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Cold conditions in Antarctica during the Little Ice Age — Implications for abrupt climate change mechanisms

N.A.N. Bertler [a,*], P.A. Mayewski [b], L. Carter [c]

[a] Joint Antarctic Research Institute, Victoria University and GNS Science, PO Box 600, Wellington 6012, New Zealand
[b] Climate Change Institute, University of Maine, Orono, ME 04469-5790, USA
[c] Antarctic Research Centre, Victoria University, PO Box 600, Wellington 6012, New Zealand

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ABSTRACT

The Little Ice Age (LIA) is one of the most prominent climate shifts in the past 5000 yrs. It has been suggested that the LIA might be the most recent of the Dansgaard–Oeschger events, which are better known as abrupt, large scale climate oscillations during the last glacial period. If the case, then according to Broecker (2000a, 2000b) Antarctica should have warmed during the LIA, when the Northern Hemisphere was cold. Here we present new data from the Ross Sea, Antarctica, that indicates surface temperatures were ~2 °C colder during the LIA, with colder sea surface temperatures in the Southern Ocean and/or increased sea-ice extent, stronger katabatic winds, and decreased snow accumulation. Whilst we find there was large spatial and temporal variability, overall Antarctica was cooler and stormier during the LIA. Although temperatures have warmed since the termination of the LIA, atmospheric circulation strength has remained at the same, elevated level. We conclude, that the LIA was either caused by alternative forcings, or that the sea-saw mechanism operates differently during warm periods.

1. Introduction

The Little Ice Age (LIA) is a prominent climate shift defined on the basis of glacier advances in Europe, and variable but cooler climate conditions throughout the Northern Hemisphere (Grove, 1988). Whilst the term LIA is conducive to a distinct climate event, occurring over a distinct time period, reconstructions show a highly variable climate pattern with marked regional differences, both in style and timing of the climate signals (Mann et al., 1999).

For this reason, the causes, timing and geographical extent of the LIA are still debated. However, three major climate modulators have likely played a role: changes in solar output (Ammann et al., 2007; Bard et al., 2000; Maasch et al., 2005; Mayewski et al., 1997, 2004b, 2006; O'Brien et al., 1996), increased volcanic activity (Crowley, 2000; Robock, 2000), and changes in the thermohaline circulation (Broecker, 2000b, 2001; Lund et al., 2006). The reason for the complex spatial and temporal expressions is likely due to the LIA's small amplitude (Table 1), which competes with other climate drivers of similar or greater amplitude, such as the El Niño-Southern Oscillation (Turner, 2004) or the Southern Annular Mode (Thompson and Solomon, 2002).

As shown in Table 1, the lower temperature and snow line associated with the LIA is about 10% that of the glacial/interglacial changes, and about 20–30% that of the Younger Dryas. However, over the past 5 kyr, the LIA is one of the most prominent climate modulations (Kreutz et al., 1997; Mayewski and Maasch, 2006). Moreover, it has been suggested that the LIA is the most recent rapid climate change (Bond et al., 1999) in a sequence of Dansgaard–Oeschger events (Broecker, 2000a), better known for their abrupt occurrences during the last glacial period. For this reason, the LIA provides an excellent opportunity to evaluate how the climate system creates and responds to rapid change.

Here we present new data from the Ross Sea, Antarctica, an important area of bottom water formation and contributor to the density driven component of the global ocean circulation (Jacobs, 2004). Our data show that LIA climate conditions were synchronous with those in the Northern Hemisphere. We then summarise previously described conditions in Antarctica during the LIA to discuss spatial and temporal differences and implications for abrupt climate change mechanisms.

2. Material and methods

2.1. Study site

New Zealand contributes to the International Trans-Antarctic Scientific Expedition (ITASE) (Mayewski et al., 2005) by collecting ice

* Corresponding author.
E-mail address: Nancy.Bertler@vuw.ac.nz (N.A.N. Bertler).

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Table 1
Comparison of approximate changes in snowline (relative to 1975 AD) and global/hemispherical temperature (relative to preindustrial temperature) during major climate shifts. Data for full glacial temperature change are derived from Schneider von Diemling et al. (2006); all other data from Broecker (2000b).

	Lowering of the snowline (m)	Decrease in temperature (°C)
Glacial to interglacial	~900–950	5.8 ± 1.4
Younger Dryas	~350	~3–4
Little Ice Age	~100	0.6

cores from coastal locations in the Ross Sea region (Fig. 1, Map 2). Victoria Lower Glacier (VLG), in the northernmost McMurdo Dry Valleys, is a small (5×30 km) valley glacier. It flows from its ice divide westward into the Victoria Valley and eastward towards the coast, where it feeds the Wilson Piedmont Glacier. The ice of VLG is locally accumulated, and lies within 22 km of seasonally open ocean. The ice core came from the highest point of the glacier, the ice divide, which lies at 626 m above sea level and is underlain by over 600 m of ice.

As characteristic of the McMurdo Dry Valleys, annual snow precipitation is low. Snow pit data indicate that VLG average annual snow accumulation is 0.033 ± 0.013 m water equivalent per yr (w.e.a^{-1}) for the past ~40 yrs (Bertler et al., 2004a,b). An average annual temperature of −22 °C comes from 15 m-deep temperature measurements in a borehole (Bertler et al., 2004a,b). However, the McMurdo Dry Valleys experience some of the largest seasonal temperature amplitudes on Earth with Victoria Valley recording summer maxima of 10 °C and winter minima of −60 °C (Doran et al., 2002a,b). This exceptional range is caused by the ice free area experiencing strong solar heating during the summer, and radiative cooling during winter (King and Turner, 1997). The winter cooling is particularly strong in Victoria Valley as the valley is sheltered from katabatic winds and hence creates ideal conditions for a stable winter stratification of the lower troposphere, which enhances effective radiative cooling (Doran et al., 2002a,b).

2.2. Data

During the 2001/02 field season, a 180 m-deep ice core was recovered at the ice divide of VLG. This paper focuses on top 50 m of the core, where detailed analyses with ~2.5 cm resolution were carried out. The core was processed using a continuous melter system (Osterberg et al., 2006). 1912 ice core samples were analysed for stable isotope ratios ($\delta^{18}O$, δD, d excess), major ions (Na, Ca, K, Mg, Cl, NO_3, SO_4) and trace element (Fe, Al, Sr, P, Cu, Si) concentrations. In addition, 144 high-resolution tritium measurements were conducted on the top 5 m of the ice core (Patterson et al., 2005). The analytical methods and precision are described in Appendix A.

2.3. Chronological framework

Due to low snow accumulation rates, annual layer counting is not a viable option for dating the VLG ice core. The upper 4 m of the core were dated through correlation with a 4 m-deep snow pit record from the same site. The snow pit data were sampled with 1 cm resolution and dated using annual layer counting of seasonal fluctuations of sodium with a precision of ±1 yr for the 36 yr record (Bertler et al., 2004a,b). Average annual accumulation over this time period is 0.033 ± 0.013 m w.e. a^{-1}. The tritium measurements were used to identify major peaks caused by nuclear testing between 1957 and 1966 as well as seasonal tritium variations. The dating error of the tritium measurements is <0.3 yrs (Patterson et al., 2005).

An age model was extrapolated to the remaining core using a firn decompaction model based on the density regression function:

$$z = z_r\left(\frac{(p_i-p)^d-(p_i-p_o)^d}{(p_r-p_o)^d-(p_i-p_o)^d}\right) \qquad (1)$$

where the density (p) of ice : $p_i=0.917$ g/cm^3, measured density at the surface : $p_o=0.200$ g/cm^3, density at the reference depth z_r: $p_r=0.600$ g/cm^3, reference depth : $z_r=8$ m, best fit with the measured density profile: $d=-1/0.38$. From this follows:

$$p = a-(bz + c)^d \qquad (2)$$

where: $a=p_i$, $b=[(p_i-p_r)^d-(p_i-p_0)]/z_r$, $c=(p_i-p_0)$, $d=-1/0.38$. If the accumulation rate (mass of ice per unit area per unit time)

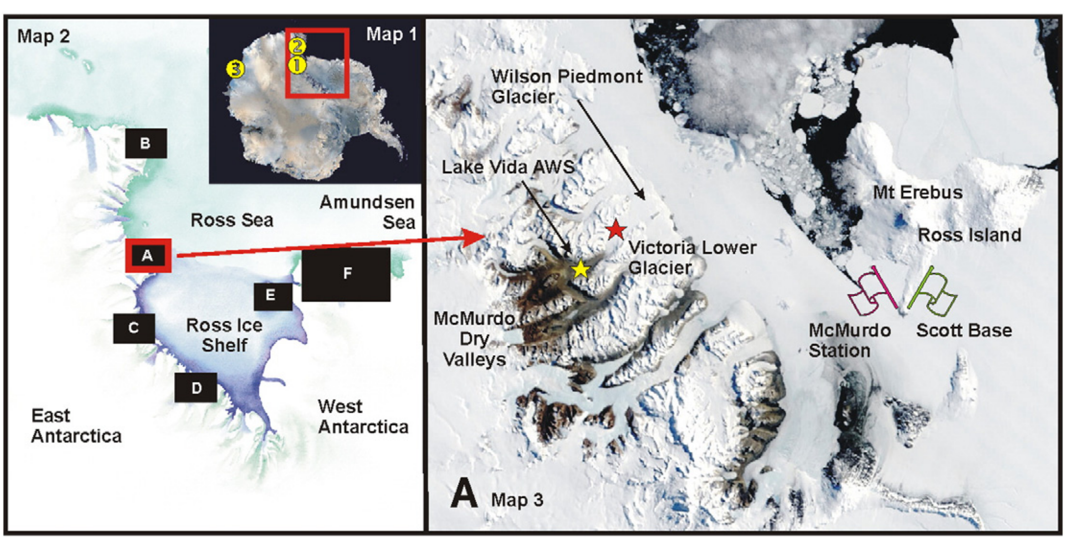

Fig. 1. Location map: 1) map of Antarctica with red square locates Map 2. Yellow numbers denote locations of ice core records: ❶ Taylor Dome, ❷ Talos Dome, and ❸ Law Dome. Source map: NASA, Radar Image. 2) Map of the Ross Sea region. Black squares indicate core locations of the NZ ITASE programme. Square A locates Map 3. Source map: Latitudinal Gradient Programme (Howard-Williams et al., 2006). 3) McMurdo Sound showing the drill site (red star) on Victoria Lower Glacier and location of Lake Vida automatic weather station (yellow star). Source map: NASA Goddard Space Flight Center image from moderate-resolution imaging spectroradiometre (MODIS) sensor (J. Descloitres, MODIS Land Rapid Response Team).