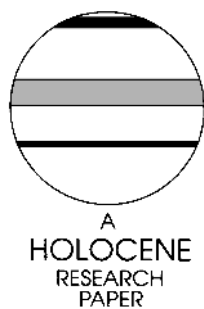


Holocene glacier fluctuations of Flatebreen and winter-precipitation changes in the Jostedalsbreen region, western Norway, based on glaciolacustrine sediment records

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Abstract: The history of Holocene glacier variations of Flatebreen, an independent glacier close to the SW part of the Jostedalsbreen ice cap, has been reconstructed from lacustrine sediments in the proglacial lake Jarbuvatnet. The sedimentary succession shows evidence of three main episodes of Holocene glacier expansion. The first is recorded in the basal part of the core up to 370 cm. According to the age/depth relationship in the sediment core (based on 12 AMS radiocarbon dates), this glacier expansion episode terminated about 10200 cal. yr BP. The second major glacier phase lasted from 8400 to 8100 cal. yr BP, while the third was initiated around 4000 cal. yr BP and has continued up to the present. At 43 cm in the core, the medium silt content increases significantly, accompanied by a minor increase in the sand content. This textural change is interpreted as the first time that the terminus of Flatebreen extended into an upstream lake at 1083 m a.s.l. The age model suggests that this event took place around 800 cal. yr BP (~AD 1150), as a response to the initial 'Little Ice Age' glacier expansion after the 'Mediaeval Warm Period'. By using a Holocene-inferred summer-temperature curve from central southern Norway in the exponential relationship between annual winter precipitation (snow) and ablation-season temperature at the ELA, periods of higher winter precipitation than the 1961–90 normal in the Jostedalsbreen region are inferred for 9700–9400, 9200–8300, 8200–6500, 5700–5100, 4700–4600, 4500–4300, 3800–3000, 2100–1800, 1600–1300 and 1200–1000 cal. yr BP, and from 900 cal. yr BP to the present. The intervening periods of lower than normal winter precipitation correlate with periods of enhanced ice-rafting in the North Atlantic.

Key words: Proglacial lake sediments, glacier history, equilibrium-line altitude, Holocene winter-precipitation variations.

Introduction

In Scandinavia, several natural archives reveal how Holocene climate has changed. Palynological and plant macrofossil studies have documented the vegetation history and major climate changes (e.g., Berglund, 1986). Changes in the pine-tree limit have been interpreted as a result of variations in temperature during the germination season (Kullman, 1998). Holocene summer temperature has been reconstructed with annual time resolution

from dendrochronological and dendroclimatological studies (Briffa *et al.*, 1992; Grudd, 1998; Eronen *et al.*, 1999; Kalela-Brundin, 1999).

Glaciers are sensitive indicators of changes in summer temperature and winter precipitation. Radiocarbon dates obtained from organic material from beneath terminal moraines have yielded maximum ages of glacier advances (Matthews, 1985; 1991; Matthews and Caseldine, 1987). While dates obtained from moraine sequences commonly reveal discontinuous information on glacier

variations, continuous records of Holocene glacier fluctuations may be obtained from distal lacustrine sediments and peat sections intercalated with glacially derived minerogenic sediments (Karlén, 1976; 1981a; 1981b; 1988; 1993; Nesje and Dahl, 1991a; 1991b; Nesje and Kvamme, 1991; Nesje *et al.*, 1991; 1994; 1995; 2000; Karlén and Matthews, 1992; Matthews and Karlén, 1992; Dahl and Nesje, 1994; 1996; Karlén *et al.*, 1995).

Holocene climate has until recently been considered to be more or less stable with no abrupt changes on the scale of those which characterized the glacial climate, as reconstructed from ice cores (e.g., Dansgaard *et al.*, 1993). Data obtained recently from terrestrial and marine archives, however, indicate several significant Holocene climate oscillations. These palaeoclimate records demonstrate that a considerable part of the Holocene has been characterized by brief and abrupt millennial-scale climatic events (O'Brien *et al.*, 1995; Alley *et al.*, 1997; Bond *et al.*, 1997; Campbell *et al.*, 1998; Barber *et al.*, 1999).

In Jarbuvatnet (named Flatebrevatnet II by Karlén and Matthews, 1992), located close to Briksdal at the western side of Jostedalsbreen (Figures 1 and 2), Karlén and Matthews (1992) and Matthews and Karlén (1992) obtained a 1.7 m long core comprising stiff, homogeneous grey silt/clay and eight thin, but distinct, moss layers between 130 and 170 cm depth in core. Radiocarbon dates of two 2–3 cm thick moss layers at 152–154 and 167–170 cm indicated the presence of Flatebreen, a minor glacier at the SE margin of Myklebustbreen, at least since 5610 (5715–5585) cal. yr BP (4890 ± 80 ^{14}C yr BP), with intensified glacial activity after 5305 (5445–5085) cal. yr BP (4600 ± 70 ^{14}C yr BP) and

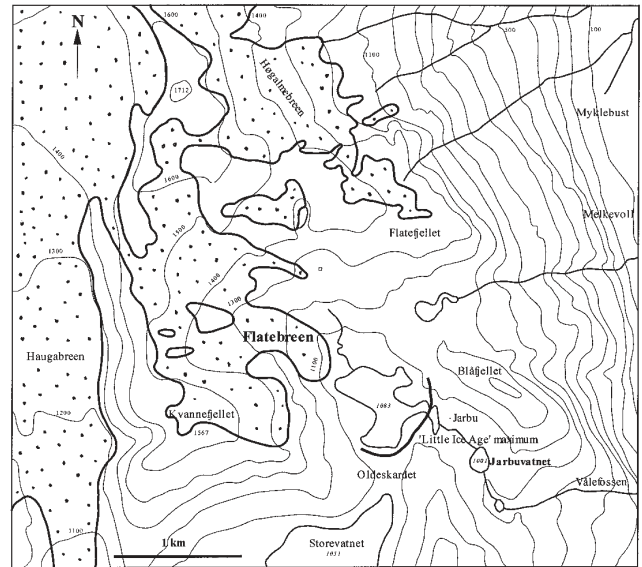


Figure 2 The area around Flatebreen and Jarbuvatnet. Present glaciers are stippled.

in particular subsequent to about 4800 cal. yr BP (4200 ^{14}C yr BP). Stimulated by the results presented from the initial coring in Jarbuvatnet, two sediment cores were retrieved from lake ice in the spring of 1996. This paper reports the results from this second coring in Jarbuvatnet. Together with previous data on Holocene

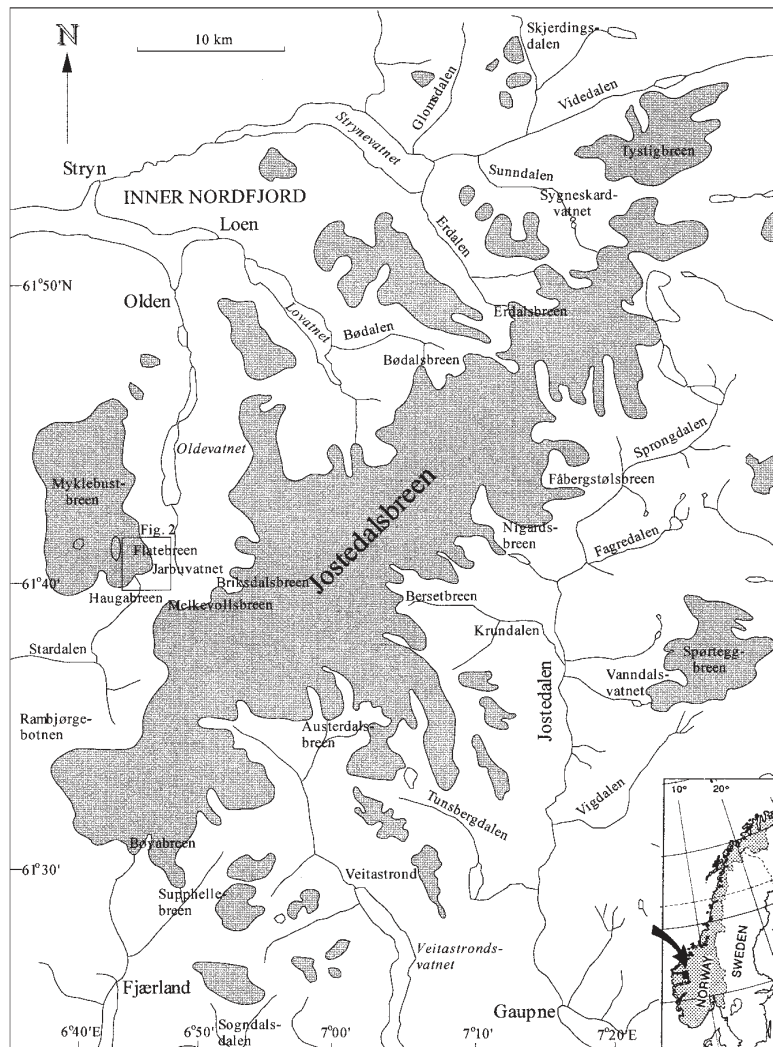


Figure 1 Location map of the Jostedalsbreen region.

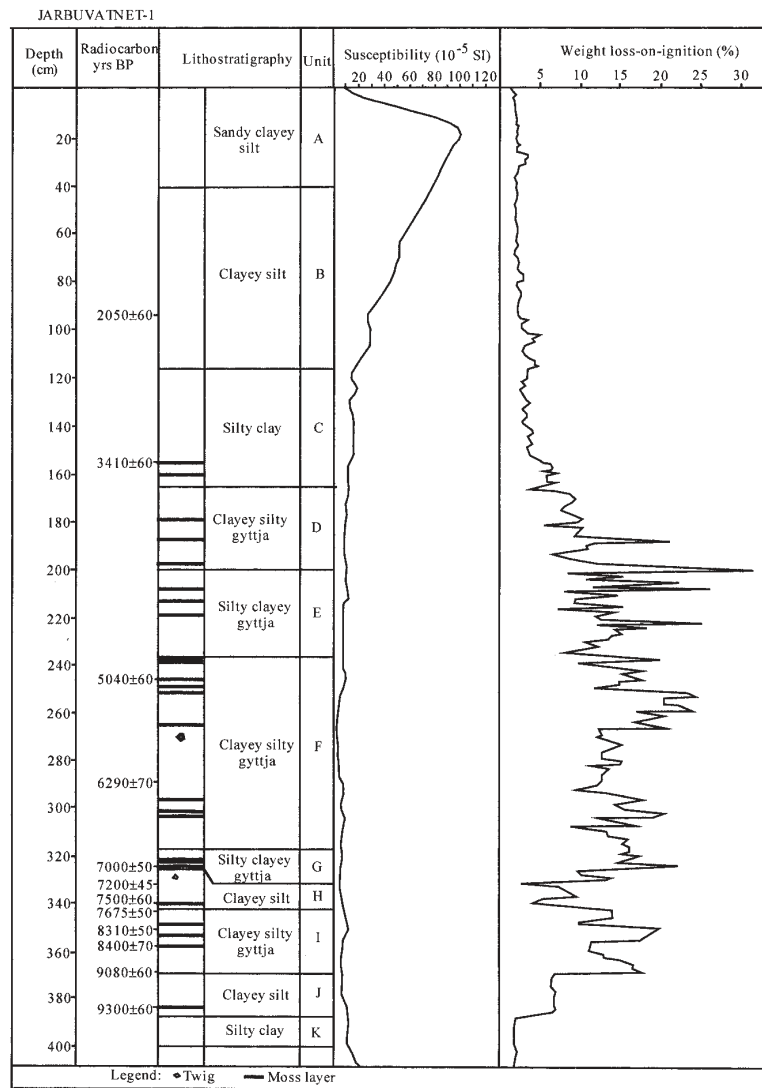


Figure 3 Lithostratigraphy, radiocarbon dates (± 1 sigma), magnetic susceptibility and weight loss-on-ignition in core Jarbuvatnet-1.

glacier variations of Jostedalsbreen (e.g., Nesje *et al.*, 1991), the records from Sygneskardvatnet (Nesje *et al.*, 2000) and Jarbuvatnet are combined to produce Holocene glaciation and equilibrium-line altitude (ELA) curves from the Jostedalsbreen region. By using an exponential relationship between annual precipitation as snow and ablation-season temperature at the ELA, a Holocene winter-precipitation curve has been reconstructed for the Jostedalsbreen region.

Study site

Flatebreen, a 1.47 km² glacier with an eastern aspect (Østrem *et al.*, 1988), is located SE of Myklebustbreen (50 km²), and SW of Jostedalsbreen (487 km²), the largest glacier on mainland Europe (Figure 1). The proglacial stream from Flatebreen first reaches a lake at 1083 m a.s.l. before it enters Jarbuvatnet (1001 m), from which the sediment cores were retrieved (Figure 2). Marginal moraines show that during the 'Little Ice Age' maximum Flatebreen reached a position 890 m beyond its present position (Figure 2). Jarbuvatnet is located approximately 1.4 km and 0.5 km in front of the present glacier margin and the 'Little Ice Age' marginal position, respectively. Flatebreen reaches a maximum altitude of 1680 m, while the glacier terminus is at *c.* 1090 m, an altitudinal range of 590 m. The present ELA of Flatebreen has been calculated as 1420 m using an accumulation area ratio (AAR) of 0.6.

Methodology

The coring was carried out from lake ice during the spring of 1996. Two cores were retrieved approximately 20 m apart at a water depth of 12 m from the central, deepest and flat-bottomed part of the lake. The cores were retrieved by a piston corer with a 11 cm core tube constructed to obtain up to 6 m of sediments (Nesje, 1992). The cores were stored in a cold room until opening. After opening, the sediment layer closest to the tube wall was removed and the sediment surface was cleaned carefully. Lithofacies and sedimentological structures and textures were described before the cores were split into 1 cm slices and put into plastic bags and stored in a cold room.

Lake sediments are considered one of the best archives of Holocene palaeoclimatic information in Scandinavia (e.g., Karlén and Matthews, 1992; Karlén, 1998; Karlén *et al.*, 1995; 1999). Seasonal, annual and decadal variations in glacier activity influence sediment production and deposition in proglacial lakes. Clastic sediments from upstream glaciers and from adjacent surface runoff from rainfall and snowmelt throughout the summer settle out of suspension and become deposited in the lakes. Lakes downstream from temperate glaciers and lakes surrounded by dense vegetation are commonly characterized by relatively high sedimentation rates and thereby high time resolution. If not affected by bioturbation, the seasonal depositional variation may also result in the annual production of laminae/varves. However, the sediments may be subject to disturbances from landslides,

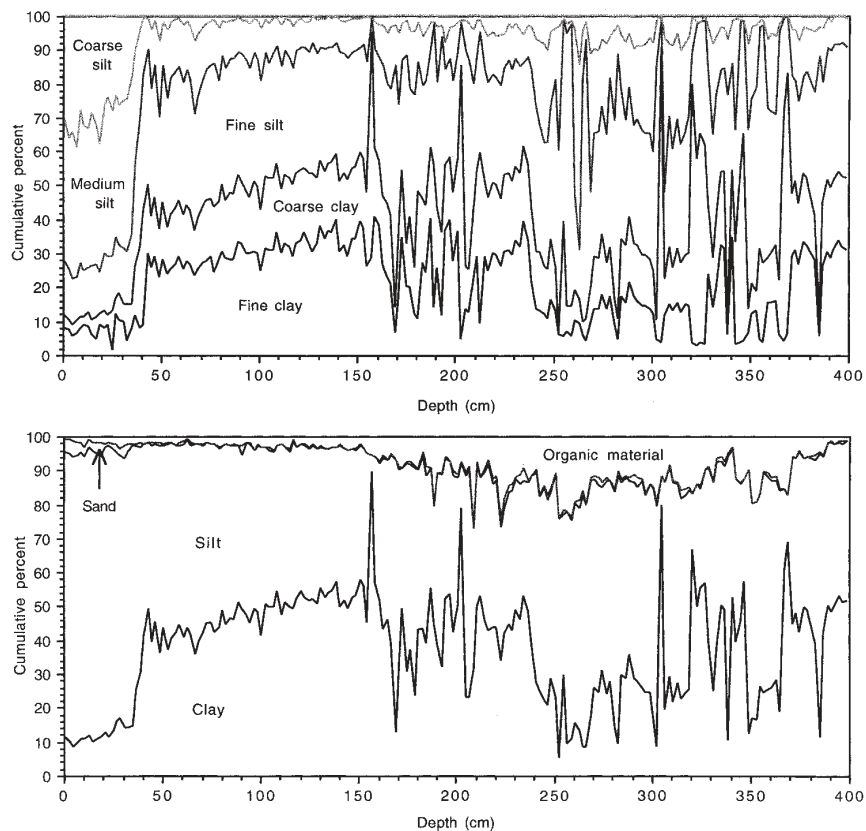


Figure 4 Top: cumulative weight percentage of fine and coarse clay, and fine, medium and coarse silt in core Jarbuvatnet-1 (the sand fraction is excluded). Bottom: cumulative weight percentage of clay, silt, sand and organic material in core Jarbuvatnet-1.

turbidites, avalanches or debris flows from adjacent valley sides, erosion by surface or bottom currents, lake ice, resuspension, diagenetic reactions combined with diffusional migration of soluble components, and human activity in the lake catchment.

Grain-size variations are indicators of glacier activity of wet-based glaciers due to the nature of glacially eroded sedimentary particles which are transported downstream and produce characteristic signatures in proglacial lake sediments (e.g., Boulton, 1978; Matthews *et al.*, 2000). The grain sizes deposited in proglacial lakes depend mainly on bedrock lithology, lake size, transport distance and the number of intervening lakes acting as sediment traps (e.g., Smith, 1978). To analyse the grain-size distribution in core Jarbuvatnet-1, a Micromeritics Sedigraph 5100 Particle Size Analysis System was used. This device measures particle diameters ranging from 0.1 to 300 microns (μm) equivalent spherical diameters by sending x-rays through suspended material (Sedigraph 5100, 1993). Together with the Sedigraph 5100, a MasterTech 51 Automatic Sampling Device was used, enabling 18 samples to be run consecutively (MasterTech 51, 1993). Approximately 1–2 cm^3 of sediment from each analysed layer (every 2 cm) was wet sieved through a 300 μm mesh using a 0.05% calgon deflocculation solution [$(\text{NaPO}_3)_6$] and stored overnight in *c.* 70 ml of calgon solution. Before placing the samples in the automatic sampler, the sediment was deflocculated ultrasonically. The sedigraph data were grouped into the following grain-size fractions; fine (<0.001 mm) and coarse (0.001–0.002 mm) clay, fine (0.002–0.006 mm), medium (0.006–0.020 mm), coarse (0.020–0.060 mm) silt, and fine (0.060–0.200 mm) and medium (0.200–0.600 mm) sand.

Weight loss-on-ignition (LOI) is an effective method for estimating the organic content of lacustrine sediments (e.g., Dean, 1974; Heiri *et al.*, 2001). It has been demonstrated that there is a close relationship between total organic carbon (TOC) and LOI, where the latter gives approximately 2% higher values, most probably as a result of evaporation of crystalline water from hydroxyl

groups in layered minerals (Snowball and Sandgren, 1996). In fine-grained, clayey material the latter may represent a significant part of the LOI values. The samples were dried overnight at 105°C in ceramic crucibles before the dry weight was measured (normally 1–3 g). In the furnace, the samples were subject to gradually rising temperatures for half an hour and ignited at 550°C for one hour (Dean, 1974). The samples were then placed in a desiccator and weighed at room temperature. The weight loss-on-ignition was calculated as percent of dry weight. To test if the length of the ignition time has any effect on the LOI values, 100 samples (from another core) were ignited for an extra hour. The mean (± 1 sigma) deviation between the two runs was only 0.73 \pm 0.55 % ($r = 0.99$). LOI has been widely used in reconstructing Holocene glacier variations from glaciolacustrine sediments where minerogenic sedimentation is inversely related to organic content (Karlén, 1976; 1981b; Nesje *et al.*, 1991; 2000).

Magnetic susceptibility of lacustrine sediments is a useful indicator of erosion and transport of clastic sediments in lake catchments (Snowball and Thompson, 1990; Snowball *et al.*, 1999). Colder climates without a stabilizing vegetation cover commonly cause high susceptibilities due to increased erosion and deposition of minerogenic sediments (e.g., Stockhausen and Zolitschka, 1999). Commonly, magnetic susceptibility reflects the concentration of magnetic minerals (e.g., Thompson and Oldfield, 1986). Mineral magnetic measurements have also been used as an indicator of glacier activity (Sandgren and Risberg, 1990; Nesje *et al.*, 1991; 1994; Matthews and Karlén, 1992; Snowball, 1993; Dahl and Nesje, 1994; 1996; Snowball and Sandgren, 1996; Sohlenius, 1996). Increased glacier activity in the lake catchment and thereby increased erosion and input of clastic sediments causes higher minerogenic content, as also reflected in the LOI content. Periods of insignificant and reduced glacier activity in the lake catchment are characterized by low production of glacially derived sediments. Increased magnetic susceptibility has therefore been related to the amount of allochthonous clastic

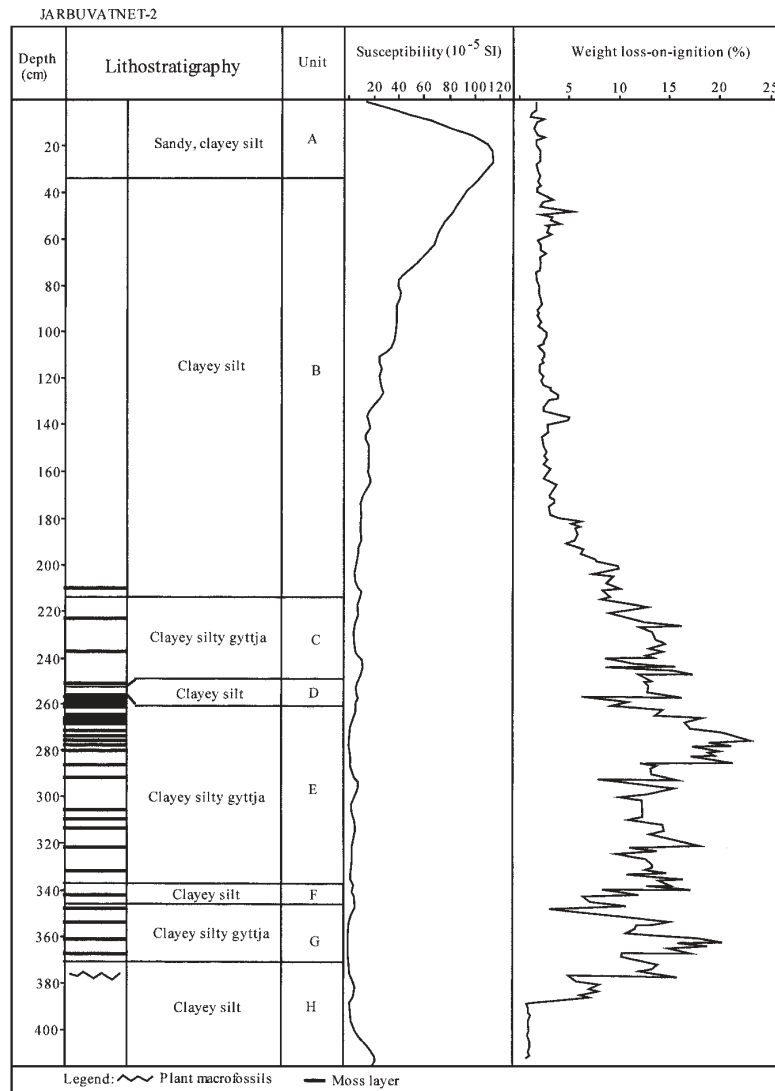


Figure 5 Lithostratigraphy, magnetic susceptibility and weight loss-on-ignition in core Jarbuvatnet-2.

material transported into the lake (e.g., Thompson *et al.*, 1975). However, magnetic susceptibility may also reflect non-glacial inputs to the lake, supplied by surface runoff during rainfall, floods and mass movement events (snow avalanches and debris flows) from adjacent valley sides (e.g., Karlén and Matthews, 1992; Nesje *et al.*, 1995). Whole core, pass-through, volume susceptibility at 2 cm resolution was carried out on the two Jarbuvatnet cores using a Bartington MS2B sensor.

Support for the use of LOI and magnetic susceptibility as indicators of glacier-size variations is provided by data obtained through a study of sediment yield from nine Norwegian glaciers (Roland and Haakensen, 1985), which shows a strong positive correlation ($r = 0.86$) between glacier size and calculated sediment transport in proglacial rivers. Variations in glacier size are mainly determined by variations in equilibrium-line altitude (ELA), the main climatic factors contributing to variations in the ELA being winter accumulation and summer ablation.

Accelerator mass spectrometry (AMS) radiocarbon dating on bulk samples was carried out at Beta Analytic Inc., Florida, USA, and at the R.J. Van de Graff Laboratorium, University of Utrecht, The Netherlands, following standard procedures for AMS radiocarbon dating. The radiocarbon ages are corrected for $\delta^{13}\text{C}$. Calibration of the radiocarbon ages to calendar years BP (BP = AD 1950) was done using the calibration program CALIB 4.1.2 for atmospheric samples (Stuiver *et al.*, 1998).

Results

Core Jarbuvatnet-1

Core Jarbuvatnet-1 (411 cm long) was obtained from 12 m water depth in the central part of lake Jarbuvatnet. The core has been divided into eleven sedimentary units (Figure 3). Units A, B, C, H, J and K are dominated by clastic sediments with low organic content. Units A and B show relatively high magnetic susceptibility and low (~2%) LOI values, whereas unit C has low susceptibility values and increasing LOI content downward. Units D, E, F, G and I are characterized by low magnetic susceptibility values and LOI values generally higher than 10%. Sedigraph analysis at 2 cm intervals (Figure 4) shows that the upper 40 cm consist of sandy clayey silt. Between 40 and 155 cm, the percentage of clay increases at the expense of silt. In the depth interval between 155 and 240 cm, the clay and silt content varies considerably; however, between the latter and 305 cm the silt content increases while the clay content decreases. The lower part of the core is characterized by large grain-size variations, with a generally decreasing sand content towards the bottom of the core.

Core Jarbuvatnet-2

Core Jarbuvatnet-2 (409 cm long), retrieved from 12 m water depth and 20 m from core Jarbuvatnet-1, was divided into eight

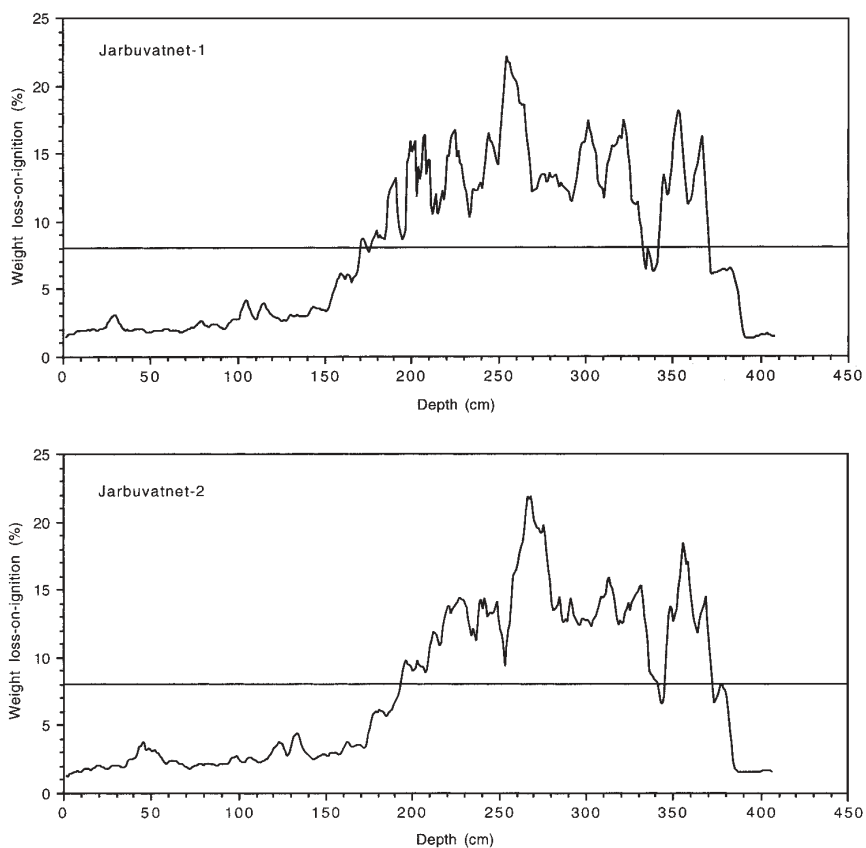


Figure 6 Smoothed (5 cm running mean) weight loss-on-ignition curves in cores Jarbuvatnet-1 and Jarbuvatnet-2. The horizontal lines at 8% marks the loss-on-ignition value below which the glacier in the catchment was clearly present according to the sediment texture in the study cores.

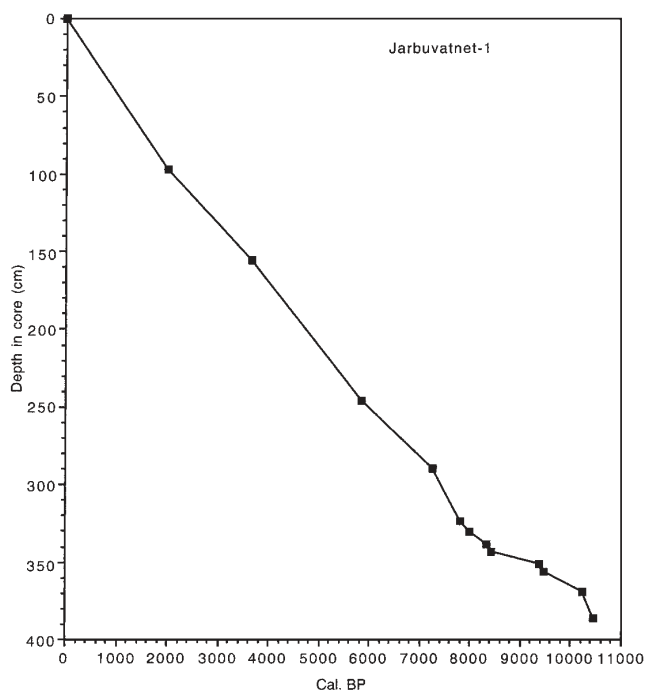


Figure 7 Age/depth model for core Jarbuvatnet-1 based on linear interpolation between the intercept calendar ages (Table 1).

sedimentary units (A–H) (Figure 5). Units A, B, D, F and H are dominated by minerogenic material and low organic content. Units C, E and G, on the other hand, consist of clayey silty gyttja (LOI >10%). The magnetic susceptibility values are highest in the upper 80 cm of the core, peaking around 25 cm.

Radiocarbon dating, time resolution and accumulation rates

Cores Jarbuvatnet-1 and 2 show an almost identical sediment succession and LOI pattern (Figures 4, 5 and 6). The horizontal lines at ~8% in Figure 6 indicate the transition between bluish-grey clastic sediments typical of sediments deposited along the present glacier meltwater stream and more brown-coloured, organic-rich sediments deposited when the glacier is interpreted to have been very small and/or periodically melted away from the lake catchment. Since the two cores are almost identical, core Jarbuvatnet-1 was arbitrarily chosen for detailed AMS radiocarbon dating. Altogether, 12 AMS radiocarbon dates were obtained on gyttja and moss (unidentified) layers in core Jarbuvatnet-1 (Figure 3; Table 1). An age/depth model for Jarbuvatnet-1 was obtained by linear interpolation between the radiocarbon-dated levels (Figure 7; Table 1). The time resolution between the radiocarbon dated levels (based on intercept calendar ages) in Jarbuvatnet-1 varies from 13 yr cm⁻¹ (369–386 cm) to 118 yr cm⁻¹ (343–351 cm). The accumulation rate varies between 0.09 mm yr⁻¹ (343–351 cm) and 0.79 mm yr⁻¹ (369–386 cm) with a mean time resolution of 35 yr cm⁻¹ and an average accumulation rate of 0.42 mm yr⁻¹ in core Jarbuvatnet-1 (Table 2).

The age model for Jarbuvatnet-2 was obtained by graphically correlating the LOI record to the corresponding record from Jarbuvatnet-1. The correlation was performed on the unsmoothed data using AnalySeries 1.1 (Paillard *et al.*, 1996). The correlation was straightforward for most of Jarbuvatnet-2, despite significant differences in amplitude over some intervals. The correlation resulted in 42 control points which were used to create an age-depth model for Jarbuvatnet-2 (Figure 8, above).

Table 1 Radiocarbon dates from core Jarbuvatnet-1 (the age calibration is based on Stuiver *et al.*, 1998)

Depth (cm)	Dated material	Lab. code	¹⁴ C age	Intercept cal. yr BP	1 sigma cal. yr BP	δ ¹³ C
96–98	Bulk sediment	Beta-96599	2050 ± 60	1995	2115–1930	–25.8
156	Moss	Beta-96600	3410 ± 60	3665	3715–3575	–26.1
246	Moss	Beta-96601	5040 ± 60	5830	5895–5665	–23.9
290	Gyttja	Beta-96602	6290 ± 70	7245	7270–7100	–23.3
324	Gyttja	UtC-6556	7000 ± 50	7805	7925–7755	–25.0
331	Bulk sediment	UtC-6557	7200 ± 45	7990	8050–7925	–25.5
338	Moss	UtC-6558	7500 ± 60	8340	8375–8200	–25.9
343	Gyttja	UtC-6559	7675 ± 50	8420	8535–8405	–26.2
351	Gyttja	Beta-96603	8310 ± 50	9360	9465–9155	–24.4
356	Moss	UtC-6560	8400 ± 70	9450	9515–9305	–26.1
369	Gyttja	UtC-6561	9080 ± 60	10220	10240–10195	–25.0
385–386	Moss	Beta-96604	9300 ± 60	10435	10580–10295	–23.3

Table 2 Time resolution and accumulation rates in core Jarbuvatnet-1

Depth interval (cm)	Time resolution (yr cm ⁻¹)	Accumulation rate (mm yr ⁻¹)
0–97	21	0.49
97–156	28	0.35
156–246	24	0.42
246–290	32	0.31
290–324	16	0.61
324–331	26	0.38
331–338	50	0.20
338–343	16	0.63
343–351	118	0.09
351–356	18	0.56
356–369	59	0.17
369–386	13	0.79
Mean:	35	0.42

Grain-size variations

Figure 4 (top) shows variations in the cumulative weight percent of five different clay and silt fractions in core Jarbuvatnet-1 and the cumulative weight percent of the clay, silt, sand and organic fractions (bottom).

Holocene glacier history of Flatebreen

The smoothed 5 cm running mean LOI curves, the magnetic susceptibility and the grain-size variations (Figures 3, 5 and 8), together with visual and sediment textural criteria are considered to reflect glacier activity in the lake catchment. In the Jarbuvatnet cores, there is evidence of three major glacier expansion episodes. According to the age/depth model, episode 1 ended by 10200 cal. yr BP, episode 2 lasted from about 8400 to 8100 cal. yr BP, and episode 3 began around 4000 cal. yr BP and lasted up to the present (Figure 8). The ~10200 and 8400–8100 cal. yr BP glacier episodes detected by LOI and sediment texture are not represented by significant variations in magnetic susceptibility. The reason for this is probably that the glacier did not reach the upper proglacial lake (1083 m) and therefore did not produce such a strong magnetic susceptibility signal as the subsequent Neoglacial and ‘Little Ice Age’ expansion episodes when the glacier terminus extended across the lake rendering it a less efficient sediment trap for relatively coarse grains. The glacier may have totally melted from the lake catchment during several intervals, especially around 6500–6000 cal. yr BP, but also possibly around 10000, 9300, 7800, 7500, and at times between about 5300 and 4700 cal. yr BP. Dur-

ing the time intervals possibly with no glaciers in the lake catchment, the ELA must have been 260 m higher than at present. After the present glacier had become extensive (at 170 cm, ~4000 cal. yr BP), the percentage of silt and clay in the core shows considerably less variations than during periods with likely small glaciers (Figure 8). At 43 cm in the core, however, the medium silt content increases considerably, accompanied by a small, but significant, increase in the sand content. This transition is again interpreted as a reflection of when the terminus of Flatebreen reached across the upstream lake at 1083 m (Figure 2), causing an increased transport of coarser material down into Jarbuvatnet. According to the age/depth model, this event occurred around 800 cal. yr BP (~AD 1150), immediately after the ‘Mediaeval Warm Period’ (Figure 8).

Glacier episode 1, terminating about 10200 cal. yr BP, can be firmly correlated with the Erdalen Event, represented by terminal moraines up to 1 km beyond the ‘Little Ice Age’ moraines formed by the outlet glaciers from the Jostedalbreen ice cap. The Erdalen Event has been dated at 9100 ± 200 ¹⁴C yr BP [10035 (10295–9910) cal. yr BP] (Nesje *et al.*, 1991; Nesje and Kvamme, 1991). The Erdalen Event is evidently the same event as detected in marine sediments in the North Atlantic (Bond *et al.*, 1997) and the Boreal Oscillation described from Lake Holzmaar, Germany (Brathauer *et al.*, 2000).

Glacier episode 2, between 8400 and 8100 cal. yr BP, is clearly the same widespread event as recorded in the GRIP and GISP2 Greenland ice cores, in lacustrine and proglacial sites, and marine sediments. In both the GRIP (Dansgaard *et al.*, 1993) and GISP2 (Grootes *et al.*, 1993) Greenland ice cores (Figure 9), as well as in lacustrine sequences (Karlén, 1976; 1988; Karlén *et al.*, 1995; Grafenstein *et al.*, 1998; Nesje *et al.*, 2000) and marine records (Bond *et al.*, 1997; Klitgaard-Kristensen *et al.*, 1998), this widespread event was centred around 8200 cal. yr BP (e.g., Alley *et al.*, 1997). The 8400–8000 cal. yr BP oscillation has in central south Norway (at Hardangerjøkulen) been termed the Finse event by Dahl and Nesje (1994; 1996). Barber *et al.* (1999) suggested that this ‘8200 event’ was triggered by a drainage episode from the glacial lakes Agassiz and Ojibway (dammed by a remnant of the Laurentide ice sheet) around 8470 cal. yr BP (Figure 9).

Glacier episode 3, initiated around 4000 cal. yr BP, represents the Neoglacial phase, including the ‘Little Ice Age’, of Flatebreen.

Holocene glacier history in the Jostedalbreen area

A large number of studies have contributed to the reconstruction of glacier and climate fluctuations in the Jostedalbreen region (Mottershead *et al.*, 1974; Mottershead and Collin, 1976;

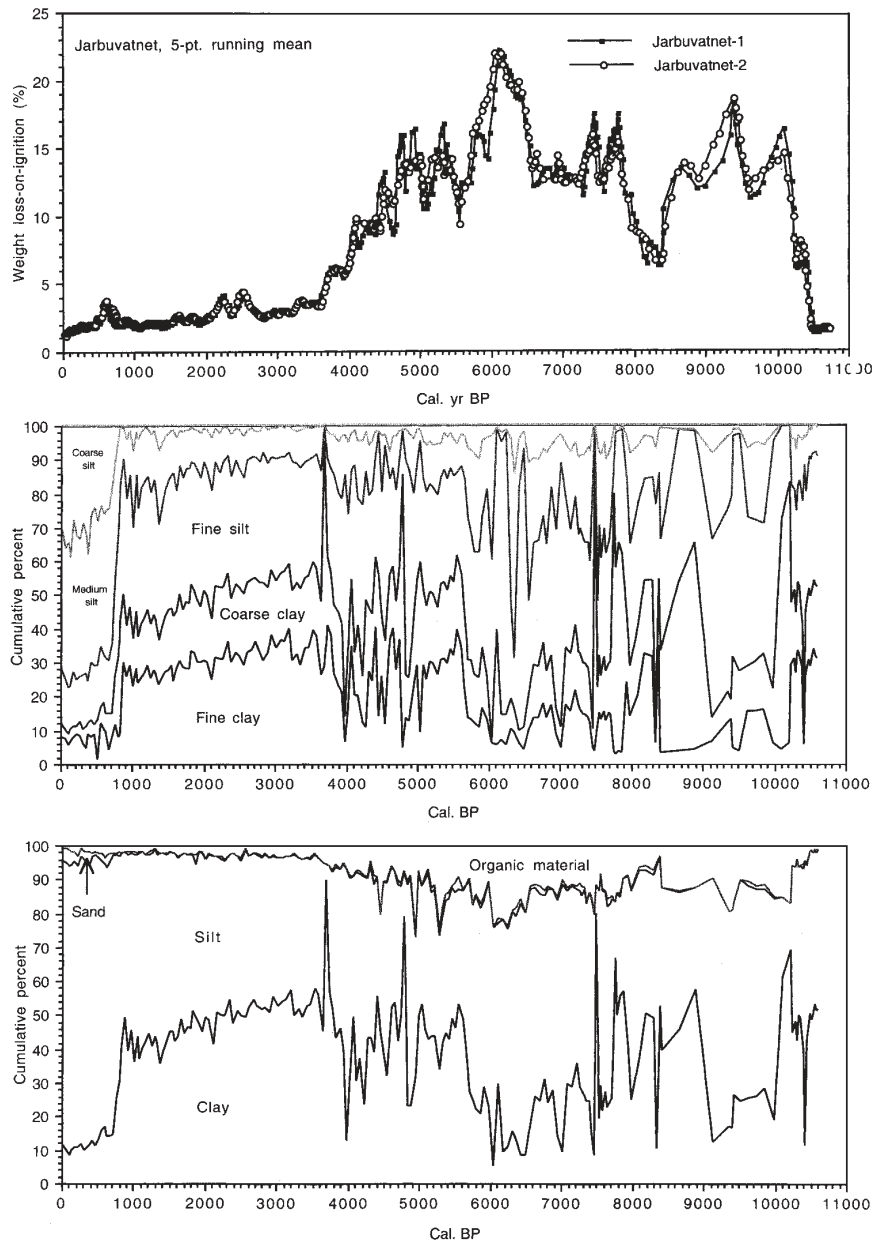


Figure 8 The smoothed (5 pt running mean) weight loss-on-ignition curves from cores Jarbuvatnet-1/2 and the SediGraph data from core Jarbuvatnet-1 according to the age/depth model.

Kvamme, 1984; 1989; Matthews and Caseldine, 1987; Nesje and Dahl, 1991b; Nesje *et al.*, 1991; 2000; Nesje and Kvamme, 1991; Nesje and Rye, 1993; Torske, 1996). The 'Little Ice Age' history of glacier and climate fluctuations is based on moraine stratigraphic evidence (e.g., Matthews and Dresser, 1983), historic evidence (Grove and Battagel, 1983; Grove, 1988) and lichenometry (Andersen and Sollid, 1971; Erikstad and Sollid, 1986; Bickerton and Matthews, 1993). The terrestrial evidence indicates that the outlet glaciers from the Jostedalbreen Plateau advanced around 9100 ± 200 ^{14}C yr BP [10035 (10295–9910) cal. yr BP] (Erdalen Event), to form distinct terminal moraines beyond the 'Little Ice Age' moraines. In addition, it has been suggested that at least the northern part of the ice cap melted away during the early Holocene, and that the glacier was reformed around 5300 ^{14}C yr BP (~6100 cal. yr BP) (Nesje *et al.*, 1991; 2000; Nesje and Kvamme, 1991). The glacier and climate oscillation around 8200 cal. yr BP (The Finse Event) registered in the Syngneskardvatnet (Nesje *et al.*, 2000) and Jarbuvatnet (this study) lacustrine sequences, was not recorded in the previous studies. Unequivocal evidence indicates

that the 'Little Ice Age' advance represented the maximum Neoglacial position of glaciers in the Jostedalbreen region (Matthews and Shakesby, 1984; Matthews, 1991).

The previous evidence of Holocene glacier variations in the Jostedalbreen region (Nesje *et al.*, 1991) has been combined with the data from Syngneskardvatnet (Nesje *et al.*, 2000) and Jarbuvatnet to produce a revised Holocene glaciation curve for the Jostedalbreen region (Figure 10). The combined record indicates periods of glacier advances and/or relatively high glacier activity during the last 8000 years, around 1100, 1400, 1600, 1800, 2000, 2300, 2400, 2600, 2800, 3100, 3200, 3300, 3600, 3900, 4100, 4300, 4700, 4900, 5100, 5600, 6000, 6600, 7300, 7600, 8200, 8300, 8900, 9700 and around 10100 cal. yr BP. Complementary periods of low glacier activity occurred at 1000, 1300, 1500, 1700, 1900, 2200, 2500, 2700, 2900, 3400, 3800, 4000, 4200, 4600, 4800, 5000, 5400, 5900, 6200, 7500, 7800, 8700 and 9400 cal. yr BP. It should, however, be pointed out that non-glacial causes for some of the minor fluctuations in this curve cannot be ruled out.

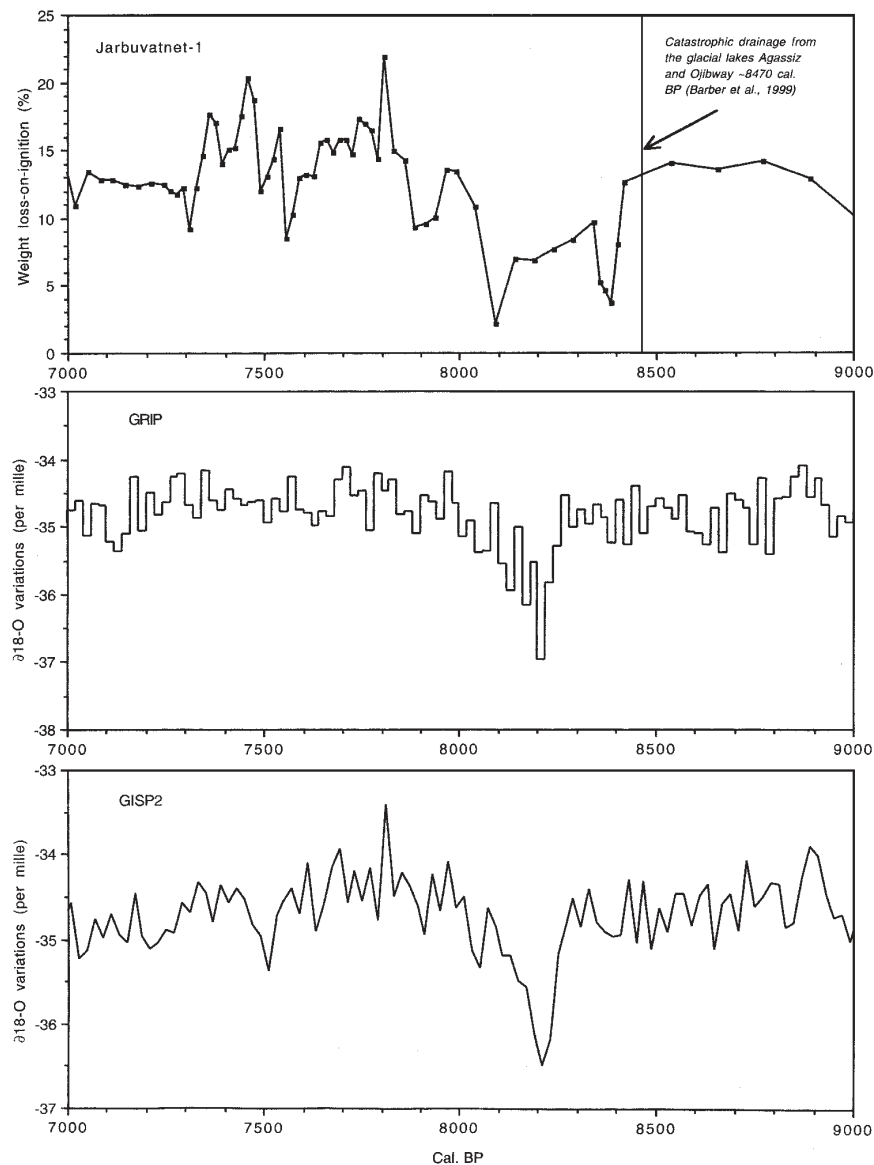


Figure 9 The percentage weight loss-on-ignition in core Jarbuvatnet-1 compared with $\delta^{18}\text{O}$ variations in the GRIP (Dansgaard *et al.*, 1993) and GISP2 ice cores (Grootes *et al.*, 1993). The vertical line at 8470 cal. yr BP indicates the catastrophic drainage from the glacial lakes Agassiz and Ojibway ~8470 cal. yr BP (Barber *et al.*, 1999).

Holocene variations in winter precipitation in the Jostedalbreen region

Based on data from 10 modern Norwegian glaciers in maritime and continental climate regimes, an exponential relationship between mean ablation-season temperature (t) 1 May–30 September and winter accumulation (A) 1 October–30 April at the ELA has been demonstrated (Figure 11) (Liestøl in Sissons, 1979; Sutherland, 1984), and expressed by the regression equation (Ballantyne, 1989):

$$A = 0.915 e^{0.339t} \quad (R^2 = 0.989, r = 0.994, P < 0.0001) \quad (1)$$

where A is in metres water equivalent and t is in $^{\circ}\text{C}$. The high correlation ($r = 0.99$) between these two variables for different glaciers reflects that higher levels of mass turnover at the ELA require higher ablation and thus higher summer temperatures to balance the annual mass budget. This relationship is of worldwide application (Dahl and Nesje, 1992; 1996; Dahl *et al.*, 1997; see also Loewe, 1971; Ohmura *et al.*, 1992).

Based on the regression equation above, mean winter precipi-

tation (A) can be quantified when mean ablation-season temperature (t) is known (see Dahl and Nesje, 1996, for further details). The procedure calculates what mean winter precipitation is or has been at the present ELA of a glacier in steady state when the ablation-season temperature is given. Variations in winter precipitation at other elevations can be calculated by using a precipitation elevation gradient of *c.* 8% per 100 m (Haakensen, 1989; Dahl and Nesje, 1992; Laumann and Reeh, 1993).

To reconstruct variations in Holocene winter precipitation at Jostedalbreen, we converted the Holocene glaciation curve for Jostedalbreen (Figure 10) to an ELA curve, following the procedure used for Hardangerjøkulen (Dahl and Nesje, 1994; 1996). The ELA curve is adjusted for land uplift using shore displacement data from Svendsen and Mangerud (1987) (Figure 12A). Holocene summer (ablation-season) temperature variations are based on a Holocene July temperature curve at Finse, central southern Norway, reconstructed from chironomids from lake sediments (Velle, 1998).

The Holocene winter-precipitation variations (Figure 12B) are calculated on the basis of the modern (1961–90) ablation-season temperature (11.5°C) and accumulation-season precipitation (766 mm) normals at the meteorological station Oppstryn (altitude 201

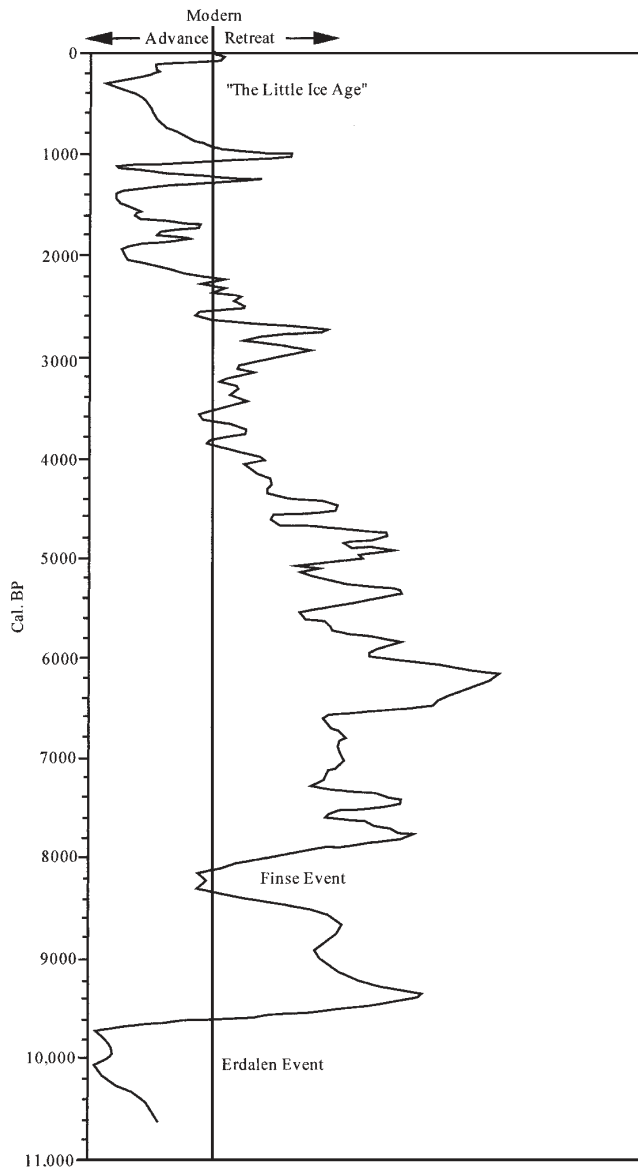


Figure 10 Holocene glaciation curve for the Jostedalbreen area based on Nesje *et al.* (1991) and the Jarbuvatnet (this study) and Sygneskardvatnet (Nesje *et al.*, 2000) proglacial lacustrine records.

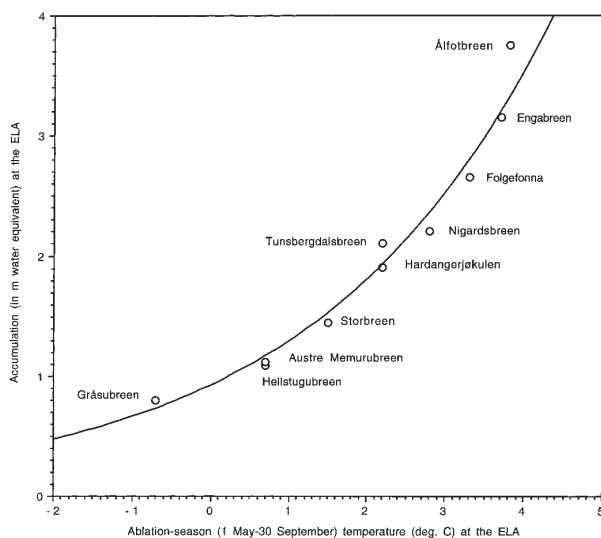


Figure 11 Mean ablation-season temperatures plotted against accumulation at the equilibrium line for 10 Norwegian glaciers. Adapted from Sutherland (1984).

m) at the NW side of Jostedalbreen. The winter-precipitation variations are calculated for the present steady-state (1560 m) at Nigardsbreen, which is representative for most of the ice cap. A calculated mean ablation-season temperature of 2.8°C at the steady-state ELA of Nigardsbreen (Liestøl in Sissons, 1979), yields an adiabatic lapse rate of 0.64°C 100 m⁻¹. In equation (1), the modern accumulation-season precipitation at the steady-state ELA of Nigardsbreen is 2365 mm, an increase of 8.5% per 100 m altitudinal rise. This is in close agreement with estimates (8–10%) given by Haakensen (1989), Dahl and Nesje (1992), and Laumann and Reeh (1993). By using this approach, periods of higher winter precipitation over the 1961–90 normal in the Jostedalbreen region occurred around 9700–9400, 9200–8300, 8200–6500, 5700–5100, 4700–4600, 4500–4300, 3800–3000, 2100–1800, 1600–1300 and 1200–1000 cal. yr BP, and from 900 cal. yr BP to the present. The most prolonged period of high winter precipitation was from 7400 to 6500 with values about 40% higher than at present. By contrast, periods of lower winter precipitation than the 1961–90 normal occurred before about 9700, and around 9400–9200, 8300–8200, 6500–5700, 5100–4700, 4600–4500, 4300–3800, 3000–2100, 1800–1700, 1300–1200, and 1000–900 cal. yr BP (Figure 13). The driest period was centred around 10000 cal. yr BP (28% compared to the present = 100%), immediately after the Erdalen Event. Apparently, precipitation starvation caused the glacial retreat after this readvance. From this record, the total precipitation amplitude during the Holocene at Jostedalbreen (range between highest and lowest century mean values) has been ~2800 mm.

Possible links between atmospheric circulation in the North Atlantic region, glacier mass balance in western Norway and ice-rafting in the North Atlantic ocean

Interannual variability in the atmospheric circulation over the North Atlantic and Nordic seas and the adjacent NW European continent has been attributed to the North Atlantic Oscillation (NAO). This oscillation is associated with changes in the west-lies in the North Atlantic and NW Europe (Hurrell, 1995; Hurrell and van Loon, 1997). A NAO index for the period AD 1864–1995 has been presented based on air pressure gradients between Iceland and the Azores (Hurrell, 1995). During the first half of the 1990s the NAO tended to remain in an extreme phase (positive NAO index) and explains a substantial part of the observed temperature and precipitation anomalies during wintertime in western Norway (e.g., Hurrell, 1995). This is also reflected in the winter snow accumulation (or winter balance given in metres water equivalent) on glaciers in maritime southern Norway; years with high NAO index corresponding to years of high winter balance, and vice versa (Figure 13, top). The Holocene winter-precipitation curve for Jostedalbreen may therefore reflect periods during the Holocene with prevailing mild and wet winter conditions ('positive NAO index weather regime') and periods with prevailing cold and dry winters ('negative NAO index weather regime'), and thus large-scale Holocene variability in the atmospheric circulation over NW Europe. This is further supported by the strong correlation between periods of dry (and probably cold) winters in western Norway (Figure 13, centre) and periods of enhanced ice-rafting recorded in a marine core (VM 29–191) west of Ireland (Bond *et al.*, 1997) (Figure 13, bottom). During each of these episodes, which peaked around 10000, 9300, 8200, 6300, 4900, 4000, 2700, 1300 and 1000 cal. BP, cool, ice-bearing waters from north of Iceland were advected as far south as the latitude of Great Britain.

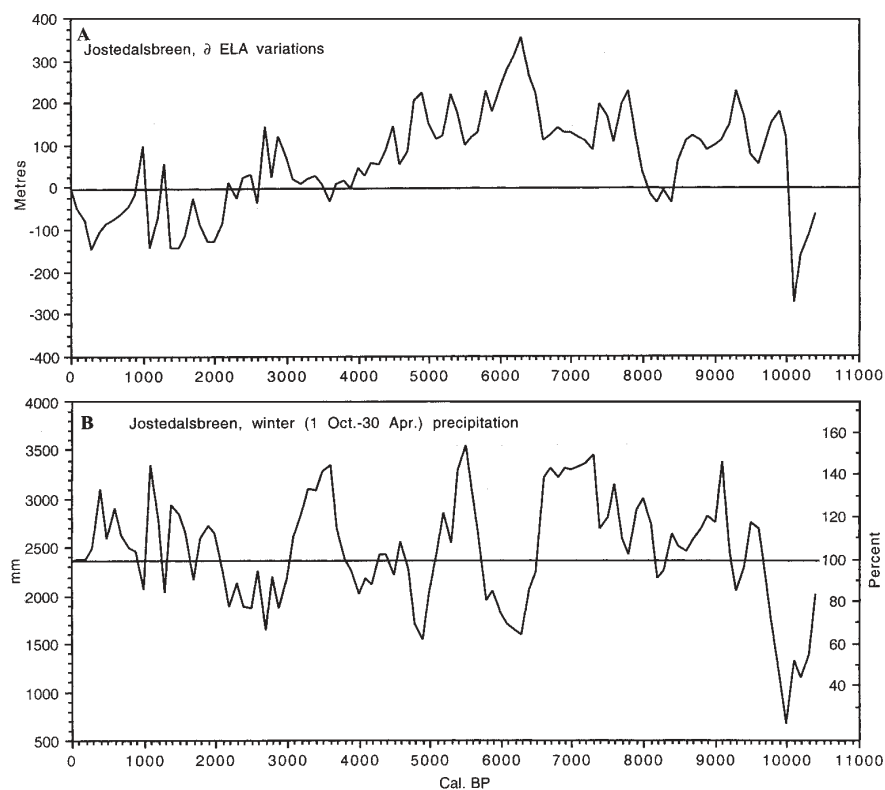


Figure 12 (A) Holocene equilibrium-line altitude (ELA) curve constructed for the Jostedalbreen area and adjusted for land uplift based on Svendsen and Mangerud (1987). (B) Calculated Holocene variations (mm and percentage) in winter precipitation at the modern (1962–98) steady-state ($B_n = 0$) ELA of Nigardsbreen (1560 m) based on the modern (1961–90) ablation-season temperature (11.5°C) and accumulation-season precipitation (766 mm) normals at the meteorological station Oppstryn (altitude 201 m) on the NW side of Jostedalbreen.

Conclusions

(1) The history of Holocene glacier variations of Flatebreen at the SW part of the Jostedalbreen ice cap, as recorded in the distal glacial lake Jarbuvatnet, shows evidence of three major glacier episodes: the first episode ended around 10200 cal. yr BP, the second episode lasted from 8400 to 8100 cal. yr BP, and the third episode reflects the relatively extensive glacierization of the last 4000 calendar years. In the intervening periods when the glacier was relatively small and probably periodically melted from the lake catchment, the ELA was up to 260 m higher than at present. Following extensive glacier development after ~ 4000 cal. yr BP, the percentage of silt and clay in the core shows considerably less variation than during the previous interval. Around 800 cal. yr BP the silt (especially medium silt) content increases considerably accompanied by a small, but significant, increase in the sand content, interpreted as an reflection of the terminus of Flatebreen extending across an upstream lake at 1083 m a.s.l. near the beginning of the 'Little Ice Age'.

(2) The earliest glacier episode recorded in Jarbuvatnet has been correlated with the Erdalen Event, which is represented by terminal moraines around 1 km beyond the 'Little Ice Age' moraines formed by the outlet glaciers from the Jostedalbreen ice cap. Around Jostedalbreen, the Erdalen Event has been dated to 9100 ± 200 ^{14}C yr BP [10035 (10295–9910) cal. yr BP] (Nesje *et al.*, 1991; Nesje and Kvamme, 1991). The second glacial phase, between 8400 and 8100 cal. yr BP, is evidently the same event as recorded in Greenland ice cores, in lacustrine and proglacial sites elsewhere, and in marine sediments (e.g., Alley *et al.*, 1997). In central south Norway (at Hardangerjøkulen) this climatic oscillation has been termed the Finse Event by Dahl and Nesje (1994; 1996).

(3) During the two periods with suggested little or no glacier

activity in the lake catchment from about 10000 to 8400 cal. yr BP and from 8100 to about 4000 cal. yr BP, periods of low minerogenic input and/or maximum organic productivity within and around the lake are recorded at about 10000, 9400, 8700, 7800, 7500, 6600–6000, 5900, 5400, 5000, 4800 and 4600 cal. yr BP. Levels of lower organic production and/or increased supply of minerogenic particles during the suggested period of small glaciers and/or ice-free conditions are recorded around 9600, 8900, 7600, 7300, 6600, 6000, 5800, 5100, 4900, 4700 and 4400 cal. yr BP.

(4) A Holocene glaciation curve has been produced by combining earlier evidence presented by Nesje *et al.* (1991) with the proglacial lake records from Syngeskardvatnet (Nesje *et al.*, 2000) and Jarbuvatnet. Assuming that the major fluctuations are of glacial origin, lower ELA and/or increased glacier activity are indicated around 150, 800, 1100, 1400, 1600, 1800, 2000, 2300, 2400, 2600, 2800, 3100, 3200, 3300, 3600, 3900, 4100, 4400, 4700, 4900, 5100, 5800, 6000, 6600, 7300, 7600, 8200, 8300, 8900, 9600 and 10100 cal. yr BP. Complementary periods of reduced glacier activity and/or higher ELA occurred at 1000, 1300, 1500, 1700, 1900, 2200, 2500, 2700, 2900, 3400, 3800, 4000, 4200, 4600, 4800, 5000, 5400, 5900, 6200, 7500, 7800, 8700 and 9400 cal. yr BP.

(5) Using an exponential relationship between accumulation season precipitation at the ELA and ablation season temperature at the ELA gives periods of higher winter precipitation than during the 1961–90 normal period at 9700–9400, 9200–8300, 8200–6500, 5700–5100, 4700–4600, 4500–4300, 3800–3000, 2100–1800, 1600–1300 and 1200–1000 cal. yr BP, and from 900 cal. yr BP to the present. The most prolonged period of high winter precipitation was from 7400 to 6500 cal. yr BP (values about 40% higher than at present).

(6) Periods of lower winter precipitation than the 1961–90

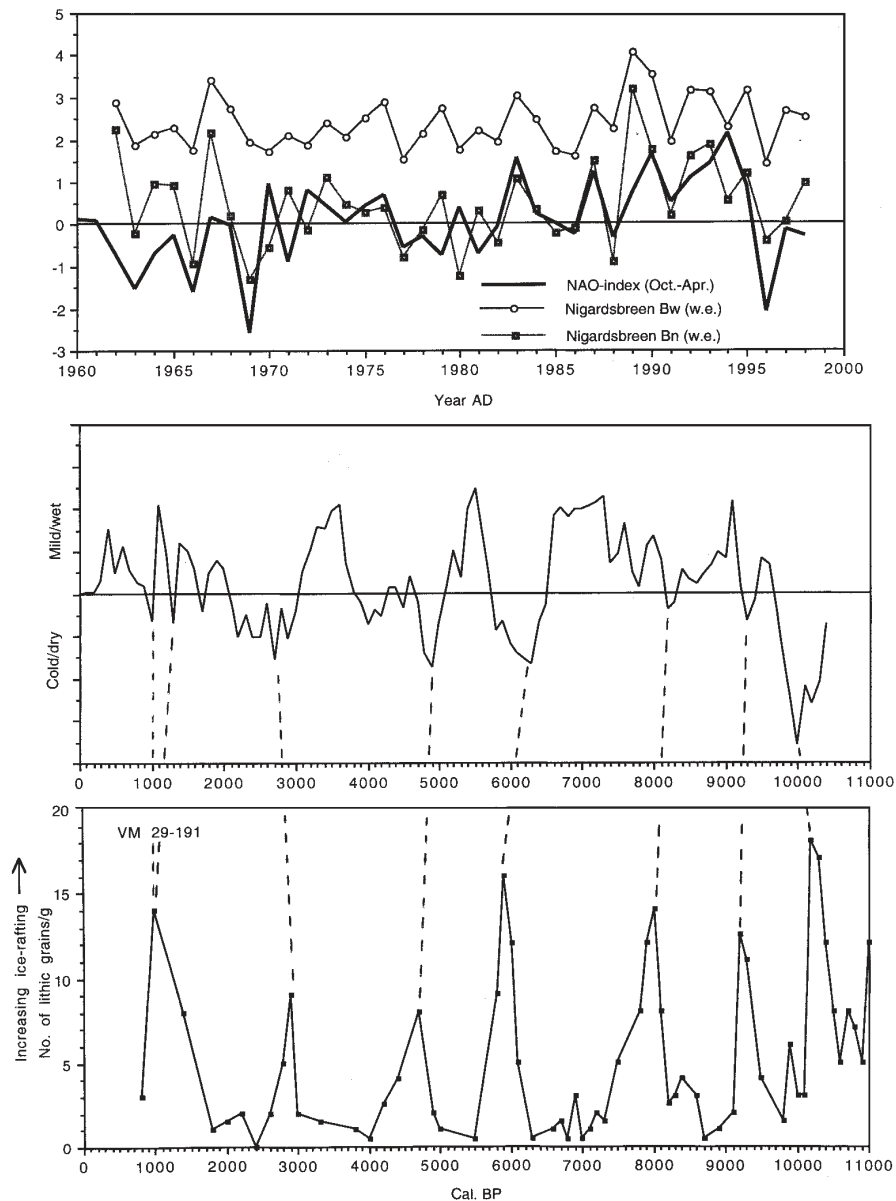


Figure 13 Top: winter balance (Bw) and net balance (Bn) (both in metres water equivalents) at Nigardsbreen compared with the NAO-index (October–April) between 1962 and 1998. Mass balance data are from Kjöllmoen (1998) and updated by the Norwegian Water Resources and Energy Directorate and monthly NAO-indexes from Internet site www.cgd.ucar.edu/cas/climind/nao_monthly.html. The monthly index of the NAO is based on difference of normalized sea-level air pressure (SLAP) between Ponta Delgada, Azores, and Stykkisholmur, Iceland, from 1865 to the end of June 1998. The SLAP anomalies at each station were normalized by division of each monthly pressure by the long-term (1865–1984) standard deviation. Centre: The Holocene winter-precipitation curve for Jostedalbreen indicating periods of mild/wet winters and cold/dry winters. Bottom: periods of enhanced ice-rafting inferred from core VM 29–191 west of Ireland (Bond *et al.*, 1997).

normal occurred before 9700, and around 9400–9200, 8300–8200, 6500–5700, 5100–4700, 4600–4500, 4300–3800, 3000–2100, 1800–1700, 1300–1200 and 1000–900 cal. yr BP. The driest period was centred around 10000 cal. yr BP (28% of the present), immediately after the Erdalen Event. As the modern (1962–) glacier mass balance variations in western Norway are strongly related to the North Atlantic Oscillation index, the Holocene winter-precipitation curve presented for Jostedalbreen may reflect large-scale Holocene variations in atmospheric circulation during winter ('North Atlantic Oscillation weather regime') in the North Atlantic region. This is further supported by evidence that periods of low winter precipitation appear to be more or less synchronous with periods of enhanced ice-rafting in the North Atlantic during the Holocene.

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