Lateglacial and early Holocene palaeoclimatic reconstruction based on glacier fluctuations and equilibrium-line altitudes at northern Folgefonna, Hardanger, western Norway

JOSTEIN BAKKE,1,2* SVEIN OLAF DAHL1,2 and ATLE NESJE1,3

1 Bjerknes Centre for Climate Research, University of Bergen, Allelgt. 55, N-5007 Bergen, Norway
2 Department of Geography, University of Bergen, Fossveinlesgate 6, N-5020 Bergen, Norway
3 Department of Earth Science, University of Bergen, Allelgt. 41, N-5007 Bergen, Norway


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ABSTRACT: Northern Folgefonna (c. 23 km²), is a nearly circular maritime ice cap located on the Folgefonna Peninsula in Hardanger, western Norway. By combining the position of marginal moraines with AMS radiocarbon dated glacier-meltwater induced sediments in proglacial lakes draining northern Folgefonna, a continuous high-resolution record of variations in glacier size and equilibrium-line altitudes (ELAs) during the Lateglacial and early Holocene has been obtained. After the termination of the Younger Dryas (c. 11 500 cal. yr BP), a short-lived (100–150 years) climatically induced glacier readvance termed the ‘Jondal Event 1’ occurred within the ‘Preboreal Oscillation’ (PBO) c. 11 100 cal. yr BP. Bracketed to 10 550–10 450 cal. yr BP, a second glacier readvance is named the ‘Jondal Event 2’. A third readvance occurred about 10 000 cal. yr BP and corresponds with the ‘Erdalen Event 1’ recorded at Jostedalsbreen. An exponential relationship between mean solid winter precipitation and ablation-season temperature at the ELA of Norwegian glaciers is used to reconstruct former variations in winter precipitation based on the corresponding ELA and an independent proxy for summer temperature. Compared to the present, the Younger Dryas was much colder and drier, the ‘Jondal Event 1’/PBO was colder and somewhat drier, and the ‘Jondal Event 2’ was much wetter. The ‘Erdalen Event 1’ started as rather dry and terminated as somewhat wetter. Variations in glacier magnitude/ELAs and corresponding palaeoclimatic reconstructions at northern Folgefonna suggest that low-altitude cirque glaciers (lowest altitude of marginal moraines 290 m) in the area existed for the last time during the Younger Dryas. These low-altitude cirque glaciers of suggested Younger Dryas age do not fit into the previous reconstructions of the Younger Dryas ice sheet in Hardanger. Copyright © 2005 John Wiley & Sons, Ltd.

KEYWORDS: Younger Dryas; Preboreal Oscillation (PBO); Jondal Event; Erdalen Event; glacier fluctuations; equilibrium-line altitudes (ELAs); winter precipitation; grain-size analyses; Norway.

Introduction

The extent of the Younger Dryas readvance in the Hardangerfjord, western Norway (Fig. 1), has been discussed during the last few years (Helle et al., 1997; Mangerud, 2000; Helle, 2004). Studies by Folkestad (1972), Aarseth and Mangerud (1974), Holtedahl (1975) and Mangerud (2000) indicate that the continental ice sheet terminated in the outer parts of the Hardangerfjord during the latest part of the Younger Dryas. Reconstructed sea-level fluctuations in inner parts of Hardangerfjorden, however, indicate a final deglaciation prior to Allerød or earlier without any major readvance during the Younger Dryas (Helle et al., 1997; Helle, 2004). An important boundary condition for this readvance is that the regional equilibrium-line altitude (ELA) must have been well below the highlying mountain areas surrounding the wide and deep Hardangerfjord. Of special interest in this context is the Folgefonna Peninsula with three plateau glaciers at present (Fig. 1). If a readvance took place in Hardangerfjorden during the Younger Dryas, the Folgefonna Peninsula must have produced a significant part of the glacier ice necessary to fill up the fjord. It is therefore important to evaluate the ELA lowering at the Folgefonna Peninsula during the Younger Dryas and early Holocene.
Amongst the large number of Lateglacial and early Holocene climate reconstructions available from NW Europe, those from western Norway have been inferred from records of Younger Dryas and early Holocene glacier variations (e.g. Larsen et al., 1984; Nesje et al., 1991, 2000a; Nesje and Dahl, 2001; Dahl and Nesje, 1992, 1994, 1996; Dahl et al., 2002), from biological proxies (e.g. Paus, 1988, 1989; Birks et al., 1994, 2000; Birks and Ammann, 2000) and from variations in weight loss-on-ignition (Nesje and Dahl, 2001). Off western Norway, marine climate records from the deglaciation are available from the southeast Norwegian Sea based on diatom data (Koc Karpuz and Jansen, 1992), and from the Troll area in the North Sea based on percentage variations of a cold water planktonic foraminifera (Klitgaard-Kristensen et al., 2001). However, records of early Holocene glacier fluctuation in Scandinavia are sparse. The first climatically induced glacier readvance recorded at Jostedalsbreen is the double ‘Erdalen Event’, radiocarbon dated at 10,100–9,700 cal. yr BP (Nesje et al., 1991; Dahl et al., 2002).

Figure 1  The inset map shows the geographical distribution of glaciers in southern Norway and the assumed Younger Dryas margin (solid line). The main map shows northern Folgefonna and the surrounding area. Note the position of the lakes Vetlavatn and Vassdalsvatn, and the marginal moraines deposited by low-altitude cirque glaciation at Dребрёке and Stormyr. Marginal moraines deposited by northern Folgefonna or by local cirque glaciers are marked as dark shaded lines. In the lower valley of Jondal some remnants of marginal moraines were deposited by the Late Weichselian Scandinavian Ice Sheet.

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Reconstructions of glacier fluctuations in areas isolated from the Younger Dryas continental ice sheet may provide data on glacier fluctuations during the time span. It is suggested that the large climate oscillations caused by meltwater pulses into the North Atlantic during the early Holocene had large effects on the climate along the west coast of Norway (Nesje et al., 2004). Both meltwater pulses from the Laurentide Ice Sheet (LIS) and variations in solar radiation are therefore relevant with respect to the response of maritime glaciers in Norway.

The purpose of this paper is to reconstruct variations in glacier magnitude/ELAs and winter precipitation during the Lateglacial and early Holocene on the Folgefonna Peninsula. We also discuss local implications of these reconstructions with respect to the age of marginal moraines formed by low-altitude cirque glaciers in the area, and implications with respect to the regional ice-sheet configuration in Hardanger during the Lateglacial and early Holocene. Finally, we establish an event chronology for the Lateglacial/early Holocene transition based on glacier fluctuations/ELAs in western Norway. This event chronology is discussed against a proxy for solar radiation (10Be fluxes from GISP ice core), a proxy for Meridional Overturning Circulation (MOC) (Chapman and Shackleton, 2000) and with respect to major meltwater pulses into the North Atlantic (Clark et al., 2001; Fisher et al., 2002; Teller et al., 2002). By comparing the result from the Folgefonna glacier with other proxies for climate change in the North Atlantic region it is our aim to improve understanding of the underlying factors leading to glacier expansion and decay during the early Holocene along the coast of western Norway.

Study area

The northern Folgefonna ice cap covers an area of 23 km² and is the seventh largest glacier in Norway. It has a circular configuration with an altitudinal range from 1644 to 1200 m, and a modern mean ELA of about 1465 m. There are three north-facing outlet glaciers from the ice cap: Jordalsbreen, Jukladsbreen and Juklavassbreen, which drain the eastern part of the plateau glacier. Three outlet glaciers Jordalsbreen (10 km²) and three outlet glaciers Jordalsbreen (10 km²) and three outlet glaciers Jordalsbreen (10 km²) and two bulk AMS radiocarbon dates were obtained from the Vetlavan and Vassdalsvatn cores (Figs 1 and 3A). When the glacier is behind this local watershed, organic gyttja dominates sedimentation in the lake. Three cores were retrieved from this lake.

Vassdalsvatn has input of glacial meltwater-induced sediments at present (Figs 1 and 3B) and is sensitive whenever northern Folgefonna is very small or completely melted away. Two cores were retrieved from Vassdalsvatn.

Both glacier-fed lakes were cored using a modified piston corer taking up to 6 m long cores with a diameter of 110 mm (Nesje, 2004). When the glacier is behind this local watershed, organic gyttja dominates sedimentation in the lake. Three cores were retrieved from this lake.

The bedrock in the upper Jondal catchment consists mainly of acid metandesite, metadacite, quartzite, migmatite and migmatitic schist of Precambrian age (Sigmond, 1985; Askvik, 1989). The vegetation is sparse around northern Folgefonna, and except for some marginal moraines in front of the major outlet glaciers, there is only a thin and discontinuous cover of colluvium and till in the area.

Based on a combination of data from two meteorological stations along Hardangerjorden (Station no. 4949, Ullensvang Forsoksgård, 12 m a.s.l., 1962–1988; Station no. 5013, Omafar, 1 m a.s.l., 1962–1990) (Klimaavdelingen, 1993b), the present mean summer temperature (Tj) from 1 May to 30 September at the modern ELA (1465 m a.s.l.) of northern Folgefonna, using an environmental lapse rate of 0.6 °C/100 m (e.g. Sutherland, 1984), gives a mean Tj close to 4.0 °C. The present mean winter precipitation in Jondal (Pw) from 1 October to 30 April is 1434 mm (Station no. 5696, Kvaå, 342 m a.s.l., 1961–1990) (Klimaavdelingen, 1993a). Based on a mean observed exponential increase in winter precipitation with altitude of 8%/100 m in southern Norway (Haaken, 1989; Dahl and Nesje, 1992), the corresponding Pw at the ELA of northern Folgefonna is ca. 3350 mm.

Research approach and methods

The reconstruction of Lateglacial and early Holocene glacier fluctuations at northern Folgefonna involved several approaches:

1 Aerial photographs (Widerøe, 1962) and field observations were combined to produce a glacial geomorphological map for the upper Jondal catchment with special emphasis on former marginal moraines and former glacial meltwater channels.
2 Primarily to identify moraines older than the historical ‘Little Ice Age’ maximum, lichenometry based on Rhizocarpon geographicum (Matthews, 1994) and Schmidt-hammer rebound values (McCarroll, 1994), were used to establish relative-age chronologies for the marginal moraines in front of three outlet glaciers from northern Folgefonna and at moraines formed by two low-altitude cirque glaciers.
3 Various methods related to glacier-fed lakes all use a conceptual model of glacial meltwater-induced sedimentation in which the minerogenic (non-organic) component of the sediments is related to the occurrence of a glacier in the catchment (Karlen, 1981; Leonard, 1985; Dall et al., 2003). Two distinct glacier-fed lakes—Vetlavan and Vassdalsvatn (Figs 1 and 3)—were cored in an attempt to obtain absolute dating control on the timing and magnitude of Late-glacial and early Holocene glacier fluctuations in the Jondal catchment.
4 Finally, the interpretations based on lake records have been compared with the moraine chronology for absolute dating of the ELA fluctuations during the Younger Dryas and early Holocene.

Vetlavan only records glacial meltwater-induced sediments when the outlet glacier Jordalsbreen from northern Folgefonna advances beyond a local bedrock threshold (Figs 1 and 3A). When the glacier is behind this local watershed, organic gyttja dominates sedimentation in the lake. Three cores were retrieved from this lake.

Vassdalsvatn has input of glacial meltwater-induced sediments at present (Figs 1 and 3B) and is sensitive whenever northern Folgefonna is very small or completely melted away. Two cores were retrieved from Vassdalsvatn.

Both glacier-fed lakes were cored using a modified piston corer taking up to 6 m long cores with a diameter of 110 mm (Nesje, 1992). The bathymetry of the two lakes was explored using a Garmin Fishfinder 160 echo sounder. Laboratory analyses included weight loss-on-ignition (LOI) (Heiri et al., 2001), bulk density (dry and wet) and water content (Menounos, 1997), and grain-size analysis using a Micromeritics Sedigraph 5100 (X-ray determination).

Seventeen and two bulk AMS radiocarbon dates were obtained from the Vetlavan and Vassdalsvatn cores respectively. Terrestrial plant macrofossils for AMS radiocarbon dating were sparse or lacking at both sites. As both lakes are located in acid Precambrian granite gneiss, however, this is not considered to cause a major problem for age-depth modeling (Barnekow et al., 1998; Lowe and Walker, 2000). All dating results are shown in Table 1, and are presented in the text as calibrated years before present (cal. yr BP) according to CALIB 4.4 (Stuiver and Reimer, 1993) if not otherwise stated. Intercepts are given as median intercept if there is more than one intercept.

Calculations of former glacier ELAs at the plateau glacier are made by using an Accumulation Area Ratio (AAR) of 0.7 (Dahl and Nesje, 1996), whereas the cirque glaciers are
Figure 2  Photo showing the northern Folgefonna ice cap seen from southern Folgefonna. The ice cap is almost circular and is located on a mountain plateau at an altitude of about 1300 m.
reconstructed using an AAR of 0.6 (Dahl et al., 1997). The calculation of the accumulation area distribution (AAR) was carried out electronically using the vector-based GIS program MapInfo 6.0 on an N-50 map datum.

Results

Moraine chronology

The moraine chronology in front of outlet glaciers from northern Folgefonna indicates up to seven successively smaller glacier halts or advances/readvances with deposition of marginal moraines (Fig. 1). Beyond these moraines there are some sparsely distributed remnants after an even older glacier advance. However, due to differences in aspect and slope, the moraine chronology is not consistent around northern Folgefonna. A relative moraine chronology was established by use of lichenometry and Schmidt-hammer rebound values (R-values) on the moraines (Figs 4 and 5). All moraines labelled in Figure 1 were measured with Schmidt-hammer (Fig. 5), and two main clusters with R-values were identified. Based on a compilation of lichen measurements performed at the proximal side of marginal moraines around northern Folgefonna (Tvede, 1972; Bjelland, 1998; Bakke, 1999; Simonsen, 1999) in areas with historical data, three major glacier advances, which occurred during the ‘Little Ice Age’ about AD 1750, 1870 and 1930, respectively, have been identified (Fig. 4).

Based on observations in southern Norway, lichen-growth curves reflecting Rhizocarpon geographicum cannot be used for reliable (absolute) dating for more than 400–500 years back in time (Matthews, 1994). Hence, lichen diameters on the remaining sets of marginal moraines frequently indicate an age of formation well beyond this time interval. Calibrated against the ‘Little Ice Age’ moraines, Schmidt-hammer rebound values (Fig. 5) indicate that two marginal moraines may have formed prior to the ‘Little Ice Age’, whereas the rebound values for the remaining three sets of marginal moraines suggested an age of deposition during the Lateglacial or early Holocene.

Marginal moraines formed by two low-altitude cirque glaciers have been investigated at Drebrekke and Stormyr in Jondal (Fig. 1). N-NE of Grytingsfjellet mountain (alt. 1092 m), two sets of marginal moraines and indications of a third have been deposited by a small glacier at Drebrekke. The eastern lateral moraine is well marked and can be traced uphill to an altitude of 400 m a.s.l., whereas the outer terminal moraine extends down to a lowest altitude of 290 m a.s.l. (Figs 6 and 7). The farm inside the marginal moraines at Drebrekke has a history back to the 15th century (Kolltveit, 1953). This indicates that no glacier formed at Drebrekke during the ‘Little Ice Age’, and this is confirmed by lichen measurements on the marginal moraines. Schmidt-hammer R-values indicate an age of formation which is comparable with the three oldest sets of marginal moraines around northern Folgefonna (Fig. 5).

On the northern flank of Storafjell mountain (alt. 1133 m), two distinct sets of marginal moraines formed by a larger cirque glacier are situated at Stormyr (Fig. 1). Taking into account 4–5 m of adjacent peat, the moraines have a height of 7–11 m. The northwestern lateral moraine can be traced to an altitude of 590 m. Lichen measurements and Schmidt-hammer R-values on the marginal moraines indicates a similar age of formation as the moraines at Drebrekke (Fig. 5).

Lithostratigraphy and radiocarbon dates

Vetlavatn

Based on cores I, III and IV from Vetlavatn, the combined lithostratigraphy has been subdivided into 10 units, with core IV as the most representative (Figs 8 and 9). The content of cumulative medium silt including weight LOI from cores III and IV are shown in Fig. 10. Minor lithological variations between the cores are suggested to primarily reflect increasing distance away from the stream inlet/outlet in the western part of the lake (Fig. 3). Details concerning the AMS radiocarbon dates used for the age–depth model are shown in Table 1.
Unit J consists of a grey diamicton with angular gravel-sized particles in a matrix of silt and clay, and it has an average LOI of 0.8%. The diamicton is hard and impossible to penetrate with the coring equipment. In core I, this unit extends from 87.5 to 80 cm, in core III from 151 to 129 cm, while it is missing in core IV. Unit I consists of a light-grey coarse silt to sand, grading into light-grey silt (unit H). The LOI varies from a minimum of 0.8% in Unit I to a maximum in Unit H of 4.5%. The top of Unit H is dated to 10,450 $^14$C yr BP (Beta-148429) at 148 cm in core IV. The grey Unit G consists of gyttja silt with LOI values from 4.5% to 8%, dated to 10,200 ± 80 $^14$C yr BP (Beta-115403) at 69.5 cm in core I and to 10,220 ± 70 $^14$C yr BP (Beta-148431) at 118 cm in core III. In Unit F light-grey silt grades upwards into a darker grey with a mean LOI of 4.0%. The 5 mm thick layer appears in sharp contrast to surrounding units, and it is radiocarbon dated at 10,950 $^14$C yr BP (Beta-148430), and at 144 cm in core IV to 9,780 ± 60 $^14$C yr BP (Beta-148428), respectively. Unit E consists of grey silty clayey gyttja becoming brownish yellow upwards, and with LOI values from 4.0% to 12.4%. A radiocarbon date from this unit yielded an age of 9,660 $^14$C yr BP (Beta-115402) at 61.5 cm in core I. In Unit D, a distinct 5 mm thick layer of light-grey silt has a mean LOI of 3.7%, and is bracketed in core IV by radiocarbon dates of 9,330 ± 60 $^14$C yr BP.

Table 1  Radiocarbon dates from Vetlavatn and Vassdalsvatn

<table>
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<tr>
<th>Core</th>
<th>Depth (cm)</th>
<th>Laboratory number</th>
<th>Radiocarbon age</th>
<th>Intercept</th>
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<th>$\delta^{13}$C</th>
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<td>Vetlavatn I</td>
<td>15</td>
<td>T-13603A</td>
<td>6785 ± 160</td>
<td>7680</td>
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<td>20</td>
<td>T-13604A</td>
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Figure 4  Lichen growth curves for *Rhizocarpon geographicum* in the marginal zones of Nigardsbreen and an adjusted mountain curve based on the curve from Middletbreen at Hardangerjøkulen used to date moraines from different parts of the Folgefonna glacier. An early ‘Little Ice Age’ (LIA) glacial advance took place at Folgefonna close to AD 1750, whereas later readvances occurred between AD 1870 and 1890 and during the AD 1930s.
Figure 5  Schmidt-hammer rebound values ($R$-values) from marginal moraines at the northern part of the ice cap, northern Folgefonna. The figure shows that marginal moraines deposited during the Lateglacial and early Holocene can be separated from moraines formed during the late Holocene.

Figure 6  Drebrekke farm in Jondal located on marginal moraines formed by a small cirque glacier of suggested Younger Dryas age N-NE of Grytingsfjellet mountain.
14C yr BP (Beta-148427) and 9310 ± 60 14C yr BP (Beta-148426) at 138 and 136 cm, respectively. Unit C consists of grey silty-clayey gyttja with LOI values varying from 7% to 10%, whereas Unit B is a distinct 5 mm thick layer of light-grey silt with a mean LOI of about 3.0%. The unit is bracketed by radiocarbon dates in core I of 9050 ± 60 14C yr BP (Beta-115401) at 58 cm, of 8990 ± 60 14C yr BP (Beta-115400) at 53 cm and by 8840 ± 60 14C yr BP (Beta-115399) at 50 cm. The homogeneous brownish gyttja representing Unit A is found in all three cores, and it has LOI values varying from a maximum of 31% to a minimum of 6.4%. The unit is radiocarbon dated in core I to 7640 ± 135 14C yr BP (T-13605) at 33 cm, to 7475 ± 30 14C yr BP (T-13604A) at 20 cm and to 6785 ± 160 14C yr BP (T-13603A) at 15 cm. A sample taken from Unit A at 46 cm in core I was radiocarbon dated to 8950 ± 145 14C yr BP (T-13606); this appears to be rather old (note however the large standard deviation). In core IV, the lower part of Unit A is dated at 8100 ± 50 14C yr BP (Beta-148425) at 118 cm and the upper part at 2980 ± 40 14C yr BP (Beta-148424) at 23 cm. The grain-size analyses of core III and IV showed increased content of clay and fine silt throughout the units B, C and D.

Vassdalsvatn

For this study, the lithostratigraphy in Vassdalsvatn is primarily used to complement Vetlavatn and to investigate whether or not northern Folgefonna glacier melted away during the early Holocene. The radiocarbon-dated stratigraphy and sediment parameters are fully presented in Bakke et al. (2005). It is suggested that light-grey clayey silt reflects the existence of the northern Folgefonna glacier in the catchment, whereas gyttja is likely to indicate the absence of the glacier. The first transition from light-grey glacier-meltwater induced clayey silt to gyttja after the deglaciation is dated at 6280 ± 60 14C yr BP (7195 cal. yr BP) (UIC-6695) in core II, whereas a sediment layer rich in plant macrofossils, interpreted to be a flood deposit, is dated to 8260 ± 80 14C yr BP (9235 cal. yr BP) (Beta-102935) in core I (see Table 1 for details). The suggested flood appears to have eroded upstream peat deposits with re-sedimentation in the central basin/channel of Vassdalsvatn where core I was retrieved.

Glacier variations and equilibrium-line altitudes at northern Folgefonna

The reconstructed Lateglacial and early Holocene glacier fluctuations are primarily based on a combination of the radiocarbon-dated lithostratigraphies from Vetlavatn and Vassdalsvatn and the moraine chronology. The record from Vassdalsvatn indicates whenever the northern Folgefonna glacier existed during the investigated time span, whereas the Vetlavatn record indicates whenever the glacier advanced beyond the local watershed that prevents direct input of glacial melt-water-induced sediments from northern Folgefonna to this lake.
Figure 8  Lithostratigraphy of three cores retrieved from Vetlavatn. The radiocarbon dates are shown as radiocarbon years before present together with independent depth scales (cm) for each core. The dashed lines show the correlation between lithostratigraphical units and in the right column the suggested age for the different units in calibrated years before present (AD 1950). See Fig. 9 for key to symbols.

<table>
<thead>
<tr>
<th>Core 1</th>
<th>Core III</th>
<th>Core IV</th>
<th>Composite interpretation</th>
<th>Age-depth model</th>
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<td>Lithostratigraphy</td>
<td>Depth (cm)</td>
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<td>8950 145</td>
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at present. Hence, by combining these records with the moraine chronology, it is possible to reconstruct the number, age and magnitude of Lateglacial and early Holocene glacier fluctuations at northern Folgefonna. The reconstructed ELA variations are adjusted for land uplift (Figs 11 and 12). In Fig. 12 vertical bars indicate the uncertainty in ELA between the events whereas the lower solid line indicates the estimate used when reconstructing former winter precipitation.

The present temperature–precipitation–wind ELAs (TPW-ELAs) at the northern outlets of northern Folgefonna are calculated (AAR ¼ 0.7) to ca. 1465 m, whereas estimates from the outlet glaciers to the west and to the east show TPW-ELAs of ca. 1465 m and ca. 1460 m, respectively. This demonstrates that the mean value of all local TPW-ELAs at northern Folgefonna may be regarded as a regional temperature–precipitation ELA (TP-ELA), which makes it possible to neglect the effect of leeward accumulation of dry snow by wind (Dahl and Nesje, 1996; Dahl et al., 1997, 2003).

By using an AAR of 0.7 for plateau glaciers in steady state (e.g. Dahl and Nesje, 1996), it is possible to transform the reconstructed outlet glaciers into corresponding TP-ELAs. During the ‘Little Ice Age’ the TP-ELA is estimated to have been 1360 m in all three aspects. This gives a lowering of the TP-ELA of 105 m compared to the present value. For the
Lateglacial and early Holocene glacier events it is difficult to separate the different ELAs based on the marginal moraines, as these are located very close to each other. If not adjusted for glacio-isostatic land uplift, the estimated TP-ELA was close to 1210 m (255 m lowering compared to the present) during the Younger Dryas and about 1320 m (lowering of 145 m) during the early Holocene glacier advances.

The former cirque glacier at Drebrekke has been reconstructed based on marginal moraines, and the former TPW-ELA (405 m) has been calculated using an AAR of 0.6 (Fig. 7). Adjusted for Holocene glacio-isostatic land uplift of 100 m (Fig. 11), the TPW-ELA lowering compared to the present TP-ELA of 1465 m at northern Folgefonna was 1160 m. The similar reconstructed TPW-ELA at the former Stormyr cirque glacier is 730 m. Based on a similar adjustment for Holocene glacio-isostatic land uplift of 100 m, the lowering of the TPW-ELA compared to the present TP-ELA of 1465 m at northern Folgefonna is 835 m.
Pre-Younger Dryas

The basal diamicton in Vetlavatn (unit J) is suggested to be a basal till deposited when northern Folgefonna covered Vetlavatn (Fig. 7). Exact dating of this till has not been obtained.

Younger Dryas

Units I/H were probably deposited when the glacier was situated at the distinct terminal moraine at the western lake shore of Vetlavatn (Fig. 1). The sediments of Units I/H are characterised by a low organic content and a high proportion of coarse silt, and the radiocarbon dates are well within the middle to later part of the Younger Dryas (see Beta-148429, Beta-148131 and Beta-115403 in Table 1 and Fig. 8). The TP-ELA lowering adjusted for land uplift is estimated to be 355 m during the Younger Dryas.

Post-Younger Dryas (ca. 11 500–11 150 cal. yr BP)

As, or when, Unit G was deposited in Vetlavatn, the glacier is suggested to have retreated from the western lake shore to behind the local threshold further upstream. The high minerogenic content in Unit G is probably due to paraglacial reworking of older glacier-derived sediments by fluvial erosion (e.g., Ballantyne, 1995). After an early glacier maximum, the minerogenic input to the lake shows a gradual decrease during this period (Fig. 10). The TP-ELA lowering adjusted for land uplift is estimated to be 190 m during the time span 11 500–11 150 cal. yr BP.

‘Jondal Event 1’/PBO (ca. 11 150–11 050 cal. yr BP)

Based on low LOI values, a relatively high content of coarse silt and high sedimentation rates, a glacier advance beyond the local watershed upstream of Vetlavatn is suggested to have produced Unit F. The glacier meltwater pulse (phase 2) representing Unit F is recorded in cores III and IV, while the lack of this unit in core I may be explained by later fluvial erosion close to the inlet (Fig. 3). AMS radiocarbon dates also indicate that there is a hiatus in core I during this period. The TP-ELA lowering adjusted for land uplift is estimated to be 230 m during the ‘Jondal Event 1’.

Post–‘Jondal Event 1’ (ca. 11 050–10 550 cal. yr BP)

Just after the ‘Jondal Event 1’, the glacier retreated behind the local watershed upstream of Vetlavatn, and the corresponding Unit E with a low content of coarse silt and relatively high LOI values, shows no indications of glacier meltwater input to the lake. The TP-ELA lowering adjusted for land uplift is calculated to be 160 m during the time span 11 050–10 550 cal. yr BP.

‘Jondal Event 2’ (ca. 10 550–10 450 cal. yr BP)

Based on low LOI values, a relatively high content of coarse silt and increased sedimentation rates, the glacier advanced across the local watershed and glacier meltwater was rerouted into Vetlavatn when Unit D was deposited. This unit is found in all the investigated cores from Vetlavatn, and based on the AMS radiocarbon dates the ‘Jondal Event 2’ lasted for about 100 years. The TP-ELA lowering adjusted for land uplift is estimated to be 220 m during the ‘Jondal Event 2’.

Post–‘Jondal Event 2’ (ca. 10 450–10 000 cal. yr BP)

After the ‘Jondal Event 2’, the glacier retreated behind the local upstream watershed, and Unit C with high LOI values suggesting no glacier meltwater input was deposited in Vetlavatn. This unit is recorded in all cores. After an early maximum, the minerogenic input of coarse silt indicative of paraglacial reworking shows a gradual decrease to a minimum during this time span. The TP-ELA lowering adjusted for land uplift is calculated to be 150 m during the time span 10 450–10 000 cal. yr BP.

‘Erdalen Event 1’ (ca. 10 000–9900 cal. yr BP)

Represented by Unit B, and characterised by low LOI values and a distinct increase in coarse silt in all three cores, the glacier again advanced across the local upstream watershed for a short period, and glacier meltwater was rerouted towards Vetlavatn. Based on the AMS radiocarbon dates, the episode is correlated with the ‘Erdalen Event 1’ at Jostedalsbreen (Dahl et al., 2002). The TP-ELA lowering adjusted for land uplift is calculated to have been 210 m during the ‘Erdalen Event 1’ at northern Folgefonna.

Post–‘Erdalen Event 1’ (ca. 9900–9000 cal. yr BP)

Unit A consists of homogeneous gyttja with high LOI values in the upper part of all investigated cores, including the ‘Little Ice Age’ sequence in cores III and IV. This was also confirmed by a short gravity core covering the upper 50 cm of the sediments. Based on the marginal moraines, however, the ‘Little Ice Age’ advance was the largest glacier event at northern Folgefonna after the ‘Erdalen Event 1’. Any marginal moraines formed by northern Folgefonna during the time span from ca. 9900–9000 cal. yr BP were therefore erased by the ‘Little Ice Age’ glacier readvance(s). Based on the Vassdalsvatn cores, however, the northern Folgefonna glacier existed during this time span and did not melt completely away before about ~7200 cal. yr BP. The TP-ELA lowering adjusted for land uplift is estimated to have been 140 m during the time span from 9900 to 9000 cal. yr BP at northern Folgefonna.

Palaeoclimatic reconstruction

A close exponential relationship between mean ablation-season temperature \(t\) (°C) (1 May–30 September) and mean solid winter precipitation \(A\) (metres of water equivalent) (1 October–30 April) at the ELA of Norwegian glaciers in maritime to continental climatic regimes has been demonstrated (Sissons, 1979; Ballantyne, 1990; Dahl and Nesje, 1996):

\[
A = 0.915^{0.339} \times t^2 \quad (r^2 = 0.989, P < 0.0001)
\]

The ‘Liestøl equation’ implies that if either the winter precipitation or the ablation-season temperature at the ELA is known,
the other factor can be calculated. It also implies that if the former ELA is known, it is possible to quantify how the winter precipitation has fluctuated if an independent proxy for mean ablation-season temperature is used in the calculation (Dahl and Nesje, 1996; Dahl et al., 1997).

Mean Lateglacial and early Holocene ablation-season temperatures

Reconstructed summer temperatures (July) (Fig. 13) from Kråkenes at Vågsøy, western Norway (Fig. 1) (Birks and

Figure 13  (A) Compiled July temperature curve for the Lateglacial and early Holocene in western Norway based on Birks and Ammann (2000) adjusted for land uplift. (B) Holocene variations in winter precipitation at northern Fjellfonna derived from equilibrium-line variations, Fig. 12 and the ‘Liestøl-equation’. The line in the middle is the average estimate based on the temperature data. Maximum and minimum estimates for the calculations are based on variations in the temperature–precipitation ELA (TP-ELA).
Amann, 2000), are suggested to be representative for the Folgefonna Peninsula as both areas are part of the same maritime climate regime. The deviation in July temperature from present at Kråkenes has been transformed to deviation in July temperature from present at Folgefonna. This is then transformed into changes in ablation-season temperature as an alteration in July temperature is inferred to be representative for the summer season (1 May–30 September). The transformation from July temperature to ablation-season temperature is tested through a regression between July temperature and ablation-season temperature for Bergen ($r = 0.74$). As a cirque glacier existed in the catchment at Kråkenes during the Younger Dryas (Larsen et al., 1984), glacier meltwater had an increasing chilling impact on lake temperature with increasing air temperature during summer time. As a consequence, water-living organisms (such as chironomids and cladocera) may not be used for reliable temperature reconstructions during this time span. Hence, for the Lateglacial (Younger Dryas) the summer-temperature reconstruction based on terrestrial plant macrofossils (Birks and Ammann, 2000) has been used, whereas chironomids have been used for the early Holocene part (ca. 11 500–10 000 cal. yr BP) (Brooks and Birks, 2000). As chironomids were not analysed from 10 000 to 9 000 cal. yr BP, terrestrial plant macrofossils are used during this time span also (Birks and Ammann, 2000). The compiled summer-temperature (July) reconstruction (Fig. 13) has a suggested standard error for both proxies of $\pm 1^\circ$C. As only negligible adjustments relative to sea level have occurred at Kråkenes since the Younger Dryas, the reconstructed temperature curve is not adjusted for land uplift (Svendsen and Mangerud, 1987).

**Mean Lateglacial and early Holocene winter precipitation**

By combining the reconstructed TP-ELA curve adjusted for land uplift with the compiled summer-temperature curve from Kråkenes in equation (1), variations in mean solid winter precipitation have been quantified according to Dahl and Nesje (1996), and are shown in Fig. 13B. The values are given as absolute variations relative to mean modern values and as variations in percentage (mean 1961–1990 = 100%) (Klimaavdelingen, 1993b). Implications of the suggested standard error for the summer-temperature proxies of $\pm 1^\circ$C and uncertainties in the ELA reconstruction have been taken into account and are shown with vertical bars in Fig. 13B.

**Discussion**

**Early deglaciation and age of low-altitude cirque glaciers**

The sedimentological investigations in Vetlavatn close to northern Folgefonna show an internally consistent AMS radiocarbon dated lithostratigraphy not covered by glaciers since ca. 12 500 cal. yr BP (Fig. 8, Table 1). The chronology obtained is consistent compared to other known climate events in the North Atlantic (e.g. PBO, ‘Erdalen Event’) which strengthens its reliability. Bondevik and Mangerud (2002) dated the Younger Dryas glacier maximum to 11 700–11 600 cal. yr BP at Os just north of outer Hardangerjorden (Fig. 1). If representative, this indicates that little glacier ice was produced at northern Folgefonna during the Younger Dryas. Combined with reconstructed sea-level fluctuations in inner parts of Hardangerjorden showing a final deglaciation in the Allerød or earlier (Helle et al., 1997), Jondal may have been deglaciated prior to the Younger Dryas. As Jondal is situated well inside the suggested margin of the Younger Dryas Scandinavian ice sheet at Halsøy in the outer parts of Hardangerjorden (Fig. 1) (e.g. Follestad, 1972; Aarseth and Mangerud, 1974; Holtedahl, 1975; Mangerud, 2000), the area is important for the ice-sheet configuration in this part of western Norway.

Figure 13A indicates that no period after the Younger Dryas/Holocene transition had mean ablation-season temperatures colder than 9–10°C at the reconstructed TPW-ELA at Drebrekke (305 m a.s.l.). This is more than 4°C warmer than at any glacier ELA in southern Norway at present, and the estimated increases in regional winter precipitation as snow based on variations in the TP-ELA of northern Folgefonna were not enough to compensate for the high summer temperatures during the early Holocene.

The regional implications of low-altitude Younger Dryas cirque glaciers in Jondal for the reconstructed Scandinavian ice sheet in Hardanger are shown in Fig. 14. The reconstructed northern Folgefonna and the cirque glacier at Drebrekke during the Younger Dryas demonstrate that Hardangerjorden most likely was deglaciated prior to the Younger Dryas, and that the production of glacier ice on surrounding mountains/plateaux was too restricted to fill up the wide and deep fjord during this event. This strongly supports the reconstructed sea-level fluctuations in inner parts of Hardangerjorden indicating a final deglaciation in the Allerød or earlier (Helle et al., 1997; Helle 2004). The suggested margin of the Younger Dryas Scandinavian ice sheet at Halsøy in outer Hardangerjorden (e.g. Follestad, 1972; Holtedahl, 1975; Mangerud, 2000) is discontinuously mapped, and it may be older and/or have a local origin south of the main fjord. It also implies that the glacier advance dated by Bondevik and Mangerud (2002) to late Younger Dryas at Os just north of outer Hardangerjorden most likely had a local origin in the Gulfjellet area east of Bergen. As a consequence, the extent of the Younger Dryas glacier(s) in the Hardanger region may have been significantly less extensive than previously suggested (e.g. Mangerud, 2000), and a major revision with implications for the Younger Dryas Scandinavian ice sheet in western Norway is therefore required.

**Climate-induced early Holocene glacier advances**

After the Younger Dryas, the rapid retreat of the fjord glaciers has been associated with calving (e.g. Holtedahl, 1975; Andersen, 1980; Andersen et al., 1995). Hence, and commonly referred to as Preboreal stages (e.g. Nesje and Dahl, 1993), fjord glaciers are suggested to have either readvanced or at least halted their general retreat as a response to steep and dynamically unstable glacier profiles. When the glacier became grounded and more dynamically stable on rock thresholds where the fjords become shallower, and/or where the valleys/fjords are relatively narrow, the glaciers formed frontal deposits as a response to the steep profiles (Kjenstad and Solliid, 1982; Solliid and Reite, 1983; Anda, 1984; Rye et al., 1987).

The first direct evidence of climate-induced glacier advances after the Younger Dryas has previously been pre-'Little Ice Age' moraines from the Erdalen Event readvance(s) at Jostedalsbreen, Grovabreen, Hardangerjokulen and western Jotunheimen (see Dahl et al. (2002) and references therein). By using rerouting of glacier meltwater across a local watershed in front of Nigardsbreen, firm evidence for a two-phase Erdalen Event
Figure 14 Suggested Younger Dryas fjord glacier scenarios along the Hardangerfjorden modified from Follestad (1972). The upper bold dotted line shows the reconstructed Younger Dryas fjord glacier after Follestad (1972), whereas the lower bold punctuated line marks the highest possible ice sheet/fjord glacier based on the Younger Dryas cirque glacier at Drebekke in Jondal.
associated with two readvances has been achieved for this glacier (Dahl et al., 2002). The first Erdalen Event readvance took place between 10 000 and 9900 cal. yr BP, whereas the second occurred close to 9700 cal. yr BP.

Comparison with ELA and winter precipitation records in western Norway

Younger Dryas

Few records estimating the ELA lowering during the Younger Dryas are available from western Norway. Using modern glaciers further inland as a reference, Follestad (1972) estimated the ELA lowering of reconstructed glaciers of suggested Younger Dryas age to be 350 to 400 m at the southwestern Folgefonna Peninsula. Based on results in the present paper, however, some of the reconstructed glaciers used by Follestad (1972) may be older.

Based on a reconstructed Younger Dryas cirque glacier at Kråkenes on Vågsøy in outer Nordfjord, Larsen et al. (1984) estimated the ELA lowering to be about 700 m. As no glaciers exist in a similar setting in outer Nordfjord at present, an extrapolation of the modern ELA based on glaciers further inland (Liestøl, 1967) was used in their estimation. By assuming the winter precipitation as snow to be similar to the present values, Larsen et al. (1984) attributed the ELA lowering of 700 m to be the result of a drop in summer temperature of ca. 6–8 °C. However, the present mean winter precipitation at Kråkenes is much less than some few tens of kilometres further inland, and makes the extrapolation of the modern ELA towards Kråkenes unlikely. Because of local topographic conditions, it is also difficult to compare an ELA lowering based on a reconstructed TPW-ELA of a cirque glacier at Kråkenes with the reconstructed TP-ELA lowering at northern Folgefonna.

By using the ELA of modern glaciers in inner Nordfjord as a reference, Fareth (1987) and Rye et al. (1987) estimated the ELA lowering during the Younger Dryas to be 400–500 m in this region. Based on the modern TP-ELA of a small plateau glacier at Storelogo close to Innvik, inner Nordfjord, Dahl and Nesje (1992) estimated the ELA lowering during the Younger Dryas to be about 500 m. All estimates on the Younger Dryas ELA lowering using modern glaciers in inner Nordfjord as a reference are of the same order as the estimate of 355 m from northern Folgefonna (Fig. 12).

Based on a similar approach to that used at northern Folgefonna, the estimated winter precipitation as snow was estimated to be less than 60% compared to modern values in inner Nordfjord (Dahl and Nesje, 1992). This is wetter than the similar estimate of about 30% during the suggested Younger Dryas at northern Folgefonna (Fig. 13), and may be explained by a shorter distance from Nordfjord to a suggested seasonally ice-free North Atlantic (e.g. Koc Karpuz and Jansen, 1992).

‘Jondal Event 1’/PBO (ca. 11 150–11 050 cal. yr BP)

The glacier readvance during the ‘Jondal Event 1’/PBO with a TP-ELA lowering of about 230 m is shown to be primarily the result of somewhat lower summer temperatures for about 100 years (Figs 13 and 15). No other climate-induced glacier advances/readvances have been demonstrated from western Norway during the PBO.

‘Jondal Event 2’ (ca. 10 550–10 450 cal. yr BP)

This climate-induced glacier readvance with a TP-ELA lowering of about 220 m is inferred to be the result of a marked increase in winter precipitation (Figs 13 and 15). ‘Jondal Event 2’ may be contemporaneous with the cirque glaciation recorded by Ekeland (1991) at Sunnmøre, and it is suggested to be the first Holocene climate-induced glacier readvance/advance initiated by an increase in winter precipitation.

‘Erdalen Event 1’ (ca. 10 000–9900 cal. yr BP)

The TP-ELA lowering of 210 m at northern Folgefonna during the ‘Erdalen Event 1’ is shown to be primarily the result of a marked increase in winter precipitation (Figs 13 and 15). This is in agreement with the conclusions of Dahl et al. (2002) from Nigardsbreen, a southeastern outlet glacier from Jostedalsbreen. The calculated winter precipitation values during the ‘Erdalen Event 1’ appear to have been among the highest during the entire Holocene.

‘Erdalen Event 2’ (ca. 9700 cal. yr BP)

No ‘Erdalen Event 2’ has been recorded at northern Folgefonna. At Nigardsbreen (with a southeasterly aspect), however, this glacier (re)advance seems to have been caused by a marked drop in summer temperature which reactivated already existing ice masses (Dahl et al., 2002). Primarily because of dating uncertainties it is not obvious whether other sites have recorded the first or the second Erdalen Event glacier readvance (e.g. Dahl and Nesje, 1992, 1996; Matthews et al., 2000; Nesje et al., 2001). Why the ‘Erdalen Event 2’ is not recorded at northern Folgefonna is therefore not clear. However, the aspect of the investigated outlet glacier(s) at northern Folgefonna and the lack of a sensitive site may be of importance.

Atmosphere–ocean interaction during the Lateglacial and early Holocene

Vetlavatn provides the first Scandinavian record demonstrating climate-induced glacier fluctuations during the Lateglacial/early Holocene transition. As the transition from glacial to interglacial conditions is not well understood, the atmosphere–ocean interaction leading to glacier advance and retreat in this region is of major scientific interest.

Among several hypotheses introduced to explain the apparent climate instability during the Lateglacial/early Holocene transition, the most important are as follows.

- Large freshwater outbursts into the North Atlantic may explain (some) abrupt climatic deteriorations during this time span (e.g. Broecker et al., 1989, 1990; Clark et al., 2001; Fisher et al., 2002; Teller et al., 2002; Nesje et al., 2004).
- Variations in solar and/or geomagnetic forcing may explain the observed climate instability, and have been studied by use of 10Be and 14C records from the Greenland ice cores as a direct signal of changes in the production rates of the cosmogenic radionuclides (Finkel and Nishiizumi, 1997; Björck et al., 2001).
- Fluctuations in the Atlantic MOC may strongly influence the climate in the North Atlantic region, and a lightness index...
based on deep-marine sediments has been used to study variations in the production of North Atlantic Deep Water (NADW) (Chapman and Shackleton, 2000).

In Fig. 15, reconstructed records of freshwater outbursts into the North Atlantic, solar and/or geomagnetic forcing and the production of NADW are shown with the Lateglacial and early Holocene glacier fluctuations at northern Folgefonna.

Based on variations in 10Be from Greenland ice cores, the input of solar energy was low during the Younger Dryas (Finkel and Nishiizumi, 1997; Bjo¨rck et al., 2001), and there was a major meltwater pulse associated with this cold spell in the North Atlantic (e.g. Broecker et al., 1989, 1990; Clark et al., 2001; Fisher et al., 2002; Teller et al., 2002) (Fig. 15). Hence, the combined effect of this meltwater outburst and the low solar forcing apparently played a major role for a dry and cold climate in western Norway during the Younger Dryas.

Both the meltwater pulse and the solar forcing minimum ended at the termination of the Younger Dryas. During 'Jondal Event 1'/PBO there was a new low in the input of solar energy, and another meltwater pulse occurred in the North Atlantic (Bjo¨rck et al., 1997, 2001). Hence, the mechanisms behind the rather cold and dry 'Jondal Event 1' are likely to be closely related to what happened during the Younger Dryas, but on a much smaller scale. Based on the lightness index (Chapman and Shackleton, 2000), a weak reduction in the thermohaline circulation in the North Atlantic took place just prior to the 'Jondal Event 1'/PBO (Fig. 15).

The initiation of the 'Jondal Event 2' took place in a period without meltwater pulses to the North Atlantic, and the glacier readvance terminated in the middle of one. Solar forcing based on 10Be was high during 'Jondal Event 2' (Bjo¨rck et al., 2001), and the thermohaline circulation was rather high just prior to this episode (Chapman and Shackleton, 2000). Hence, the high winter precipitation values estimated for the 'Jondal Event 2' may be the result of increased evaporation from warmer surface waters in the North Atlantic. The high winter precipitation values during this event (Fig. 13) may represent an early Holocene occurrence of relatively mild, southwesterly winds during winter time in western Norway. Based on modern instrumental records, these characteristics are associated with a positive North Atlantic Oscillation (NAO) mode in this region (e.g. Nesje et al., 2000b).

Predating the 'Jondal Event 2' and a North Atlantic meltwater pulse (Fig. 15), Bjo¨rck et al. (2001) linked a cooling event at 10,300 cal yr BP and one of the largest Holocene 10Be flux peaks. Contemporaneous, or somewhat prior to this 10Be flux peak, was a marked reduction in the thermohaline circulation of the North Atlantic (Chapman and Shackleton, 2000). No climate-induced glacier advance/readvance has so far been associated with this cooling event. The 'Erdalen Event 1' is associated with a lack of meltwater pulses, strong solar forcing.
(Björck et al., 2001) and a distinct increase in the thermohaline circulation of the North Atlantic (Chapman and Shackleton, 2000). Taking into account the high winter precipitation values to obtain the observed glacier readvance, the mechanism behind ‘Erdalen Event 1’ may be analogous to ‘Jondal Event 2’.

The ‘Erdalen Event 2’ apparently took place in a period with no meltwater pulses, a rather high input of solar energy (Björck et al., 2001) and a reduced thermohaline circulation in the North Atlantic (Chapman and Shackleton, 2000). No glacier readvance has been associated with ‘Erdalen Event 2’ at northern Folgefonna, but it has been recorded as a distinct glacier readvance at Nigardsbreen, a southeasterly valley-outlet glacier to Jostedalsbreen (Dahl et al., 2002) (Fig. 15).

Conclusions

Based on the presented results and discussion the following conclusions and implications of local, regional and systematic importance are suggested:

1. The northern Folgefonna ice cap was isolated from the Scandinavian ice sheet during the late Allerød and the entire Younger Dryas. This contradicts the previously presented model (e.g. Mangerud, 2000) where the Folgefonna Peninsula is suggested as a main source of glacier ice filling up Hardangerfjorden during this time span. The shift from a dry and cold Younger Dryas climate mode to the relatively warm and humid Holocene climate was rapid. As a consequence, northern Folgefonna is suggested to have shifted from being controlled by summer temperature to being controlled by winter precipitation during this transition.

2. Based on the radiocarbon-dated lithostratigraphy from Vettlavatn, lowering of the ELA, estimated Holocene winter precipitation values at northern Folgefonna and variations in Holocene summer temperatures, the low-altitude cirque glacier at Drebrekke between Hardangerfjorden and northern Folgefonna existed for the last time during the Younger Dryas. The existence of a cirque glacier in this topographical setting limits the maximum altitude for the Scandinavian ice sheet during the Younger Dryas to well below the proposed model by Mangerud (2000) (Fig. 14).

3. The ‘Jondal Event 1’ is a climatically induced glacial readvance dated to 11 100 cal yr BP, with a TP-ELA lowering of ca. 230 m. The event was contemporaneous with the temperature drop during the Preboreal Oscillation (e.g. Björck et al., 1997).

4. The climatically induced ‘Jondal Event 2’ occurred ca. 10 550–10 450 cal yr BP, and had a TP-ELA lowering of about 220 m. ‘Jondal Event 2’ is the first Holocene glacier readvance/advance initiated by an increase in winter precipitation (Fig. 13).

5. An ‘Erdalen Event 1’ glacier readvance with a TP-ELA lowering of 210 m occurred at northern Folgefonna ca. 10 000–9900 cal yr BP. The glacier readvance was primarily the result of a marked increase in winter precipitation (Fig. 13), and the estimated values were among the highest during the entire Holocene.

6. The apparent lack of an ‘Erdalen Event 2’ at northern Folgefonna is poorly understood, but may be the result of a shift in the atmospheric circulation giving relatively more winter precipitation to glaciers with an aspect towards south-southeast.

7. The climate-induced early Holocene glacier advances/readvances at northern Folgefonna were apparently related to large freshwater outbursts to the North Atlantic, variations in solar and/or geomagnetic forcing and by fluctuations in the thermohaline circulation of the North Atlantic (Fig. 15):

- ‘Jondal Event 1’ is closely related to a low input of solar energy and to a meltwater pulse to the North Atlantic.
- ‘Jondal Event 2’ occurred in a period without meltwater pulses to the North Atlantic, solar input was high and the thermohaline circulation was strong. The high winter precipitation values estimated for this event may therefore be the result of increased evaporation from warmer surface waters in the North Atlantic. Hence, ‘Jondal Event 2’ may represent an early Holocene occurrence of relatively warm, southwesterly winds during winter time in western Norway equivalent to a positive North Atlantic Oscillation (NAO) mode based on instrumental data in this region (cf. Nesje et al., 2000b).
- The ‘Erdalen Event 1’ is, like the ‘Jondal Event 2’, associated with a lack of meltwater pulses, a strong solar forcing and a distinct increase in the thermohaline circulation. The winter precipitation values during this event may have been among the highest during the entire Holocene.
- The ‘Erdalen Event 2’ may be linked to a reduced thermohaline circulation. Whether there is a coupling to a possible shift in the atmospheric circulation during this event is not known, but if such a shift took place this may explain the apparent lack of an ‘Erdalen Event 2’ at northern Folgefonna.

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