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Mean annual temperature in New Zealand during the last glacial maximum derived from dissolved noble gases in groundwater

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ABSTRACT

This study presents a reconstruction of mean annual surface temperature in New Zealand over the last glacial period using groundwater noble gas paleothermometry. Low resolution ^{14}C-derived mean recharge ages of groundwater from the Deep Moutere, Deep Wairau, and Taranaki aquifers range from roughly 41,500 yr to present, including the last glacial maximum (LGM). Modeled noble gas temperatures of probable glacial-age samples range from roughly 3.7–6.2 °C cooler than present. We present an error-weighted mean cooling of 4.6 ± 0.5 °C relative to present during last glacial period. The screened depth intervals of some wells sampled in this study allow for a degree of mixing during extraction between groundwater layers of different recharge age. Mixing with modern groundwater may slightly elevate the noble gas temperatures (NGTs) of glacial-age samples while making them appear substantially younger. Given the uncertainty in dating, we cannot rule out a larger LGM temperature depression of up to ∼6 °C. The ∼4.6 °C cooling estimate agrees with a number of terrestrial paleoclimate reconstructions near the study area as well as the majority of nearby paleoceanographic temperature studies.

1. Introduction

Regional mean annual temperature changes since the last glacial maximum (LGM), around 26,500 to 17,000 yr before present, are important metrics for understanding the behavior of the climate system on glacial timescales. At the poles, borehole measurements (e.g. Cuffey and Clow, 1997) and stable-isotope measurements of both ice and trapped bubbles in ice cores (e.g. Jouzel et al., 2007) have been used to reconstruct temperature and have indicated an LGM-to-modern temperature difference of up to 20–25 °C in the Arctic and around 10 °C in Antarctica. In the southern mid-latitudes, attempts at LGM temperature reconstruction on both land and sea have varied by both location and technique. Terrestrial estimates of mean annual temperature using fossil assemblages of pollen and beetles on average show cooling of roughly 4–5 °C relative to present, but ranging from ∼3–7 °C, during the LGM (McGlone, 2002; Newnham et al., 1989; Sandiford et al., 2003; Shulmeister et al., 2001; Wilmshurst et al., 2007). Modeled changes in equilibrium snowline altitude (ELA) based on cosmogenic nuclide-dated moraines in the Southern Alps of New Zealand imply ∼6–7 °C cooler-than-present mean LGM summer temperatures (Golledge et al., 2012; Putnam et al., 2013). Marine LGM paleotemperature reconstructions around 45–46°S (Barrows and Juggins, 2005).

This study determines mean surface temperatures in central New Zealand at low elevation over the last glacial period through the late Holocene from measured concentrations of dissolved neon, argon, krypton, and xenon in groundwater. Because of their chemical inertness and relatively constant atmospheric concentrations over glacial–interglacial timescales, noble gases are ideal conservative tracers of physical processes. The noble gas groundwater paleothermometer exploits the dependence of dissolved noble gas concentrations on temperature and has been widely used to constrain mean annual surface temperature at the time of recharge (e.g. Andrews and Lee, 1979; Mazor, 1972; Stute et al., 1995). Where groundwater recharged during the LGM is available, this method can derive LGM-versus-modern mean annual

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surface temperature, integrated over time periods of hundreds to thousands of years due to intra-aquifer dispersion and mixing. Paleogroundwater recharged during the last glacial period may be dated by ^{14}C activity with minimum uncertainty of ±2000 yr (Phillips et al., 1989; Stute and Schlosser, 1993). Though limited in temporal resolution, dissolved noble gases enable quantitative paleotemperature reconstructions based on well understood physics.

Here, we measure dissolved noble gases in groundwater recharged over the last ~41,500 yr collected in three New Zealand aquifer systems from ~39–42°S. Recharge temperature is determined assuming a closed system equilibration (CE) model and using inverse modeling to solve for noble gas temperature (NGT), entrapped air, and a fractionation parameter governing the partial dissolution of entrapped air (Aeschbach-Hertig et al., 1999; Peeters et al., 2002). NGTs of these groundwater samples are consistent with a glacial–interglacial temperature change of 4.6 ± 0.5 °C. Given the limited number of samples and large uncertainties associated with dating, these measurements suggest a possible range of LGM cooling from ~3.7–6.2 °C relative to present. This study is the first LGM application of noble gas paleothermometry in the southern mid-latitudes.

1.1. Prior LGM temperature reconstructions around New Zealand

The NZ-INTIMATE project has drawn on a number of terrestrial and marine proxy reconstructions to examine climatic shifts in New Zealand over the last 30,000 yr (Alloway et al., 2007; Lorrey et al., 2012). LGM climate in New Zealand likely exhibited moist, moderate conditions in the western part of the then-connected land mass and drier, continental conditions east of the main ranges (Lorrey et al., 2012). Terrestrial and marine proxies have been used to understand regional changes since the last glacial period in vegetation type, biodiversity, precipitation, temperature, and other key climate variables. For the purpose of this study, we explicitly consider only quantitative temperature reconstructions.

On northern North Island, LGM temperature is estimated to be 4–5 °C colder than present from pollen records preserved at Pukaki Crater near 37°S (Sandiford et al., 2003). This is substantially colder than marine assemblage-based LGM estimates of 2.8 °C (Barrows and Juggins, 2005) and under 1 °C (Samson et al., 2005) colder than present in the nearby Bay of Plenty at approximately the same latitude. Southeast of Pukaki Crater, pollen assemblages indicate LGM temperature depressions of 4.5–5.3 °C at Lake Rotomanuka (Newnham et al., 1989) and 5.2–6.7 °C at Lake Maratoto (Lorrey et al., 2012; Wilmshurst et al., 2007), both near 38°S. On southeastern North Island, two pollen records from Lake Poukawa (~40°S) suggest LGM cooling of 4–5 °C (McGlone, 2002) and 6.5–7.8 °C (Shulmeister et al., 2001), respectively, although the coldest estimate is likely erroneous (Lorrey et al., 2012). The 4–5 °C agrees well with nearby offshore paleoceanographic studies around 40°S and 178°E which estimate an LGM temperature depression of roughly 5 °C independently from alkenones (Pahnke and Sachs, 2006), δ^{18}O in planktonic foraminifera (Nelson et al., 2000), and assemblages (Barrows and Juggins, 2005). Temperature estimates based on Mg/Ca ratios in foraminifera just south of these studies, around 40.4°S, indicate more substantial LGM cooling of 6–7 °C (Marr et al., 2013).

On the South Island, fossil beetle assemblages imply roughly 3–5.5 °C cooler LGM temperatures in the Awatere Valley near 42°S (Marra et al., 2004), while ELA-based temperature reconstructions in the Southern Alps (~44°S) suggest LGM summer cooling of 6–7 °C (Golledge et al., 2012; Putnam et al., 2013). Off the eastern coast of the South Island, south of the Chatham Rise, marine assemblages, Mg/Ca ratios, alkenones all indicate larger LGM cooling than in the north, from ranging 4–9 °C colder than present (Barrows and Juggins, 2005; Hayward et al., 2008; Pahnke and Sachs, 2006). Two studies immediately off the west coast of the South Island imply LGM cooling of 6–7 °C around 42°S from alkenone (Pelejero et al., 2006) and marine assemblage records (Hayward et al., 2008). Fig. 1 displays the approximate locations and general LGM temperature depression ranges for 25 marine and 8 terrestrial studies alongside the locations of the 12 groundwater samples analyzed in this study.

1.2. Study area

Twelve wells were sampled (11 successfully analyzed) from three aquifers on the North and South islands of New Zealand, from roughly 39–42°S (Fig. 1). All samples were collected from or nearby wells sampled in past hydrological studies, from which published ^{14}C and δ^{13}C or ^{3}H measurements were available in order to estimate recharge ages. Six wells of likely glacial recharge age, two of mid-Holocene recharge age, and three of modern recharge age were sampled (Morgenstern et al., 2008; Stewart et al., 2004; Taylor and Evans, 1999). The Moutere region, situated in northwest South Island, is characterized by precipitation-based recharge. The aquifers sit within the 30 km-wide Moutere Depression, a valley system between the Tasman Mountains and mountains east of Nelson, NZ (Stewart et al., 2004). The Wairau groundwater region, east of the Moutere Depression near Blenheim, N.Z. is characterized by glacial and alluvial deposits from the nearby Wairau River. It sits in a valley formed by the Wairau fault, bounded by schist and greywacke. The Deep Wairau Aquifer, from which paleogroundwater samples NZ5, NZ6, and NZ8 were sampled, consists of unsorted Quaternary gravel, silt, sand, and clay (Morgenstern et al., 2008). Samples from the Taranaki-region, located on southwestern North Island, were collected from the Whenuakura formation, which is characterized by pebbly sands, siltstone, and shellbeds. It sits below Taranaki volcanics and marine terraces (Taylor and Evans, 1999).

2. Methods

2.1. Noble gas groundwater paleothermometry

This study infers mean surface temperatures of New Zealand from the last glacial period, including the LGM, through the late Holocene from modeled NGTs derived from measured concentrations of dissolved neon, argon, krypton, and xenon in groundwater. With low temporal resolution, dissolved groundwater noble gas concentrations enable reconstruction of equilibrium ground temperature at the water table, which reflects mean annual surface temperature at the time of recharge (Aeschbach-Hertig and Solomon, 2013; Aeschbach-Hertig et al., 2000, 1999; Stute and Schlosser, 1993, 2000). At the water table, ground air with assumed atmospheric concentrations of Ne, Ar, Kr, and Xe dissolves into groundwater according to Henry's Law, which relates dissolved concentration to gas partial pressure by a solubility constant governed by temperature and salinity (Clever, 1979; Weiss, 1971, 1970). Noble gas partial pressures in the unsaturated zone can be slightly higher than atmospheric values in areas of high subsurface biological activity (Hall et al., 2012). Large seasonal surface temperature variations decay with depth and have been shown to converge around the mean annual surface temperature at about 10 m (Stute and Schlosser, 1993). Measured dissolved noble gas concentrations therefore reflect the solubility equilibrium reached at the water table at the time of recharge and enable estimation of a recharge temperature. Water level fluctuations result in the partial or complete dissolution of air bubbles resulting in concentrations in excess to the solubility equilibrium