Glacial Fluctuations since the Medieval Warm Period at Rothera Point (western Antarctic Peninsula).

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Abstract

At global scale there is no evidence for synchronous multi-decadal warm (Medieval Warm Period, MWP) or cold (Little Ice Age, LIA) periods in the late Holocene. On the other hand, globally there is good correspondence in timing between MWP or LIA and phases of glacier retreat and advance, respectively, with local exceptions mainly explained by the precipitation regime. Antarctica exhibits contrasting patterns, both regarding the existence of these two historical climatic periods in the records and, the glacial responses to climatic forcings.

Here we present evidence for glacial retreat corresponding to the MWP and a subsequent LIA advance at Rothera Point (67°34′S; 68°07′W) in Marguerite Bay ,Western Antarctic Peninsula. Deglaciation started ca. 961-800- cal yr BP cal or before, reaching a position similar to or even more retreated than the current state, with the subsequent period of glacial advance commencing between 671 and 558 cal yr BP, and continuing at least until 490 to 317 cal yr BP. Based on new radiocarbon dates, during the MWP the rate of glacier retreat was 1.6 m y^{-1}, which is comparable with recently observed rates (respectively, ca. 0.6 m y^{-1} between 1993 and 2011 and 1.4 m y^{-1} between 2005 and 2011). Moreover, despite the recent air warming rate being higher, the glacial retreat rate during the MWP was similar to the present, suggesting that increased snow accumulation in recent decades may have counterbalanced the higher warming rate.

Introduction

Several global scale recent studies have emphasised the absence of evidence for globally synchronous multi-decadal warm or cold intervals.

Paleoclimatic reconstructions show generally cold conditions between ca. 370 and 70 years BP, interrupted in some regions by warm decades during the Eighteenth Century (e.g. Masson-Delmotte et al., 2013) However, other studies have identified a relatively warm period referred to as the Medieval Warm Period (MWP) between ca.1200 and 700 BP, followed by a cold phase referred to as the Little Ice Age (LIA) between ca.550 and 250 BP (e.g. Mann et al., 2009) and, finally, by the recent warming period (since 1950 AD, Table 1).

Synchronicity in the timing of temperature anomalies is not always apparent between the two Hemispheres. During the warm MWP temperature anomalies were notably cooler in the Southern than the Northern Hemisphere before 850 cal yr BP as well as around 550 cal yr BP, but warmer between 720 and 600 cal yr BP (Neukom et al., 2014). In contrast, synchronicity of cold temperature anomalies in both Hemispheres was present between 356 and 273 cal yr BP (Neukom et al., 2014).

Other studies have also suggested that a 'bi-polar seesaw' pattern, whereby as the Arctic warms the Antarctica cools and *vice versa*, is apparent in the 20th Century Arctic and Antarctic temperature records (Chylek et al., 2010). This phenomenon has also been reported at millennial scale in ice core studies since the last glacial maximum (e.g. Blunier et al., 2001, 2010).In the Antarctic Peninsula (AP) region studies have used different proxies (e.g. ice core isotopes; diatoms, TEX86) to suggestthe absence of a warmer period during the last millennium corresponding to the MWP and, rather, that a gradual cooling period that started ca. 3500 cal yr BP (Shevenell et al.,1996; Mulvaney et al., 2012). In contrast, Domack et al. (2006) identified an MWP ending at about 700 cal. yr BPwhilst Khim et al. (2002) suggested a period of warmer surface ocean temperatures existed betweenca. 735–560 cal. yr BP, and Shevenell et al. (2011) showed a pronounced late Holocene warming (cal 1,600 to 500 yr BP) reaching temperatures higher than those seen currently.

The subsequent cold phase (LIA) is also not well defined or synchronous among Antarctic studies, especially on both sides of the AP.

On the western Antarctic Peninsula (WAP), evidence from several proxies indicates a colder phase with glacier advance occurring broadly between 700 and 150 cal yr BP (Domack et al., 1995; Bentley et al., 2009). However, other paleoclimatic datasets are contradictory, with Liu et al., (2005) showing the existence of a warming period between 450 and 200 yr BP in the South Shetlands while other studies have found no compelling evidence for the LIA in this region (Heroy et al., 2008; Milliken et al., 2009).

On the eastern AP (EAP), an ice core from James Ross Island displayed evidence for warming exceeding rates of 1.5°C per century (similar to the rate of warming recorded in the Twentieth Century) between 432-319 yr BP and 279-173 yr BP (Mulvaney et al., 2012). The absence of evidence for either a clear MWP or a widespread LIA on the EAP is also apparent in lake sediment analyses (Hodgson et al., 2013; Sterken et al., 2012).

At a global scale, there is good correspondence in timing between the MWP and a phase of glacier retreat, as well as between the LIA cold phase and a period of glacier advance that represented the Holocene glacier advance peak (Table 1; Nesje et al., 2011; Humlun et al., 2005).

Glacier response to climate variation was heterogeneous and complex during the MWP because glaciers were more restricted in extent than at present in the WAP (Hall et al., 2010), Southern Greenland (Larsen et al. 2011), Spitsbergen (Humlun et al., 2005) and Norway (Nesje et al., 2011).

However, in other regions such as Patagonia (Strelin et al., 2008), New Zealand (Schaefer et al., 2009) and East Greenland (Lowell et al., 2013), glaciers advanced during this period.
The heterogeneity of glacier response to climate variability emphasises that glacier mass balance is determined by several factors, including air temperature, precipitation regime, radiative balance of the glacier surface and other dynamic characteristics (e.g., glacier size, thickness, slope, surging behaviour, debris coverage, etc)

In the AP region there are few specific terrestrial records of glacial advance and/or retreat over the last millennium. Dating of peat adjacent to the present ice front in the South Shetland Islands (Hall, 2007) indicated that, between ca. 790 and 664 cal yr BP, the ice cover was no more extensive than now. Similarly, Hall et al. (2010), dated moss fragments in organic-rich sediments found in areas deglaciated in *ca.* 2004, suggesting that the glacier was at or behind its present position over the period 924-740 cal year BP.
Here we present a record of terrestrial organic material re-exposed by recent glacier retreat at a location in the WAP regionthat provides evidence for events that are consistent with (a) MWP glacial retreat, (b) subsequent LIA advance, and (c) glacial retreat associated with the rapid regional warming in recent decades.
Further, we attempt comparison of past rates of glacial retreat with contemporary rates in order to assess whether the impacts of recent climate warming on local glacial dynamics are comparable with those over the past millenium.

Material and Methods

The study site is located in the southern WAP, at Rothera Point (67°34'S; 68°07'W) in Marguerite Bay at the southern limit of the Wormald Ice Piedmond. This part of the glacier, locally known as the 'ice ramp', is located between 10 and 110 m a.s.l., and has been monitored since 1989 (Fig. 1). This glacier has retreated rapidly in recent decades, experiencing a surface lowering of 0.32 m water equivalent (w.e.) between 1989 and 1997 (Smith et al., 1998).
In order to minimise impact on the sparse vegetation found in the study area only the minimum quantity of moss and underlying soil required for dating were collected.
The mosses and the underlying organic sediment were separated with a pipette under magnifying glasses and a binocular microscope, in the Bonner Laboratory at the British Antarctic Survey Rothera research station, before being sealed in polyethylene bags and frozen at -20°C. They were kept frozen until being sent to Beta Analytic laboratories (Miami, USA) for radiocarbon dating.

There, moss samples were subjected to an acid-alkali-acid pre-treatment while the two sediment samples were given acid washes according to Beta Analytic standard procedures. After pre-treatment, samples for radiocarbon dating were prepared for AMS by converting them into solid graphite form.

Calibrated ages were calculated with the software OxCal 4.2 (Bronk Ramsey, 2009) using the SHCal13^{14}C Southern Hemisphere atmosphere dataset (Hogg et al., 2013). Radiocarbon age data are reported as conventional radiocarbon years BP (^{14}C yr BP) ±σ and as calibrated age ranges with a 2σ error (95.4%) (cal yr BP; relative to AD 1950) (Table 1).

Taxonomic nomenclature of moss species follows Ochyra et al. (2008).

Results

The area deglaciated between 1988 and 2010 was surveyed in February 2009 and January 2010 (Fig. 1) to document the vegetation exposed after ice retreat. Scattered mosses were found amongst the boulders in this area underlain by, in some cases, 1-2 cm of moss-rich peat. Two of these sites (M11 and A) were located adjacent to the current ice front (Fig. 2a-f). Moss samples were collected along a transect from the glacier front to a distance of c. 100 m, on surfaces recently deglaciated after 2011, 2011-2005, and before 1993 (Fig. 1) All moss samples were identified to be *Andreaea depressinervis* Cardot or*Polytrichastrum alpinum* (Hedw.) G.L.Sm., typical fellfield species well represented in the local area (Convey and Smith, 1997). At all sampling locations along the transect the mosses showed no apparent damage, and were in life position and apparently living as illustrated in Fig. 2g. No epilithic lichens were apparent along the transect, in striking contrast to their widespread colonization of the rocky knolls adjacent to Rothera Point (with communities dominated by *Usnea sphacelata* and *Umbilicaria decussata*). The organic-rich sediments immediately underlying the re-exposed mosses were also sampled. At each sampling location the ages of the mosses and the underlying sediments were assessed using AMS radiocarbon dating (Table 2).

The ^{14}C ages obtained allowed reconstruction of the late Holocene to recent evolution of the Wormald Ice Piedmont glacier front. The organic-rich sediments from points A and B provide minimum ages of deglaciation (745-574 cal yr BP and 961-800 cal yr BP, respectively) indicating that the period of deglaciation started around 961-800- cal yr BP cal or before, reaching a position similar to or even more retreated than that of the contemporary glacier. The subsequent glacial advance commenced between 671 and 558 cal yr BP (indicated by the burial age of the mosses in site A), and continued at least until 490 to 317 cal yr BP, when the moss at site B was over-run by the glacier.

Discussion and conclusions

The timing of deglaciation recorded here (961-671 cal yr BP) is consistent with the ages of deglaciation reported by Hall et al. (2010) at Anvers Island (924-740 cal yr BP). Hodgson et al. (2013), working on sediments from Narrow Lake, Pourquoi-Pas Island (67°37S), reported enhanced nutrient enrichment evident after 1150 (1230-1080) cal yr BP, interpreted as indicating a period of warming that is also consistent with the results of the current study.

The subsequent glacial advance after 671 cal yr BP that is inferred from our data is comparable with Hall's (2007) interpretation of the timing of renewed glacier advances in the South Shetland Islands associated with the LIA, and also coincides with the colder phase documented on the WAP broadly between 700 and 150 cal yr BP (Bentley et al., 2009; Domack et al., 1995; Liu et al., 2005). In contrast, Hodgson et al. (2013) did not find any indication of cooling between 1150 and 400-410 cal yr BP.

Our new ^{14}C ages indicate that deglaciation during the MWP at Rothera was almost synchronous with that which occurred at Anvers Island and with deglaciation recorded in southern Alaska (Wiles et al., 2008), but in antiphase with mot records from the Northern Hemisphere (e.g. Holzhauser et al., 2005; Humlun et al., 2005; Matthews and Dresser, 2008). However, the onset of the LIA based on our new data was almost contemporary with most evidence from the Northern Hemisphere (e.g. Holzhauser et al., 2005), although do not permit estimation of the duration of the LIA at this location.

Our new ^{14}C ages also allow estimation of the rate of glacier retreat during the MWP and comparison of this with recent glacier dynamics over the last 20 years. During the MWP the rate of glacier retreat was 1.6 m y^{-1}, which is higher and/or comparable with the rates measured in recent years (respectively ca. 0.6 m y^{-1} between 1993 and 2011 and 1.4 m y^{-1} between 2005 and 2011).

Of the available proxy data for air temperature during the MWP in the WAP, it is likely that the best paleotemperature profile is provided by the sea surface temperature (SST) record inferred at Palmer for the period 1600 and 500 cal yr BP[8]. The rate of SST increase during the first centuries of this period was ca. 0.3°C $decade^{-1}$, somewhat lower than the recent air temperature warming rate of

0.5°C decade^{-1} over the last 35 years (or of the 1°C decade^{-1} during the period 1978-2000) measured at Rothera Point (Chapman and Walsh, 2007; Guglielmin et al., 2014).

The similarity in glacial retreat rates between the MWP and recent decades at our study site contrasts with the trend of air warming, which is much higher in the recent period. This could suggest that other factors, such as increased snow accumulation, may have counterbalanced the higher warming rate of recent years in the mass balance of the glacier, as has recently been documented for the some Northern Hemisphere glaciers (Colucci and Guglielmin, 2014; Nesje et al., 2008). Local snow accumulation data are not available for this glacier although precipitation increases have been predicted in coastal regions of the maritime Antarctic, with some data available supporting this general prediction (Turner et al., 2009, 2013). If it is assumed that the trend of snow accumulation recorded in the closest ice core available (drilled at Gomez, 73.59°S,70.36°W, ca 750 km SSE) is comparable to the Rothera area, then we can infer that the increase in snow accumulation described since 1850 AD (from a decadal mean of 0.49 m_{weq} y^{-1} in 1855–1864 to 1.10 m_{weq} y^{-1} in 1997–2006, Thomas et al., 2008, 2009) has been partially counterbalanced by higher rates of ice melt due to increased air temperatures in recent years. Moreover, given the forecast increase of precipitation in the Twenty-first Century (Uotila et al., 2007) we suggest that glaciers in the WAP may experience reduced rates of recession despite the air temperature increase. Our data may allow hypothesize potential different glacier evolution at WAP differently from what modelled by Davies et al., (2014) and based on the behaviour of an EAP glacier.

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Figure Captions

Figure 1. Location of the study area and glacial variations during the last 18 years. Legend: green dots = sampled sites; yellow line = glacier front in 1993; blue line = glacier front in 2005; purple line = glacier front in 2011.

Figure 2. Photographs of the sampled sites: A and B) M11; C and D) site A; E and F) site B, with G) detail of *Andreaea* spp. in life position.

Table 2. Main characteristics of the analysed samples. The calibrated ages were calculated with the software OxCal 4.2 using the SHCal13 ^{14}C Southern Hemisphere atmosphere dataset, and are reported as ranges with a 2σ error (95.4%) (cal yr BP; relative to AD 1950)

Sample	**Lab. code**	**Material**	**Measured radiocarbon age**	**$^{13}C/^{12}C$**	**Conv Age BP**	**cal yr BP age**	**Position in the map (Fig. 1)**
Rothera 3	Beta - 260750	moss	340±40	-22.7	380±40	490-317	B
Rothera 1	Beta - 260749	organic sediment	1000±40	-22.8	1040±40	961-800	B
Rothgra2009-1	beta266189	moss	670±40	-22.6	710±40	671-558	A
Rothgra2009-2	beta266190	organic sediment	800±40	-25.2	800±40	745-554	A
M11	Beta - 356172	moss	540±40	-22.8	580±30	631-504	M11