Earth and Planetary Science Letters 315-316 (2012) 12–23

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Uncertainties in elevation changes and their impact on Antarctic temperature records since the end of the last glacial period

Mark Siddall [a,*], Glenn A. Milne [b], Valérie Masson-Delmotte [c]

[a] Department of Earth Sciences, University of Bristol, Bristol, UK
[b] Department of Earth Sciences, University of Ottawa, Ottawa, Canada
[c] Laboratoire des Sciences du Climat et de l'Environnement (IPSL/CEA-CNRS-UVSQ UMR 8212), Gif-sur-Yvette, France

ARTICLE INFO

Article history:
Accepted 23 April 2011
Available online 20 May 2011

Keywords:
ice sheet
Antarctica
isostasy
ice cores
termination

ABSTRACT

This study presents a sensitivity analysis considering the influence of elevation changes associated with both ice thickness and land height changes on water stable isotope temperature proxies from Antarctic ice cores. We compare results from three different ice sheet models and three different Earth viscosity models at a 10 ice core sites. As expected, the ice-thinning signal at West Antarctic sites is the largest contributor to elevation-induced temperature changes. The signal predicted by the ice models considered produced 100–200% of the total glacial to interglacial signal in δD, indicating that the deglacial ice thinning is overestimated by an amount approaching an order of magnitude at some locations. This indicates that the total volume loss in these models is considerably overestimated. Furthermore, the predicted rate of this change is not supported by the isotope data and so, again, most likely reflects inaccuracies in the adopted ice models. Estimates of contemporary ice mass changes inferred from satellite gravity data corrected using any of these models with therefore be biased as a result. The isostatic signal acts to reduce the total elevation change at most sites and has a relatively small magnitude (a few% to ~20% of that due to the ice thickness change) so is secondary at most sites and for most of the time. However, our results indicate that it could be the dominant control on elevation at some West Antarctic sites during the Holocene, resulting in a secular cooling signal of ~10–20‰ in δD. None of the models capture the Holocene isotopic depletion trend present at several sites in East Antarctica.

1. Introduction

Antarctic ice core stable isotope records are fundamental to contemporary understanding of past climate variability (Blunier and Brook, 2001; EPICA Members, 2006, 2004; Jouzel et al., 2007; Masson-Delmotte et al., 2010a,b; Petit et al., 1999; Petit et al., 1999). These records are known to be related to changes in local temperature modulated by precipitation intermittency (e.g. Sime et al., 2009) but can be also affected by changes in moisture origin, air mass trajectories and changes in local altitude (see Masson-Delmotte et al., 2008 and Stenni et al., 2010 for a recent discussion). Their interpretation in terms of past climate change is therefore not straightforward.

Elevation effects on Antarctic ice-core records due to ice flow and changes in ice sheet thickness over time have been modeled for several ice cores from East Antarctica (e.g. Huybrechts et al., 2007; Parrenin et al., 2007). These approaches typically take account of glacio-isostasy using a relatively simple model of crustal response to loading to determine the contribution of this process to ice surface elevation. For example Parrenin et al. (2007) use a simple relaxation term. Such models are typically forced by scenarios of accumulation changes derived from one ice-core record or marine data (Pollard and DeConto, 2009) and scaled for all Antarctica. Most published data or syntheses of ice core data do not include corrections for elevation effects (see e.g. Masson et al., 2000; Masson-Delmotte et al., 2010a,b; 2011). A notable exception was the calculation of temperature performed by Jouzel et al. (2007) for the EPICA Dome C ice core using the elevation calculation performed by Parrenin et al. (2007). The ice-core records shown in this paper have no prior elevation correction but have been corrected for flow effects in some cases (see Table 1).

This paper focuses on the effect of changing altitude on Antarctic ice-core temperature proxy data and, in particular, the effect of isostasy on ice surface altitude at ice-core locations. We compute land height changes using a state-of-the-art glacial isostatic adjustment (GIA) model. Three different ice history models and Earth viscosity models are considered (see Methods for details) to generate predictions which can be compared to temperature proxy data in ice cores located across the Antarctic ice sheets (Fig. 1). Our aim is to make an initial assessment of the magnitudes of these effects at the sites of ice core records and the uncertainties associated with them during the last 21 kyr, a period for which the elevation effects vary in magnitude and timing in comparison with climate-related effects.

The last 21 kyr encompasses (i) the Holocene, when the impact of elevation changes on the records is important because of the relative

* Corresponding author.
E-mail address: mark.siddall@bristol.ac.uk (M. Siddall).

0012-821X/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2011.04.032

Table 1
Details of the ice core sites used in this paper and references. See text for discussion of site characteristics.

Site	Latitude	Longitude	Altitude (m)	Data	Character (East/West, Dome/Coastal/Flowing etc.)	Surf. vel. ($m yr^{-1}$)
Taylor Dome[a]	77°48′S	158°43′E	2365	$\delta^{18}O$	West[b], Dome, Ross Sea sector, 1.5 km South of ice divide[c]	0.3[c]
Byrd[d]	88°01′S	119°31′W	1530	$\delta^{18}O$	West, Flowing, 190 km from WAIS ice divide[e]	1.98[e]
Siple Dome[f]	81°40′S	148°49′W	621	$\delta^{18}O$	West, Dome, 0.5 km South from ice divide[g]	0.14[g]
Talos Dome[h]	72°49′S	159°11′E	2315	$\delta^{18}O$	West[b], Dome, Ross Sea sector, 6 km from Dome summit along the SE ice divide[i]	0.14[i]
EDML[j]	75°00′S	00°04′E	2892	$\delta^{18}O$	East, Flowing (corrected), Ice divide[k]	0.75[k]
Vostok[l]	78°28′S	106°48′E	1260	δD	East, Dome, Flowing (not corrected), 280 km from ice divide Ridge B[m]	3.0[m]
Komsomolskaia[n]	74°05′S	97°27′E	3499	δD	East, Flowing (not corrected),	–
EPICA Dome C[o]	75°06′S	123°21′E	3233	δD	East, Dome, 1.4 km west of the Dome C summit[i]	0.11[i]
Law Dome[p]	66°46′S	112°48′E	1370	δD	East, Dome, Coastal, 4.6 km from Dome summit[q]	2.9[q]
Dome Fuji[r]	77°30′S	37°30′E	3810	$\delta^{18}O$	East, Dome, About 10 km WNW of Dome summit[s]	0.16[s]

[a] Steig et al., 1998.
[b] For the purpose of this study, though these locations are also sometimes defined as East Antarctic.
[c] Morse et al., 2007.
[d] Hammer et al., 1994.
[e] Hamilton et al., 1998.
[f] Brook et al., 2005.
[g] Nereson, 1998.
[h] Stenni et al. 2010.
[i] Urbini et al., 2008.
[j] EPICA Community Members, 2006.
[k] Wesche et al., 2007.
[l] Petit et al., 1999.
[m] Bell et al., 2002.
[n] Nikolaiev et al., 1988.
[o] EPICA Community Members, 2004.
[p] Morgan et al., 1997.
[q] Morgan et al., 1997.
[r] Kawamura et al., 2007.
[s] Motoyama et al., 2008.

stability of the climate (Masson et al., 2000) and (ii) the end of the last glacial period when relatively large, rapid changes in climate may coincide with large changes in elevation because of the importance of sea level changes for the Antarctic grounding line and therefore ice flow. This period is marked by two millennial isotopic events, during the Antarctic Cold Reversal (Jouzel et al., 1995) and the early Holocene optimum (Masson et al., 2000, Masson-Delmotte et al., in prep). These

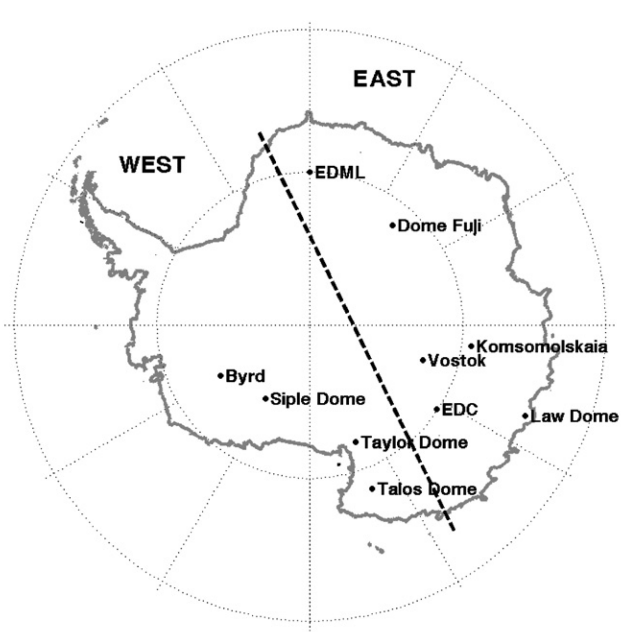

Fig. 1. Map of the ice core sites discussed in this paper including the definition of 'East' and 'West' Antarctica used in this analysis. Details and references are given in Table 1.

two millennial events are Antarctic counterparts to northern hemisphere abrupt events linked with the Bolling-Allerod and Holocene abrupt warming (Ganopolski and Roche, 2009; Masson-Delmotte et al., 2010a,b; Siddall et al., 2010). In a similar fashion, glacial Antarctic Isotopic Maxima are systematic bipolar see saw counterparts to Dansgaard-Oeschger Greenland abrupt warming events (e.g. Capron et al., 2010; EPICA Members, 2006).

The Holocene period is of particular interest given that the relative contribution of isostasy to the total elevation changes is expected to be largest during this period. This is particularly true for West Antarctica, where the largest changes in ice thickness occur during the late glacial and early Holocene resulting in a strong isostatic signal during the mid-to-late Holocene, a period when ice thickness changes are relatively small in many areas. In particular, we aim to identify correlations between isostatic predictions and isotope records to identify signals that could be associated with elevation changes rather than climate change. For example, it has been suggested that the Holocene cooling trend in some East Antarctic ice cores might be linked to a small elevation gain (<50 m) rather than a climate cooling trend (Masson-Delmotte et al., 2000). Climate modeling studies suggest that southern hemisphere orbital insolation changes during the Holocene may induce contrasted seasonal temperature trends, with for instance spring cooling (Renssen et al., 2004; Timmermann et al., 2009). Obtaining further constraints on past elevation changes is therefore critical to extract glaciological and isostatic versus climatic imprints in ice core interglacial records.

2. Data

Ice core stable isotope records from Antarctica have been studied in detail over the last several decades and temperature reconstructions have been produced. Here we consider 10 ice core records from both the West and East Antarctic regions (see Fig. 1). Table 1 gives the sources of these data. The database comprises six records from East