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A 100 000-year record of annual and seasonal rainfall and temperature for northwestern Australia based on a pollen record obtained offshore

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ABSTRACT: Pollen recovered from core tops of deep-sea cores from offshore northwestern Western Australia were used to build climatic transfer functions applied to sediment samples from major rivers bordering the ocean in the same region and a deep-sea core offshore Northwest Cape. Results show for the last 100 000 years, with a gap in the record spanning the 64 000 to 46 000 years interval, that from about 100 000 to 82 000 yr BP, climatic conditions represented by rainfall, temperature and number of humid months, were significantly higher than today's values. For the entire record, the coldest period occurred about 43 000 to 39 000 yr BP but it was wetter than today, whereas the Last Glacial Maximum saw a significant reduction in summer rainfall, interpreted as a result of the absence of monsoonal activity in the region. The Holocene can be divided into two distinct phases: one peaking around 6000 cal. yr BP with highest rainfall and summer temperatures; the second one commencing at 5000 cal. yr BP and showing a progressive decrease in summer rainfall in contrast to an increase in winter rainfall, paralleled by a progressive decrease in temperatures. Copyright © 2006 John Wiley & Sons, Ltd.

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KEYWORDS: aridity; BIOCLIM; Holocene; Late Quaternary; transfer function; core tops; LGM.

Introduction

The application of numerical methods to compare modern and fossil pollen spectra, specifically to provide quantitative and refined interpretations of past climatic conditions, has improved in recent years. Many studies deal with temperate regions of the northern hemisphere (Cheddadi *et al.*, 1998; Fauquette *et al.*, 1999; Lotter *et al.*, 2000; Rosén *et al.*, 2001; Bigler *et al.*, 2002; Magny *et al.*, 2003; Klotz *et al.*, 2003). However, there is an increasing body of work dealing with quantitative climatic reconstructions for other regions of the world (e.g. tropical Africa (Bonnefille *et al.*, 1992; Vincens *et al.*, 1993; Bonnefille and Chalié, 2000; Peyron *et al.*, 2000) and India (Bonnefille *et al.*, 1999; Anupama *et al.*, 2000; Barboni and Bonnefille, 2001), as well as for southeastern and northeastern Australia (Kershaw and Bulman, 1994, 1996; D'Costa and Kershaw, 1997; Moss and Kershaw, 2000)).

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Previously, in a study of modern pollen from semi-arid southwestern Australia, Newsome (1999) reported good correspondence between the patterns of vegetation and pollen distribution. Nevertheless, so far much of the western half of the Australian continent lacks modern pollen sites and numerical methods have not been applied to fossil pollen data. In this paper, we present a modern pollen study on coastal river sediment samples from the northern part of Western Australia (WA) and the Northern Territory (NT). This follows with transfer functions derived from existing marine core-top samples offshore WA (van der Kaars and De Deckker, 2003). The transfer functions are then applied to the coastal fluvial samples, allowing for comparison of reconstructed parameters with actual climatic data from these sites. Additionally, the developed transfer functions are applied to fossil pollen spectra from a deep-sea core offshore Northwest Cape, WA (Fig. 1). A detailed description and interpretation of the palynological record from this core has already been presented elsewhere (van der Kaars and De Deckker, 2002), but here we evaluate the newly developed transfer functions against the previously published palaeoecological reconstruction.

The following major bioclimatic zones occur in WA: (1) Northern WA: grass-rich open *Eucalyptus* forests and open

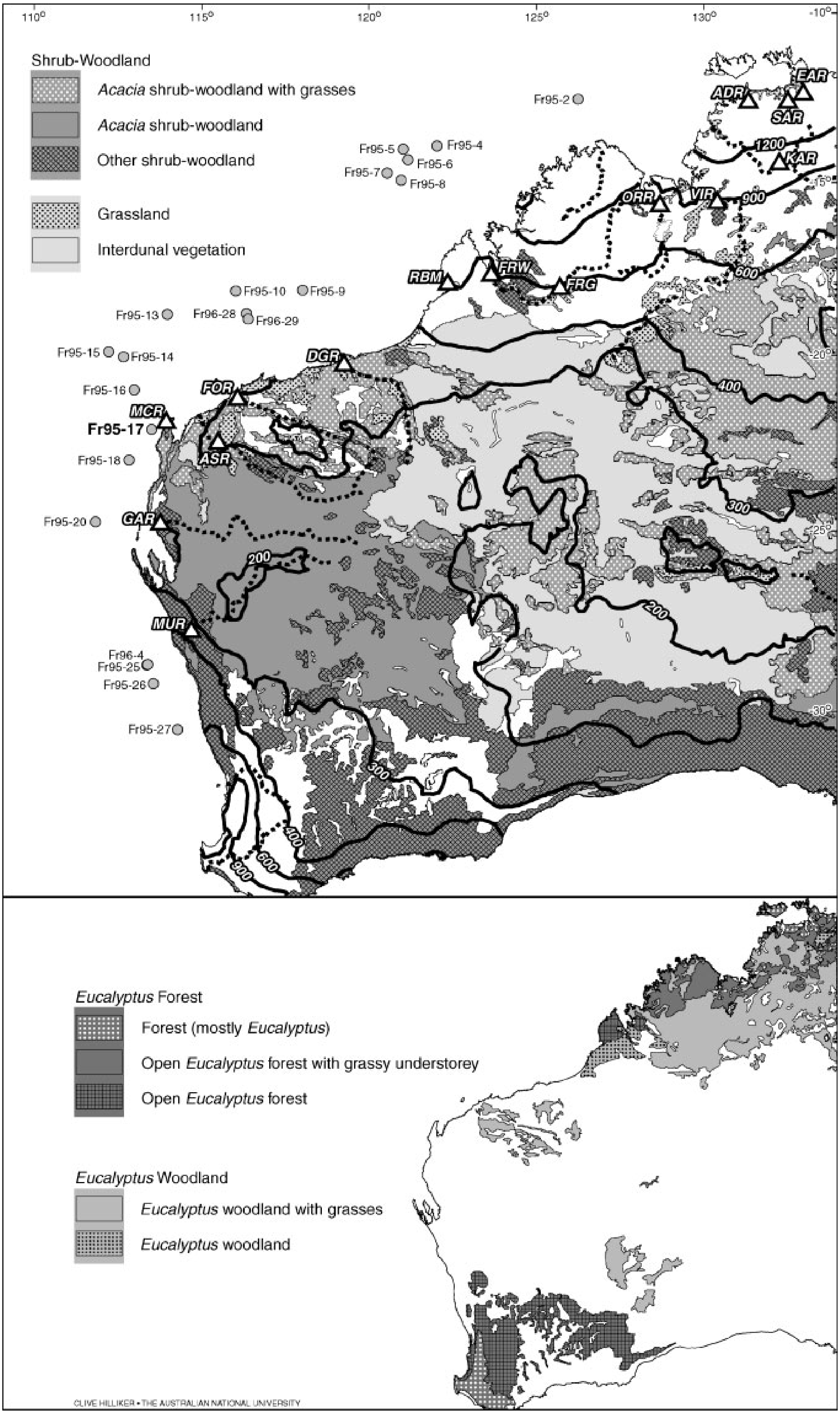

Figure 1 Location of core-top (circles) and river sample (triangles) sites in relation to mean annual rainfall and main (ephemeral) rivers (heavy dashed lines) in relation to generalised vegetation categories (simplified after AUSLIG (1990)). The map was constructed with Generic Mapping Tools, GMT version 4 (Wessel and Smith, 1998) while the rainfall data was derived from the CRU CL 2.0 dataset (New *et al.*, 2002)

Eucalyptus woodlands with an annual precipitation of more than 600 mm and predominantly summer rain; (2) Northwestern WA: open *Eucalyptus* woodlands with *Acacia*, and grasslands with an annual precipitation of 400 to 600 mm and predominantly summer rain; (3) Northwestern WA: open *Acacia* shrublands with grasses and grasslands with an annual precipitation of 300 to 400 mm and predominantly summer rain; (4) Central WA: open *Acacia* shrublands with an annual precipitation of less than 300 mm and winter as well as some summer rain; and (5) Southwestern WA: open *Eucalyptus* forests and mixed shrublands with an annual precipitation of 300 to 600 mm and predominantly winter rain.

Materials and methods

Calibration set

The calibration set comprises selected marine core-top samples obtained during two RV *Franklin* cruises (see Fig. 1) that have been analysed palynologically by van der Kaars and De Deckker (2003). Their results indicate in general a good correspondence between the bioclimatic zones onshore and the marine pollen assemblages offshore WA. For the present study, only the samples with a 'dryland' pollen count of more than 90 were included. The set contains 21 samples and 65 pollen taxa, 24 of which were used in the development of the transfer functions. Climatic parameters were assigned to the core-top samples by taking nearby onshore data from available climatic maps (source: http://www.bom.gov.au [2003]).

Test set

The test set (Table 1) is made up of 15 coastal inland river sediment samples taken in WA and NT (Fig. 1). The rivers in northern and western Australia from the East Alligator River (Arnhem-Land) to the Murchison River (WA) were sampled to obtain fine-grained sediment representative of material in suspension during floods.

The tidally influenced East Alligator, South Alligator and Adelaide Rivers were sampled from boat ramps during low tide, approximately 50 km upstream of the river mouths. The lower part of these boat ramps, exposed during low tide, is coated in thick, fine-grained mud. Suspended matter in these rivers is carried upstream and downstream by tides, homogenised, and deposited on the river beds, banks and boat ramps during times of low water energy, thus representing a large part of the catchment, downstream as well as upstream.

The Katherine, Victoria and Ord Rivers were sampled from bank sediments, as close as possible to the water's edge. Sampled during the dry season, these bank sediments represent several wet seasons of flooding and deposition of sediment.

The Fitzroy, DeGrey, Fortescue and Ashburton Rivers shrink dramatically to small streamlets during the dry season. Here, depressions in the rocky riverbed, acting as natural sediment traps, were sampled. They contain and concentrate suspended matter from the flood event of at least the previous wet season, which should be representative of the whole catchment area. The distance to the respective river mouths is between 50 and 200 km.

The Gascoyne and Murchison Rivers were sampled from river banks sediment. Again, these layered deposits contain several seasons of flooding and deposition.

All the river samples mentioned above were previously the subject of clay mineral analyses by Gingele *et al.* (2001b).

Pollen from local vegetation will, of course, accumulate on the surface of the respective sample, taken at the various river locations. However, the large size of the sample and the rapid deposition after a flooding event ensures that samples and everything contained within are representative of a large part of the catchment area of each respective river.

Sample processing and palynological analysis follow the standard procedures outlined in van der Kaars and De Deckker (2003). Estimates for climate at each site were derived by the climatic prediction system BIOCLIM (Busby, 1991). The BIOCLIM program can model the present-day climate of Australia from a network of weather stations. It then allows for a range of climatic parameters to be generated for any site for which longitude, latitude and altitude are given. The parameters generated for this study were mean monthly rainfall, maximum and minimum temperature from which the mean annual rainfall, mean summer rainfall, mean winter rainfall, mean maximum temperature, mean minimum temperature, mean temperature of the coldest month, the number of humid months and the number of dry months were calculated. A month receiving more than 100 mm of precipitation was classified as humid and a

Table 1 Coastal river sediment samples

Site code	Site name	Latitude °S	Longitude °E	Altitude (m)	Sample dry weight (g)	Pollen concentration (dryland pollen/g)
ADR	Adelaide River	12.6603	131.3359	10	7.42	9190
SAR	South Alligator River	12.6577	132.5057	10	5.22	5245
EAR	East Alligator River	12.4252	132.9650	20	5.23	1995
KAR	Katherine River	14.4619	132.2586	85	7.02	233
VIR	Victoria River	15.6102	130.4012	20	3.57	3027
ORR	Ord River	15.6896	128.6882	30	7.13	1953
FRG	Fitzroy River (Geikie Gorge)	18.1066	125.7003	115	6.35	11 300
FRW	Fitzroy River (Willare Bridge)	17.7275	123.6408	10	7.27	3697
RBM	Roebuck Bay Mudflats	17.9766	122.3472	0	8.27	670
DGR	De Grey River	20.3118	119.2558	25	10.05	2937
FOR	Fortescue River	21.2934	116.0841	55	9.53	37 407
ASR	Ashburton River	22.5438	115.4987	70	6.5	13 691
MCR	Mangrove Creek, Northwest Cape	21.9657	113.9430	5	7.77	1495
GAR	Gascoyne River	24.8289	113.7700	10	8.61	12 417
MUR	Murchison River	27.8280	114.6888	175	6.02	29 664

month receiving less precipitation than twice its averaged mean temperature was classified as dry.

Fossil set

The fossil pollen set consists of 103 samples from deep-sea core Fr10/95-GC17 and contains 60 pollen taxa (see van der Kaars and De Deckker, 2002). The core was taken at a water depth of 1093 m, at 22° 02.74′ S, 113° 30.11′ E, some 60 km west off Northwest Cape, WA, and has already been the subject of several studies (Martínez *et al.*, 1999; Takahashi and Okada, 2000; De Deckker, 2001; Gingele *et al.*, 2001a; Murgese, 2004; Olley *et al.*, 2004) The pollen record covers the last 100 ka, with a hiatus from approximately 64 to 46 ka BP (see van der Kaars and De Deckker, 2002; Gingele *et al.*, 2001a). All dates presented in this paper are calibrated years from which a marine reservoir age of 400 years has been systematically subtracted after calibration calculations (see also Olley *et al.*, 2004).

Transfer functions

Transfer functions for climatic parameters were developed using the weighted averaging partial least squares regression (WAPLS) method of ter Braak and Juggins (1993) and further developed with the C^2 program by Juggins (2003). The principle behind this technique is that a taxon will be most abundant in sites with values close to its optimum for a specific climatic parameter. The resulting function reflects this by applying specific taxon coefficients to the values of every taxon included in the transfer function for each of the climatic parameters. Given the relatively low number of sites in our calibration set, we opted for this approach instead of the Modern Analogue Technique (Overpeck *et al.*, 1985), as the latter approach would rely on matching fossil pollen assemblages to their nearest modern assemblage chosen from a limited number of marine core sites.

Following Birks (1998) and Lotter *et al.* (2000), we performed WAPLS on the square root of the percentage values for pollen taxa in the calibration set and on the untransformed values of the climatic parameters. Subsequently, the WAPLS model with the smallest number of 'useful' components and low root mean square error of prediction (RMSEP) in leave-one-out cross-validation was selected for further use. The transfer function for estimating the value of climatic parameter, P, is

$$P = \Sigma_k c_a \sqrt{y_a} / \Sigma_k \sqrt{y_a}$$

where k is the number of taxa in the transfer function and c_a and y_a are respectively the taxon coefficient and the percentage value for taxon a.

Results

Coastal river sediment samples

The results of palynological analysis on the coastal river sediment samples from WA and NT are summarised in a pollen diagram (Fig. 2) displaying selected pollen taxa, all expressed as percentage values calculated from the 'dryland' pollen sum. Pollen concentration varied from 233 to 37 407, with an average of 8995 dryland pollen per gram of sediment, while a total of 65 pollen taxa were recognised. All the 24 taxa present in the marine core-top samples and used in the development of the transfer functions, with the exception of Asteraceae Liguliflorae, were also present in the river sediment samples. Note that *Stachystemon* type (Euphorbiaceae) has been re-classified here as *Micrantheum* type (Euphorbiaceae). Four sites (KAR, ORR, RBM and MUR; for nomenclature, see Table 1) show dominance of a single taxon, while Myrtaceae values show relatively little variation between the sites. Nevertheless, overall, the composition of the pollen assemblages appears to reflect faithfully vegetational changes along the north–south transect and the general patterns are broadly similar to those exhibited by the marine core-top samples from offshore WA already described in van der Kaars and De Deckker (2003). For instance, Palmae and high Cyperaceae values are restricted largely to northern sites while high Casuarinaceae, Asteraceae Tubuliflorae and Amaranthaceae/Chenopodiaceae values are restricted largely to southern sites.

Pollen transfer functions

The pollen transfer functions selected from the WAPLS models and their characteristics are presented in Table 2. The transfer functions for some of the parameters contain negative taxon coefficients for some taxa; for instance, *Acacia*-type has a negative taxon coefficient in the function for mean winter rainfall, while Asteraceae Tubuliflorae has a negative coefficient in the mean annual rainfall and mean summer rainfall functions. These negative taxon coefficients are most probably an indication that the environmental optimum of those taxa is at the low end of the sampled range. Thus, *Acacia* type is likely to occur primarily in marine core-top sites adjacent to areas with no or very low winter rainfall and Asteraceae Tubuliflorae to areas with low and predominantly winter rainfall, which is indeed the distribution pattern reported by van der Kaars and De Deckker (2003). The application of the transfer function to the test set (Fig. 3) demonstrates that, in general, there is a good agreement between reconstructed and observed climatic parameters for the river sediment sample sites. Actual values for individual parameters show relatively large discrepancies between reconstructed and observed values for several sites, amongst which the ORR, KAR and FOR sites feature more regularly.

Climatic estimates from core Fr10/95-GC17

The reconstructed climatic parameters for the fossil pollen set are summarised in Fig. 4 and the zonation follows that of van der Kaars and De Deckker (2002). All 24 taxa used in the development of the transfer functions were also present in core Fr10/95-GC17. Zones P7 to P5b (100 to 40 ka BP) have generally high estimates for mean annual and mean summer rainfall and number of humid months, with an overall trend of lower values towards zone P5b (46 to 40 ka BP) and highest values at the base of zone P7 (100 ka BP). Mean winter rainfall shows a gradual increase from the base of zone P7 to the top of zone P5b, a pattern that is broadly followed by the temperature estimates. The coldest period for the whole record occurs in the top part of zone P5b and the basal part of zone P5a (43 to 39 ka BP). The number of dry months fluctuates, but averages around 9 during this period. Zone P5a (40 to 35 ka BP) represents a transition to apparently drier conditions, with lower annual rainfall, hardly any summer rain or humid months and increased temperatures and a larger number of dry months. In zone P4 (35 to 19.9 ka BP),

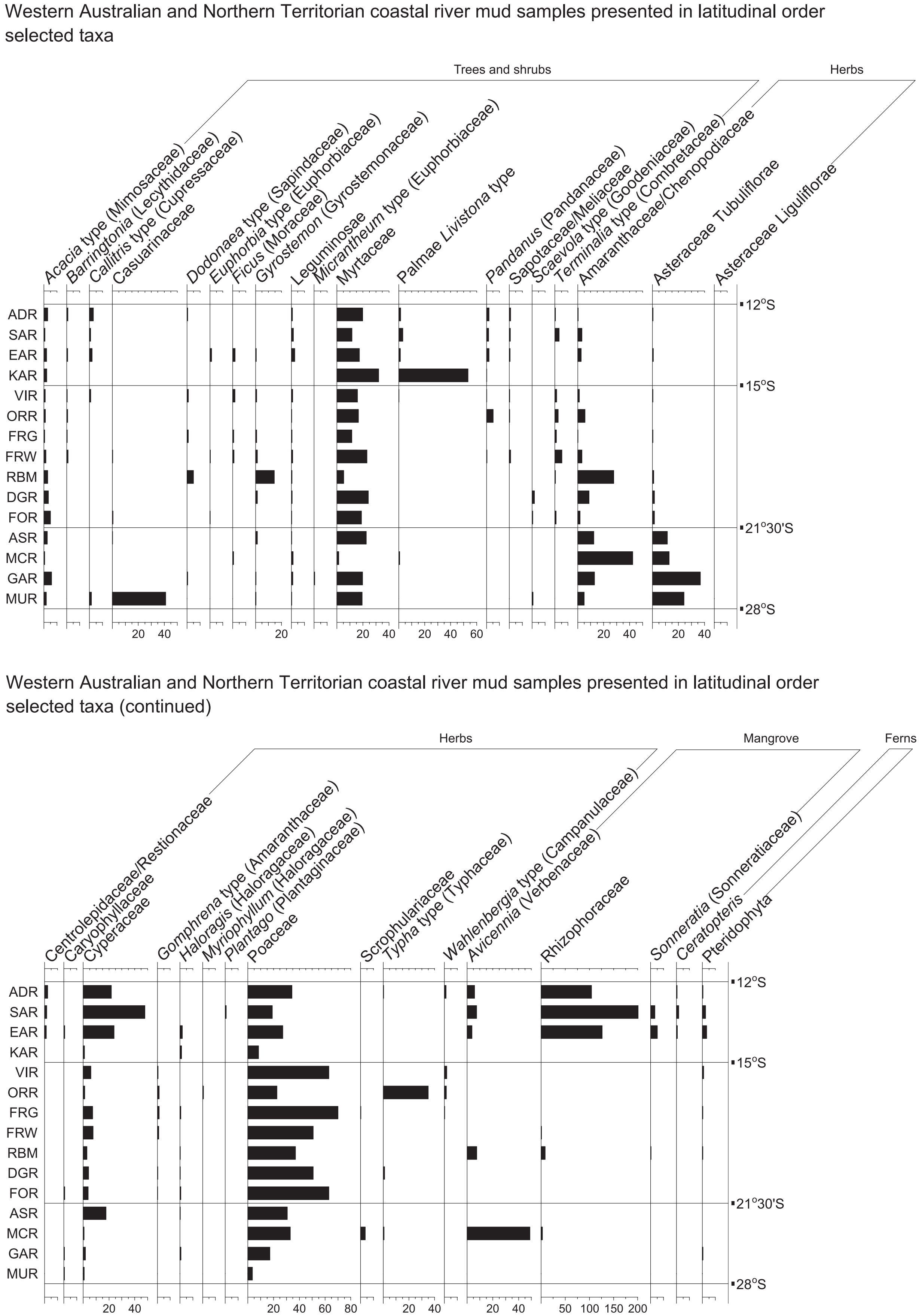

Figure 2 Pollen diagram for northwest Western Australian and Northern Territorian coastal river sediment samples, showing percentage bars for selected pollen and spore taxa. All percentage values are calculated from the dryland pollen sum. For details of sites, refer to Table 1

dry conditions, with lower annual rainfall, very low summer rain and no humid months prevail, while temperatures and the number of dry months are generally high. Zone P3 (19.9 to 14.1 ka BP) sees fluctuating and slightly elevated annual and summer rainfall values, with somewhat reduced winter rain, while temperature estimates show a moderate increase. This trend continues in zone P2 (14.1 to 4.3 ka BP) with higher annual and summer rainfall values and temperature estimates. For the top part of this zone, around 6 ka BP, years with one humid month are suggested. A reversal is seen in zone P1 (4.3 to 0.4 ka BP) with reduced annual and summer rainfall values and temperature estimates and increased winter rain values. The number of dry months increases to 10 from the base of zone P4 (35 ka BP) and, with some minor fluctuations, stays unchanged for the rest of the record.

Discussion

Possible causes for the discrepancies between the observed and WAPLS values of the climatic parameters for the test set include the following. Both calibration and test sets contain a relatively small number of samples increasing the weight of outlier samples in the obtained transfer functions as well as in the test results. Additionally, the calibration set is made up of marine core-top samples, thereby recording a more regional pollen signal. In contrast, the test set is made up of river mud samples which contain assemblages that possibly relate to entire river catchments as the samples represent flood events during which sediment from the entire catchment would have been combined and deposited near the coast. Furthermore, the nature of the test sites will introduce a certain bias towards wetter, riparian-type vegetation, especially since the samples originated from fluvial sediments.

Comparison of the climatic estimates from the pollen transfer function and the original palaeoecological interpretation by van der Kaars and De Deckker (2002) reveals a broad similarity between both reconstructions (see Table 3 for a summary and comparison), but the statistical approach applied here offers a more continuous reconstruction that can be easily compared against other transfer functions obtained from core Fr10/95-GC17. Apart from some small variations in the specified contribution of summer and winter rainfall and slightly higher rainfall estimates in the WAPLS reconstruction, the trends in rainfall quantities and distribution follow corresponding patterns. The challenge now is to compare sea-surface temperature reconstructions for the same core with those presented here, and this will be published elsewhere.

Conclusions

Climatic transfer functions derived from marine core-top samples provide an exciting new approach for the reconstruction of climatic parameters derived from pollen spectra obtained from marine cores. This approach will be especially useful in those parts of the world where there is a scarcity of modern pollen data onshore.

We clearly show the suitability of using fluvial sediment samples in the vicinity of the ocean as an alternative source for obtaining modern pollen spectra for northwestern and northern Australia where lakes and bogs are virtually absent owing to the nature of the landscape and the prescribed aridity.

Table 2 Franklin core-top samples WAPLS transfer functions, summary of results. Calculation is based on all dryland pollen taxa that occur more than twice, but excluding the non-native genera *Pinus* and *Podocarpus*

Climatic parameter	Mean annual rainfall	Mean summer rainfall	Mean winter rainfall	Mean maximum temperature	Mean minimum temperature	Mean temperature coldest month	Number of humid months	Number of dry months
Model type	WA-PLS	WA-PLS	WA-PLS	WA-PLS	WA-PLS	WA-PLS	WA-PLS	WA-PLS
Number of PLS components	2	3	2	3	2	2	3	3
Apparent								
$r^2_{apparent}$	0.95	0.97	0.90	0.95	0.94	0.93	0.97	0.94
RMSE	71 mm	35 mm	34 mm	0.76 °C	0.77 °C	0.87 °C	0.3	0.3
Average bias	−0.5 mm	−0.7 mm	−0.1 mm	−0.01 °C	0.004 °C	−0.007 °C	−0.01	0.005
Maximum bias	64 mm	46 mm	39 mm	0.63 °C	0.88 °C	0.72 °C	0.5	0.6
Cross-validation jack-knifing								
$r^2_{jack\text{-}knifed}$	0.71	0.73	0.54	0.64	0.66	0.67	0.75	0.54
RMSEP	183 mm	104 mm	75 mm	2 °C	1.81 °C	1.91 °C	0.9	1
Average bias	14 mm	7 mm	−2 mm	−0.06 °C	0.18 °C	0.1 °C	0.04	0.04
Maximum bias	208 mm	114 mm	85 mm	1.81 °C	1.82 °C	1.95 °C	1.7	1.8

WA-PLS: Weighted Averaging Partial Least Squares.
r^2: coefficient of determination between observed and predicted values.
RMSEP: Root Mean Square Error of Prediction.

Table 2 (*Continued*)

Taxon coefficients for transfer functions pertaining to selected climatic parameters

Climatic parameter	Mean annual rainfall	Mean summer rainfall	Mean winter rainfall	Mean maximum temperature	Mean minimum temperature	Mean temperature coldest month	Number of humid months	Number of dry months
Acacia type	1807.2	1496.6	−643.7	44.4	33.7	34.3	11.0	8.2
Callitris type	2592.0	853.4	−361.7	48.1	38.5	38.8	7.9	−4.1
Casuarinaceae	2168.3	709.8	363.3	15.0	15.0	13.7	10.4	0.1
Dodonaea type	1074.4	321.7	−66.5	37.0	24.8	25.0	2.7	5.1
Euphorbia type	1673.2	1092.1	100.0	20.4	9.5	6.8	18.7	14.3
Gyrostemon	551.3	250.7	355.6	27.3	14.5	18.1	2.3	3.7
Leguminosae	−2445.9	−1277.3	−118.4	55.1	13.0	17.8	−14.8	18.9
Micrantheum type	862.2	857.7	−105.0	30.9	19.3	20.5	7.2	10.8
Myrtaceae	1613.1	408.8	519.9	17.2	12.2	12.0	7.1	1.7
Palmae	1141.2	523.8	−907.2	46.3	56.3	43.5	−4.7	13.6
Scaevola type	2560.3	955.5	156.0	14.8	6.1	8.5	12.8	7.2
Terminalia type	2123.6	2038.9	−821.8	56.2	34.4	53.1	18.0	1.4
Amaranthaceae/Chenopodiaceae	−883.3	−325.5	−123.7	43.2	16.2	17.8	−5.4	17.0
Asteraceae Liguliflorae	312.7	−395.2	8.1	56.3	12.0	13.9	1.4	6.8
Asteraceae Tubuliflorae	−1546.7	−1288.2	586.8	16.8	−0.3	−2.0	−10.7	17.5
Caryophyllaceae	558.1	1354.3	−1104.6	96.1	41.7	43.8	−1.7	16.1
Centrolepidaceae/Restionaceae	1111.6	−346.4	814.0	−4.0	0.7	−4.0	4.1	13.8
Cyperaceae	1801.7	1012.8	−105.8	33.3	25.5	28.0	8.5	4.4
Haloragis	1172.0	−433.3	792.3	−4.0	18.9	8.2	−0.1	10.2
Myriophyllum	−403.1	−482.7	578.6	35.8	16.5	19.8	−5.9	−3.5
Plantago	2465.4	1254.3	−585.8	67.7	25.7	40.6	16.3	0.5
Poaceae	897.3	594.3	−285.5	39.7	31.0	30.3	1.8	8.5
Scrophulariaceae	1425.8	1164.1	367.7	25.3	16.9	21.6	11.7	1.0
Typha type	3253	820.1	1026.6	8.5	12.9	7.6	14.7	−4.1

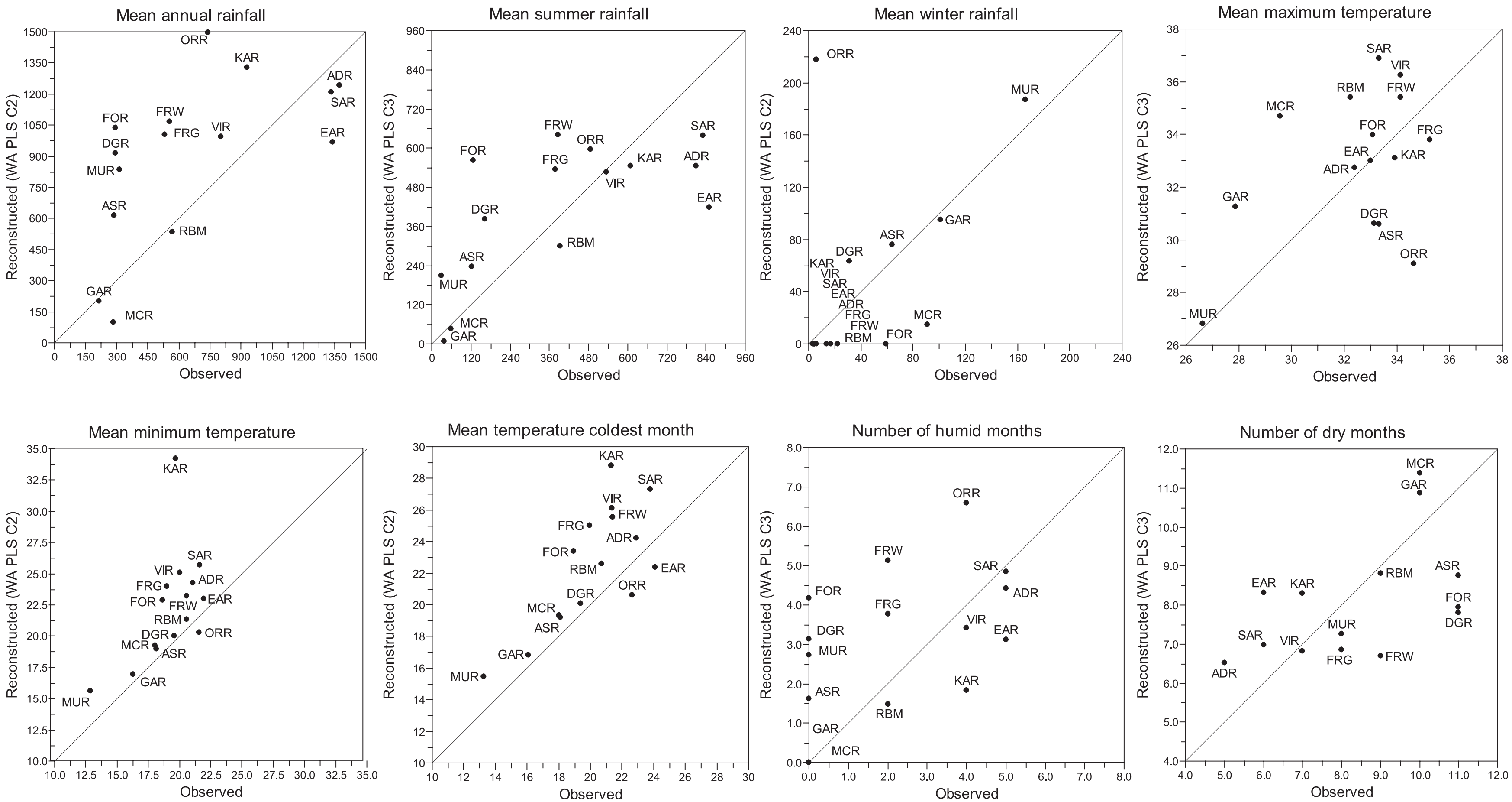

Figure 3 Graphs showing relationship between Weighted Averaging Partial Least Squares based transfer function estimates and observed values of selected climatic parameters for Western Australian and Northern Territorian coastal fluvial samples. It should be noted that, for the mean winter rainfall and the number of humid months, all reconstructed values that were negative have been replaced by zeros

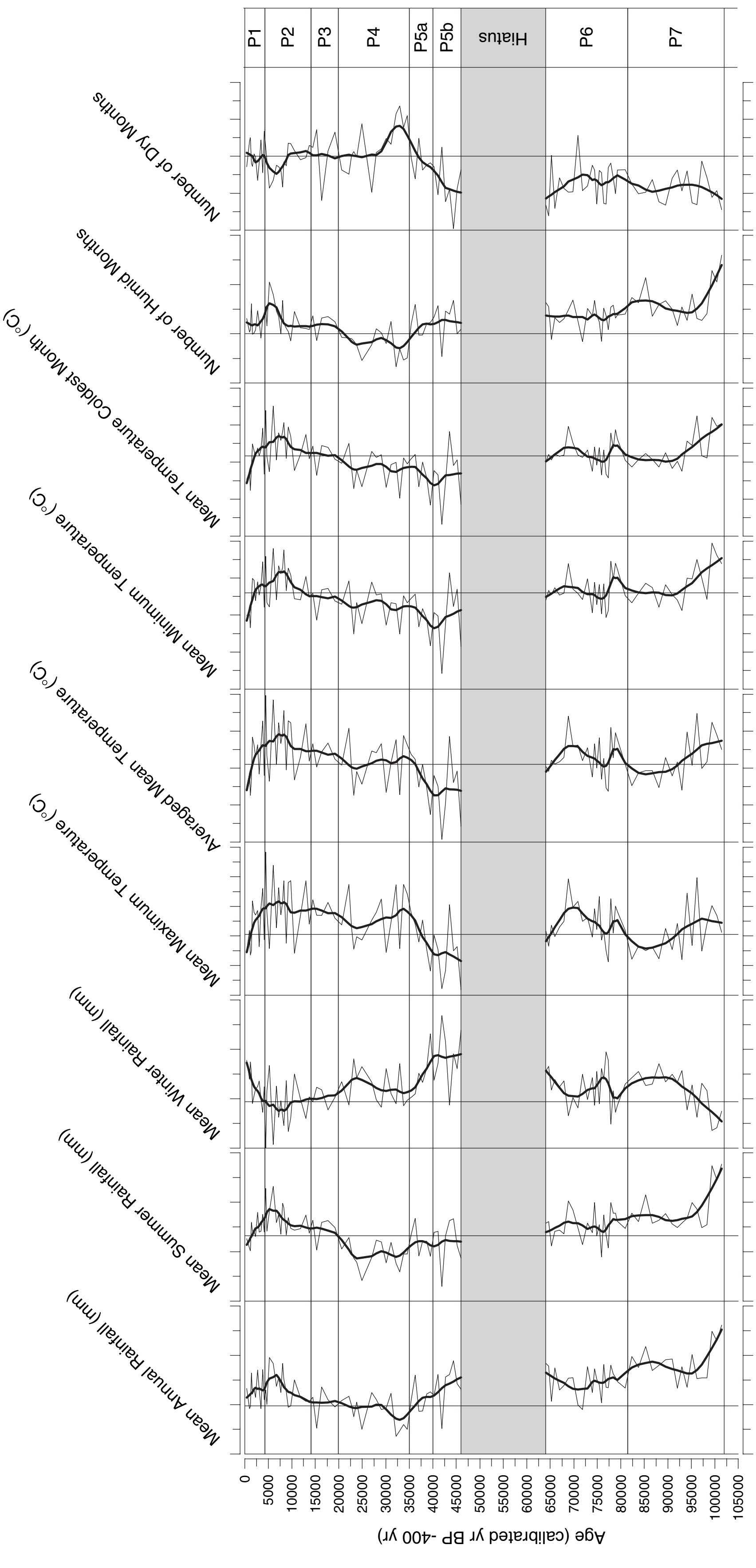

Figure 4 Diagram showing Weighted Averaging Partial Least Squares based estimated of selected climatic parameters for gravity core Fr10/95-GC17. The zonation is taken from van der Kaars and De Deckker (2002); heavy black lines indicate lowess 0.1 smooth. The present-day value for each parameter for Northwest Cape, as derived by BIOCLIM (Busby, 1991), is indicated by the vertical line

Table 3 Summary of palaeoclimatic reconstructions for Fr10/95-GC17 based on the present study and from van der Kaars and De Deckker (2002)

This study							van der Kaars and De Deckker (2002)	
Age range (ka BP)	Pollen zone	Rainfall estimates (range; mean) (mm)			Temperature estimates (range; mean) (°C)		Rainfall estimates (mm)	Remarks
		Annual	Summer	Winter	Mean maximum	Mean minimum		
4.3–0.4	P1	275–515; 380	5–160; 80	70–180; 130	28–32; 30	15–19; 17	≤300	increasing aridity
14.1–4.3	P2	285–590; 405	70–265; 140	0–170; 80	28–35; 31	16–20; 18	300–400	some heavy summer rain
19.9–14.1	P3	160–410; 305	5–130; 95	80–125; 105	30–31; 31	16–17; 17	≤300	rapid climate fluctuations
35–19.9	P4	105–375; 260	0–60; 15	85–180; 125	28–32; 30	15–18; 16	±200	driest period
40–35	P5a	260–480; 345	0–135; 50	105–230; 150	27–31; 29	14–17; 16	200–300	summer and winter rain
46–40	P5b	155–565; 420	0–130; 65	85–270; 185	25–31; 28	13–18; 16	≥300	mostly winter rain
81.5–64	P6	270–550; 440	0–205; 105	50–190; 120	27–33; 30	16–19; 17	300–400	some summer rain
101.5–81.5	P7	400–785; 560	95–355; 170	35–170; 115	27–33; 29	16–20; 18	≥300–400	some summer rain

Around 100k yr BP, the Northwest Cape area experienced a relatively humid climate with high annual rainfall and high summer (monsoonal) rain. Such a wet phase has not been recorded in the region ever since. The vegetation was significantly different from today with open grass-rich *Eucalyptus* woodlands. It is regrettable that we do not have sediment downcore that represents the basal part of the last interglacial corresponding to MIS 5e for comparison with the Holocene.

A significant change in rainfall activity, especially shown through the winter rainfall, and a temperature increase, both in winter and summer, commenced at 40 ka and culminated around 35–32 ka with the lowest mean annual rainfall and the highest mean maximum temperature registered for that period preceding the glacial. The interval spanning 32–20 ka and representing the onset and completion of full glacial conditions, saw the driest conditions for the last 100 000 years with virtually no summer rain. This confirms previous interpretations (De Deckker *et al.*, 2002; van der Kaars and De Deckker, 2002) that summer monsoonal regime and associated rain failed to reach northwest Western Australia. During that time, the vegetation was dominated by herbs, mostly Asteraceae, Poaceae and Chenopodiaceae, while *Callitris* had become a significant element amongst the trees and shrubs, partly replacing *Eucalyptus*. The coldest temperatures for the 32–20 ka interval occurred between 25 and 23 ka but were not as cold as witnessed for the interval of 43–39 ka (Fig. 4). Climatic conditions significantly improved after 15 ka BP with mean annual rainfall, and more importantly mean summer rainfall, increasing before peaking around 6–7 ka BP. This finding agrees favourably with an onset of full monsoon conditions over northwestern Australia by at least 14 ka BP as proposed by Wyrwoll and Miller (2001). The averaged mean temperature systematically climbed before reaching a peak around 8 ka BP. Some fluctuations were seen since, but after that, and definitely from 5 ka BP, climatic conditions changed with mean summer rainfall progressively decreasing and matched by an opposite trend for mean winter rainfall. This phenomenon is paralleled by a progressive decrease in land temperatures, and coincides with a similar trend obtained from reconstructions of sea-surface temperatures obtained for core Fr10/95-GC17 through the courtesy of T. T. Barrows (De Deckker, 2001; van der Kaars and De Deckker, 2002). We have been unable to address the possible impact of humans on the vegetation at the time through possible fire activity as no pattern of change is decipherable in the record (see van der Kaars and De Deckker, 2002).

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References

Anupama K, Ramesh BR, Bonnefille R. 2000. Modern pollen rain from the Biligirirangan-Melagiri hills of the southern Eastern Ghats, India. *Review of Palaeobotany and Palynology* **108**: 175–196.

AUSLIG 1990. *Vegetation. Atlas of Australian Resources*, Vol. 6. Division of National Mapping: Canberra.

Barboni D, Bonnefille R. 2001. Precipitation signal in the pollen rain from tropical forests, South India. *Review of Palaeobotany and Palynology* **114**: 239–258.

Bigler C, Larocque I, Peglar SM, Birks HJB, Hall RI. 2002. Quantitative multiproxy assessment of long-term patterns of Holocene environmental change from a small lake nearby Abisko, northern Sweden. *The Holocene* **12**: 481–496.

Birks HJB. 1998. Numerical tools in palaeolimnology—Progress, potentialities, and problems. *Journal of Paleolimnology* **20**: 307–322.

Bonnefille R, Chalié F. 2000. Pollen-inferred precipitation time-series from equatorial mountains, Africa, the last 40 kyr BP. *Global and Planetary Change* **26**: 25–50.

Bonnefille R, Chalié F, Guiot J, Vincens A. 1992. Quantitative estimates of full glacial temperatures in equatorial Africa from palynological data. *Climate Dynamics* **6**: 251–257.

Bonnefille R, Anupama K, Barboni D, Pascal J, Prasad S, Sutra JP. 1999. Modern pollen spectra from tropical South India and Sri Lanka: altitudinal distribution. *Journal of Biogeography* **26**: 1255–1280.

Busby JR. 1991. BIOCLIM—a bioclimatic analysis and prediction system. In *Nature Conservation: Cost Effective Biological Surveys and Data Analysis*, Margules CR, Austin MP (eds). CSIRO: Melbourne; 64–68.

Cheddadi R, Mamakowa K, Guiot J, de Beaulieu J-L, Reille M, Andrieu V, Granoszewski W, Peyron O. 1998. Was the climate of the Eemian stable? A quantitative climate reconstruction from seven European pollen records. *Palaeogeography, Palaeoclimatology, Palaeoecology* **143**: 73–85.

D'Costa D, Kershaw AP. 1997. An expanded recent pollen database from South-eastern Australia and its potential for refinement of palaeoclimatic estimates. *Australian Journal of Botany* **45**: 583–605.

De Deckker P. 2001. Records of environmental changes in the Australian sector of PEP II Point to broad trends of Climate Change. *PAGES News* **9**(2): 4–5.

De Deckker P, Tapper NJ, van der Kaars S. 2002. The status of the Indo-Pacific Warm Pool and adjacent land at the Last Glacial Maximum. *Global and Planetary Change* **35**: 25–35.

Fauquette S, Guiot J, Menut M, de Beaulieu J-L, Reille M, Guenet P. 1999. Vegetation and climate since the last interglacial in the Vienne area (France). *Global and Planetary Change* **20**: 1–17.

Gingele FX, De Deckker P, Hillenbrand C-D. 2001a. Late Quaternary fluctuations of the Leeuwin Current and palaeoclimates on the adjacent land masses: clay mineral evidence. *Australian Journal of Earth Sciences* **48**: 867–874.

Gingele FX, De Deckker P, Hillenbrand C-D. 2001b. Clay mineral distribution in surface sediments between Indonesia and NW Australia—source and transport by ocean currents. *Marine Geology* **179**: 135–146.

Juggins S. 2003. *C^2 User Guide. Software for Ecological and Palaeoecological Data Analysis and Visualisation*. University of Newcastle: Newcastle upon Tyne.

Kershaw AP, Bulman D. 1994. The relationship between modern pollen samples and the environment in the humid tropics region of northeastern Australia. *Review of Palaeobotany and Palynology* **83**: 83–96.

Kershaw AP, Bulman D. 1996. A preliminary application of the analogue approach to the interpretation of Late Quaternary pollen spectra from southeastern Australia. *Quaternary International* **33**: 161–171.

Klotz S, Guiot J, Mosbrugger V. 2003. Continental European Eemian and early Würmian climate evolution: comparing signals using different quantitative reconstruction approaches based on pollen. *Global and Planetary Change* **36**: 277–294.

Lotter AF, Birks HJB, Eicher U, Hofmann W, Schwander J, Wick L. 2000. Younger Dryas and Allerød summer temperatures at Gerzensee (Switzerland) inferred from fossil pollen and cladoceran assemblages. *Palaeogeography, Palaeoclimatology, Palaeoecology* **159**: 349–361.

Magny M, Bégeot C, Guiot J, Marguet A, Billaud Y. 2003. Reconstruction and palaeoclimatic interpretation of mid-Holocene vegetation and lake-level changes at Saint-Jorioz, Lake Annecy, French Pre-Alps. *The Holocene* **13**: 265–275.

Martínez JI, De Deckker P, Barrows TT. 1999. Palaeoceanography of the last glacial maximum in the eastern Indian Ocean: planktonic foraminiferal evidence. *Palaeogeography Palaeoclimatology Palaeoecology* **147**: 73–99.

Moss PT, Kershaw AP. 2000. The last glacial cycle from the humid tropics of northeastern Australia: comparison of a terrestrial and a marine record. *Palaeogeography, Palaeoclimatology, Palaeoecology* **155**: 155–176.

Murgese SD. 2004. *Late Quaternary palaeoceanography of the eastern Indian Ocean based on benthic foraminifera*. PhD thesis, The Australian National University, Canberra.

New M, Lister D, Hulme M, Makin I. 2002. A high-resolution data set of surface climate over global land areas. *Climate Research* **21**: 1–25.

Newsome JC. 1999. Pollen-vegetation relationships in semi-arid southwestern Australia. *Review of Palaeobotany and Palynology* **106**: 103–119.

Olley JM, De Deckker P, Roberts RG, Fifield LK, Yoshida H, Hancock G. 2004. Optical dating of deep-sea sediments using single grains of quartz: a comparison with radiocarbon. *Sedimentary Geology* **169**: 175–189.

Overpeck JT, Webb T III, Prentice IC. 1985. Quantitative interpretation of fossil pollen spectra: dissimilarity coefficients and the method of modern analogs. *Quaternary Research* **23**: 87–108.

Peyron O, Jolly D, Bonnefille R, Vincens A, Guiot J. 2000. Climate of East Africa 6000 ^{14}C Yr B.P. as inferred from pollen data. *Quaternary Research* **54**: 90–101.

Rosén P, Segerström U, Eriksson L, Renberg I, Birks HJB. 2001. Holocene climatic change reconstructed from diatoms, chironomids, pollen and near-infrared spectroscopy at an alpine lake (Sjuodjijaure) in northern Sweden. *The Holocene* **11**: 551–562.

Takahashi K, Okada H. 2000. The paleoceanography for the last 30,000 years in the southeastern Indian Ocean by means of calcareous nannofossils. *Marine Micropaleontology* **40**: 83–103.

ter Braak CJF, Juggins S. 1993. Weighted averaging partial least squares regression (WA-PLS): an improved method for reconstructing environmental variable from species assemblages. *Hydrobiologia* **269/270**: 485–502.

van der Kaars S, De Deckker P. 2002. A Late Quaternary pollen record from deep-sea core Fr10/95, GC17 offshore Cape Range Peninsula, northwestern Western Australia. *Review of Palaeobotany and Palynology* **120**: 17–39.

van der Kaars S, De Deckker P. 2003. Pollen distribution in marine surface sediments offshore Western Australia. *Review of Palaeobotany and Palynology* **124**: 113–129.

Vincens A, Chalié F, Bonnefille R, Guiot J, Tiercelin J-J. 1993. Pollen-derived rainfall and temperature estimates from Lake Tanganyika and their implication for late Pleistocene water levels. *Quaternary Research* **40**: 343–350.

Wessel P, Smith WHF. 1998. New, improved version of Generic Mapping Tools released. *EOS Transactions American Geophysical Union* **79**: 579.

Wyrwoll K-H, Miller GH. 2001. Initiation of the Australian summer monsoon 14,000 years ago. *Quaternary International* **83–85**: 119–128.

