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Calendar-dated glacier variations in the western European Alps during the Neoglacial: the Mer de Glace record, Mont Blanc massif

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A B S T R A C T

Holocene glacier records from the western European Alps are still sparse, although a number of sites are well suited to constraining pre- and early- Little Ice Age (LIA) glacier advances. The present study provides the first dendrochronologically-based and calendar-dated Neoglacial glacier chronology for the Mont Blanc massif, French Alps. It is based on the analysis of over 240 glacially buried *Pinus cembra* subfossil logs and wood remains found either embedded-in-till or as detrital material in the Mer de Glace right lateral moraine. Only a few of the samples were found to be 'formally *in situ*' but we show that some logs were 'virtually *in situ*' (not rooted but showing little or no evidence of reworking) and could be used to accurately reconstruct past glacier margin behavior in space and time. Uncertainties regarding the other samples may relate to original growth location and/or to outer wood decay. The resulting dates (followed by a '+') were therefore considered maximum-limiting ages for glacier advances. The main burial events – interpreted as glacier advances – occurred between ca 1655+ and 1544+ BC, between ca 1230+ and 1105+ BC, between ca 1013+ and 962+/937+ BC, at ca 802–777 BC, after 608+ BC, between 312 and 337 AD, between ca 485+ AD and 606+ AD, between 1120 and 1178 AD, between ca 1248 and 1278+/1296 AD, and after 1352+ AD. These advances predate the late LIA maxima known from historical sources. The magnitude of the advances gradually increased to culminate in three near-Neoglacial maxima during the 7th, 12th and 13th centuries AD, followed by a first LIA/Neoglacial maximum in the second half of the 14th century AD. The pattern of Neoglacial events described here is coherent with Central and Eastern Alpine glacier chronologies. This indicates marked synchronicity of late Holocene glacier variability and forcing at a regional scale, although occasional differences could be detected between 'Western' and 'Eastern' records. The Mer de Glace record also confirms the link between the timing of sediment erosion in a high-elevation glaciated Alpine catchment and subsequent deposition in the sub-alpine Lake Bourget.

1. Introduction

Holocene climate variability has been subject to a great deal of attention in recent decades (Mayewski et al., 2004; Wanner et al., 2008, 2011), mostly due to the emergence of evidence that climate warming during the late 20th/early 21st century has been on a scale that is unprecedented for at least the last millennium (Büntgen and Tegel, 2011; Trachsel et al., 2012) and probably beyond (Marcott et al., 2013; Miller et al., 2013). Consequently, climate researchers need accurate data on the amplitude and timing of Holocene climate change in order to assess the range of natural variability, identify the main forcings, and model future climate variations (Masson-Delmotte et al., 2013).

Abbreviations: BWP, Bronze Age Warm Period; EACC, Eastern Alpine Conifer Chronology; ELA, Equilibrium Line Altitude; FMA, First Millennium Advance; GI, Göschenen 1 Period; GII, Göschenen 2 Period; GA, Great Aletsch Glacier; GO, Gorner Glacier; GP, Gepatsch Glacier; HMA, High Medieval Advance; LBo, Lake Bourget; LBr, Lake Bramant; LG, Lower Grindelwald Glacier; LIA, Little Ice Age; MBM, Mont Blanc Massif; MCA, Medieval Climate Anomaly; MdG, Mer de Glace; MDG, Mer de Glace upper moraine sector; MOTT, Mer de Glace lower moraine sector; MRW, Mean Ring Width; MTL, Minimum Tree Lifespan; NAO, North Atlantic Oscillation; PA, Pasterze Glacier; RLM, Mer de Glace right lateral moraine; TSI, Total Solar Irradiance.

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High-elevation environments are particularly sensitive to rapid climate changes (e.g. Gottfried et al., 2012). Reconstructions of Holocene climate variability in the European Alps have been produced using a variety of proxies, including paleoecological indicators of treeline variations (Haas et al., 1998; Tinner and Theurillat, 2003; Nicolussi et al., 2005; Blarquez et al., 2010; Berthel et al., 2012), lithological and geochemical properties of lake sediments (Schmidt et al., 2008; Giguet-Covex et al., 2012), chironomid assemblages (Heiri et al., 2003; Millet et al., 2009; Ilyashuk et al., 2011), and stable isotope ratios of speleothem calcite (Vollweiler et al., 2006; Boch and Spötl, 2011). Limitations of such studies can be either: (i) reconstruction uncertainties resulting from proxy calibration, (ii) the relatively weak chronological constraints and (iii) a marked anthropogenic impact during the late Holocene hindering the identification of a climate signal (e.g. Giguet-Covex et al., 2014).

Glaciers are widely accepted to be reliable indicators of climate variations on inter-annual to multi-millennial timescales (Denton and Karlén, 1973; Hoelzle et al., 2003; Beedle et al., 2009; Six and Vincent, 2014). Glacier length changes are an expression of changes in the glacier's mass balance (mainly influenced by summer temperature and winter precipitation, e.g. Oerlemans, 2001) delayed by a time lag (Müller, 1988; Jóhannesson et al., 1989). They have been successfully used to infer local climatic parameters such as the equilibrium line altitude (ELA) (Klok and Oerlemans, 2003; Lüthi, 2014) or global-scale temperature variations (Leclercq and Oerlemans, 2012). Beyond the instrumental period, glacier records rely on historical documentary evidence for the last few centuries and on glacio-geomorphological (i.e. dating of moraine deposits) or glacio-lacustrine investigations, for the Holocene period.

High-resolution glacier chronologies, that is, continuous chronologies with information at a decadal or sub-decadal scale, are needed in order to assess whether past climate events occurred synchronously and decipher the underlying driving mechanisms (Clague et al., 2009; Winkler and Matthews, 2010; Kirkbride and Winkler, 2012). The only way of achieving this goal for periods older than the last few centuries is the dendrochronological dating of *in situ* glacially-sheared logs in glacier forefields (Luckman, 1995; Nicolussi and Patzelt, 2001; Holzhauser et al., 2005; Wiles et al., 2011). A tight constraint on glacier-fed lake and mire sediment deposition can also yields high-resolution chronologies (e.g. Dahl et al., 2003; Matthews and Dresser, 2008; Bakke et al., 2010), although this is an *indirect* reflection of glacier activity. What is more, there are few suitable lacustrine settings in the Alps (Leemann and Niessen, 1994; Guyard et al., 2013; Simonneau et al., 2014).

Since moraines are deposited by a glacier in balance with the climate, glacio-geomorphologically based chronologies contain valuable paleoclimatic informations. However, most end-moraine ridge stratigraphies provide only partial records of glacier advances that actually occurred (Gibbons et al., 1984; Kirkbride and Brazier, 1998; Kirkbride and Winkler, 2012). This is especially true since the LIA cold period (ca 1270–1860 AD[1]) led to some of the most prominent Holocene glacier advances in the Northern Hemisphere (Davis et al., 2009). This problem can be overcome, at least partly, by studying composite lateral moraine stratigraphies in order to obtain a more complete picture of Neoglacial advances (Röthlisberger and Schneebeli, 1979; Osborn, 1986; Holzhauser and Zumbühl, 1996; Osborn et al., 2001, 2012, 2013; Reyes and Clague, 2004; Koch et al., 2007; Jackson et al., 2008). The Neoglacial is defined here as the second part of the Holocene during which alpine glaciers experienced repeated advances close to the Holocene maxima.

The European Alps (Fig. 1a) are among the best-documented regions worldwide concerning Holocene glacier variations (Nicolussi and Patzelt, 2001; Holzhauser et al., 2005; Joerin et al., 2006, 2008; Nicolussi et al., 2006; Nussbaumer et al., 2007; Holzhauser, 2010; Luetscher et al., 2011; Goehring et al., 2011, 2012; Nicolussi and Schlüchter, 2012; Nussbaumer and Zumbühl, 2012; Schimmelpfennig et al., 2012, 2014). Even so, distribution of dated sites is spatially heterogeneous. Unlike the Central and Eastern Alps where glacio-geomorphological studies have been conducted since the 1960s (see Ivy-Ochs et al., 2009 and references therein), there have been to date very few such studies in the French Alps. Nevertheless, this region occupies a key position with respect to the main atmospheric circulations pathways (prevalence of Atlantic influences in the North and Mediterranean influences in the south; Durand et al., 2009; Fig. 1a) and hosts ~15% of the current Alpine glacier area (Paul et al., 2011; Gardent et al., 2014). Furthermore, the Mont Blanc Massif, northern French Alps (MBM; Fig. 1) has seen the emergence of glaciology as a science from the 18th century, as evidenced by several seminal works (de Saussure, 1779, 1786; Forbes, 1843; Tyndall, 1873; Viollet-le-Duc, 1876; Vallot, 1900).

The aim of the present study was to help fill this knowledge gap by using dates obtained from glacially buried subfossil wood material from the moraine of Mer de Glace to establish a reliable chronology for Neoglacial glacier variations in the MBM. We then compared our chronology with the most accurate glacio-geomorphological and lacustrine evidence for Neoglacial glacier advances in the Alps.

2. Study site

Mer de Glace (hereafter MdG; 45°55′N, 06°55′E) is the largest glacier in the French Alps. It is 11.5-km-long along the flowline, covers an area of 30.4 km^2 (without including former tributary Talèfre Glacier) and spans the elevation range from 4205 m to 1531 m a.s.l. (data: 2008; Gardent et al., 2014; Fig. 1b). Strictly speaking, the term MdG refers to the 5-km-long distal part of the glacier. Average ELA was 2880 m a.s.l. for five of the main north-facing MBM glaciers, which include the Leschaux Glacier (Fig. 1b), for the period 1984–2010 (Rabatel et al., 2013). Mean annual temperature and precipitation at the nearby Chamonix-Le Bouchet weather station (1054 m a.s.l.) were 6.5 °C and 1238 mm, respectively, for the period 1961–1990 (Météo France data).

Measurements of MdG frontal variations extend back to 1878 AD. This record indicates an overall retreat of 1.27 km from 1878 until 2013, and three periods of readvance culminating in 1896 (+174 m), 1931 (+237 m) and 1995 (+143 m) (Reynaud and Vincent, 2000; C. Vincent, pers. comm., 2014). The ‘reaction time’ of MdG is the longest of all the northward flowing glaciers in the MBM, with the glacier tongue taking 11–25 years to react to a change in summer temperature (Nussbaumer and Zumbühl, 2012). This is 11–15 years longer than the observed frontal lag of the most reactive Bossons Glacier (Martin, 1977; Reynaud, 1993; Le Roy, 2012; Fig. 1b). The MdG ‘dendro-reaction time’ (*sensu* Pelfini et al., 1997) has been calculated for the 1878–2008 AD period by cross-correlation between the MdG length record and a living *Pinus cembra* chronology distant from 6 km. The best correlation was obtained when setting a 13-years lead of the dendro-record relative

[1] Our definition of the onset of the LIA is based on Alpine glacier evidence. Glacier advances as far as the 1880 AD–1850 AD ice level had already occurred by the late 13th century AD (Nicolussi and Patzelt, 2001; see Section 6.2.7 thereafter) and the first LIA culmination occurred in the 14th century AD (Holzhauser et al., 2005). This accords with a notable decline in summer temperatures after ca 1270 AD (Büntgen et al., 2011).