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Holocene glacier variability and Neoglacial hydroclimate at Ålfotbreen, western Norway

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A B S T R A C T

Glaciers and small ice caps respond rapidly to climate perturbations (mainly winter precipitation, and summer temperature), and the mass-balance of glaciers located in western Norway is governed mainly by winter precipitation (Pw). Records of past Pw can offer important insight into long-term changes in atmospheric circulation, but few proxies are able to accurately capture winter climate variations in Scandinavia. Reconstructions of equilibrium-line-altitude (ELA) variations from glaciers that are sensitive to changes in Pw therefore provide a unique opportunity to quantify past winter climate in this region. Here we present a new, Holocene glacier activity reconstruction for the maritime ice cap Ålfotbreen in western Norway, based on investigations of distal glacier-fed lake sediments and modern mass balance measurements (1963–2010). Several lake sediment cores have been subject to a suite of laboratory analyses, including measurements of physical parameters such as dry bulk density (DBD) and loss-on-ignition (LOI), geochemistry (XRF), surface magnetic susceptibility (MS), and grain size distribution, to identify glacial sedimentation in the lake. Both radiocarbon (AMS ^{14}C) and ^{210}Pb dating were applied to establish age-depth relationships in the sediment cores. A novel approach was used to calibrate the sedimentary record against a simple ELA model, which allowed reconstruction of continuous ELA changes for Ålfotbreen during the Neoglacial (when Ålfotbreen was present, i.e. the last ~1400 years). Furthermore, the resulting ELA variations were combined with an independent summer temperature record to calculate Neoglacial Pw using the ‘Liestøl equation’. The resulting Pw record is of higher resolution than previous reconstructions from glaciers in Norway and shows the potential of glacier records to provide high-resolution data reflecting past variations in hydroclimate. Complete deglaciation of the Ålfotbreen occurred ~9700 cal yr BP, and the ice cap was subsequently absent or very small until a short-lived glacier event is seen in the lake sediments ~8200 cal yr BP. The ice cap was most likely completely melted until a new glacier event occurred around ~5300 cal yr BP, coeval with the onset of the Neoglacial at several other glaciers in southwestern Norway. Ålfotbreen was thereafter absent (or very small) until the onset of the Neoglacial period ~1400 cal yr BP. The ‘Little Ice Age’ (LIA) ~650–50 cal yr BP was the largest glacier advance of Ålfotbreen since deglaciation, with a maximum extent at ~400–200 cal yr BP, when the ELA was lowered approximately 200 m relative to today. The late onset of the Neoglacial at Ålfotbreen is suggested to be a result of its low altitude relative to the regional ELA. A synthesis of Neoglacial ELA fluctuations along the coast of Norway indicates a time-transgressive trend in the maximum extent of the LIA, which apparently seems to have occurred progressively later as we move northwards. We suggest that this trend is likely due to regional winter precipitation differences along the coast of Norway.

1. Introduction

In order to create robust projections of future climate change, it is of great importance to understand past natural climate variability, as this may help to discern the relative importance of

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natural and anthropogenic forcing on the climate system (Masson-Delmotte et al., 2013). Glaciers and ice caps are excellent climate indicators, as they respond to changes in temperature and precipitation; and thus, records of past glacier fluctuations can give information about past climate variability (Oerlemans, 2005). Presently, the annual mass-balance of small plateau glaciers located at the coast of south-western Norway is controlled mainly by winter accumulation, and mass-balance measurements from this area are therefore useful tools for exploring past variations in winter precipitation (Marzeion and Nesje, 2012). Glacier mass-balance data are, however, generally scarce; in some cases discontinuous; and extend only a few decades back in time. In order to expand records of glacier variability and associated winter precipitation beyond the instrumental record we therefore utilize natural archives, such as continuous sedimentary records from distal glacier-fed lakes.

Distal glacier-fed lakes act as traps for glacially eroded sediments that are transported by glacial meltwater streams down-valley, and by quantifying the influx of glacial sediment to these lakes it is possible to reconstruct continuous changes in upstream glacial erosion and hence glacier size through time. A large number of distal glacier-fed lakes have been investigated throughout Scandinavia, together providing an extensive overview of past glacier variability in this region (Karlén, 1976, 1981; Nesje et al., 1991; Dahl and Nesje, 1992; Karlén and Matthews, 1992; Dahl and Nesje, 1994; Matthews et al., 2000; Nesje et al., 2000b, 2001; Lie et al., 2004; Rosqvist et al., 2004; Bakke et al., 2005; Shakesby et al., 2007; Bakke et al., 2010; Vasskog et al., 2012; Bakke et al., 2013; Røthe et al., 2015; Wittmeier et al., 2015).

Some of these records present only relative changes in glacial input to the lakes, but in cases where dated moraine ridges are available to reconstruct the glacier extent at specific points in time, lake records can be calibrated to produce continuous reconstructions of changes in equilibrium-line altitude (ELA) (e.g. Nesje et al., 2001; Dahl et al., 2003; Bakke et al., 2010; Røthe et al., 2015). If an independent record of summer temperature is available, estimates of past winter precipitation can be extracted from continuous ELA reconstructions (e.g. Dahl and Nesje, 1996; Bjune et al., 2005) through the so-called ‘Liestøl equation’ described by O. Liestøl in Sissons (1979); a mathematical expression based on the empirical relationship between annual precipitation and summer temperature at the ELA of ten Norwegian glaciers.

Ålfotbreen is the westernmost ice cap in Norway, and the extreme maritime nature of this plateau glacier makes it a particularly interesting target for high-resolution reconstructions of past glacier fluctuations. From CE1963-2010, changes in the annual mass balance of Ålfotbreen have been mainly governed by the amount of winter accumulation ($R^2 = 0.71$) (data from: Kjøllmoen, 2011), but the relative importance of winter accumulation vs. summer ablation might be different when longer timescales are considered (Trachsel and Nesje, 2015). Long-term ELA reconstructions are therefore valuable tools for evaluating long-term natural variability of past winter climate. Here we present (1) a relative glacier fluctuation reconstruction of the Ålfotbreen ice cap during the Holocene; (2) a high-resolution reconstruction of Neoglacial ELA variations; (3) a constraint on the timing of the ‘Little Ice Age’ (LIA) maximum; and (4) reconstructed Neoglacial winter precipitation for the study area. Finally, we discuss the climatic implications of our findings in relation to other palaeoclimatic records in the North Atlantic region, including glacier records and winter precipitation reconstructions from other parts of Scandinavia, as well as possible forcing mechanisms that could explain the observed glacier variability.

2. Study area

2.1. Glacier, climate and bedrock

The Ålfotbreen plateau glacier (here defined as encompassing the two separate ice caps ‘Ålfotbreen’ and ‘Blåbreen’ with surrounding ice patches) covers an area of 15.5 km^2 (Andreassen et al., 2012), where the majority of the glaciated area is constrained to a limited altitude interval near the maximum elevation (Kjøllmoen, 2011; Andreassen et al., 2012). The glacier covers ~2.5 km^2 (~6%) of the total catchment area (41.5 km^2) of the downstream glacier-fed lake Grøndalsvatnet (see Section 2.2 below). Ålfotbreen (‘Å’ in Fig. 1C) and Blåbreen (‘B’ in Fig. 1C) are separated by a steep cliff in the area's tilted sedimentary Devonian bedrock (Bryhni and Lutro, 2000). Because of the distinct steps in the landscape, along with the narrow hypsometry of Ålfotbreen (altitude range <600 m), the ice cap does not feature very prominent outlet glaciers. Two adjacent north-facing outlet glaciers named Ålfotbreen (4.0 km^2; not to be confused with the ice cap itself) and Hansebreen (2.8 km^2) have been subject to mass-balance studies since CE1963 and CE1986, respectively (Kjøllmoen, 2011). During recent years the annual ELA has been raised above the highest elevation of the ice cap (>1382 m a.s.l.) several times (Kjøllmoen, 2011). See Fig. 1 for an overview of the study area, and Fig. 2 for an overview of the narrow hypsometry of the two outlet glaciers mentioned above. From here on, the term ‘Ålfotbreen’ includes both outlet glaciers mentioned above, the two ice caps Blåbreen and Ålfotbreen as well as the surrounding ice patches, unless stated otherwise.

Relative to area, Ålfotbreen has the largest annual mass turnover of the monitored glaciers in Norway, with the highest recorded values for both winter accumulation and summer ablation (Kjøllmoen, 2011). For Ålfotbreen, winter accumulation is considered more important in determining its net mass balance than summer ablation (Nesje, 2005), and a large gain in mass between CE1989-95 was mainly caused by high winter balance (Andreassen et al., 2005). Despite the large mass turnover, Ålfotbreen is ranked as the most vulnerable glacier in Norway, mainly due to its narrow hypsometric distribution above the steady-state ELA (~200 m, Fig. 2), and it might therefore be one of the first glaciers to disappear completely in a warmer future climate (Nesje et al., 2008; Andreassen et al., 2012). Inferences about past extent and fluctuations of Ålfotbreen have previously been published by Nesje et al. (1995) and Sønstegaard et al. (1999); however, neither of these studies obtained a complete Holocene glacial history. Nesje et al. (1995) focused on the late-Holocene glacier history and avalanche activity, whereas Sønstegaard et al. (1999) were targeting the deglaciation history of the area. As an isolated ice cap from the main Scandinavian ice sheet during the Younger Dryas (YD), Ålfotbreen obtained its maximum YD extent just before the deposition of the Vedde Ash Bed (Sønstegaard et al., 1999). The further history of deglaciation and Holocene glacier variations has so far been poorly constrained for Ålfotbreen (Nesje, 2009).

The present climate of the study area is maritime with a mean CE1961-1990 summer temperature (Ts; 1 May-30 September) of 12.12 °C (climate station 58070 Sandane, ca. 30 km east of Ålfotbreen; 51 m a.s.l.). Mean CE1961-1990 winter precipitation (Pw; 1 October – 30 April) at the 57680 Eikefjord climate station (ca. 20 km south-southwest of Ålfotbreen; 30 m a.s.l.) is 1677 mm (eKlima.no); and snow accumulations of up to 8–10 m during winter are not unusual at the top of Ålfotbreen (Andreassen et al., 2012).

2.2. Catchment lakes and geomorphological setting

Lake Grøndalsvatnet (~0.27 km^2; N 61°41′, E05°34′) is located