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Seasonal variations in aridity and temperature characterize changing climate during the last deglaciation in New Zealand

Elisabeth L. Sikes [a,*], Patricia M. Medeiros [a,1], Paul Augustinus [b], Janet M. Wilmshurst [c], Katherine R. Freeman [d]

[a] *Institute of Marine and Coastal Science, Rutgers University, 71 Dudley Rd., New Brunswick, NJ 08901, USA*
[b] *School of Geography and Environmental Science, University of Auckland, Auckland, New Zealand*
[c] *Landcare Research, Lincoln, Canterbury, New Zealand*
[d] *Department of Geosciences, Pennsylvania State University, University Park, PA 16802, USA*

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ABSTRACT

New multiproxy records of aridity from northern New Zealand assess the seasonality and overall pattern of wetness through the Last Glacial Coldest Period (LGCP) to the early Holocene in the subtropical Southwest Pacific. Biomass burning indicators based on terrestrial biomarkers and $\delta^{13}C$ of individual plant leaf wax carbon compounds (n-alkanoic acids) from a maar lake were used to track aridity. In combination with published sea surface temperatures and new pollen-based temperature estimates from the same core, seasonal climatological changes in the Auckland area were determined from 27 to 9 cal. ka BP. These proxies document a shift from cold and dry conditions in the Last Glacial Maximum to seasonally wetter conditions through the deglaciation. Spring became warmer first and possibly wetter while summers remained drier and initially cooler. The progression from cold-dry to warm-wet was punctuated by the Antarctic Cold Reversal (ACR) which stands out as having wetter conditions in both spring and summer and mild cooling largely concentrated in spring. The seasonal climate trends observed here can be plausibly explained by a rapid change from a subpolar climate to one with subtropical control in this region of the southwest Pacific across the Last Glacial to Interglacial transition. A southerly shift and decreasing intensity of the westerly wind belt after the LGCP is considered to have driven the early deglacial warming and pulse of wetness whereas a northward shift without a commensurate increase in intensity of the westerlies may explain conditions in the ACR.

1. Introduction

The Last Glacial–Interglacial Transition (LGIT) or last deglaciation, was an interval of rapid global climate change with complex and abrupt millennial events documented in northern hemisphere records such as Greenland ice cores (e.g., Dansgaard et al., 1993; Clark et al., 1999) and European maar lake sediment records (e.g., Allen et al., 2000; Brauer et al., 2000). In the high latitudes of the Southern Hemisphere, the last deglaciation was initiated around 19 cal. ka BP, earlier than in high northern latitudes and it was punctuated by the ~2 cal. ka BP long cool period known as the Antarctic Cold Reversal (ACR) occurring from 14.6 to 12.7 cal. ka BP (EPICA, 2006). High resolution climatic studies and improved chronologies have clarified the differential timing of short term deglacial climate events between northern and southern hemispheres (Shakun et al., 2012), establishing that the ACR in southern latitudes predates and is distinct from the Younger Dryas cooling event in northern latitudes (e.g. Samson et al., 2005; Vandergoes et al., 2005; Barrows et al., 2007; Kaplan et al., 2010; Shakun et al., 2012). The difference in timing is attributed to the polar seesaw (e.g. Lamy et al., 2007; Denton et al., 2010; Newnham et al., 2012). Nonetheless, the interhemispheric drivers and forcings of climate shifts during the deglaciation in the southwest Pacific region remains an open question (e.g. Turney et al., 2003; Turney et al., 2004; Alloway et al., 2007; Huybers and Denton, 2008; Augustinus et al., 2012).

Climatically, New Zealand is well positioned to record the influence of high versus low latitude forcing of large-scale climate change in the Southern Hemisphere (e.g. Turney et al., 2004). Its mid-latitude position straddles the boundary between the warm

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* Corresponding author. Tel.: +1 848 932 3257; fax: +1 732 932 8578.
E-mail address: sikes@marine.rutgers.edu (E.L. Sikes).

[1] Current address: Department of Marine Sciences, University of Georgia, Athens, GA 30602-3636, USA. Tel.: +1 706 542 6744.

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southwest Pacific and cold Southern Ocean placing New Zealand at the crossroads of tropical and high southern latitude climate influence throughout past glacial–interglacial transitions (Turney et al., 2003; Pepper et al., 2004; Turney et al., 2004; Vandergoes et al., 2005). Northern New Zealand has significant ENSO teleconnections modulated by ITCZ movements (Salinger et al., 2001). Here, ENSO influences are manifested in both temperature and rainfall, with El Niño events associated with statistically significant cooling in three seasons (winter, spring, and summer) and a spring drought (Gordon, 1985). These changes are driven by an enhanced zonal (south-) westerly flow over New Zealand and reflect an increase in seasonality in the region. In contrast, the South Island sits in the zone of westerly winds and has strong Antarctic and Southern Annular Mode (SAM) forcing (Goodwin et al., 2004).

The seasonality of temperature and precipitation are diagnostic of the climate drivers in New Zealand today. Changes in the magnitude and seasonality of moisture (e.g. how much rain, how often) and temperature (maximum and minimum) can be linked to present and past variations in regional and global atmospheric forcing mechanisms (Salinger and Mullen, 1999; Salinger and Griffiths, 2001; Salinger et al., 2001; Gomez et al., 2004; Shulmeister et al., 2004). Fundamental to reading the paleo-record of climate is recognizing that the response of biologically based proxies to environmental factors have seasonal bias and the divergence of these records may reflect past changes in seasonality (e.g. Vandergoes et al., 2008; Sikes et al., 2009a; McGlone et al., 2010). Employing multiple climatic proxies and considering seasonal differences in the interpretation of temperature and moisture records is necessary to improve our understanding of forcings in past climate (McGlone et al., 2004; Sikes et al., 2009a; McGlone et al., 2010). The role of seasonal climate changes on ecosystems and their resultant proxies may exert a first-order control on the expression of millennial-scale climatic events such as the ACR in different proxies and different locations (e.g. Wilmshurst et al., 2007; Vandergoes et al., 2008). In short, seasonality may complicate quantitative comparisons among records and proxies and impact the interpretation of millennial scale events during climate shifts.

The strength and latitudinal position of the Southern Hemisphere westerly winds play a fundamental role in global climate, driving mixing in the Southern Ocean (Sallée et al., 2010) and controlling local/regional temperature and moisture (Lamy et al., 2001; Shulmeister et al., 2004; Lamy et al., 2010). Marine and terrestrial studies from the Southern Ocean have been seminal in demonstrating that the latitudinal position of the wind belt and oceanic fronts have shifted in the past driving pulses of ocean upwelling and CO_2 outgassing as well as local moisture and regional temperature (e.g. Russell et al., 2006; Toggweiler et al., 2006; Anderson et al., 2009; Sikes et al., 2009a; Denton et al., 2010; Lamy et al., 2010; McGlone et al., 2010; Moreno et al., 2010; Fletcher and Moreno, 2011).

1.1. Regional setting

Oceanographically, surface water bathing the North Island is characteristically subtropical. Regional subtropical surface waters originate in the central equatorial Pacific, flowing westwards in the South Equatorial Current before heading southward along the east coast of Australia as part of the East Australian Current. General zonal movement of waters occurs across the Tasman Sea towards the northern tip of New Zealand (Tomczak and Godfrey, 1994). The marine climate is mild: modern mean summer and winter SSTs in the Bay of Plenty are 21.0 °C and 15.1 °C, respectively (Bottomley et al., 1990). The position of the northern boundary of the Southern Ocean, the Subtropical Front (STF), on the Chatham Rise is further north than in most regions of the Southern Ocean (Orsi et al., 1995). Consequently, the south and east portions of the South Island are bathed by Southern Ocean waters delivered by the STF. During the glaciation the STF was locked in its present position by the land mass (Sikes et al., 2002). Thus, in New Zealand, variations in climate can be more clearly related to changing winds independent of shifting oceanic frontal boundaries. Presently, the South Island is bathed by Southern Ocean waters and influenced by the Antarctic Circumpolar Current which is linked to the position of the westerly wind belt.

Today, the climate in New Zealand varies from warm and wet in the subtropical north, to cool and wet in the temperate south with the seasonality of temperature and precipitation diagnostic of the climate in the different regions (Wards, 1976; NIWA, 2012). Auckland, in the subtropical north, has a greater seasonality in precipitation than in temperature, a characteristic of more tropical climates. Here the wettest month has twice as much precipitation as the driest (146 mm compared to 64 mm) whereas the annual temperature range is a moderate ~8 °C (Wards, 1976; NIWA, 2012). Equatorward shifts and strengthening of the westerlies increase the incidence of both frost and drought because strengthened westerly wind flow over land, for example in the Southern Alps brings low humidity air off colder waters (Shulmeister et al., 2004).

In New Zealand, variable expression of the LGM and deglacial millennial events such as the ACR is widely recognized (e.g. Alloway et al., 2007) raising the question of whether these events are more strongly expressed in the southern latitudes dominated by zonal westerlies while northern New Zealand is subject to more tropical influences (Augustinus et al., 2011; Newnham et al., 2012). Alternately this may be caused by differing seasonal responses and sensitivity of palaeoclimatic indicators (e.g. Lowe et al., 2008; McGlone et al., 2010). In the Auckland region previous pollen records imply a strongly cooler LGM with a muted or absent ACR (e.g. Sandiford et al., 2003; Newnham et al., 2007; Augustinus et al., 2011). The ACR is only clearly expressed in the North Island pollen records from higher altitudes (Newnham and Lowe, 2000; Hajdas et al., 2006). However, the ACR has been discerned in the Auckland region in other paleoclimate proxy records (Pepper et al., 2004; Augustinus et al., 2011, 2012) and in nearby deep sea cores (Samson et al., 2005). To examine seasonal expression of aridity and temperature we employed multiple proxies across the climate transition from the Last Glacial Maximum (LGM) to the Holocene in a core retrieved from the Onepoto maar lake (Fig. 1). We present new analyses of biomass burning biomarkers and compound-specific carbon isotopes that provide a qualitative measure of dryness and new pollen-based temperature estimates that are compared to published SST records, each of which can be tied to different seasonal forcings.

2. Materials and methods

2.1. Stratigraphy

Deconvolving the response of multiple climate proxies to different environmental triggers (Huybers and Wunsch, 2003), in different depositional environments requires tight stratigraphic correlation. In Northern New Zealand, the frequent, widespread, and well dated, late Quaternary rhyolite tephra provide a single chronostratigraphy across different depositional environments permitting the relative timing among sites to be particularly well constrained (Alloway et al., 2007; Lowe et al., 2008) (Fig. 2). This allows the use of the subtle differences in a proxy's timing and response among sites to clarify the nuances in changing climate