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Numerical analyses of a multi-proxy data set from a distal glacier-fed lake, Sørsendalsvatn, western Norway

Jostein Bakke [a,b,*,2], Mathias Trachsel [a,b,1,2], Bjørn Christian Kvisvik [b,c], Atle Nesje [a,b], Astrid Lyså [d]

[a] Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway
[b] Bjerknes Centre for Climate Research, Uni Research, Allégaten 55, 5007 Bergen, Norway
[c] Department of Geography, University of Bergen, Fosswinckelsgate 6, 5020 Bergen, Norway
[d] Geological Survey of Norway, Leiv Eirikssons vei 39, 7040 Trondheim, Norway

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A B S T R A C T

Here we present a Holocene record of glacier variability as documented through physical sediment properties analysed on sediments from the distal glacier-fed Lake Nedre (Nedre = Lower) Sørsendalsvatn (918 m a.s.l.), located 35 km inland from the coast in western Norway. We emphasise comparing different sediment parameters by means of statistical methods as well as integrating chronological uncertainties along with uncertainties of reconstructed glacier variability. A multi-proxy data set consisting of sedimentological, physical, and geochemical data shows one main process, as extracted by means of principal component analysis (88% of the variance explained by the first PC), driving sediment variability in Nedre Sørsendalsvatn. The common signal extracted from the sediment data is indicative of glacial activity in the catchment and is interpreted to vary in concert with the changing glacier equilibrium-line altitude. The reconstruction of former glacier activity is in accordance with glacier variability reconstructed from other sites in western Norway, including the termination of the deglaciation at approximately 10,000 cal yr BP, the 8.2 ka BP (Finse) event, the Holocene thermal optimum between ~8000 and 5500 cal yr BP, and the onset of the Neoglacial at 5500 cal yr BP. The largest glacial extent during the Neoglacial time period took place during the 'Little Ice Age'. The combined radiocarbon chronologies from three different sediment cores provide insight into the duration of the "8.2 ka event" in the terrestrial system. The maximum glacier activity at approximately 8.2 cal BP is the culmination of a glacier advance that began around 9 cal BP and accelerated at 8.4 cal BP. The glacier advance ended abruptly at 8.0 cal BP.

1. Introduction

Alpine glaciers are commonly located in remote and high-altitude regions which are rarely covered by instrumental or historical records. Past and present sizes of alpine glaciers hold an integrated signature of atmospheric processes as their size is related to changes in both the ablation season temperature and the amount of solid winter precipitation. Robust glacier reconstruction can be an important source of knowledge regarding past climate and can provide a better understanding of natural climate variability (Jansen et al., 2007).

The Swedish scientist Wibjörn Karlén initially suggested that glacial erosion, and the associated production of rock-flour deposited in downstream lakes, could provide a continuous record of glacial fluctuations, overcoming the problem of incomplete reconstruction obtained by e.g. dating of marginal moraines or mega-fossils in glacier forelands (Karlén, 1976). The method of reconstructing glaciers based on analyses of sediments from distal glacier-fed lakes was later applied in other glaciated areas and has been further developed since, through several different approaches (e.g. Leemann and Niessen, 1994; Nesje et al., 2001; Bakke et al., 2010). The readings regarding glacial signals preserved in lake sediments now include applications of various methods. These methods measure the amount of minerogenic versus biologic matter (typically inferred from loss-on-ignition (LOI)), grain-size analysis, magnetic properties, Rare-Earth Elements, dry bulk density (DBD), and analysis of elemental composition by means of ITRAX-XRF, resulting in multivariate data sets suited to analyses by numerical methods.

* Corresponding author. Department of Earth Science, University of Bergen, Allégaten 41, 5007 Bergen, Norway.
E-mail address: Jostein.Bakke@geo.uib.no (J. Bakke).
[1] Currently at: Department of Biology, University of Bergen, Thormøhlensgate 53a, 5006 Bergen, Norway.
[2] These authors contributed equally to this manuscript.

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While numerical analytical methods have been widely and successfully applied to biological proxy data sets (e.g. Birks et al., 2010; Borcard et al., 2010), these methods are more rarely applied to sedimentological data sets (e.g. Olsen et al., 2010; Vasskog et al., 2012). Numerical methods introduce objectivity, allow for a better understanding of interrelations among proxies, provide a sound base for subsequent data interpretation, and enable us to interpret more than one proxy at a time. Applying these numerical methods to sedimentological data will therefore improve the understanding and interpretation of large data sets and thereby objectify and strengthen interpretations of past climate. Important advances have been made in age–depth modelling and uncertainty estimations of age–depth models (e.g. Haslett and Parnell, 2008; Blaauw, 2010). Chronological uncertainty is one of the most critical uncertainties in climate reconstruction, based on sedimentary archives. This uncertainty is commonly acknowledged when presenting age–depth models (e.g., Blaauw et al., 2007). However, only a few studies explore the transformation of age uncertainty into variable uncertainty (e.g. Blaauw et al., 2007; Parnell et al., 2008).

In this study, we present a lacustrine sediment record based on three c. 3.5 m-long sediment cores from the distal glacier-fed lake Nedre Sørsendalsvatn located downstream of Blåbreen in Nordfjord, western Norway (Fig. 1). A suite of sediment analyses and numerical methods has been invoked in order to identify the glacial signal and quantify the precision of the glacier reconstruction. The first objective of this study is an analysis of the sedimentary proxy data sets obtained from the three sediment cores from Nedre Sørsendalsvatn by means of numerical methods in order to better understand the interrelations of sediment variables and improve subsequent inferences on glacier size variability. To achieve this, the cores have been objectively divided into stratigraphic zones of significantly different sediment variables. We then compared three pre-defined data sets (sedimentology, geochemistry and grain-size analyses) both internally and among one another. We thereby identified phases of agreement and disagreement between different variables. These differences were attributed either to differing secondary processes in the catchment or to non-linearity between the variables. Finally, a common signal among the different variables was extracted by means of principal component analysis (PCA). A second objective of this study was to transform uncertainty in the radiocarbon-based chronology into uncertainties in our knowledge of past glacier size variability in the catchment of Nedre Sørsendalsvatn. This was achieved by using existing age–depth modelling algorithms based on bootstrapping techniques (Blaauw, 2010) in order to obtain a multitude of possible age–depth models and thereafter transform the different age–depth models into variable uncertainties. Finally, we discuss and compare the findings from Nedre Sørsendalsvatn with Holocene glacier variability elsewhere in Scandinavia and in relation to selected palaeoclimate proxy archives within the Atlantic Ocean.

2. Study area

2.1. Glacier, climate and bedrock

The lakes Øvre (=Upper) and Nedre Sørsendalsvatn (61°67′35″N, 6°28′85″E) are located in the upland mountain area to the south of Gloppenfjorden, a south-easterly trending branch of Nordfjord, at an elevation of 928 m and 918 m (Figs. 1 and 2). The topography of the area is dominated by several individual summits, with the highest, Botnafjellet (1572 m), to the southeast of the Sørsendalsvatn lakes (Figs. 1 and 2). Deep glacial troughs and cirque basins dissect the landscape. Some of the north-facing cirques and headwalls host small glaciers and large perennial snow patches. The catchment of Nedre Sørsendalsvatn covers an area of 8.5 km^2, which includes the glacier Blåbreen occupying an area of approximately 2 km^2. The bedrock in the area is of Precambrian age and is dominated by gneissic bedrock (Bryhni and Grimstad, 1970). The equilibrium-line altitude (ELA) at Blåbreen is c. 1050 m a.s.l. in years when the net balance is close to zero (Østrem et al., 1988). The present climate is semi-continental to maritime with a mean (1961–1990) summer ablation season temperature (1 May–30 September) of 12.12 °C at the meteorological station Sandane (station no. 58,070, 51 m a.s.l.) (eKlima.no). Using an environmental lapse rate of 0.65 °C/100 m (Sutherland, 1984) provides a mean summer temperature (T_s) at the present ELA (1050 m) of Blåbreen of c. 5.5 °C. Winter precipitation (P_w) (1 October–30 April) based on the Myklebust station (station no. 58,320) shows a mean (1961–1990) of 1023 mm at 315 m a.s.l. (eKlima.no). Using a suggested mean exponential increase in winter precipitation with altitude of 8%/100 m in southern Norway (Haakensen, 1989), the precipitation is calculated as close to 1800 mm at the ELA of Blåbreen. According to the “Liestøl-equation” (Liestøl in Sissons, 1979) there should be no glacier at Blåbreen based on the summer temperature and winter precipitation values. It is therefore evident that the supply of solid snow from wind drift and avalanching from Botnafjellet is important for sustaining a positive net mass balance at Blåbreen (Fig. 3).

The glacier foreland and the glacial geomorphology of Blåbreen and its surroundings were intensively studied during the 1990’s as there was discussion regarding the age of the Neoglacial moraines in the area, with implications for the moraine chronologies of entire western Scandinavia (Evans et al., 1994; Matthews et al., 1996; Evans, 1997). A well-preserved recessional moraine sequence is mapped in front of Blåbreen (Evans et al., 1994). Marginal moraines on the northern side of Lake Øvre Sørsendalsvatn are well vegetated and not dated, whereas terminal moraines closer to Blåbreen have been subject to lichen measurements by Evans et al. (1994) and Matthews et al. (1996). Evans et al. (1994) distinguished three moraine stages. Both author groups agree that the stage 3 moraines are of late-glacial age, and that stage 1 moraines formed in the early 19th century, but disagree on the age of stage 2 moraines (Fig. 1). While Evans et al. (1994) dated stage 2 moraines between 400 and 800 cal yr BP, Matthews et al. (1996) questioned the lichen measurements of Evans et al. (1994) and concluded that these moraines are at least 5000 years old, based on Schmidt hammer measurements. Based on the lake sediment study presented below, we support the view of Matthews et al. (1996) that the stage 2 moraines are of early Holocene age (see Section 5.2).

2.2. Catchment lakes

In this study, we present analyses of sediment cores retrieved from Nedre Sørsendalsvatn (Figs. 1 and 2). The present meltwater draining from the glacier Blåbreen is routed through the Øvre Sørsendalsvatn. This is a small lake of 0.34 km^2 with one main inlet, three smaller tributary streams, and one outlet in the eastern part. The river from Blåbreen enters the lake through a well-developed glaciofluvial fan delta, where the direction of the river entering the lake changes between a northerly and westerly position from year to year due to changing sediment supply and runoff over the outwash plain. Both the glaciofluvial fan delta and the lake basin of Øvre Sørsendalsvatn are traps for the sediments transported with the glaciofluvial meltwater stream, implying that only sediments in suspension are transported further downstream and into Nedre Sørsendalsvatn. Nedre Sørsendalsvatn is 460 m along its longest axis and covers an area of 0.065 km^2. The lake has two inlets, the main river from Øvre Sørsendalsvatn enters the lake in the NW corner and three smaller tributary streams enter the lake in the SW