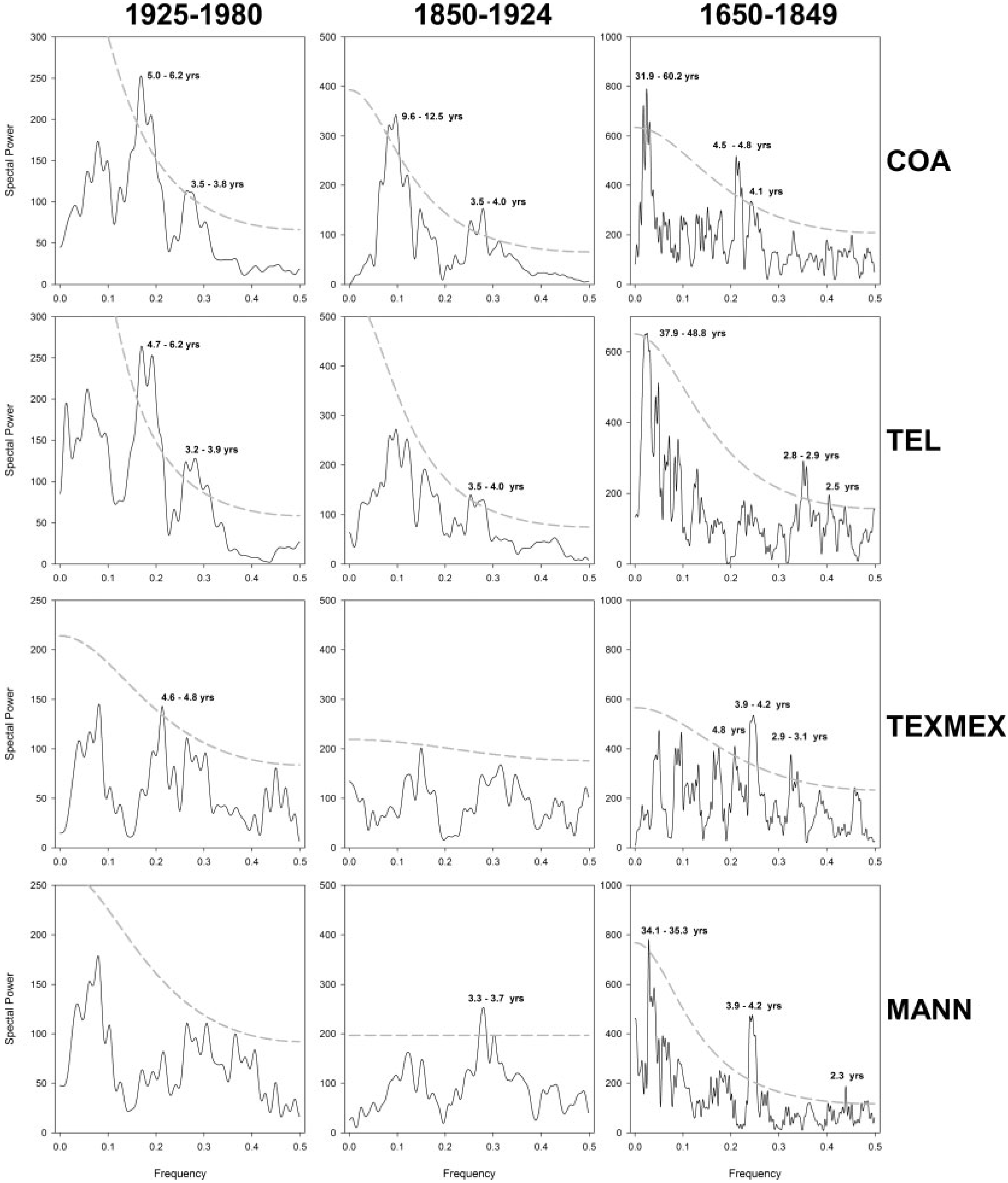

Figure 7 MTM spectra for each proxy over three different periods: 1925–1979, 1840–1924 and 1650–1849. The dashed grey line denotes the 95% confidence limit

MANN) years. A similar observation was noted by Adams *et al.* (2003), where they hypothesised that after the initial post-volcanic event warming in $T+1$ a rebound to 'La Niña-like' conditions occurred during years $T+4$, $T+5$ and $T+6$, possibly to 'synchronise the internal clock of ENSO'. We feel that such an observation overstates the results and the noted 'La Niña-like' conditions are likely simply related to the mean period of ENSO variability and again highlights that all the reconstructions portray some aspect of the ENSO system.

Summary, discussion and conclusion

Although a certain degree of understanding of ENSO variability can be gleaned from instrumental data (Allan, 2000), they are essentially too short to examine ENSO teleconnections over more than a century and explore longer-term variability at decadal and multi-decadal scales. Palaeoclimatic archives, therefore, which can be used to extend our climatic knowledge

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Table 3 Summary list of the major tropical volcanic events identified for the superposed epoch analysis (SEA). The last column denotes the volcanic explosivity index (VEI; Newhall and Self, 1982) for each volcanic event. The VEI values were taken from http://www.volcano.-si.edu/world/largeeruptions.cfm

Year	Name of volcano	Latitude	Longitude	VEI
1809	Unknown	—	—	—
1815	Tambora, Lesser Sunda Is	8.15° S	118.0° E	7
1831	Babuyan Claro, Philippines	19.31° N	121.56° E	4?
1835	Cosigüina, Nicaragua	12.59° N	87.34° W	5
1883	Krakatau, Indonesia	6.06° S	105.25° E	6
1902	Santa Maria, Guatemala	14.45° N	91.33° W	6?
1963	Agung, Indonesia	8.20° S	115.30° E	5
1968	Fernandina, Galápagos Islands	0.22° S	91.33° W	4
1982	El Chichón, Mexico	17.22° N	93.14° W	5
1991	Pinatubo, Philippines	15.08° N	120.21° E	6

well beyond the period covered by the instrumental data, are crucial to improve our understanding of past climate variability in the Tropics.

There is potentially a large dataset of annually resolved proxy archives from tropical and extra-tropical locations that will continue to be amassed, which can be used to infer information on past ENSO activity. It is crucial, however, to understand the limitations of these series with respect to (1) the temporal stability of the climatic teleconnections between the tropical Pacific and the regions where these archives are located and (2) potential dating errors in the time series. Ignoring these two issues may result in erroneous conclusions about past ENSO activity when such large datasets are utilised to reconstruct the dynamics of the ENSO system.

In this study, annually resolved proxy records from the Tropics were screened for an ENSO signal and divided into two datasets: records that were located within the central and eastern Pacific (COA) and records that were located in regions that are

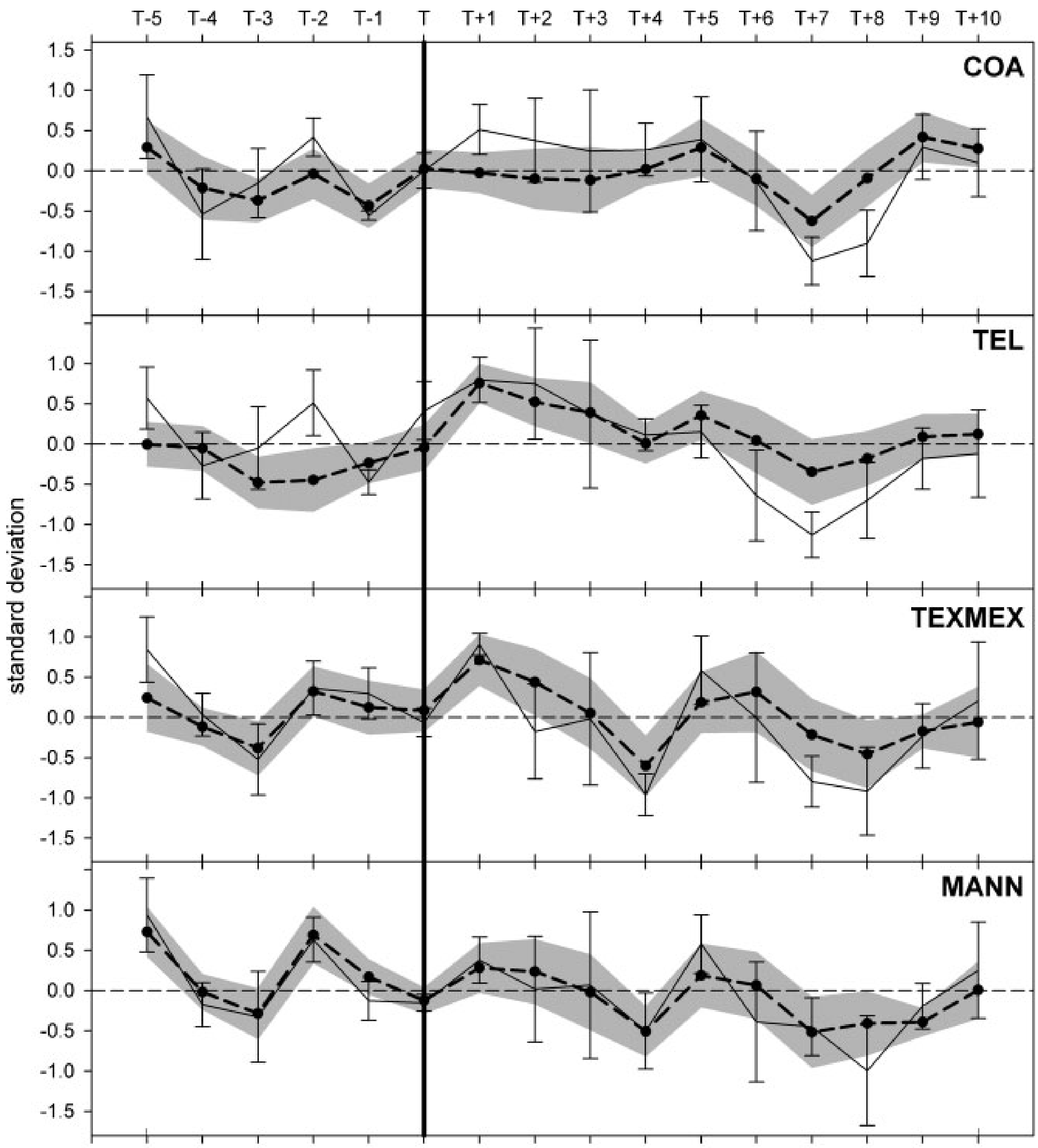

Figure 8 Superposed epoch analysis results for the four ENSO reconstructions. The dashed line (with grey 2σ error envelope) denotes the relative departures for each series averaged over 10 major volcanic events (see Table 3). The solid line (with associated 2σ error bars) details the relative departures averaged over four common volcanic events (1883, 1902, 1963 and 1968)

climatically teleconnected with the central Pacific (TEL). Using three different reconstruction methods (CPR, PCR and RegEM) two independent reconstructions of annual previous December to November NINO3.4 SSTs were developed. Both reconstructions are strongly calibrated and well verified (Figs. 3 and 4). The COA reconstruction (1607–1998) is in fact exceptional in palaeoclimate terms, as over 80% of the instrumental variance is explained over the most replicated period during calibration. Unfortunately, due to the sparse nature of proxy records from the central Pacific, the COA record weakens markedly and can only be interpreted as being robust since 1850. The TEL reconstruction (1540–1998), although not as strongly calibrated as COA ($_a r^2 = 0.63$) is still highly robust and well verified over most of its length. Of the three reconstruction methods tested, little statistical difference between the results was noted, although the RegEM approach appears slightly inferior as the variance of the reconstruction is inflated relative to the CPR and PCR 'flavours' when replication is low.

The COA and TEL series were compared to a new tree-ring-based TEXMEX reconstruction of DJF NINO3.4 SSTs (Cook *et al.*, 2008) as well as a multi-proxy based NINO3 reconstruction (Mann *et al.*, 2000). Overall, using a Kalman filter analysis, inter-proxy coherence breaks down completely around the early–mid 19th century (Fig. 6), which suggests either a problem in some of the constituent proxy records or a breakdown in the spatial teleconnections. Interestingly, however, despite the differences in the four reconstructions, a superposed epoch analysis (Fig. 8) identifies a generally consistent 'El-Niño-like' response to major volcanic events in the following year (although this analysis appears sensitive to the number of volcanic events studied), while during years $T+4$ to $T+7$ 'La Niña-like' conditions are noted. This observation generally agrees with results of Adams *et al.* (2003) and suggests that the dynamical ENSO response to such events is spatially extensive and persistent. MTM spectral analysis undertaken on the four reconstructions over the periods 1925–1980, 1850–1924 and 1650–1849 identified ENSO-like 'behaviour' in all the time series. This 'behaviour', however, does not appear to be spatially or temporally consistent. For example, although the spectra of COA and TEL are arguably quite similar (Fig. 7), the COA record expresses stronger decadal variability prior to 1925 than TEL. This observation is consistent with results detailed in Ault *et al.* (2009). Significant multi-decadal variability (30–60a) is also noted prior to 1850 in the COA, TEL and MANN records, but not in the TEXMEX series.

Fu *et al.* (1986), Folland *et al.* (1999), Trenberth and Stepaniak (2001), Trenberth *et al.* (2002) and Kao and Yu (2009) identified distinct 'types' of ENSO variability depending on location within the tropical Pacific. The results of these studies have major implications for the reconstruction of past ENSO variability. Are NINO3.4 SSTs, for example, an appropriate index for ENSO as a whole, or just one aspect of it? There are a variety of ENSO indices (NINO1 + 2, NINO3, NINO3.4, NINO4, SOI and the Multivariate ENSO index; Wolter and Timlin, 1993), with no consensus within the scientific community as to which index best defines ENSO. Hanley *et al.* (2003) explore this issue and state that the choice of which ENSO index to use is dependent upon the phase of ENSO that is to be studied. This is also suggested in Allan *et al.* (1996) and Allan (2000). Of course, spatial field reconstructions (e.g. Evans *et al.*, 2002) are the optimal answer to this problem, but such an approach must rely on teleconnections between proxy records and SSTs which, as has been suggested, may not be time stable and may depend on the seasonal response of the proxy and the season targeted for reconstruction (Stahle *et al.*, 1998; Rutherford *et al.*, 2005). A more ideal approach is the so called 'point-by-point regression' approach, utilised by Cook *et al.* (1999, 2004) for their North American drought reconstructions. This method works on the premise that only proxy records that are proximal to a given climate grid will likely be true predictors of a particular climate parameter, with a greater probability that the modelled relationship will be stable through time. Unfortunately, in the Tropics, such a methodological approach is not practical due to the sparse network of relevant proxy records, especially further back in time.

So, how can future research improve upon earlier studies (Stahle *et al.*, 1998; Mann *et al.*, 2000; Evans *et al.*, 2002; D'Arrigo *et al.*, 2005a; Braganza *et al.*, 2009)? Ultimately, the central and eastern Pacific are the key locations where new annually resolved proxy records need to be developed. Unfortunately, there are only relatively few locations in this region where relevant coral colonies could theoretically exist (Evans *et al.*, 1998). However, as has been shown with the COA reconstruction (see also Evans *et al.*, 1998), due to the relatively homogeneous nature of the central/eastern tropical Pacific climate, only a few key coral records would be needed to derive a robust ENSO reconstruction. Future work therefore needs to focus on sampling new, and extending previously sampled, coral records from this region. Importantly, and mirroring recommendations made by Lough (2004), dating control on coral proxy records could be verified and improved if a minimum of three coral heads were sampled for each location and the dendrochronological practice of 'crossdating' was employed. The extension of living coral records using fossil material (e.g. Cobb *et al.*, 2003) also provides an exciting possibility for extending short but climatically sensitive records.

Currently, for the simple reasons of dating control and proxy record replication, the TEXMEX (D'Arrigo *et al.*, 2005a; Cook *et al.*, 2008) NINO3.4-based reconstruction is likely the most robust representation of ENSO variability over recent centuries. However, it cannot yet be tested whether this is a temporally consistent representation of central Pacific SSTs, or whether it merely represents the teleconnected relationship between the central Pacific and the American southwest, which may vary over time. However, with the development of longer, exactly dated coral-based records from this crucial region in the Pacific, it would be statistically simple to assess the temporal stability of teleconnected links.

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