



A quantitative Late Quaternary temperature reconstruction from western Tasmania, Australia

Michael-Shawn Fletcher^{a,b,*}, Ian Thomas^a

^a Resource Management and Geography, University of Melbourne, Parkville, Victoria 3010, Australia

^b Instituto de Ecología y Biodiversidad, Facultad de Ciencias, Universidad de Chile, Las Palmeras 3425, Ñuñoa, Santiago, Chile

ARTICLE INFO

Article history:

Received 12 March 2010

Received in revised form

21 May 2010

Accepted 4 June 2010

ABSTRACT

Late Quaternary temperature estimates from the mid latitudes of the Australian region suggest a breakdown in the tight coupling observed between oceanic and atmospheric temperatures over the recent past that has significant implications for our understanding of the response of the Earth's climate system to global climate change and orbital forcing. Here, we present a pollen-based quantitative temperature reconstruction from the mid latitudes of Australia that spans the last 135 000 years, enabling us to address this critical issue. Gradient analysis of a pollen dataset inclusive of over 1100 Quaternary and modern pollen spectra demonstrates the dominant influence of temperature over Quaternary pollen composition and vegetation change in western Tasmania, Australia. We develop and apply a transfer function for average annual temperature that performs excellently under cross-validation ($r^2 = 0.76$; RMSEP 1 °C), is not influenced by spatial autocorrelation and that reveals a remarkably close correlation between oceanic and atmospheric temperature change over the last 135 000 years. Significantly, we report a substantially lower degree of cooling during the LGM/MIS 2 (3.7–4.2 °C below present) than previously estimated; a similar degree of cooling during MIS 4 as the LGM (ca 4 °C); and a 1 °C warming during the Last Interglacial relative to today. We conclude that atmospheric and oceanic temperature changes in this region have remained coupled throughout the substantial climatic shifts associated with glacial–interglacial cycles over the last 135 000 years. Western Tasmanian pollen records have great potential as a Southern Hemisphere terrestrial palaeothermometer and are critically located to provide significant input in to debates over the occurrence and influence of regional and global climatic episodes in the Southern Hemisphere.

© 2010 Elsevier Ltd. All rights reserved.

1. Introduction

The development of quantitative palaeoenvironmental reconstructions is a crucial step in attempting to understand past, present and future Earth system dynamics, as they permit a unique opportunity for a quantitative comparison between often disparate and complex palaeoenvironmental proxies. There is a general lack of land based continuous and quantitative temperature reconstructions from the Southern Hemisphere that span the full period between the Last Interglacial to the present that precludes a direct comparison between terrestrial temperature change and temperature change in the oceans and polar regions through this time. Advances in mathematical modelling and computational power have enabled

a proliferation of quantitative niche-based palaeoenvironmental reconstructions and some of these are now being applied to Southern Hemisphere Late Quaternary palaeoenvironmental data (e.g. Marra et al., 2004; Barrows et al., 2007a; Wilmshurst et al., 2007; Woodward and Shulmeister, 2007; Massafiero et al., 2009; Rees and Cwynar, 2009; Tonello et al., 2009), often without regard to important philosophical caveats, not the least of which include critical assumptions about the representativeness of modern bioclimatic envelopes for past species/taxa distributions and the degree of spatial autocorrelation in species datasets (Birks, 1998; Telford and Birks, 2005, 2009; Belyea, 2007). In an attempt to address the gap between the philosophical underpinnings and the application of the niche-based approach, we (i) interrogate the relationship between pollen composition and temperature through the Quaternary in western Tasmania, Australia, using a novel application of gradient analysis, (ii) develop and test a pollen-based transfer function for temperature for the effects of spatial autocorrelation and (iii) finally apply the model to continuous Late Quaternary pollen records from this part of the mid latitudes of the Southern Hemisphere.

* Corresponding author. Instituto de Ecología y Biodiversidad, Facultad de Ciencias, Universidad de Chile, Las Palmeras 3425, Ñuñoa, Santiago, Chile. Tel.: +61 56 29787420.

E-mail addresses: michael.fletcher@u.uchile.cl (M.-S. Fletcher), i.thomas@unimelb.edu.au (I. Thomas).

Millennial scale changes in solar insolation resulting from variations in the Earth's solar orbit (*sensu* Milankovitch, 1941; Berger, 1978) are considered the main driver of atmospheric and oceanic temperature change over glacial–interglacial time-scales and there is a close correlation between insolation, terrestrial vegetation and sea surface temperature (SST) change in the mid latitudes of the Southern Hemisphere during the Late Quaternary (Vandergoes et al., 2005). Attempts at quantitatively reconstructing temperature change in western Tasmania, Australia, a mountainous mid-latitude region in the Southern Hemisphere with a pronounced maritime climate, have revealed a significant correlation between decadal-scale changes in warm-season temperature on land and in adjacent Indian Ocean SST over the most recent millennia (Cook et al., 2000) that contrasts with a marked divergence between Indian Ocean SST and terrestrial temperature estimates during the Late Quaternary (Colhoun, 1985b, 2000; Colhoun et al., 1999; Barrows and Juggins, 2005; Mackintosh et al., 2006; Barrows et al., 2007a; Williams et al., 2009). A breakdown in the tight coupling between oceanic and atmospheric temperatures through the Late Quaternary, if real, has significant implications for our understanding of the response of the Earth's climate system to global climate change and orbital forcing.

Estimates of terrestrial temperature change during the Last Glacial Stage (Marine Oxygen Isotope Stage 2 – MIS 2) in western Tasmania range considerably in magnitude and vary in regards to what component of the temperature climate is being inferred: estimates based on western Tasmanian pollen records, probably reflecting the influence of temperature minima (cold-season) on vegetation (Kirkpatrick and Brown, 1987; Read and Hill, 1989; Read and Busby, 1990), report a 5–6 °C cooling during MIS 2 (Colhoun, 1985b; Colhoun and van der Geer, 1986; Colhoun et al., 1999); estimates based on snowline depression, possibly reflecting warm-season temperatures (Seltzer, 1994), depict a 6.5 °C cooling (Colhoun, 1985a); while estimates based on equilibrium line altitude estimates of glacial limits probably reflect warm-season freezing temperatures (Ohmura et al., 1992) and are between 7 and 8 °C cooler than present for MIS 2 (Mackintosh et al., 2006). Niche-based quantitative estimates of Indian and Southern Ocean MIS 2 average annual SST, conversely, report a substantially lower degree of cooling (3–4 °C) of the ocean's surface in the mid-latitudes relative to modern values (Barrows and Juggins, 2005) that is supported by recent beetle-based terrestrial temperature reconstructions from the maritime mid latitudes of the west coast of South Island New Zealand (Marra et al., 2004). There is a clear discrepancy, then, between estimates of MIS 2 SST and terrestrial temperature change in western Tasmania that implies either a substantial weakening of the oceanic influence on western Tasmanian climate during the Last Glacial Stage or inaccurate estimations of temperature change. In this paper we present a niche-based average annual temperature (AAT) reconstruction for western Tasmania that is derived from modern pollen – temperature relationships and that spans the entire period between the Last Interglacial to the present (*ca* 135 000 years (ka)), enabling a direct comparison of atmospheric and oceanic temperature change in this region.

Tasmania is a mountainous island with an oceanic climate located between 41 and 43°S that shares remarkable climatic, geographic and floral affinities with the mid latitudes of South Island New Zealand and southern South America (Fig. 1). Orographic uplift of the moisture laden Southern Hemisphere Westerly Winds (SWW) as they are advected over the north–south trending central ranges that bisect these landmasses results in distinct west (superhumid) and east (subhumid–semiarid) climatic and biogeographic zonation (Gentilli, 1972; Sturman and Tapper, 2006; Garreaud et al., 2009). The continental shelf to the west of

each of these regions is narrow, with less than 20 km exposed west of Tasmania during the MIS 2 glacial stage (Lambeck and Chappell, 2001). Unlike New Zealand and southern South America, the present day landscape of western Tasmania is free from glacial ice, yet the steep glacially moulded topography reveals a dynamic Tertiary and Quaternary glacial history (Colhoun, 2004).

The complex landscape of western Tasmania has allowed the *in situ* persistence of a relictual mesophytic Gondwanan flora throughout the climatic vicissitudes of the Tertiary and Quaternary (Hill, 2004). The distribution of modern vegetation types is governed primarily by temperature and its relation to altitude, with evidence that temperature minima exert a substantial influence over plant species distributions (Kirkpatrick and Brown, 1987; Read and Hill, 1989; Read and Busby, 1990). The relationship between temperature and vegetation is faithfully reflected in the modern pollen rain, with average annual temperature (AAT) significantly correlated to modern pollen composition (Fletcher and Thomas, 2007a). There is a close match between changes in western Tasmanian Late Quaternary pollen records and regional temperature reconstructions from Antarctica and the surrounding oceans (Colhoun and van der Geer, 1986, 1998; Colhoun et al., 1999; Colhoun, 2000) that, coupled with the close relationship between the modern pollen rain and temperature, indicates this region is ideal for using a modern pollen training set to derive quantitative estimates of temperature change from Late Quaternary pollen records using niche-based quantitative approaches.

In this paper, we use gradient analysis of a western Tasmanian modern and Quaternary fossil pollen dataset to assess the relationship between Quaternary pollen compositions and modern pollen–climate relationships. We then develop a pollen-based transfer function for AAT and apply it to two continuous Late Quaternary pollen records from this region. We aim to specifically address the following questions: (i) has temperature been the main determinant of pollen composition (read: vegetation) through the Quaternary; (ii) can modern pollen–temperature relationships be used to generate accurate temperature estimates in this region; (iii) what was the nature and magnitude terrestrial temperature change through the Late Quaternary in western Tasmania; and (iv) was there a divergence between oceanic and terrestrial temperatures during the Late Quaternary.

2. Regional setting

Tasmania (41–43°S) is a continental island that forms the southern most point of the Australian continent (Figs. 1 and 2). The island is surrounded by a narrow continental shelf and is joined to mainland Australia by a shallow sea that has been dry a number of times through the Quaternary (Lambeck and Chappell, 2001). Western Tasmania, like west coast New Zealand and Chile between 41 and 43°S, has a rugged, steep and complex topography that results in the uplift of humid air delivered by the SWW and the deposition of up to 3.5 m of rain annually. In each of these regions, the zone centred on 42°S ($\pm 2^\circ$) displays the strongest climate response to present day decadal-scale changes in the position and intensity of the SWW associated with the Southern Annular Mode (SAM) (Gillett et al., 2006). In SAM anti-phased east–west precipitation anomalies result from an increase (decrease) in SWW flow that drives an increase (decrease) in precipitation in the west, while higher (lower) evaporation resulting from intensified (weakened) foehn/föhn winds that also inhibit (permit) incursions of easterly moisture sources results in a drier (wetter) east (Hendon et al., 2007; Ummenhofer and England, 2007; Garreaud et al., 2009). The modern day west coast of Tasmania lies less than 70 km west of the highest central peaks and, under maximum estimates of sea-level lowering, less than 20 km of additional land was exposed

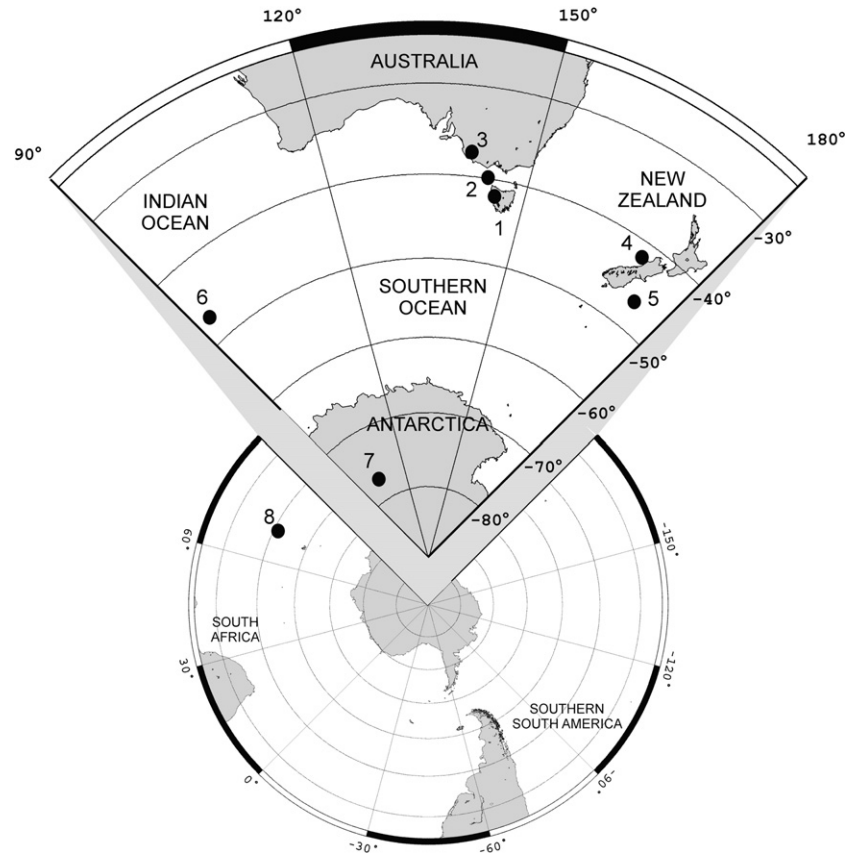


Fig. 1. Map of the study region displaying the sites mentioned in the text: 1-Western Tasmania; 2-King Island (Porch et al., 2009); 3-Naracoote, Southeast Australia (Ayliffe et al., 1998); 4-SO136-GC3 (Southern Ocean) (Barrows et al., 2007a); 5-MD88-770 (Southern Ocean) (Barrows et al., 2007a); 6-MD97-2120 (Southern Ocean) (Barrows et al., 2007a); 7-Vostok Station, Antarctica; 8-RC11-120 (Indian Ocean) (Martinson et al., 1987).

to the west during the Last Glacial Stage (MIS 2) (Lambeck and Chappell, 2001), extending the distance from the central peaks to the coast to a maximum of 90 km. Temperature is the main determinant of western Tasmanian vegetation resulting in a clear altitudinal gradation of vegetation types that is clearly reflected in the modern pollen rain (Fletcher and Thomas, 2007a).

3. Materials and methods

3.1. Gradient analysis

The modern pollen database of Fletcher and Thomas (2007a) was employed for ordination analysis and transfer function development. An unconstrained ordination using detrended correspondence analysis (DCA) of this dataset produced three axes explaining 41.3% of the variation in the data (Table 1; Fletcher and Thomas, 2007a). Coefficients of correlation were calculated between the ordination axes and AAT in that analysis, revealing a strong relationship between AAT and the main gradient in the dataset produced by the DCA (axis 1; $r^2 = 0.56$) (Table 1; Fletcher and Thomas, 2007a). In the present analysis we performed an unconstrained ordination of a western Tasmanian pollen meta-dataset inclusive of the modern pollen dataset and all available Quaternary fossil pollen data (1159 fossil spectra) from western Tasmania using DCA. Coefficients of correlation were calculated between the DCA axis 1 sample scores for the modern pollen sites produced by the meta-ordination and the AAT at each modern pollen site (Table 1). Fossil data were digitised from publications when the raw data were unavailable. Table 2 lists the site names and source of the

fossil pollen data. All gradient analysis was performed using Canoco 4.5 for Windows (Ter Braak and Smilauer, 2002).

Prior to gradient analysis, all pollen data were screened using the following criteria to facilitate integration of datasets from various sources and analysts:

- i. *Leptospermum/Baeckea* type and *Leptospermum* type, and *Melaleuca squarrosa* and *Melaleuca squamea* were grouped into *Leptospermum* and *Melaleuca* respectively.
- ii. Taxa were excluded that were not present in at least 5 sites at or above a percentage level of 1% (*sensu* McGlone and Moar, 1997), with a total of 32 pollen taxa were retained in the analysis.
- iii. Percentages were recalculated after exclusions.
- iv. Pollen data were normalised using a square-root transformation of all 32 pollen taxa.

3.2. Transfer function

Based on the strength of the relationship between the modern pollen dataset and AAT identified in our earlier analysis (Fletcher and Thomas, 2007a), a transfer function model was developed for AAT using the modern pollen dataset. The modern pollen data were subject to the same screening criteria employed in Section 3.1. Following the advice of Birks (1998), the gradient length of a detrended canonical correspondence analysis (DCCA) of the modern dataset constrained to AAT was used as a guide for selecting between a linear (Partial Least Squares – PLS) or unimodal (Weighted Averaging – WA) transfer function. Linear models are suggested for short gradient

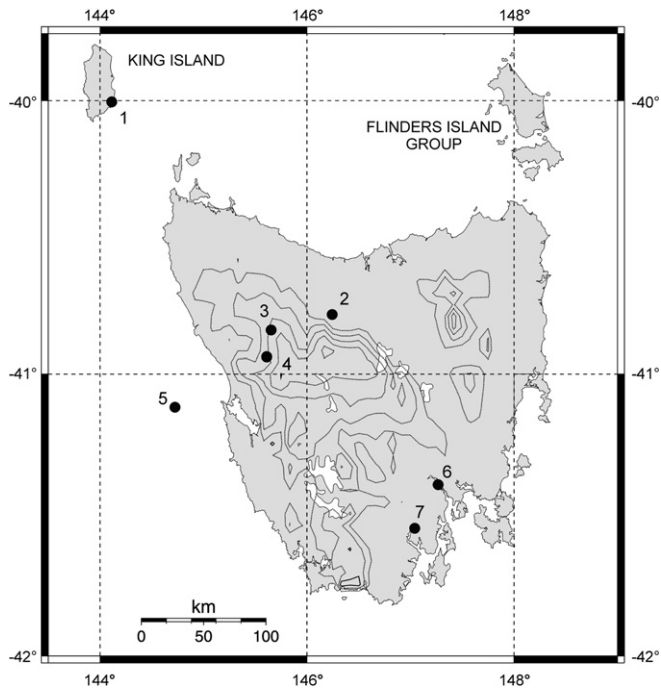


Fig. 2. Map of Tasmania and surrounds. Contours represent 200 m intervals and numbers indicate sites mentioned in the text: 1-King Island Last Interglacial beetle fauna (Porch et al., 2009); 2-MIS 5 speleothem temperature reconstruction (Goede et al., 1986); 3-Lake Selina (Colhoun et al., 1999); 4-Tullabardine Dam (Colhoun and van der Geer, 1986); 5-Ocean core SO36-07 used by Barrows and Juggins (2005) MIS 2 SST reconstruction; 6-MIS 2 aeolian deposit (Sigleo and Colhoun, 1982); 7-MIS 2 loess deposit (McIntosh et al., 2004).

lengths (<2 SD), while unimodal models are recommended for longer gradient lengths (>4 SD) (Birks, 1998). The DCCA was performed using Canoco 4.5 for Windows (Ter Braak and Smilauer, 2002). Transfer function model development was performed using the C2 data analysis computer software program (Juggins, 2007). Models were accepted that had a good coefficient of determination between observed and inferred values (r^2), had a low root mean square error of prediction (RMSEP) and a low mean and maximum bias (*sensu* Birks, 1998). The C2 program performs bootstrapping (leave-one-out) cross-validation on the model performance and calculates an r^2_{boot} , RSMEP and mean and maximum bias under cross-validation. Additional components, PLS regressions of model residuals, were included if they increased the coefficient of determination between observed and inferred AAT estimates by 5% or more (*sensu* Birks, 1998).

3.3. Spatial autocorrelation

Moran's I statistic can be used as a measure of spatial autocorrelation in a univariate dataset (Cliff and Ord, 1973; Legendre, 1993; Davis et al., 2003) and was used to assess the degree of spatial

Table 1

Selected statistical outputs of the detrended correspondence analysis for the modern pollen database of Fletcher and Thomas (2007a) and for the Quaternary meta-dataset. The data are: the number of samples, percent variance explained by the ordination axes and the correlation coefficient between AAT and the modern pollen sample DCA axis 1 scores.

Dataset	No. of samples	Percent variation (%)	AAT v DCA axis 1 (r^2)
Modern	99	41.3	0.56
Modern and Fossil (meta-dataset)	1258	38.1	0.5

Table 2

List of sites (and source) used in the western Tasmanian Quaternary pollen meta-dataset.

Site Name	Source
Boco Valley	(Fletcher, 2009)
Crotty Road	(Colhoun and van de Geer, 1987b)
Dante Rivulet	(Colhoun and Fitzsimons, 1996)
Darwin Crater	(Colhoun and van der Geer, 1998)
Governor Bog	(Colhoun et al., 1991)
Harlequin Hill	(Fletcher and Thomas, 2007b)
Henty Bridge	(Colhoun, 1985b)
Lake Fiddler	(Harle et al., 1999)
Lake Johnston	(Anker et al., 2001)
Lake Selina	(Colhoun et al., 1999)
Lake StClair	(Hopf et al., 2000)
Langdon River	(Colhoun et al., 1989)
Marine Core	(van der Geer et al., 1994)
Melaleuca Inlet	(Thomas, 1995; Macphail et al., 1999)
Mill Bay	(Fletcher and Thomas, 2010)
Moxon's Saddle	(Fletcher, 2009)
Newall Creek	(van de Geer et al., 1989)
Newton Creek	(Colhoun et al., 1993)
Ocean Beach	(Fletcher, 2009)
Perched Lake	(Fletcher, 2009)
Poets Hill Lake	(Colhoun, 1992)
Roseberry	(Colhoun and van de Geer, 1987a)
Smelter Creek	(Colhoun et al., 1992)
Stonehaven Creek	(Fletcher, 2009)
Tullabardine Dam	(Colhoun and van der Geer, 1986)
Vale of Belvoir	(Fletcher, 2009)

autocorrelation present in the selected transfer function AAT estimates (*sensu* Davis et al., 2003). Spatial data in the form of x and y coordinates are measured against a third variable, z – here the residuals between observed and predicted AAT estimates produced by the selected transfer function model, to produce Moran's I value for groups of sites at different spatial scales (distance classes or lag intervals). A test of the statistical significance of Moran's I value for each lag interval using Monte Carlo permutations can reveal whether detected spatial patterning is 'real' (read: significant at $P < 0.05$). We have adopted the approach of Legendre and Fortin (1989) who employ Bonferroni's Correction to account for the increase in likelihood of erroneously returning a significant result (type I error) when re-sampling from the same dataset for each distance class, lowering the P value to $0.05/n$ (where n is the number of distance classes) and resulting in a global error rate of $P < 0.05$ (Legendre and Fortin, 1989). ROOKCASE, an Excel 97/2000 Visual Basic (VB) add-in for exploring global and local spatial autocorrelation (Sawada, 1999) was used to calculate Moran's I and the results are presented as a correlogram, where Moran's I is plotted on the ordinate against distances among localities (distance classes) on the abscissa (*sensu* Legendre and Fortin, 1989).

3.4. Reconstructions

The selected transfer function was applied to two Late Quaternary pollen profiles from western Tasmania (Fig. 2): Lake Selina (516 m a.s.l.; $41^{\circ}53'S$; $145^{\circ}36'E$) (Colhoun et al., 1999) and Tullabardine Dam (230 m a.s.l.; $41^{\circ}41'S$; $145^{\circ}39'E$) (Colhoun and van der Geer, 1986). Data for these profiles were digitised from the original publications and fossil pollen data were screened using the same criteria employed for the gradient analysis (Section 3.1).

4. Results

4.1. Gradient analysis

Correlations between the DCA axes scores for the modern pollen subset and AAT, number of samples included in the analysis and

percent of variance explained by the DCA axes for both the meta-ordination and ordination of the modern pollen dataset are presented in Table 1. The results of the meta-ordination reveal a remarkable preservation of the relationship between the modern surface samples and AAT after the inclusion of all available Quaternary pollen spectra, indicating that AAT has played a key role in vegetation dynamics over the entire Quaternary period in western Tasmania, as it does today. As previously noted (Section 2.1) the distribution of many Tasmanian plant species are probably governed by their tolerance to freezing temperatures (cold-season) and it is possible that the relationship between western Tasmanian pollen composition and AAT in our analysis reflects this relationship, much in the way that AAT inferred from ice-cores in Antarctica probably reflect the temperature at the time of snowfall (Jouzel et al., 1987, 1993). We have elected to discuss the results primarily in terms of AAT, making reference to seasonality where applicable.

4.2. Transfer function

The DCCA of the modern dataset constrained to AAT produced a gradient length of 3.09SD, between the thresholds suggested by Birks (1998) for linear or unimodal methods and we elected to run both methods (PLS, WA and WA-PLS) in this analysis. The modern analogue technique (MAT) was also tested to provide a comparative model in which no *a priori* assumptions of the data are made. Table 3 presents the r^2 and r^2_{boot} values of observed versus estimated AAT, RMSEP and the mean and maximum bias of each model under cross-validation, with the selected model, WA, displaying the highest r^2 (0.8) and r^2_{boot} (0.76) values and the lowest RMSEP (1 °C) and lowest mean (−0.003 °C) and maximum bias (1.3 °C). Model improvement provided by additional PLS components was insufficient for their retention.

4.3. Spatial autocorrelation

The correlogram in Fig. 3 shows the results of the Moran's I statistical test for spatial autocorrelation within the model residuals (observed–estimated WA estimates). The correlogram resembles the results of Moran's I statistic generated on a dataset consisting of 100 randomly generated numbers (Legendre and Fortin, 1989; Fig. 1i) and, after the application of Bonferroni's Correction (to restore the global P value to 0.05) to 999 Monte Carlo permutations, Moran's I statistic was not significant for any distance class. These results indicate that the residuals produced by the transfer functions are not spatially autocorrelated and, by extension, nor are the estimates produced by the model or the modern pollen data (*sensu* Legendre and Fortin, 1989).

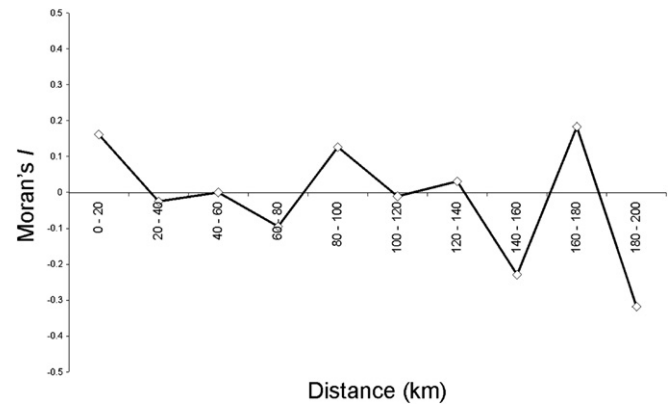


Fig. 3. Correlogram displaying the results of the Moran's I statistic for detecting spatial autocorrelation performed on the residuals between observed and predicted estimates of the weighted averaging AAT model. Moran's I is plotted on the abscissa and distance classes (lag intervals) are plotted on the ordinate. After 999 Monte-Carlo permutations and an application of Bonferroni's Correction to restore the global P value to 0.05, Moran's I was not significant in any lag-interval, indicating no significant influence of spatial patterning on the temperature estimates (*sensu* Legendre and Fortin, 1989).

4.4. Reconstructions

The reconstructed AAT curves for Lake Selina and Tullabardine Dam are presented in Fig. 4 along with regional Late Quaternary temperature reconstructions. The chronology of the records is based on calibrations of the original published radiocarbon assays (using Calib 6.0.1; Stuiver et al., 2010) and a correlation between the temperature reconstructions and the Vostok temperature reconstruction beyond the radiocarbon chronology (Jouzel et al., 1987). Chronological control of these records is poor, with few dates and the use of bulk samples incorporating substantial amounts of sediment (Colhoun and van der Geer, 1986; Colhoun et al., 1999) that result in large error ranges (often greater than ± 1 ka), precluding discussion in terms of timing of temperature changes and reducing confidence when discussing the potential lead/lag effects of these vegetation based proxies when compared to other palaeotemperature proxies. There is a clear relationship between the timing (within the range and error of independent dating of each record) and magnitude of Late Quaternary temperature change on land in western Tasmania and regional temperature reconstructions (Fig. 4). Beyond the limits of independent dating, tuning of the temperature reconstructions to the Vostok record renders discussion in terms of timing prone to circularity.

Table 3

Statistical outputs of the transfer function for AAT. Outputs of the selected model, weighted averaging (WA), are italicised.

Model Type	r^2	r^2_{boot}	RMSEP (°C)	Mean Bias _{boot} (°C)	Max. Bias _{boot} (°C)	
MAT	0.750072	0.762805	1.09374	−0.170714	1.69991	
PLS	component 1	0.744274	1.13401	−0.0326668	2.1114	
	component 2	0.843519	0.613263	−0.0558677	1.46574	
	component 3	0.862299	0.592603	0.981255	−0.0547309	1.50901
	component 4	0.874317	0.567835	1.02851	−0.0310249	1.44558
	component 5	0.88248	0.536171	1.09544	−0.0261443	1.40214
WA	<i>0.804391</i>	<i>0.76502</i>	<i>1.00473</i>	<i>−0.0358667</i>	<i>1.34249</i>	
WA-PLS	component 1	0.887436	1.00381	−0.0346073	1.40796	
	component 2	0.775004	0.792672	0.971319	−0.0513285	1.25385
	component 3	0.712018	0.776566	1.06704	−0.0515403	1.17051
	component 4	0.691397	0.765056	1.13205	−0.0434102	1.17547
	component 5	0.654166	0.748787	1.22026	−0.0360682	1.27998

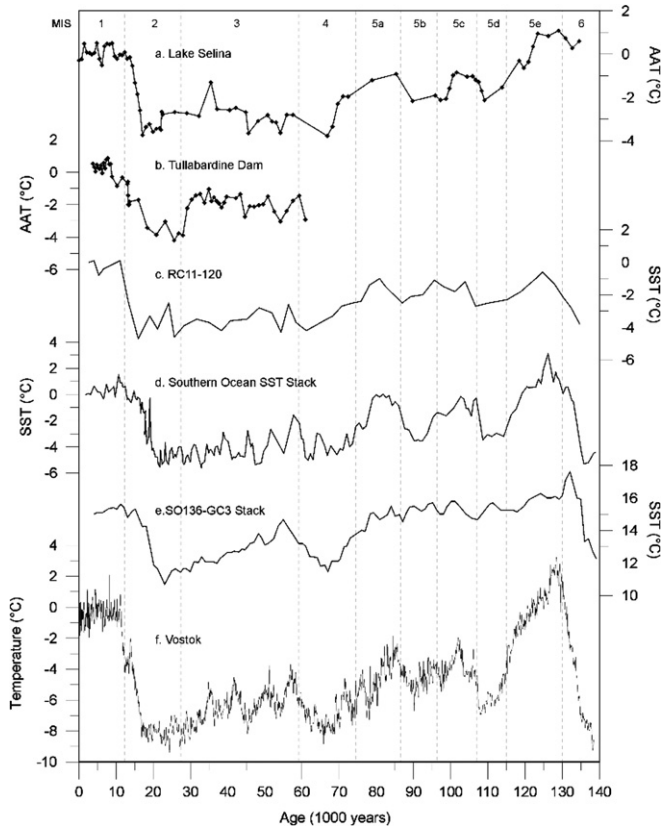


Fig. 4. Comparison of western Tasmanian Late Quaternary AAT reconstructions with regional temperature reconstructions. (a) Lake Selina AAT reconstruction (this paper). (b) Tullabardine Dam AAT reconstruction (this paper). (c) Ocean Core RC11-120 SST reconstruction (Mashiotta et al., 1999). (d) Southern Ocean SST composite record derived from ocean cores MD88-770 and MD97-2120 (Barrows et al., 2007a). (e) Composite SST reconstruction from ocean core SO136-GC3 (Barrows et al., 2007a). (f) Vostok ice core temperature reconstruction (Jouzel et al., 1987). Location of sites is indicated in Fig. 1.

5. Discussion

5.1. Western Tasmanian pollen assemblages and temperature

Belyea (2007) summarises the main assumptions that underpin the use of niche-based approaches to palaeoenvironmental reconstructions, central tenets of which are the assumptions that (i) the taxa in the modern training set are the same entities observed in the fossil data and that the response of these entities to the environmental gradient of interest has not changed over the time span represented by the fossil assemblage. Furthermore, it is usually impossible to ascertain whether the training set covers the full potential niche-space of all biological entities of interest or whether, for example, historical factors such as vicariance and/or significant environmental shifts have resulted in the sampled populations occupying a fraction of their potential niche space. Nor is it easy to verify whether the environmental gradient of interest is the sole governing factor of change over the time-span analysed. Caution, then, should be employed when interpreting any niche-based palaeoenvironmental reconstructions.

Despite these caveats, niche-based reconstructions provide a unique opportunity for producing quantitative reconstructions from diverse and complex multivariate biological data, enabling quantitative comparisons between disparate palaeoenvironmental proxies. While not eliminating the tenuous assumptions mentioned above, the preservation of the strong relationship between the modern surface sample axis scores and AAT after the inclusion of all

available Quaternary fossil pollen spectra in our gradient analysis (Table 1) indicates that temperature has been a significant factor in determining fossil pollen assemblages in western Tasmania through the Quaternary, and, by extension, vegetation dynamics in this region through this time. This partially addresses concerns over the validity of using the relationship between modern pollen assemblages and temperature for reconstructing Quaternary palaeotemperatures in this region. Furthermore, the results of the Moran's *I* statistic on the model residuals (Fig. 3) indicates that the temperature estimates are not significantly affected by spatial patterning in the modern pollen assemblages, a problem known to result in significant biases in palaeoenvironmental reconstructions (Telford and Birks, 2005, 2009).

5.2. Late Quaternary climates

There is a clear relationship between the Late Quaternary temperature reconstructions from Lake Selina and Tullabardine Dam and regional temperature proxies (Fig. 4), and it is clear that, at the coarse temporal scale represented in this analysis, the western Tasmanian climate system has responded in tandem with the regional climate system. Following is a discussion of AAT estimates of key periods during the Late Quaternary, their implication for western Tasmanian climate and, where applicable, regional climates through this time.

5.2.1. MIS 1 (the Holocene)

The timing of the western Tasmanian MIS 1 altithermal between 7.2 and 8.3 ka (0.4–0.84 °C above modern) is, despite the poor chronological control of these records, in remarkable agreement with a recent global synthesis that places the Southern Hemisphere altithermal at 7.4 ± 3.7 ka (Shakun and Carlson, 2010). Near modern AAT was achieved after 12 ka in both of the records analysed here, substantially later than indicated by a recent niche-based reconstruction from central-south Tasmania using chironomids that reports the establishment of near modern warm-season temperatures by 15 ka (Rees and Cwynar, 2009). The chironomid inferences of an early warm-season temperature rise are supported by regional SST reconstructions that indicate an early postglacial warming to levels close to, yet lower than, modern SST by ca 15 ka (e.g. Barrows et al., 2007a). The ca 3 ka offset between pollen and chironomid reconstructions may reflect (i) the response of each proxy to differential components of the temperature climate, with chironomids responsive to temperature maxima (Rees et al., 2008) and vegetation responding to temperature minima (Read and Hill, 1989), implying an increase in thermal seasonality between 15 and 12 ka; (ii) a lag in the response time of vegetation development to temperature change when compared to chironomids; (iii) an insufficient understanding of the modern-species environment relationships for either or both proxies; (iv) insufficient chronological control of the pollen records; or (v) a combination of these factors.

Denton et al. (2005) highlight the importance of seasonality in the northern hemisphere during periods of abrupt climate transitions and it is possible that the transition from the LGM to the Holocene in the present study region was characterised by increased seasonality. Contrary to this, equator to 30/60°S intra-seasonal summer and winter solar insolation gradients were less pronounced between 15 and 13 ka than between 12 and 10 ka (Dodson, 1998) and the extent and duration of Antarctic sea-ice in the Indian Ocean sector was at near modern levels by 15 ka (Crosta et al., 2004), both possible drivers of increased seasonality via the direct influence of solar radiation on the temperature climate and the northward expansion of polar air masses resulting from increased extent and duration of sea-ice, respectively. Furthermore,

Vandergoes et al. (2008) present no evidence of early postglacial warming in their warm-season chironomid reconstruction from a site in New Zealand located at a similar altitude and latitude to the study of Rees and Cwynar (2009), reporting instead warm-season temperatures up to ca 2 °C below present prior to ca 14 ka and the establishment of an essentially modern warm-season temperature regime after 13 ka, with oscillations between 14 and 13 ka attributed to the Antarctic Cold Reversal (ACR) in that study. Alternatively, Shulmeister et al. (2004) argue that intra-seasonal winter insolation values may be less appropriate for the climate of the mid latitudes of the Southern Hemisphere than inter-seasonal insolation changes (which are anti-phased with intra-seasonal variations), highlighting the period centred on 21 ka (10 ka) as a period of maximum (minimum) inter-seasonal insolation contrast that may account for the greater seasonality between 15 and 13 ka inferred from the difference between our pollen-based estimates and the chironomid-based estimates of Rees and Cwynar (2009). Clearly a more comprehensive understanding of the relationship between biological proxies and their environment is needed to resolve this issue, as are precisely dated, continuous, high-resolution, multi-proxy analyses aimed at reconstructing the various components of climate (namely precipitation and seasonal temperature).

While the poor chronological control and sample resolution of the records analysed here preclude a significant contribution in to debates over the presence/absence and timing of postglacial and Holocene climatic excursions such as the Little Ice Age, Medieval Climate Anomaly, ACR and the Younger Dryas (e.g. Stine, 1994; Bennett et al., 2000; Moreno et al., 2001; Hajdas et al., 2003; Goosse et al., 2004; Barrows et al., 2007b), the Tullabardine Dam record displays a postglacial cold reversal consistent with the timing of the ACR, while there is no identifiable trends consistent with the Younger Dryas or Holocene temperature change. It is clear that western Tasmanian pollen records have significant potential to contribute to our understanding of the nature of postglacial and Holocene (MIS 1) climate change in the Southern Hemisphere and there is an urgent need for precisely-dated high-resolution analysis of pollen profiles from this region to help address these critical issues.

5.2.2. MIS 2

MIS 2 AAT minima occur at 17 ka (−3.7 °C), 18 ka (−3.6 °C) and 22 ka (−3.5 °C) at Lake Selina, and there is a remarkable similarity between the timing of MIS 2 AAT change at Lake Selina and ocean core RC11-120 SST (located at 43°S in the Indian Ocean) (Figs. 1 and 3). Conversely, the Tullabardine Dam record, with AAT minima at 20.7 ka (−3.8 °C), 25 ka (−4.2 °C) and 28 ka (−3.8 °C), bears marked similarity to the Vostok MIS 2 section. Once again, chronological control of these records is poor, precluding discussion over the timing of temperature changes and more adequate dating of Tasmanian pollen records is required. The 3.7–4.2 °C cooling through MIS 2 is remarkably consistent with a niche-based temperature reconstruction of LGM cooling from the Awatere Valley in New Zealand (41°S) (Marra et al., 2004) and with the magnitude of SST change estimated for this region (Barrows and Juggins, 2005; Barrows et al., 2007a), implying a constant maritime influence on terrestrial temperatures in the Australasian sector of the mid southern latitudes through MIS 2 that, if robust, is insufficient to account for the extent of MIS 2 glaciation in the region (Colhoun, 2004; Mackintosh et al., 2006; McCarthy et al., 2008).

Glacier mass balance in the Southern Alps of New Zealand is strongly influenced by temperature (Anderson and Mackintosh, 2006) and SWW derived precipitation (Fitzharris et al., 1992), with increased (decreased) precipitation delivered by stronger (weaker) SWW flow resulting in glacial advance (retreat) (Fitzharris et al., 1992). A northward displacement of the SWW over

southern South America during MIS 2 resulted in higher precipitation on the mid-latitude western face of the Andes (Moreno et al., 1999) and, given the fact that recent changes in the intensity and position of the SWW display marked zonal symmetry (Gillett et al., 2006), it is possible that the SWW were north of their current position over the Tasmanian Sector during MIS 2 and that western Tasmania was in receipt of higher precipitation than present. This view is supported by (i) the zonal symmetry in SWW changes observed over the recent past (Gillett et al., 2006) and inferred through the Last Glacial Transition (Anderson et al., 2009); (ii) increased speleothem growth (wetter conditions) between 20 and 35 ka (MIS 2) at Naracoorte, southeast Australia, a location in receipt of SWW derived precipitation today (Ayliffe et al., 1998); and (iii) maximum inter-seasonal insolation gradients in the Southern Hemisphere centred on 21 ka, possibly driving increased SWW flow (Shulmeister et al., 2004). An asymmetric response of the SWW to MIS 2 cooling is predicted by some climate simulations, with a more northerly position of the SWW in the southern South American sector than the Australian sector of the mid southern latitudes (Rojas et al., 2009) and it is possible that an expanded subtropical high pressure system over the Australian continent, in combination with a greater extent and longer duration of Antarctic sea-ice in the Indian Ocean sector of the Antarctic region (Crosta et al., 2004), intensified and further strengthened SWW in the mid latitudes of the Australian sector, resulting in an increase in SWW flow and rainfall on the west coast of Tasmania and the southern tip of southeast Australia.

If western Tasmania was windier and wetter during MIS 2, evidence for dry conditions in the east of Tasmania (Fig. 2) (Sigleo and Colhoun, 1982; Bowden, 1983; McIntosh et al., 2009) requires explanation. A wetter west and drier east under increased SWW flow is entirely consistent with the present day anti-phasing of east and west Tasmanian precipitation anomalies in response to SWW in SAM: increased orographic rain on the west and stronger/drier foehn winds stripping the east of moisture (Hendon et al., 2007). Reduced vegetation cover and a substantially drier east during MIS 2 is supported by pollen and geomorphologic studies that indicate sparse vegetation and aeolian mobilisation of sediments (Macphail, 1975; Sigleo and Colhoun, 1982; Bowden, 1983; Thomas, 1993). The substantial reduction in atmospheric carbon dioxide (CO₂) during MIS 2 would have placed further physiological stress on plants in the drier east through the need for increased transpiration to meet photosynthetic requirements under reduced CO₂ levels, effectively halving the already much reduced available moisture (Farquhar, 1997), destabilising vegetation cover further and permitting increased sediment mobilisation under the increased SWW flow regime. Moreover, burning by Aboriginal people after through MIS 2 significantly altered Tasmanian vegetation patterns (Fletcher and Thomas, in press) and would have further destabilised the vegetated landscape in the east, a mechanism that has been invoked to account for substantial loess deposition in the southeast of Tasmania during MIS 2 (Fig. 2) (McIntosh et al., 2004, 2009).

An alternative explanation may lie in a methodological bias of the transfer function technique and an incomplete representation and, therefore, sampling of the Quaternary temperature gradient of western Tasmania, precluding accurate estimates of full-glacial temperatures. Compounding this is the central tendency of estimates derived from unimodal transfer functions (i.e. they perform well in the centre and poorly at the ends or outside of the sampled environmental gradient) (Telford and Birks, 2005). The temperature range of the modern pollen dataset is 6 °C (12.4–5.4 °C), with Lake Selina (9.2 °C) and Tullabardine Dam (11.1 °C) occupying positions within this range, and it is possible that the model is unable to sufficiently predict outside of the sampled range to produce accurate full glacial AAT estimates. A further consideration

is the lack of analogues for the full glacial landscape. Modern pollen spectra from present day cold climate assemblages in western Tasmania, which are concentrated in limited geographic areas (mountain tops), may not adequately reflect the full glacial environment in which cold climate assemblages occupied lower altitudes and consequently greater areas of land. Moreover, the presence of glaciers may have influenced glacial stage vegetation through, for example, disturbance from glacial outwash, absent in today's environment and potentially exacerbating the problem of non-analogue systems.

5.2.3. MIS 3

Regional temperature change during MIS 3 was variable (Barrows et al., 2007a; Woodward and Shulmeister, 2007) and this is reflected in our results (Fig. 4). The maximum temperature range during MIS 3 recorded here (0.91–1.4 °C below present) is consistent with the SST reconstruction from drill core SO136-GC3 (42°S) off the west coast of South Island New Zealand (Figs. 1 and 3) and with a chironomid-based temperature reconstruction from New Zealand (Woodward and Shulmeister, 2007). The minimum MIS 3 temperature of 3.9 °C below present at Lake Selina is significantly lower than that recorded in SO136-GC3, but is consistent with evidence for MIS 3 (41–44 ka) glaciers more extensive than during MIS 2 (Mackintosh et al., 2006). Mackintosh et al. (2006), suggest temperatures as low as 8 °C below modern to account for the MIS 3 glacial advances, yet, as previously discussed, changes in precipitation are an important component of temperate glacier mass balance in the region. Wet conditions are inferred at Naracoorte between 40 and 50 ka (Ayliffe et al., 1998) and the duration of Antarctic sea-ice in the Indian Ocean sector during MIS 3 was similar to the MIS 2 glacial phase (Crosta et al., 2004), displacing the SWW northward and possibly resulting in seasonally cold and wet conditions conducive to glacier development.

5.2.4. MIS 4

A 4 °C depression of AAT during MIS 4 at Lake Selina indicates that this glacial stage was possibly as cold as MIS 2 and is broadly consistent with regional temperature reconstructions (Fig. 4) (Barrows et al., 2007a; Burge and Shulmeister, 2007). Burge and Shulmeister (2007) estimate summer and winter temperatures between 3 °C and 5 °C below present, respectively, during what they infer as a MIS 4 fossil beetle fauna located within flood plain sediments on the west coast of South Island New Zealand (41°S), while estimates of MIS 4 average annual SST from drill core SO136-GC3 range from as cold to 1 °C warmer than MIS 2 (ca 2–4 °C below present) depending on the proxy employed (Barrows et al., 2007a). The similarity between SST and terrestrial estimates in the mid latitude of the Australasian sector of the Southern Hemisphere during this glacial phase is important, as it implies that the close coupling of ocean and land temperature in this region today persisted through the large climate shifts associated with the last two glacial phases. The apparent absence of glacial landforms associated with MIS 4 in Tasmania may be an artefact of the poor chronological control of glacial landforms in this region (Colhoun, 2004) or it may reflect lower precipitation during this stage. Burge and Shulmeister (2007) suggest a reduction in mean annual precipitation at their site of between 30 and 40% from modern values during MIS 4 and the lack of speleothem deposition between 50 and 70 ka (MIS 4) at Naracoorte corroborates this notion (Ayliffe et al., 1998). Thus, it is possible that evidence for MIS 4 glacial advances in western Tasmania have been overridden by subsequent glacial advances. Evidence for MIS 4 glaciation more extensive than MIS 2 in South Island New Zealand (McCarthy et al., 2008), though, suggests a complicated climatic – glacial history in the Australasian sector of the Southern Hemisphere mid latitudes and there is

a need for independent reconstructions of temperature and precipitation from these regions.

5.2.5. MIS 5

MIS 5 encompasses a sequence of cool and warm sub-stages that includes the Last Interglacial (MIS 5e) and series of interstadial (MIS 5a, c) and stadial (MIS 5b, d) periods that are recorded globally (e.g. Jouzel et al., 1987; Winograd et al., 1997) and that are well represented in the Lake Selina temperature curve (Fig. 4). Our results of MIS 5a temperatures lower than present conflict with the beetle-based reconstruction of Burge and Shulmeister (2007), who report near modern temperatures from fossil beetle flora contained within flood-plain sediments near sea-level on the west coast of South Island New Zealand (41°S) assumed to be MIS 5a in age. By virtue of its location virtually at sea-level and within a closed *Nothofagus* forest (Burge and Shulmeister, 2007), the fossil beetle composition may reflect a combination of microclimate effects and the relative buffering of the site from extreme temperature fluctuations by the pronounced oceanic influence when compared to Lake Selina, located at mid altitude and further from the coast. The magnitude of the transition from MIS 5b (ca 2 °C below present) to MIS 5a (ca 1 °C below present) is smaller than that reconstructed from an AAT speleothem reconstruction from central north Tasmania, which depicts a transition from MIS 5b to MIS 5a of ca 4–6 °C to –1.5 °C below present (Goede et al., 1986). This difference may reflect the location of the speleothem to the east of the central ranges (Fig. 2), implying a reduced maritime effect and greater temperature fluctuations.

Whilst there is general agreement that MIS 5e was wetter than today in the Australian region (Harle et al., 2004; Hesse et al., 2004), temperature estimates for this period range from warmer to as warm and cooler than today (Colhoun, 2000; Harle et al., 2004; Kershaw et al., 2007; Porch et al., 2009). The 1 °C warming during MIS 5e relative to modern AAT predicted by our analysis is consistent with pollen based estimates derived from southeast Australian pollen records (Kershaw et al., 2007), the establishment of lowland rainforest at Lake Selina (Colhoun et al., 1999; Fletcher and Thomas, in press), SST estimates in the surrounding oceans (Barrows et al., 2007b) and Antarctic temperature reconstructions (Jouzel et al., 1987; EPICA, 2004). Conflicting with our results are qualitative temperature estimates derived from Lake Selina that suggest an environment 0.6 °C cooler than today and a niche-based beetle and pollen reconstruction of an organic lens thought to represent MIS 5e from King Island (Fig. 2) that suggests higher precipitation, lower (–1.9–1.4 °C) AAT and greater thermal seasonality than today (Porch et al., 2009).

It is interesting to note that Porch et al. (2009) elect to classify their deposit as MIS 5e on the grounds of a number of criteria that includes the development of *Phyllocladus asplenifolius* rich cool temperate rainforest at their site. *P. asplenifolius* values are highest in western Tasmania during the Lateglacial period and the transition from the Last Interglacial (MIS 5e) to the cool stadial stage (MIS 5d) (Colhoun, 1996; Colhoun et al., 1999), indicating maximum expansion of this species under conditions cooler than full interglacial climates, a trend that is consistent with the modern distribution of this species in southeast Australian rainforest assemblages (Read and Busby, 1990). Thus, it is possible that the cooler temperature estimates for the King Island MIS 5 deposit reflect the development of vegetation after MIS 5e peak warming and maximum sea-level rise, a notion also supported by the location (below the height of maximum MIS 5e sea-level rise) and stratigraphy of that site (Porch et al., 2009). The magnitude of the difference between our MIS 5e estimate and that of Porch et al. (2009) is large (2.9°C) and it is also possible

that either (or both) reconstruction is subject to the effects of methodological biases and/or insufficient sampling of the modern environment as discussed in Section 5.1 and by Porch et al. (2009).

Furthermore, Porch et al. (2009) prudently point out that pollen based estimates of palaeoenvironmental parameters may have been influenced by the extensive modification of the vegetation landscape by humans since their arrival during MIS 3. We have recently argued that much of the modern landscape of western Tasmania represents an ancient cultural landscape dating to the Lateglacial period (Fletcher and Thomas, in press) and it is almost certain that humans have altered the configuration of vegetation and the landscape of Tasmania as a whole (McIntosh et al., 2009; Fletcher and Thomas, in press). While this should be a consideration when interpreting the results of the present analysis, the wide range of samples from both 'anthropogenic' and 'natural' vegetation types in the modern training set (Fletcher and Thomas, 2007a) and the excellent correlation between observed and predicted AAT in our model under cross-validation implies that the model is somewhat robust with respect to these effects.

6. Conclusions and future directions

This analysis has revealed temperature as a significant driver of Late Quaternary change in western Tasmanian pollen spectra and, by extension, vegetation, validating the use of modern pollen–climate relationships for reconstructing Late Quaternary temperature change in the region. Late Quaternary temperature change in western Tasmania appears to have been closely linked to changes in sea-surface temperature in the surrounding oceans and it is likely that the region has experienced a maritime climate throughout the entire Late Quaternary. We have identified a number of potential divergences between temperature and precipitation that require further investigation using multi-proxy approaches aimed at reconstructing different components of the climate system. Approaches employed in the northern hemisphere, such as isotopic reconstructions of palaeohydrology (Wolfe et al., 2007) and multi-site temperature reconstructions (Bjune et al., 2009; Seppä et al., 2009), are proving useful for reconstructing different components of the climate system that potentially permit the disentanglement of temperature and precipitation signals and allow a more comprehensive climatic reconstruction.

While subject to a number of caveats inherent in niche-based palaeoenvironmental reconstructions, this study provides the first continuous terrestrial Late Quaternary temperature reconstruction spanning the Last Interglacial to present from the mid to high latitudes of the Southern Hemisphere and presents a significant advancement of palaeoclimatic reconstructions for this region. Western Tasmania has great potential as a Southern Hemisphere palaeothermometer and is critically located to address a number of long-standing debates over the magnitude and timing of regional and global climatic excursions, such as the Antarctic Cold Reversal, Younger Dryas, Little Ice Age and the Medieval Climate Anomaly, and high-resolution, multi-proxy and precisely-dated analyses are an *a priori* for future research in this region.

Acknowledgements

We would like to acknowledge and thank Mike MacPhail, Eric Colhoun and Guus van der Geer, whose pioneering palaeoenvironmental research forms the backbone of this analysis and who set the firm foundations for Quaternary research in Tasmania. MSF was in receipt of an Australian Postgraduate Award at the University of Melbourne during the course of the research. We would like to thank the Mazda Foundation, AINSE, AIATSI and the

Institute of Ecology of Biodiversity, Chile, for fiscal and logistical support. We also thank two anonymous referees for their comments on an earlier draft and Patricio Moreno for enlightening conversations on Southern Hemisphere Quaternary environmental change.

References

- Anderson, R.F., Ali, S., Bratmillier, L.I., Nielsen, S.H.H., Fleisher, M.Q., Anderson, B.E., Burkle, L.H., 2009. Wind-driven upwelling in the southern ocean and the deglacial rise in atmospheric CO₂. *Science* 323, 1443–1448.
- Anderson, B., Mackintosh, A., 2006. Temperature change is the major driver of late-glacial and Holocene glacier fluctuations in New Zealand. *Geology* 34, 121.
- Anker, S.A., Colhoun, E.A., Barton, C.E., Peterson, M.J., Barbetti, M., 2001. Holocene vegetation and paleoclimatic and paleomagnetic history from Lake Johnston, Tasmania. *Quaternary Research* 55, 264–274.
- Ayliffe, L.K., Marinelli, P.C., Moriarty, K.C., Wells, R.T., McCulloch, M.T., Mortimer, G. E., Hellstrom, J.C., 1998. 500 ka precipitation record from southeastern Australia: evidence for interglacial aridity. *Geology* 26, 147–150.
- Barrows, T., Juggins, S., De Deckker, P., Calvo, E., Pelegero, C., 2007a. Long-term surface temperature and climate change in the Australian–New Zealand region. *Paleogeography* 22, 1–17.
- Barrows, T.T., Lehman, S.J., Fifield, L.K., De Deckker, P., 2007b. Absence of cooling in New Zealand and the adjacent ocean during the Younger Dryas chronozone. *Science* 318, 86.
- Barrows, T., Juggins, S., 2005. Sea-surface temperatures around the Australian margin and Indian Ocean during the last glacial maximum. *Quaternary Science Reviews* 24, 1017–1047.
- Belyea, L.R., 2007. Revealing the Emperor's new clothes: niche-based palaeoenvironmental reconstructing in the light of recent ecological theory. *The Holocene* 15, 683–688.
- Bennett, K.D., Haberle, S., Lumley, S.H., 2000. The last glacial–Holocene transition in Southern Chile. *Science* 290, 325–328.
- Berger, A.L., 1978. Long-term variations of daily insolation and Quaternary climatic changes. *Journal of the Atmospheric Sciences* 35, 2362–2367.
- Birks, H.J.B., 1998. Numerical tools in paleolimnology progress, potentialities, and problems. *Journal of Paleolimnology* 20, 307–332.
- Bjune, A.E., Seppä, H., Birks, H.J.B., 2009. Quantitative summer-temperature reconstructions for the last 2000 years based on pollen-stratigraphical data from northern Fennoscandia. *Journal of Paleolimnology* 41, 43–56.
- Bowden, A., 1983. Relict terrestrial dunes: legacies of a former climate in coastal north eastern Tasmania. *Zeitschrift Fur Geomorphologie* 45, 153–174.
- Burge, P.I., Shulmeister, J., 2007. An MIS 5a to MIS 4 (or early MIS 3) environmental and climatic reconstruction from the northwest South Island, New Zealand, using beetle fossils. *Journal of Quaternary Science* 22, 501–516.
- Cliff, A.D., Ord, J.K., 1973. *Spatial Autocorrelation*. Pion, London.
- Colhoun, E.A., 1985a. Glaciations of the west coast range, Tasmania. *Quaternary Research* 24, 39–59.
- Colhoun, E.A., 1985b. Pre-last glaciation maximum vegetation history at Henty Bridge, western Tasmania. *New Phytologist* 100, 681–690.
- Colhoun, E.A., 1992. Lateglacial and Holocene vegetation history at Poets Hill Lake, western Tasmania. *Australian Geographer* 23, 11–23.
- Colhoun, E.A., 1996. Application of Iversen's glacial–interglacial cycle to interpretation of the last glacial and Holocene vegetation of western Tasmania. *Quaternary Science Reviews* 15, 557–580.
- Colhoun, E.A., 2000. Vegetation and climate during the last interglacial–glacial cycle in western Tasmania, Australia. *Paleogeography, Palaeoclimatology, Palaeoecology* 155, 195–209.
- Colhoun, E.A., 2004. Quaternary glaciations of Tasmania and their ages. In: Ehlers, J., Gibbard, P.L. (Eds.), *Quaternary Glaciations: Extent and Chronology, Part III*. Elsevier, Rotterdam, pp. 353–360.
- Colhoun, E.A., van der Geer, G., Hill, R.S., Bird, T., 1989. Interglacial pollen and plant macrofossils from Langdon River, western Tasmania. *New Phytologist* 111, 531–543.
- Colhoun, E.A., van der Geer, G., Fitzsimons, S.J., 1991. Lateglacial and Holocene vegetation history at Governor Bog, king valley western Tasmania. *Journal of Quaternary Science* 6, 55–66.
- Colhoun, E.A., van de Geer, G., Fitzsimons, S.J., 1992. Late Quaternary organic deposits at Smelter Creek and vegetation history of the middle king valley, western Tasmania. *Journal of Biogeography* 19, 217–227.
- Colhoun, E.A., Bengert, S.N., Fitzsimons, S.J., van de Geer, G., Hill, R.S., 1993. Quaternary organic deposit from Newton Creek valley, western Tasmania. *Australian Geographical Studies* 31, 26–38.
- Colhoun, E.A., Pola, J.S., Barton, C.E., Heijnis, H., 1999. Late Pleistocene vegetation and climate history of Lake Selina, western Tasmania. *Quaternary International* 57–58, 5–23.
- Colhoun, E.A., Fitzsimons, S.J., 1996. Additional radiocarbon date from Dante outwash fan, King Valley, and dating of the late Wisconsin glacial maximum in western Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 130, 81–84.
- Colhoun, E.A., van der Geer, G., 1986. Holocene to middle last glaciation vegetation history at Tullabardine Dam, western Tasmania. *Proceedings of the Royal Society of London. Series B, Biological Sciences* 229, 177–207.

- Colhoun, E.A., van de Geer, G., 1987a. Pleistocene macro- and micro-plant fossils from Roseberry, western Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 121, 89–92.
- Colhoun, E.A., van de Geer, G., 1987b. Vegetation history and climate before the maximum of the last glaciation at Crotty, western Tasmania. *Papers and Proceedings of the Royal Society of Tasmania* 121, 69–74.
- Colhoun, E.A., van der Geer, G., 1998. Pollen analysis of 0–20 m at Darwin Crater, western Tasmania, Australia. *International Project of Paleolimnology and Late Cenozoic Climate* 11, 68–89.
- Cook, E.R., Buckley, B.M., D'Arrigo, R.D., Peterson, M.J., 2000. Warm-season temperatures since 1600 BC reconstructed from Tasmanian tree rings and their relationship to large-scale sea surface temperature anomalies. *Climate Dynamics* 16, 79–91.
- Crosta, X., Sturm, A., Armand, L., Pichon, J.J., 2004. Late Quaternary sea ice history in the Indian sector of the Southern Ocean as recorded by diatom assemblages. *Marine Micropaleontology* 50, 209–223.
- Davis, B.A.S., Brewer, S., Stevenson, A.C., Guiot, J., 2003. The temperature of Europe during the Holocene reconstructed from pollen data. *Quaternary Science Reviews* 22, 1701–1716.
- Denton, G.H., Alley, R.B., Comer, G.C., et al., 2005. The role of seasonality in abrupt climate change. *Quaternary Science Reviews* 24, 1159–1182.
- Dodson, J.R., 1998. Timing and response of vegetation change to Milankovitch forcing in temperate Australia and New Zealand. *Global and Planetary Change* 18, 161–174.
- EPICA, 2004. Eight glacial cycles from an Antarctic ice core. *Nature* 429, 628.
- Farquhar, G.D., 1997. Climate change: carbon dioxide and vegetation. *Science* 278, 1411.
- Fitzharris, B.B., Hay, J.E., Jones, P.D., 1992. Behaviour of New Zealand glaciers and atmospheric circulation changes over the past 130 years. *The Holocene* 2, 97.
- Fletcher, M.-S., 2009. *The Late Quaternary Palaeoecology of Western Tasmania*, Geography, University of Melbourne, Melbourne.
- Fletcher, M.-S., Thomas, I., 2007a. Modern pollen–vegetation relationships in western Tasmania, Australia. *Review of Palaeobotany and Palynology* 146, 146–168.
- Fletcher, M.-S., Thomas, I., 2007b. Holocene vegetation and climate change from near Lake Pedder, south-west Tasmania, Australia. *Journal of Biogeography* 34, 665–677.
- Fletcher, M.-S., Thomas, I., 2010. A Holocene record of sea level, vegetation, people and fire from western Tasmania, Australia. *The Holocene* 20, 351–361.
- Fletcher, M.-S., Thomas, I. The origin and temporal development of an ancient cultural landscape. *Journal of Biogeography*, in press, doi:10.1111/j.1365-2699.2010.02363.x.
- Garreaud, R.D., Vuille, M., Compagnucci, R., Marengo, J., 2009. Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology* 281, 180–195.
- van de Geer, G., Fitzsimons, S.J., Colhoun, E.A., 1989. Holocene to middle last glaciation vegetation history at Newall Creek, western Tasmania. *New Phytologist* 111, 549–558.
- van der Geer, G., Heusser, C.J., Lynch-Stieglitz, J., Charles, C.D., 1994. Palaeoenvironments of Tasmania inferred from a 5–75 Ka. marine pollen record. *Palynology* 18, 33–40.
- Gentili, J., 1972. *Australian Climate Patterns*. The Griffin Press, Adelaide.
- Gillett, N.P., Kell, T.D., Jones, P.D., 2006. Regional climate impacts of the southern annular mode. *Geophysical Research Letters* 33, L23704.
- Goede, A., Green, D.C., Harmon, R.S., 1986. Late Pleistocene palaeotemperature record from a Tasmanian speleothem. *Australian Journal of Earth Sciences* 33, 333–342.
- Goosse, H., Masson-Delmotte, V., Renssen, H., Delmotte, M., Fichetef, T., Morgan, V., Van Ommen, T., Khim, B.K., Stenni, B., 2004. A late medieval warm period in the Southern Ocean as a delayed response to external forcing? *Geophysical Research Letters* 31, L06203.
- Hajdas, I., Bonani, G., Moreno, P.I., Ariztegui, D., 2003. Precise radiocarbon dating of late-glacial cooling in mid-latitude South America. *Quaternary Research* 59, 70–78.
- Harle, K.J., Hodgson, D.A., Tyler, P., 1999. Palynological evidence for Holocene palaeoenvironments from the lower Gordon River valley, in the world heritage area of southwest Tasmania. *The Holocene* 9, 149–162.
- Harle, K.J., Kershaw, A.P., Clayton, E., 2004. Patterns of vegetation change in southwest Victoria (Australia) over the last two glacial–interglacial cycles: evidence from Lake Wangoom. *Proceedings of the Royal Society of Victoria* 116, 107–139.
- Hendon, H.H., Thompson, D.W.J., Wheeler, M.C., 2007. Australian rainfall and surface temperature variations associated with the Southern Hemisphere annular mode. *Journal of Climate* 20, 2452–2467.
- Hesse, P.P., Magee, J.W., van der Kaars, S., 2004. Late Quaternary climates of the Australian arid zone: a review. *Quaternary International* 118, 87–102.
- Hill, R.S., 2004. Origins of the southeastern Australian vegetation. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* 359, 1537–1549.
- Hopf, F.V.L., Colhoun, E.A., Barton, C.E., 2000. Late-glacial and Holocene record of vegetation and climate from Cynthia bay, Lake StClair, Tasmania. *Journal of Quaternary Science* 15, 725–732.
- Jouzel, J., Lorius, C., Petit, J.P., Genthon, C., Barkov, N.I., Kotlyakov, V.M., Petrov, V.M., 1987. Vostok ice core: a continuous isotope temperature record over the last climatic cycle (160,000 years). *Nature* 329, 403–408.
- Jouzel, J., Barkov, N.I., Barnola, J.M., Bender, M., Chappellaz, J., Genthon, C., Kotlyakov, V.M., Lipenkov, V., Lorius, C., Petit, J.P., 1993. Extending the Vostok ice-core record of palaeoclimate to the penultimate glacial period. *Nature* 364, 407–412.
- Juggins, S., 2007. *C2 Data Analysis, 1.5.0 (Build 1)*. University of Newcastle, Newcastle.
- Kershaw, A.P., McKenzie, G.M., Porch, N., Roberts, R.G., Brown, J., Hejnis, H., Orr, M. L., Jacobsen, G., Newall, P.R., 2007. A high-resolution record of vegetation and climate through the last glacial cycle from Caledonia Fen, southeastern highlands of Australia. *Journal of Quaternary Science* 22, 481–500.
- Kirkpatrick, J.A., Brown, M.J., 1987. The nature of the transition from sedgeland to alpine vegetation in southwest Tasmania. I. Altitudinal vegetation change on four mountains. *Journal of Biogeography* 14, 539–549.
- Lambeck, K., Chappell, J., 2001. Sea level change through the last glacial cycle. *Science* 292, 679.
- Legendre, P., 1993. Spatial autocorrelation: trouble or new paradigm. *Ecology* 74, 1659–1673.
- Legendre, P., Fortin, M.-J., 1989. Spatial pattern and ecological analysis. *Vegetatio* 80, 107–138.
- Mackintosh, A.N., Barrows, T., Colhoun, E.A., Fifield, L.K., 2006. Exposure dating and glacial reconstruction at Mt. Field, Tasmania, Australia, identifies MIS 3 and MIS 2 glacial advances and climatic variability. *Journal of Quaternary Science* 21, 363–376.
- Macphail, M.K., 1975. Late pleistocene environments in Tasmania. *Search* 6, 295–300.
- Macphail, M.K., Pemberton, M., Jacobson, G., 1999. Peat mounds of southwest Tasmania: possible origins. *Australian Journal of Earth Sciences* 46, 667–677.
- Marra, M.J., Smith, E.G.C., Shulmeister, J., Leschen, R., 2004. Late Quaternary climate change in the Awatere Valley, South Island, New Zealand using a sine model with a maximum likelihood envelope on fossil beetle data. *Quaternary Science Reviews* 23, 1637–1650.
- Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C.J., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high resolution 0–300,000-year chronostratigraphy. *Quaternary Research*, 1–29.
- Mashiotta, T.A., Lea, D.W., Spero, H.J., 1999. Glacial–interglacial changes in subantarctic sea surface temperature and 18o-water using foraminiferal Mg. *Earth and Planetary Science Letters* 170, 417–432.
- Massaferro, J.I., Moreno, P.I., Denton, G.H., Vandergoes, M., Dieffenbacher-Krall, A., 2009. Chironomid and pollen evidence for climate fluctuations during the Last Glacial Termination in NW Patagonia. *Quaternary Science Reviews* 28, 517–525.
- McCarthy, A., Mackintosh, A., Rieser, U., Fink, D., 2008. Mountain glacier chronology from Boulder Lake, New Zealand, indicates MIS 4 and MIS 2 ice advances of similar extent. *Arctic, Antarctic, and Alpine Research* 40, 695–708.
- McGlone, M.S., Moar, N.T., 1997. Pollen–vegetation relationships on the subantarctic Auckland islands, New Zealand. *Review of Palaeobotany and Palynology* 96, 317–338.
- McIntosh, P.D., Kiernan, K., Price, D.M., 2004. An aeolian sediment pulse at c. 28 kyr BP in southern Tasmania. *Journal of the Royal Society of New Zealand* 34, 369–379.
- McIntosh, P.D., Price, D.M., Eberhard, R., Slee, A.J., 2009. Late Quaternary erosion events in lowland and mid-altitude Tasmania in relation to climate change and first human arrival. *Quaternary Science Reviews* 28, 850–872.
- Milankovitch, M., 1941. *Canon of Insolation and the Ice-Age Problem*. IPST Press, Jerusalem.
- Moreno, P.I., Lowell, T.V., Jacobson, G.L., Denton, G.H., 1999. Abrupt vegetation and climate changes during the last glacial maximum and last termination in the Chilean Lake District: a case study from Canal de la Puntilla (41 degrees S). *Geogr. Ann. Ser. A-Phys. Geogr* 81A, 285–311.
- Moreno, P.I., Jacobson, G.L., Lowell, T.V., Denton, G.H., 2001. Interhemispheric climate links revealed by a late-glacial cooling episode in southern Chile. *Nature* 409, 804–808.
- Ohmura, A., Kasser, P., Funk, M., 1992. Climate at the equilibrium line of glaciers. *Journal of Glaciology* 38, 397–411.
- Porch, N., Jordan, G.J., Price, D.M., Barnes, R.W., Macphail, M.K., Pemberton, M., 2009. Last interglacial climates of south-eastern Australia: plant and beetle-based reconstructions from Yarra Creek, King Island, Tasmania. *Quaternary Science Reviews* 28, 3197–3210.
- Read, J., Busby, J.R., 1990. Comparative responses to temperature of the major canopy species of Tasmanian cool temperate rainforest and their ecological significance. II. Net photosynthesis and climate analysis. *Australian Journal of Botany* 38, 185–205.
- Read, J., Hill, R.S., 1989. The response of some Australian temperate rain forest tree species to freezing temperatures and its biogeographical significance. *Journal of Biogeography* 16, 21–27.
- Rees, A.B.H., Cwynar, L.C., 2009. Evidence for early postglacial warming in Mount Field National Park, Tasmania. *Quaternary Science Reviews* 29, 443–454.
- Rees, A.B.H., Cwynar, L.C., Cranston, P.S., 2008. Midges (Chironomidae, Ceratopogonidae, Chaoboridae) as a temperature proxy: a training set from Tasmania, Australia. *Journal of Paleolimnology* 40, 1159–1178.
- Rojas, M., Moreno, P.I., Kageyama, M., Crucifix, M., Hewitt, C., Abe-Ouchi, A., Ohgaito, R., Brady, E.C., Hope, P., 2009. The Southern Westerlies during the last glacial maximum in PMIP2 simulations. *Climate Dynamics* 32, 525–548.
- Sawada, M., 1999. ROOKCASE: an Excel 97/2000 Visual Basic (VB) add-in for exploring global and local spatial autocorrelation. *Bulletin of the Ecological Society of America* 80, 231–234.

- Seltzer, G.O., 1994. Climatic interpretation of alpine snowline variations on millennial time scales. *Quaternary Research* 41, 154–159.
- Seppä, H., Björne, A.E., Telford, R.J., Birks, H.J.B., Veski, S., 2009. Last nine-thousand years of temperature variability in Northern Europe. *Climate of the Past Discussions* 5, 1521–1552.
- Shakun, J.D., Carlson, A.E., 2010. A global perspective on Last Glacial maximum to Holocene climate change. *Quaternary Science Reviews*. doi:10.1016/j.physletb.2003.10.071.
- Shulmeister, J., Goodwin, I., Renwick, J., Harle, K., Armand, L., McGlone, M.S., Cook, E. J., Dodson, J.R., Mayewski, P., Curran, M., 2004. The Southern Hemisphere westerlies in the Australasian sector over the last glacial cycle: a synthesis. *Quaternary International* 118–119, 23–53.
- Sigleo, W.R., Colhoun, E.A., 1982. Terrestrial dunes, man and the late Quaternary environment in southeastern Tasmania. *Palaeogeography, Palaeoclimatology, Palaeoecology* 39, 87–121.
- Stine, S., 1994. Extreme and persistent drought in California and Patagonia during medieval time. *Nature* 369, 546–549.
- Stuiver, M., Reimer, P.J., Reimer, R., 2010. CALIB Radiocarbon Calibration Version 6.0.1. Sturman, A.P., Tapper, N.J., 2006. *The Weather and Climate of Australia and New Zealand*. Oxford University Press, USA.
- Telford, R.J., Birks, H.J.B., 2005. The secret assumption of transfer functions: problems with spatial autocorrelation in evaluating model performance. *Quaternary Science Reviews* 24, 2173–2179.
- Telford, R.J., Birks, H.J.B., 2009. Evaluation of transfer functions in spatially structured environments. *Quaternary Science Reviews* 28, 1309–1316.
- Ter Braak, C.J.F., Smilauer, P., 2002. *Canoco for Windows Version 4.5*. Biometris Plant Research International, Wageningen, The Netherlands.
- Thomas, I., 1993. Late pleistocene environments and aboriginal settlement patterns in Tasmania. *Australian Archaeology* 36, 1–11.
- Thomas, I., 1995. "Where Have All the Forests Gone?" New Pollen Evidence from Melaleuca Inlet in Southwestern Tasmania, IAG 1993 Conference Proceedings. Monash Publications in Geography, Melbourne, pp. 295–301.
- Tonello, M.S., Mancini, M.V., Seppä, H., 2009. Quantitative reconstruction of Holocene precipitation changes in southern Patagonia. *Quaternary Research* 72, 410–420.
- Ummenhofer, C.C., England, M.H., 2007. Interannual extremes in New Zealand precipitation linked to modes of Southern Hemisphere climate variability. *Journal of Climate* 20, 5418–5440.
- Vandergoes, M.J., Newnham, R.M., Preusser, F., Hendy, C.H., Lowell, T.V., Fitzsimons, S.J., Hogg, A.G., Kasper, H.U., Schlüchter, C., 2005. Regional insolation forcing of late Quaternary climate change in the Southern Hemisphere. *Nature* 436, 242–245.
- Vandergoes, M.J., Dieffenbacher-Krall, A.C., Newnham, R.M., et al., 2008. Cooling and changing seasonality in the Southern Alps, New Zealand during the Antarctic Cold Reversal. *Quaternary Science Reviews* 27, 589–601.
- Williams, M., Cook, E., van der Kaars, S., Barrows, T., Shulmeister, J., Kershaw, P., 2009. Glacial and deglacial climatic patterns in Australia and surrounding regions from 35 000 to 10 000 years ago reconstructed from terrestrial and near-shore proxy data. *Quaternary Science Reviews* 28, 2398–2419.
- Wilmshurst, J.M., McGlone, M.S., Leathwick, J.R., Newnham, R.M., 2007. A pre-deforestation pollen-climate calibration model for New Zealand and quantitative temperature reconstructions for the past 18 000 years BP. *Journal of Quaternary Science* 22, 535–547.
- Winograd, I.J., Landwehr, J.M., Ludwig, K.R., Coplen, T.B., Riggs, A.C., 1997. Duration and structure of the past four interglaciations. *Quaternary Research* 48, 114–154.
- Wolfe, B.B., Falcone, M.D., Clogg-Wright, K.P., Mongeon, C.L., Yi, Y., Brock, B.E., Amour, N.A.S., Mark, W.A., Edwards, T.W.D., 2007. Progress in isotope paleohydrology using lake sediment cellulose. *Journal of Paleolimnology* 37, 221–231.
- Woodward, C.A., Shulmeister, J., 2007. Chironomid-based reconstructions of summer air temperature from lake deposits in Lyndon Stream, New Zealand spanning the MIS 3/2 transition. *Quaternary Science Reviews* 26, 142–154.