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The Last Termination in the South Indian Ocean: A unique terrestrial record from Kerguelen Islands (49°S) situated within the Southern Hemisphere westerly belt

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ABSTRACT

The awareness of the significance of the Southern Ocean in the Earth's climate system has become increasingly obvious. The deglacial atmospheric CO_2 rise during warming periods in Antarctica has been attributed to CO_2 ventilation from the deep ocean caused by enhanced upwelling around the Antarctic Divergence. It has been hypothesized that, more intense Southern Hemisphere westerly winds aligned with the Antarctic Circumpolar Current due to a southward shift of the wind belt from its Last Glacial Maximum equator-ward position, are the main drivers. Reconstructions of past changes in atmospheric circulation in the Southern Hemisphere are still scarce and the overall picture is patchy with sometimes contradictory results. For obvious reasons, most terrestrial records originate from southern South America and New Zealand. Here we present a terrestrial record from the Indian sector of the Southern Ocean, from Kerguelen Islands located at 49°S. A peat record is investigated using a multi-proxy approach (pollen and plant macrofossils, magnetic susceptibility, XRF analyses, biogenic silica content, Rock-Eval6 analysis and humification degree). Peat accumulation starts at about 16,000 cal yr BP with relatively warm and dry conditions. The most prominent change in our proxy data occurs at 13,600 cal yr BP, when peat ponds were established on the peat surface, resulting in lacustrine-type deposits, as a result of very high humidity, and with proxies implying very windy conditions. Within chronological uncertainties, this onset coincides with the onset of the so-called Oceanic Cold Reversal, based on the deuterium excess data in the EPICA Dome C ice core record. Kerguelen Islands are located in the moisture source area of Dome C and a change in atmospheric circulation at that time could explain both records. Around 12,900 cal yr BP, at the end of the Antarctic Cold Reversal, pond/lake sediments give way to more peaty deposits, with proxies suggesting slightly drier, less windy and probably warmer conditions. Kerguelen Islands became less influenced by the Southern Hemisphere westerly winds and these conditions were amplified during the early Holocene climate optimum as found in Antarctic ice core records.

1. Introduction

It is known from Greenland ice core records that, during the Last Termination (c. 22,000–11,500 cal yr BP after Lowe et al., 2008), the North Atlantic region was characterized by a sudden return to cold conditions, a period/event called the Younger Dryas (YD)/GS 1

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(12,900–11,700 cal yr BP), after an initial abrupt warming during the Bølling–Allerød/GI-1 period/events (14,700–12,900 cal yr BP) (Lowe et al., 2008). In comparison, temperature changes in Antarctica are more gradual. Cold events in Greenland correlate with periods of warming in Antarctica and *vice versa*, related to the 'bipolar seesaw' mechanism (Broecker, 1998; Stenni et al., 2011). In Antarctica, deglacial warming starts at about 18,350 cal yr BP, culminating in the Antarctic Isotopic Maximum 1 (AIM 1, Stenni et al., 2011; Veres et al., 2013), and was interrupted by a return to colder conditions, or a pause in the warming, during the Antarctic Cold Reversal (ACR, 14,650–12,900 cal yr BP) after which a second warming occurred and continued into the Holocene. Based on deuterium-excess data from the EPICA Dome C ice record (EDC), Stenni et al. (2001) report an Oceanic Cold Reversal (OCR) in the moisture-source area for precipitation of EDC, which is the South Indian Ocean, with an onset about 1000 years later then the ACR. Whether the OCR is related to a change in sea surface temperature in the source area or a shift in the moisture source itself, due to a change in atmospheric circulation at basin scale is not yet clear (Stenni et al., 2011).

Outside the Antarctic continent, in the mid latitudes of the Southern Hemisphere (SH), palaeoclimatic records in general and terrestrial ones in particular, are still sparse in comparison with the same latitudes in the Northern Hemisphere. However, during the last decades, there has been a reinforced effort to reconstruct past environmental and climatic changes in the SH mid latitudes. One of the questions that has received considerable attention is whether SH mid latitudes show an Antarctic or a Northern Hemisphere palaeoclimatic signature: for example, was the YD a global or Northern Hemisphere (NH) climate event (e.g. Bennett et al., 2000; Andres et al., 2003; Williams et al., 2005; Barrows et al., 2007). Some SH records reveal cooling events which are synchronous with the NH YD cooling such as in the Taylor Dome ice core record (Steig et al., 1998) and a marine record south (34°S) of Australia (Andres et al., 2003) challenging the bipolar seesaw hypothesis. In the case of the Taylor Dome ice core, the integrity of the time scale has been questioned (Stenni et al., 2011) and in a marine setting, one has to take into account the marine reservoir age, especially during the Last Termination when changes in ocean circulation resulted in possibly fluctuating reservoir ages (Siani et al., 2013). Lately, a growing consensus is that the southern mid-latitudes show an Antarctic palaeoclimatic signature (e.g. Denton et al., 2010), although its northern limit is uncertain. A second research topic that has received extensive attention is the role of the Southern Ocean (SO) and related to this, shifts of the Southern Hemisphere westerly belt (SHW), in releasing CO_2 from the deep ocean during warming phases in Antarctica (Toggweiler et al., 2006; Anderson et al., 2009; Denton et al., 2010; Lamy et al., 2010; Siani et al., 2013). A conceptual model has been presented by Toggweiler et al. (2006) suggesting a pole-ward shift of the SHW from its equator-ward Last Glacial Maximum (LGM) position, aligning the SHW with the Antarctic Circumpolar Current (ACR), favouring ventilation of CO_2 to the atmosphere around Antarctica at the Antarctic divergence. Anderson et al. (2009), hypothesize that during cold periods in the North Atlantic, the Inter-tropical Convergence Zone (ITCZ) has a more southward location, pushing the SHW southward resulting in increased CO_2 ventilation and warming in Antarctica. Denton et al. (2010) invoke a reduced Atlantic Meridional Overturning Circulation (AMOC) followed by expanded sea ice in the North Atlantic, and in consequence a higher seasonality, as the way to spread cold events throughout the North Atlantic and the tropics, with a southward shift of the ITCZ (weakening of the Asian Monsoon) and the SHW as a result.

In relation to the LGM equator-ward location of the SHW, a recent proxy data comparison, highlighted that an equator-ward shift or strengthening of the SHW could explain much of the proxy records, but that other processes could also be involved (Kohfeld et al., 2013). In a follow-up study, a modelling approach was used together with a model-data comparison (Sime et al., 2013). None of the models that reproduce realistic LGM moisture/precipitation data – the most common used proxy for reconstructing changes in SHW – show a large equator-ward shift in the SHW.

We therefore think that more proxy data based evidence is needed to test the different hypotheses on mechanisms and internal feedbacks of the climate system in relation to latitudinal shifts and/or strengthening of the SHW, changing ocean circulation, CO_2 out-gassing and changing temperature in Antarctica and the SH mid latitudes.

The SH mid latitudes constitute the SO, with southern South America, and to a lesser extent New Zealand, as the main land areas. In consequence the vast majority of the terrestrial proxy records originate from these areas. However, dispersed in the SO, islands and island groups occur, which can be targeted as a potential source for terrestrial palaeoclimatic archives. Here we present the results of a multi-proxy study of a 16 000 year old peat sequence from Kerguelen Islands, a sub-Antarctic archipelago located at 49°S in the Indian Ocean, situated in the moisture-source area of the EDC ice core record. In this paper we will concentrate on the Last Termination focussing on the following questions: (i) how did climate evolve during the Last Termination in the Indian sector of the SO, (ii) did any cold reversal occur at Kerguelen Islands and if so, what is its timing, (iii) how does the climate history relate to the climate reconstructions from the EDC ice core, and (iv) can we relate our results to changes (latitudinal shifts and/or strengthening/weakening) of the SHW?

2. Study area

The Kerguelen archipelago (49°S–69°E, Fig. 1A and B) is a French island group in the South Indian Ocean. The main island, with an area of c. 7200 km^2, is by far the largest of the sub-Antarctic islands (*sensu* Lewis-Smith, 1984) and is surrounded by numerous smaller islands. The archipelago is an emerged part of the vast Kerguelen-Gaussberg oceanic plateau and is of volcanic origin, dominated by basaltic lava flows. The western part of the main island is mountainous (with a mean elevation around 800 m), while the eastern part (Péninsule Courbet) is flat and characterized by glacial and glaciofluvial deposits and landforms (Hall, 1984). The highest point is the Mont Ross volcano with an altitude of 1850 m asl. The minimum age of the first volcanic formations on Kerguelen Islands is about 40 Myr (Giret et al., 2003) and the volcanic activity still persists today in the Rallier du Baty Peninsula. A small ice cap with outlet glaciers occurs in the western part of the archipelago (Cook ice cap, Fig. 1B) covering c. 12% of the island (Giret et al., 2003; Van der Putten et al., 2010). However, based on the presence of U-shaped valleys, moraines and fjords, it is clear that ice-cover was much larger in the past, but the exact extent and timing of previous glaciations is poorly constrained. Some studies suggest that these glacial landforms are not of LGM age and that the ice extent at that time was rather restricted (e.g. Nougier, 1970). In contrast, Hall (1984) suggested a more extensive ice-cover during the LGM with an equilibrium line altitude of c. 200 m. The timing of the last deglaciation is also not well known and is mainly based on a few basal radiocarbon dates of peat deposits (Hodgson et al., 2014; Van der Putten et al., 2010).

Nowadays, the Kerguelen archipelago is situated in the core of the SHW, within the Antarctic Circumpolar Current (ACC), at the Polar Front (PF) (Fig. 1A). This makes it a valuable site for reconstructing past changes in atmospheric and oceanic circulation