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

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Abstract: Northern Folgefonna (c. 23 km^2), is a nearly circular maritime ice cap located on the Folgefonna Peninsula in Hardanger, western Norway. By combining marginal moraines and 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. BP), a short-lived (150-200 years) climatically induced glacier readvance termed 'Jondal Event 1' occurred within the 'Preboreal Oscillation' (PBO) c. 11,200 cal. BP. Bracketed to 10,550-10,350 cal. BP, a second glacier readvance is named the 'Jondal Event 2'. A third readvance occurred about 10,000 cal. BP and corresponds to 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 makes it possible to reconstruct former variations in winter precipitation if the corresponding ELA is known and combined with an independent proxy for summer temperature. Compared to at present, the Younger Dryas was much colder and drier, the 'Jondal Event 1' / PBO was colder and somewhat drier, the 'Jondal Event 2' was much wetter, whereas 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 asl.) 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 Hordaland.

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

Introduction

The transition from glacial to interglacial conditions is well understood. Of special interest is the general climatic implications of the Younger Dryas which close to 11,500 cal. yr BP terminates the last glacial stage and precedes the present interglacial, the Holocene.

A large number of Lateglacial and early-Holocene climate reconstructions are available from NW Europe. In western Norway climate reconstructions from the last deglaciation and early-Holocene have been inferred from records of Younger Dryas and early-Holocene glacier variations (e.g. Larsen *et al.*, 1984; Nesje *et al.*, 1991; Dahl and Nesje, 1992; 1994; 1996b; 2000a; 2001a; Dahl *et al.*, 2003), from biological proxies (e.g. Paus, 1988; 1989; Birks *et al.*, 1994; Birks and Ammann, 2000; 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).

The INTIMATE group suggested that the Greenland ice core GRIP should constitute the stratotype for the last termination (Björck *et al.*, 1998; Lowe *et al.*, 2001). These data have been used to calibrate different proxies from all over the Northern Hemisphere, and are also reproduced from European tree-ring chronologies (Friedrich *et al.*, 2001). A recent chironomid-based summer-temperature curve from Whitrig Bog, SE Scotland (Brooks and Birks, 2000) is in addition relevant for this study.

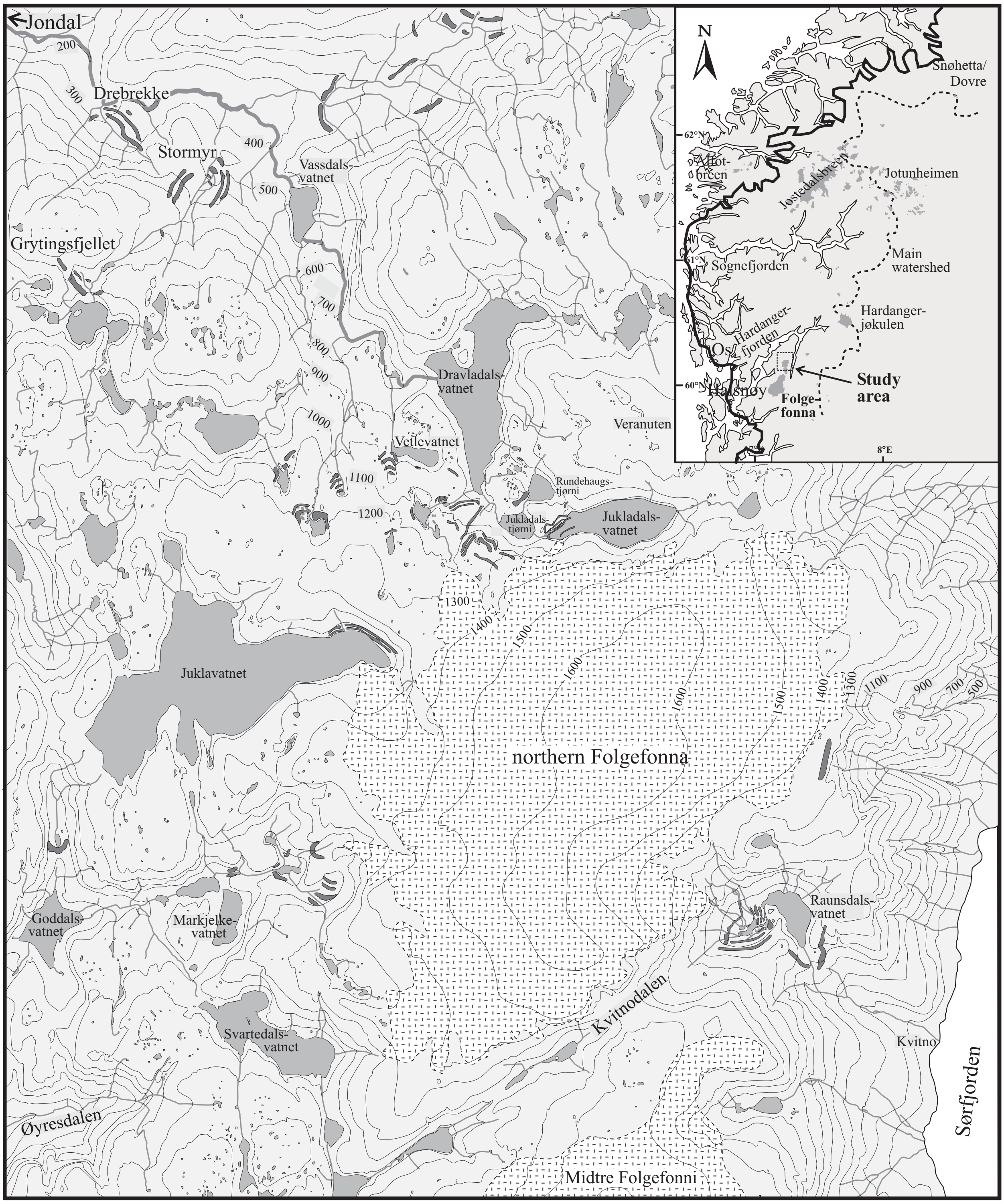

Figure 1 The incised map shows the geographical distribution of glaciers in southern Norway. The dotted frame shows the study area. The main map is showing the ice cap northern Folgefonna and the surrounding area. Note the position of the proglacial lakes Vetlavatn and Vassdalsvatn, and the sites with marginal moraines deposited by low-altitude cirque glaciation at Drebrekke 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 there are some remnants of marginal moraines deposited by the Late Weichselian Scandinavian Ice Sheet.

Terrestrial archives reflecting the Lateglacial/early-Holocene transition in western Norway must be beyond the Younger Dryas continental ice sheet in western Norway (Fig. 1). Due to calving, the continental ice sheet is suggested to have retreated far inland along Hardangerfjorden prior to a major readvance in the order of 100 km during the Younger Dryas (Aarseth and Mangerud, 1974; Mangerud, 2000) (Fig. 1). However, reconstructed sea-level fluctuations in inner parts of Hardangerfjorden indicate a final deglaciation prior to the Younger Dryas (Helle *et al.*, 1997). To have a major Younger Dryas readvance, the regional equilibrium-line altitude (ELA) must have been well below all high-lying mountain areas surrounding the wide and very deep Hardangerfjord. Of especial interest in this context is the Folgefonna Peninsula with three large plateau glaciers at present. If a readvance took place

Figure 2 Photo showing the northern Folgefonna ice cap seen from southern Folgefonna to the south. The ice cap is almost circular and is located on a mountain plateau at an altitude of about 1300 m.

in Hardangerfjorden during the Younger Dryas, the Folgefonna Peninsula must have produced a large part of the glacier ice necessary to fill up the fjord. Findings of marginal moraines after low-altitude cirque glaciers down to 290 m asl. in Jondal well inside the suggested front of the Younger Dryas ice sheet in Hardangerfjorden have challenged this model (Bakke *et al*., 2000).

By coring proglacial lakes draining northern Folgefonna and combine periods with AMS radiocarbon dated input of glacier-induced sediments with marginal moraines, the main objective of this paper is to reconstruct variations in glacier magnitude / ELAs and winter precipitation during the Lateglacial and early-Holocene in this region. We also want to discuss local implications of these reconstructions with respect to the age of marginal moraines after former low-altitude cirque glaciers in the area, and to discuss implications with respect to the regional ice-sheet configuration in Hardanger during the Lateglacial and early-Holocene. Finally, we want to establish an event chronology for the Lateglacial / early-Holocene transition based on glacier fluctuations / ELAs in western Norway.

Study area

The ice cap northern Folgefonna covers an area of 23 km^2, 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 ELA of about 1465 m. There are five major outlet glaciers from the ice cap; Jordalsbreen, Juklavassbreen, Botnabreen, Dettebrea and Jukladalsbreen (Figs. 1 & 2). About 12 km^2 of northern Folgefonna drains northwards, and this Jondal catchment includes 9 smaller and bigger lakes. No other glaciers exist in this catchment.

The bedrock in the upper Jondal catchment mainly consists of acid meta-andesite, metadacite, quartzite, migmatite and migmatitic schist of Precambrian age (Sigmond, 1985; Askvik, 1995). The vegetation is meagre around northern Folgefonna, and except for some marginal moraines in front of the major outlet glaciers, there is only a sparse cover of colluvium and till in the area (Bakke, 1999).

Based on a combination of two meteorological stations along Hardangerfjorden (Station no. 4949, Ullensvang Forsøksgård, 12 m a.s.l., 1962-1988; Station no. 5013, Omastrand, 1 m a.s.l., 1962-1990) (Klimaavdelingen, 1993b), the present mean summer temperature (Ts) from 1 May to 30 September is 12.7^{o}C at sea level in Jondal. Using an environmental lapse rate of 0.6^{o}C / 100 m (e.g. Sutherland, 1984; Dahl and Nesje, 1992), this gives a mean Ts close to 4.0^{o}C at the modern ELA of 1465 m at northern Folgefonna. At a local meteorological station about 11 km from the present glacier terminus of northern Folgefonna (Station no. 5696, Kvåle, 342 m a.s.l., 1961-1990) (Klimaavdelingen, 1993a), the present mean winter precipitation (Pw) from 1 October to 30 April is 1434 mm. Based on a mean observed exponential increase in winter precipitation with altitude of 8 % / 100 m in southern Norway (Haakonsen, 1989; Dahl and Nesje, 1992, and references therein), the corresponding Pw at the ELA of northern Folgefonna is c. 3350 mm.

Research approach and methods

The reconstruction of Lateglacial and early-Holocene glacier fluctuations at northern Folgefonna involved

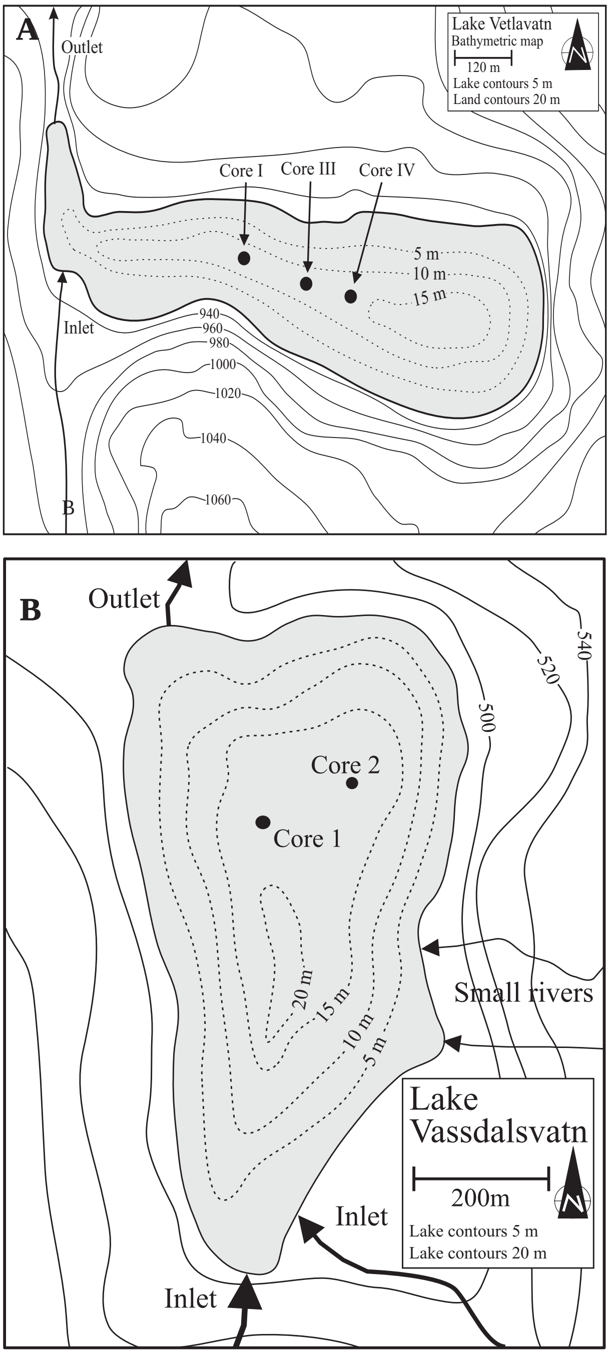

Figure 3 (A) Bathymetric map of lake Vetlavatn showing the location of the retrieved piston cores. Core I to IV is taken with increasing distance away from the inlet/outlet. Northern Folgefonna did not reroute glacier meltwater to lake Vetlavatn during the 'Little Ice Age'.(B) Bathymetric map for lake Vassdalsvatn showing the location of the retrieved piston cores. Note that core I is taken close to the main 'river stream channel' running through the lake.

several approaches:

- Air phothographs (Widerøe, 1962) and field observations were combined to produce a detailed glacial-geomorphological map in 1:5000 for the Jondal catchment with special emphasis on former marginal moraines, glacier-meltwater channels, glaciofluvial deposits, marine terraces and various ice-flow indicators.

- Primarily to sort out moraines older than the historical 'Little Ice Age' maximum, lichenometry based on *Rhizocarpon geographicum* (Matthews, 1994) and Schmidt-hammer rebound values according to 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 after two former low-altitude cirque glaciers.

- The accumulation of distinct marginal moraines is suggested to be closely related to (rather) short periods when a glacier was in steady state, and younger glacier advances may also erase older marginal moraines (e.g. Matthews, 1991; Dahl and Nesje, 1994). Hence, proglacial sites (lacustrine and terrestrial) beyond the maximum extent of the suggested glacier advances in the studied time span are taken into account to obtain continuous records of glacier fluctuations. Various methods related to proglacial sites are all based on a conceptual model of glacier-meltwater induced sedimentation in which the minerogenic (nonorganic) component of the sediments is related to the occurrence of a glacier in the catchment (Karlén, 1981; Leonard, 1985; Dahl *et al*., 2003). In this study, the two proglacial lakes Vetlavatn and Vassdalsvatn (Figs. 1&3) were cored in an attempt to obtain absolute dating control on the timing and magnitude of Lateglacial and early-Holocene glacier fluctuations in the Jondal catchment.

Lake Vetlavatn, at an altitude of 915 m asl., covers an area of 0.1 km^2 (Fig. 3a), and is situated in a glacially eroded bedrock basin with the longest axis oriented east-west in a length of 700 m. The proglacial lake only receives glacier-meltwater induced sediments when the outlet glacier Jordalsbreen from northern Folgefonna advances beyond a local bedrock threshold. When the glacier is behind this local watershed, organic gyttja dominates the sedimentation in the lake. Four cores were retrieved from this lake.

Lake Vassdalsvatn, at an altitude of 490 m asl., covers an area of 0.17 km^2 (Fig. 3b), and is the seventh proglacial lake downstream from northern Folgefonna along the present meltwater stream in Jondal. The lake is located in a glacially eroded bedrock basin, and it has an input of glacier-meltwater induced sediments at present. Lake Vassdalsvatn is suggested to reflect for whenever northern Folgefonna is very small or melted completely away. Two cores were retrieved from lake Vassdalsvatn.

Both proglacial lakes were cored using a modified piston corer taking up to 6 m long cores with a diameter of 110 mm (Nesje, 1992). The laboratory analysis included weight loss-on-ignition (LOI) (Heiri *et al*., 2001), bulk density (wet and dry) and water content (Menounos, 1997), and grain-size analysis using a Micromeretics Sedigraph 5100 (x-ray determination). See Dahl *et al*. (2003) for an evaluation of the principal use of these techniques to record former glacier fluctuations.

Seventeen and two bulk AMS radiocarbon dates were carried out from lakes Vetlavatn and Vassdalsvatn, 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 regarded to be a problem for age-depth modelling (Barnekow *et al.*, 1998; Lowe and Walker, 2000). All results are shown in Table 1, and are presented in the text as calibrated years before present (cal. BP) according to INTCAL 98 (Stuiver *et al.*, 1998) if not otherwise stated.

The estimates of former glacier ELAs are based on observations of modern analogues and accumulated knowledge from previous works (Dahl *et al.*, 2003). Calculations at the plateau glacier are made by using an Accumulation Area Ratio (AAR) of 0.7 (Dahl and Nesje, 1996a), whereas the cirque glaciers are reconstructed using an AAR of 0.6 (Dahl *et al.*, 1997). The calculation of the area distribution 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 eight successively smaller glacier advances / readvances with deposition of marginal moraines. Beyond these moraines there are some sparsely distributed remnants after an even older glacier advance. Suggested to be the result of differences in aspect and slope, the moraine chronology is not consistent around northern Folgefonna.

A relative moraine chronology was established by use of lichenometry (Fig. 4a) and Schmidt-hammer rebound values (Fig. 4b) on the moraines. 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), three major glacier advances which occurred during the ’Little Ice Age’ culminated about AD 1750, 1870 and 1930, respectively (Fig. 4a).

Based on observations in southern Norway, lichen-growth curves reflecting *Rhizocarpon geographicum* can not be used for reliable (relative) dating for more than 400-500 years backwards in time (Matthews, 1994). Hence, lichen diameters on the remaining five 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. 4b) indicate that two marginal moraines may have formed c. 3,000-1,000 years ago, 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 suggested to have been formed by two low-altitude cirque glaciers have been investigated at Drebrekke and Stormyr in Jondal (Fig. 1). Bellow the mountain Grytingsfjellet (alt. 1092 m asl.), two sets of marginal moraines and indications of a third have been deposited by a small cirque glacier formed in a poorly developed cirque at Drebrekke. The eastern lateral moraine is well marked and can be traced to an altitude of 400 m, while the outer terminal moraine can be mapped to a lowest altitude of 290 m asl. (Figs. 5 & 6).

The farm inside the marginal moraines at Drebrekke has a history which can be followed back to the 15th century (Kolltveit, 1953). This suggests that no glacier formed at Drebrekke during the ‘Little Ice Age’, and this is confirmed by lichen measurements on the marginal moraines. Schmidt-hammer rebound values indicate an age of formation which is comparable with the three oldest sets of marginal moraines around northern Folgefonna.

At the northern flank of the mountain Storafjell (alt. 1133 m), two distinct sets of marginal moraines formed by a rather large cirque glacier are situated

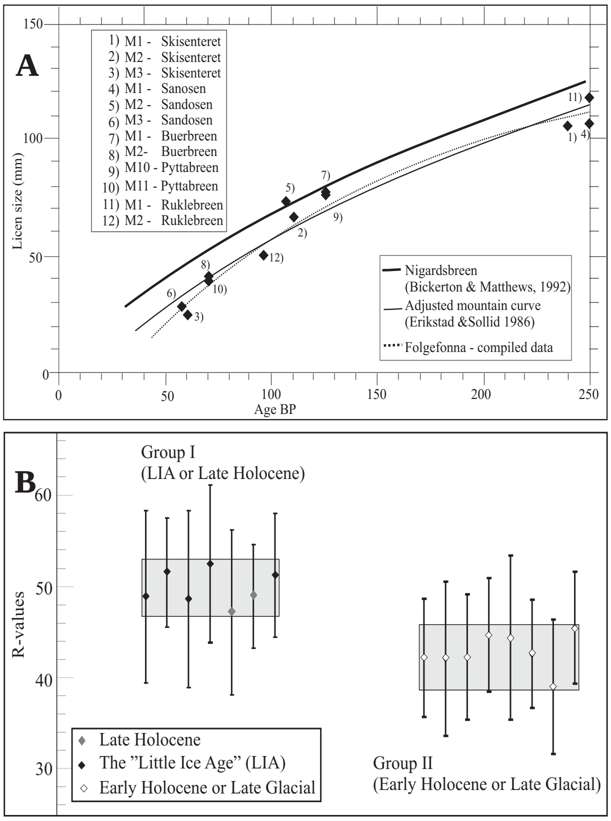

Figure 4 (A) Growth curves for the lichen *Rhizocarpon geographicum* in the marginal zones of Nigardsbreen and a composite mountain curve based on the curve from Midtdalsbreen at Hardangerjøkulen fit well with observations from different parts of the Folgefonna glacier. Based on the suggested growth rate, an early ‘Little Ice Age’ (LIA) glacial advance took place at Folgefonna close to 1750 AD, whereas marked later readvances occurred between AD 1870 - 1890 and during the AD 1930s. (B) Schmidt-hammer rebound values (R-values) from marginal moraines at the northern part of the ice cap northern Folgefonna. The figure shows how marginal moraines deposited during the Lateglacial and early-Holocene can be separated from moraines formed during the late-Holocene based on R-values.

Figure 5 Photo showing the Drebrekke farm in Jondal. The Drebrekke farm lies on marginal moraines formed by a small cirque glacier of suggested Younger Dryas age N-NE of the mountain Grytingsfjellet (proximal side to the right on the photo). The lowermost part of the outer moraine ends at an altitude of 290 m. Hence, the Drebrekke site gives the maximum elevation for a fjord glacier if there existed a Hardangerfjord glacier during the Younger Dryas in this region (see Fig. 14).

north of a mature cirque at Stormyr (Fig. 1). Taken into account 4-5 m of 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 rebound values on the marginal moraines indicate a similar age of formation as at Drebrekke (Fig. 4b).

Lithostratigraphy and radiocarbon dates

Lake Vetlavatn

Based on cores I, III and IV from lake Vetlavatn, the combined lithostratigraphy may be subdivided into ten units, with core 4 as the most representative (Figs. 7 & 8). The content of cumulative medium silt including weight LOI from cores III and IV are shown in Fig. 9. 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. 3a). Details concerning the AMS radiocarbon dates used for age-depth control 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%. In core I, the unit is running 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, turning into the light-grey Unit H consisting of silt. The LOI varies from a minimum of 0.8% in Unit I to a maximum in Unit H of 4.5%. The end of Unit H is dated to

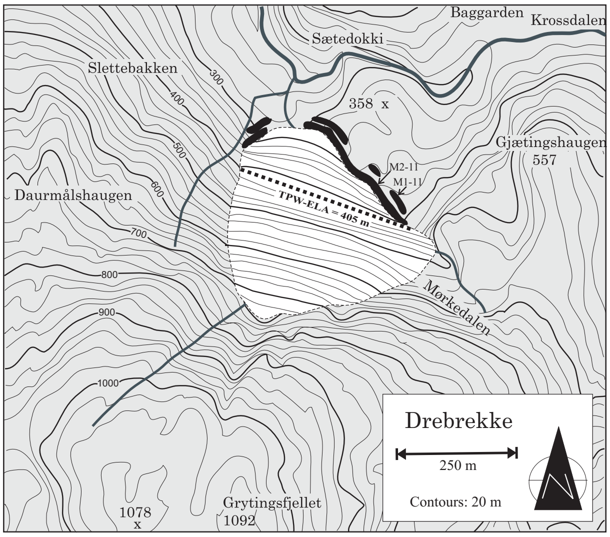

Figure 6 The reconstructed cirque glacier at Drebrekke in Jondal with a temperature-precipitation-wind equilibrium-line altitude (TPW-ELA) of 405 m, which is a lowering of the ELA of 1150 m compared with the present situation at the ice cap northern Folgefonna. The extension of the glacier is based on lateral moraines and cirque topography. The contours are reconstructed using the shape of modern cirque glaciers in Norway.

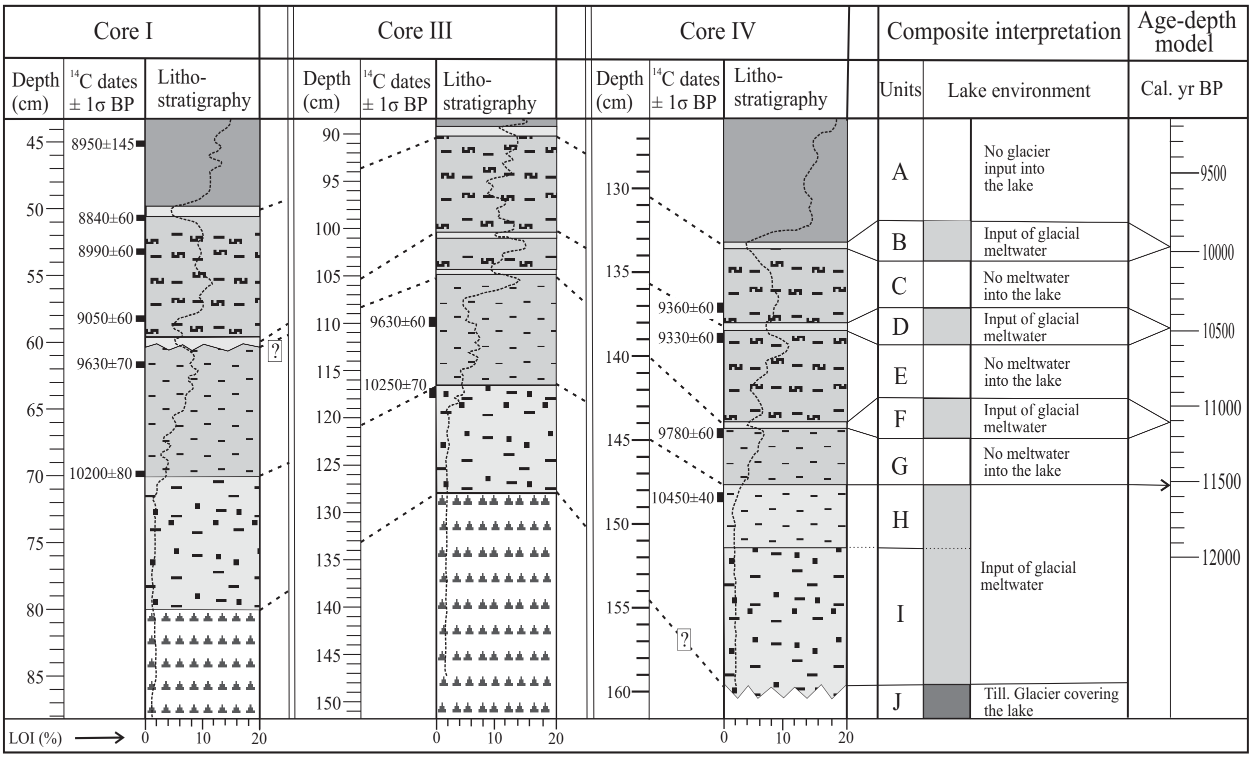

Figure 7 Compiled lithostratigraphy from three cores derived from lake Vetlavatn. The radiocarbon dates are shown in radiocarbon years before present together with independent depth scales (cm) for each core. The dashed lines show the correlation between lithostratigrapical units and the right column the suggested age for the different units in calibrated years before present (=1950). Probably because of erosion by the river, the units H, G and F are missing in core I.

10,480±40 ^{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 14C yr BP (Beta-115403) at 69.5 cm in core I and to 10,250±70 14C yr BP (Beta-148431) at 118 cm in core III. In Unit F light-grey silt turns into a more greyish colour upwards with a mean LOI of 4.0%. The 5 mm thick layer appears in sharp contrast to surrounding units, and it is present and radiocarbon dated at 109.5 cm in core III to 9630±60 ^{14}C yr BP (Beta-148430), and at 144 cm in core IV to 9830±60 14C yr BP (Beta-148428), respectively. Unit E consists of grey silty-clayey gyttja that is turnng into brownish yellow upwards, and with LOI values from 4.0 to 12.4%. A radiocarbon date from this unit yielded an age of 9660±70 ^{14}C yr BP (Beta-115403) 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

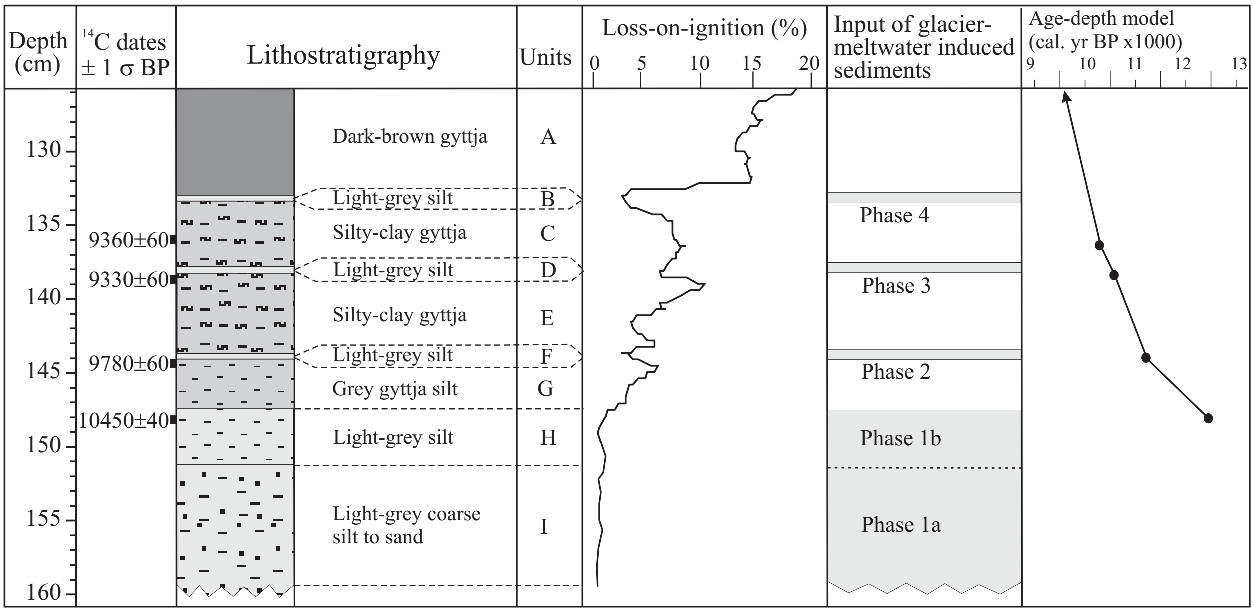

Figure 8 Lithostratigraphy with radiocarbon dates and environmental interpretation from Core IV in lake Vetlavatn. Note the changing sedimentation rate upwards in the core.

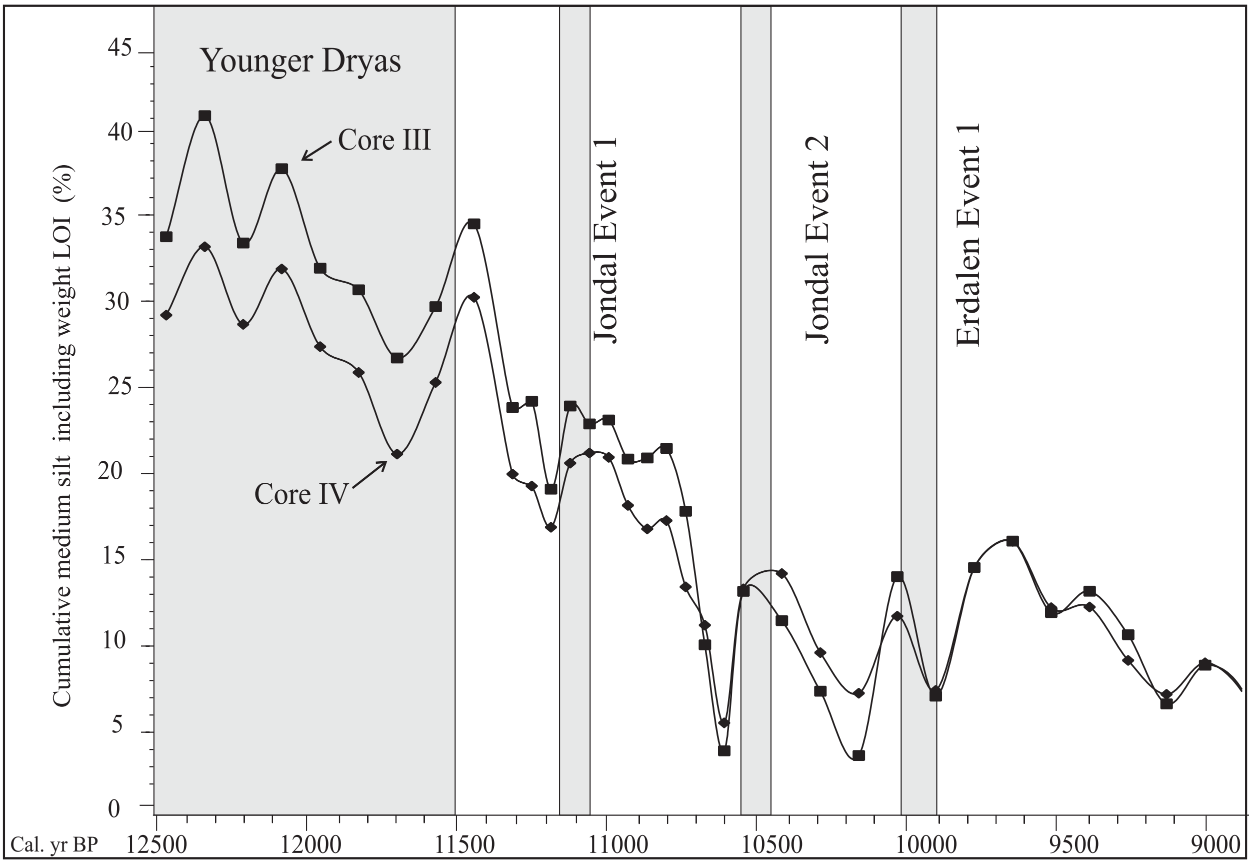

Figure 9 Cumulative medium silt against loss-on-ignition for core III and IV in lake Vetlavatn on a calendar year scale. The figure shows that the input of silt dcreased after the Younger Dryas with small peaks during the early-Holocene events. Probably because of increased precipitation, the content of medium silt increases after the 'Erdalen Event 1'.

radiocarbon dates of 9380±60 ^{14}C yr BP (Beta-148427) and 9360±60 ^{14}C yr BP (Beta-148426) at 138 and 136 cm, respectively. Unit C consists of grey silty-clay 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 ^{14}C yr BP (Beta-115401) at 58 cm, of 8990±60 ^{14}C yr BP (Beta-115401) at 53 cm and by 8840±60 ^{14}C yr BP (Beta-115401) 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 about 6.4%. It is radiocarbon dated in core I to 7640±135 ^{14}C BP (T-13605) at 33 cm, to

Table 1 Radiocarbon dates from Vetlavatn. All dates are AMS bulk dates.

Core	Depth	Laboratory number	Radiocarbon age	Intercept	2 sigma cal. yr BP	ϑ ^{13}C
Vetlvatnt I	15	T-13603A	6785±160	7680	7934 - 7468	-29.6
Vetlavatn I	20	T- 13604A	7475±26	8482	8783 - 7789	-29.9
Vetlavatn I	33	T-13605	7640±135	8402	8502-8315	-27.9
Vetlavatn I	46	T-13606	8950±145	9959	10034-9859	-29.1
Vetlavatn I	50	Beta-115399	8840±60	9890	9920-9850	-27.5
Vetlavatn I	53	Beta-115400	8990±60	9975	10005-9940	29.0
Vetlavatn I	58	Beta-115401	9050±60	10005	10035-9975	-28.4
Vetlavatn I	61.5	Beta-115403	9660±70	10920	10960-10625	-28.8
Vetlavatn I	69.5	Beta-115403	10200±80	11960	12155-11680	-27.6
Vetlavatn III	110	Beta-148430	9630±60	8890	11160-10690	-28.1
Vetlavatn III	118	Beta-148431	10250±70	11940	12360-11580	-26.9
Vetlavatn IV	23	Beta-148424	2980±40	3160	3260-3000	-25.2
Vetlavatn IV	118	Beta-148425	8150±50	9020	9130-8990	-28.1
Vetlavatn IV	136	Beta-148426	9360±60	10520	10670-10270	-28.3
Vetlavatn IV	138	Beta-148427	9380±60	10540	10690-10380	-28.3
Vetlavatn IV	144	Beta-148428	9830±60	11190	11250-11130	-28.1
Vetlavatn IV	148	Beta-148429	10480±40	12500	12820-12080	-26.6
Vassdalsvatn II	171	UtC-6695	6280±60	7195	7220-7095	-27.1
Vassdalsvatn I	368-372	Beta-102935	8260±80	9235	9375-9025	-25.0

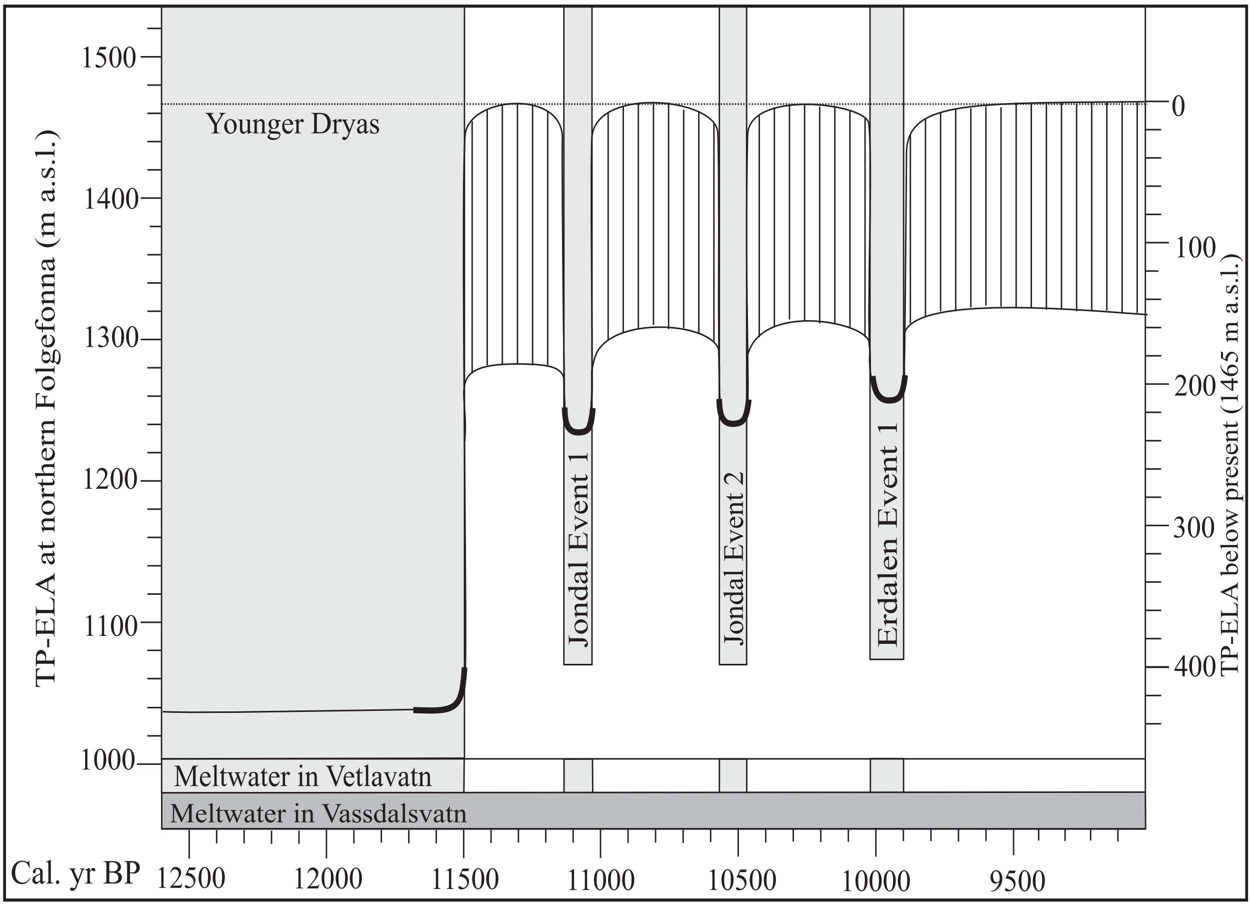

Figure 11 Reconstructed Lateglacial and early-Holocene glacier fluctuations and TP-ELAs at northern Folgefonna. Note that the TP-ELA curve is adjusted for land uplift. Vertical bars indicate possible ELA altitude range during periods without meltwater input to lake Vetlavatn.

7475±30 ^{14}C yr BP (T-13604A) at 20 cm and to 6785±160 ^{14}C yr BP (T-13603A) at 15cm. A sample taken from Unit A at 46 cm in core I was radiocarbon dated to 8950±145 ^{14}C yr BP (T-13606), and is suggested to be somewhat too old. However, the deviation may be explained by a large standard deviation. In core IV, Unit A is dated at 8150±50 ^{14}C yr BP (Beta-148425) at 118 cm and to 2980±40 ^{14}C yr BP (Beta-148424) at 23 cm.

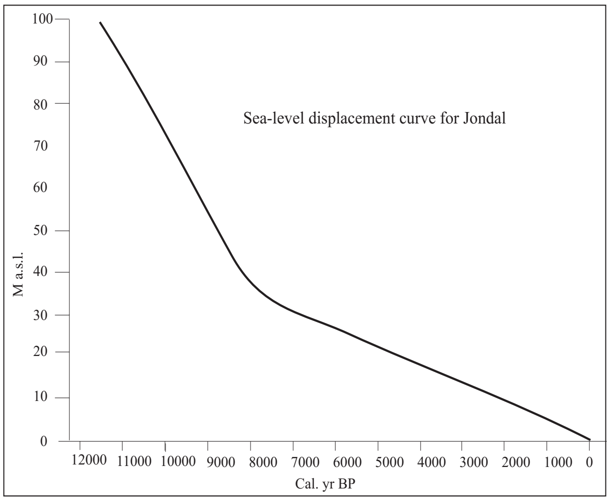

Figure 10 Sea-level displacement curve for Jondal based on the equidistant sea-level (ESL) diagram from Hamborg (1983) used for adjusting the winter precipitation estimates during the early-Holocene at northern Folgefonna.

Lake Vassdalsvatn

For this study, the lithostratigraphy in Lake Vassdalsvatn is primarily used to complement lake Vetlavatn and to indicate whether northern Folgefonna was melted away during the studied time span or not. Light-grey clayey silt is suggested to reflect the existence of northern Folgefonna in the catchment, whereas gyttja is likely to indicate whenever the glacier was melted away. The first transition from light-grey glacier-meltwater induced clayey silt to gyttja after the deglaciation is dated at 7200 cal. yr BP (UtC-6695) in core II, whereas a sediment layer rich in plant macrofossils is interpreted to be a flood deposit dated to 9200 cal. yr BP (Beta-102935) in core I (see Table 1 for details). The suggested flood eroded upstream peat deposits with resedimentation in the central basin/channel of lake Vassdalsvatn where core I is retrieved (see Bakke *et al.* in prep. for further discussion).

Glacier variations and equilibrium-line altitudes at northern Folgefonna

The Lateglacial and early-Holocene glacier fluctuations are primarily based on a combination of the radiocarbon dated lithostratigraphies from lakes Vetlavatn and Vassdalsvatn and the moraine chronology at northern Folgefonna. The record from lake Vassdalsvatn indicates whenever northern Folgefonna existed during the investigated time span, whereas lake Vetlavatn record indicates whenever the glacier advanced beyond a local watershed which prevents direct input of glacier-meltwater induced sediments from northern Folgefonna to this lake 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 present temperature-precipitation-wind ELAs (TPW-ELAs) at the northern outlets of northern Folgefonna is 1465m, whereas estimates from the outlet glaciers to the west (Botnabreen) and to the east (Dettebrea) show TPW-ELAs of 1465 m and 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 input of leeward accumulation of dry snow by wind (see Dahl and Nesje, 1996 and Dahl *et al*., 1997; 2003, and references therein for definitions and further discussion).

By using an AAR of 0.7 for plateau glaciers in steady state (e.g. Dahl and Nesje, 1996a), it is possible to transform the reconstructed outlet glaciers into corresponding TP-ELAs. During the ‘Little Ice Age’ the TP-ELA is estimated to 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 out the different ELAs based on the marginal moraines alone as these are located very close to each other. If not adjusted for glacio-isostatic land uplift, the estimated TP-ELA was close to 1220 m (lowering 245 m) during the suggested Younger Dryas and about 1320 m (lowering 145 m) during the early-Holocene glacier advances compared to at present. In general, the reconstructed glacier variations at northern Folgefonna are related to the local topography, while the reconstructed ELAs are adjusted for glacio-isostatic land uplift (Fig. 10) (Dahl and Nesje, op. cit.; Dahl *et al*., 2003).

The former cirque glacier at Drebrekke has been reconstructed based on marginal moraines, and the former TPW-ELA has been calculated by the use of an AAR of 0.6 to 405 m (Fig. 6). Adjusted for a Holocene glacio-isostatic land uplift of 100 m (Fig. 10), the TPW-ELA lowering compared to the present TP-ELA of 1465 m at northern Folgefonna is 1160 m.

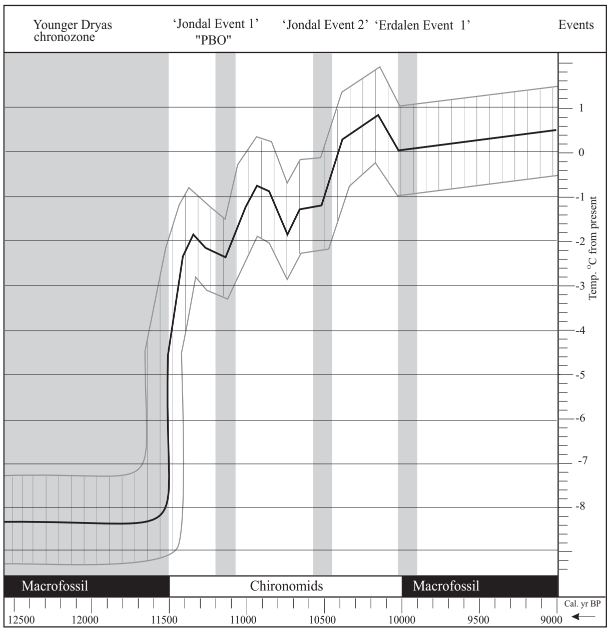

Figure 12 Compiled ablation-season temperature curve for the Lateglacial and early-Holocene in western Norway based on Birks and Ammann (2000) and adjusted for land uplift.

The similar reconstructed TPW-ELA at the former Stormyr cirque glacier is 730 m. Adjusted for a Holocene glacio-isostatic land uplift of 100 m (Fig. 10), the lowering of the TPW-ELA compared to the present TP-ELA of 1465 m at northern Folgefonna is 835 m.

Lateglacial and early-Holocene variations in glacier magnitude at northern Folgefonna and the corresponding TP-ELA adjusted for glacio-isostatic land uplift are shown in Figure 11.

Prior to the Younger Dryas (unit J)

The basal diamicton in Lake Vetlavatn is suggested to be a basal till deposited by a warm based glacier (Fig. 7). When the basal till was deposited is not known.

Glacier magnitude and TP-ELA c. 12,500-11,500 cal. yr BP (the 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 are characterized 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. 7). A low amount of glacier meltwater derived sediments and low sedimentation rates are suggested to be the result of a cold based / polythermal glacier in the zone of continuous permafrost during this stage.

The TP-ELA lowering adjusted for land uplift is estimated to be 335 m during the suggested Younger Dryas.

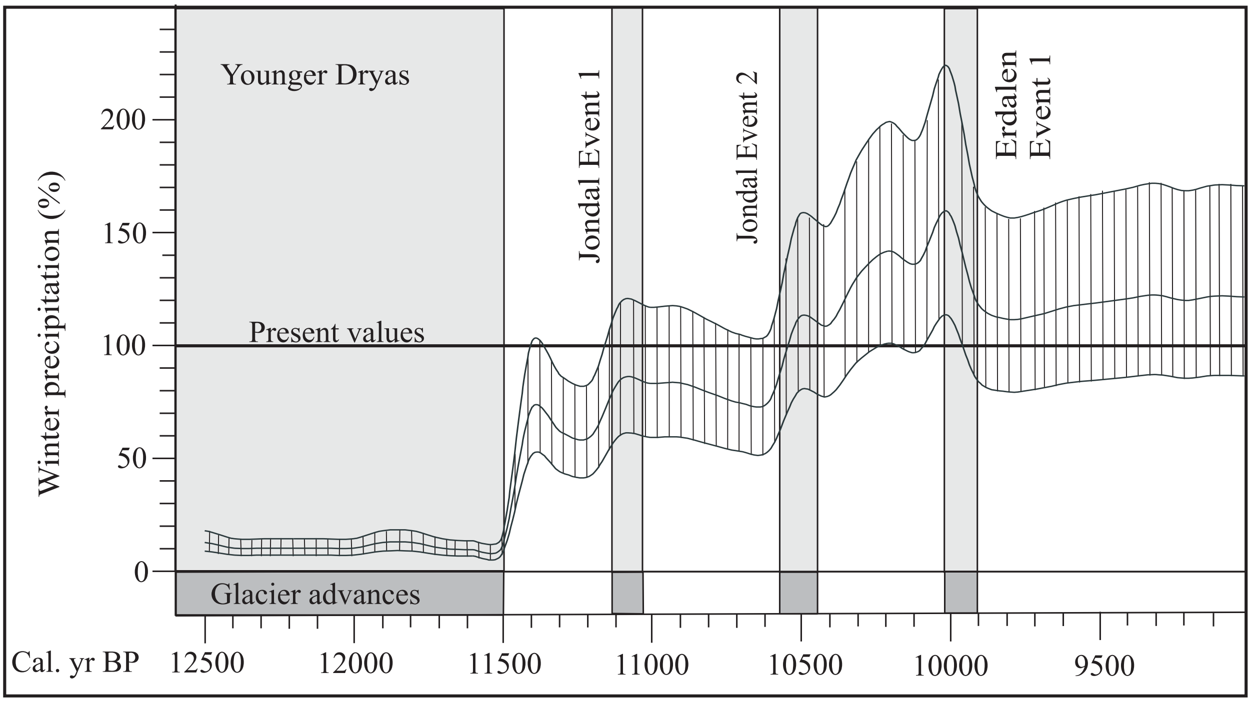

Figure 13 Holocene variations in winter precipitation derived from the 'Liestøl-equation' for the ice cap northern Folgefonna. The middle line is the average estimate based on the temperature data. Maximum and minimum estimates for the calculations are based on variations in the temperature-precipitation ELA (TP-ELA). The Vassdalsvatn core indicates that northern Folgefonna has existed during the entire investigated time span (TP-ELA lower than or equal to 1500 m), while Vetlavatn sorts out the events where the TP-ELA are close to 1320 m. For the rest of the time span the TP-ELA varies between 1500 and 1350 m.

Glacier magnitude and TP-ELA c. 11,500-11,150 cal. yr BP

Just prior to or when Unit G was deposited in lake 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 because of reworking of older glacier-derived sediments by fluvial erosion (Ballantyne, 1995). After an early maximum, the minerogenic input to the lake shows a gradual decrease during this period (Fig. 9). 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.

Glacier magnitude and TP-ELA c. 11,150-11,050 cal. yr BP (the 'Jondal Event 1'/PBO)

Because of low LOI values, a relatively high content of coarse silt and high sedimentation rates, a glacier advance beyond the local watershed upstream of lake Vetlavatn is suggested to have occurred when Unit F was deposited. The glacier meltwater pulse (phase 2) representing Unit F is found in cores III and IV, while the lack of this unit in core I is suggested to be the result of later fluvial erosion close to the inlet (Fig. 3a). 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'.

Glacier magnitude and TP-ELA c. 11,050-10,550 cal. yr BP

Just after the 'Jondal Event 1', the glacier retreated behind the local watershed upstream of lake Vetlavatn, and Unit E with a low content of coarse silt and relatively high LOI values has no indications of glacier meltwater input to the lake. Suggested to be the result of later fluvial erosion near the inlet, Unit E is present in core IV, is found as a minor sequence in core III, and is lacking in core I (Figs. 3a & 7). The TP-ELA lowering adjusted for land uplift is estimated to be 160 m during the time span 11,050-10,550 cal. yr BP.

Glacier magnitude and TP-ELA c. 10,550-10,450 cal. yr BP (the 'Jondal Event 2')

Based on low LOI values, a relatively high content of coarse silt and increased sedimentation rates, the glacier had advanced across the local watershed and glacier meltwater was rerouted into lake Vetlavatn when Unit D was deposited. This unit is found in all the investigated cores from Lake 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'.

Glacier magnitude and TP-ELA c. 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 and no glacier meltwater input was deposited in lake Vetlavatn and found in all cores. After an early maximum, the minerogenic input of coarse silt suggested to indicate paraglacial reworking shows a gradual decrease to a minimum during this time span. The TP-ELA lowering adjusted for land uplift is estimated to be 150 m during the time span 10,450-10,000 cal. yr BP.

Glacier magnitude and TP-ELA c. 10,000-9900 cal. yr BP (the 'Erdalen Event 1')

Represented by Unit B characterized 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 lake Vetlavatn. Based on the AMS radiocarbon dates, the episode is suggested to represent the 'Erdalen Event 1' at Jostedalsbreen (Dahl *et al.*, 1997).

The TP-ELA lowering adjusted for land uplift is estimated to be 210 m during the 'Erdalen Event 1' at northern Folgefonna.

Glacier magnitude and TP-ELA c. 9900-9000 cal. yr BP

Unit A consists of homogenous gyttja with high LOI values in the upper part of all investigated cores, including the 'Little Ice Age' period in cores III and IV. This was also confirmed by a HTH-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'. All marginal moraines formed by northern Folgefonna during the time span from c. 9900-9000 cal. yr BP were therefore erased by the 'Little Ice Age' glacier(s). Based on lake Vassdalsvatn, however, northern Folgefonna existed during this time span and did not melt completely away before about 7200 cal. yr BP (see Bakke *et al.* in prep. for further discussion).

The TP-ELA lowering adjusted for land uplift is estimated to be 140 m during the time span from 9900-9000 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 (m 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 *et al.*, 1997, and references therein):

$$A = 0.915\ e0.339t \quad (r^2 = 0.989,\ P<0.0001) \qquad \text{(Eq.1)}$$

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, 1996a; Dahl *et al.*, 1997).

Mean Lateglacial and early-Holocene ablation-season temperatures

Suggested to be representative for northern Folgefonna, reconstructed summer temperatures (July) from Kråkenes at Vågsøy, western Norway (Fig. 1) (Birks and Ammann, 2000), have been used in the calculations. 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 (chironomids, cladoceras etc.) can 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 (c. 11,500-10,000 cal. yr BP) (Brooks and Birks, 2000). As chironomids are not analysed from 10,000-9,000 cal. yr BP, terrestrial plant macrofossils are used during this time span (Birks and Ammann, 2000). The compiled summer-temperature (July) reconstruction (Fig. 12) is suggested to be representative for the ablation-season temperature at northern Folgefonna during the Lateglacial and early-Holocene (Fig. 12). A suggested standard error for both proxies corresponding to ± 1°C has been included in the figure. As only neglible 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 Eq. 1, variations in mean solid winter precipitation have been quantified according to Dahl and Nesje (1996), and shown in Figure 13. The values are given as absolute variations relative to mean modern values and as variations in percent (mean 1961-1990 = 100%) (Klimaavdelingen, 1993b). Implications of the suggested standard error for the used summer temperature proxies of ± 1°C have been taken into account and included in Figure 13.

Discussion

Early deglaciation and age of low-altitude cirque glaciers

The sedimentological investigations in lake Vetlavatn close to northern Folgefonna show a consistent AMS radiocarbon dated lithostratigraphy not covered by

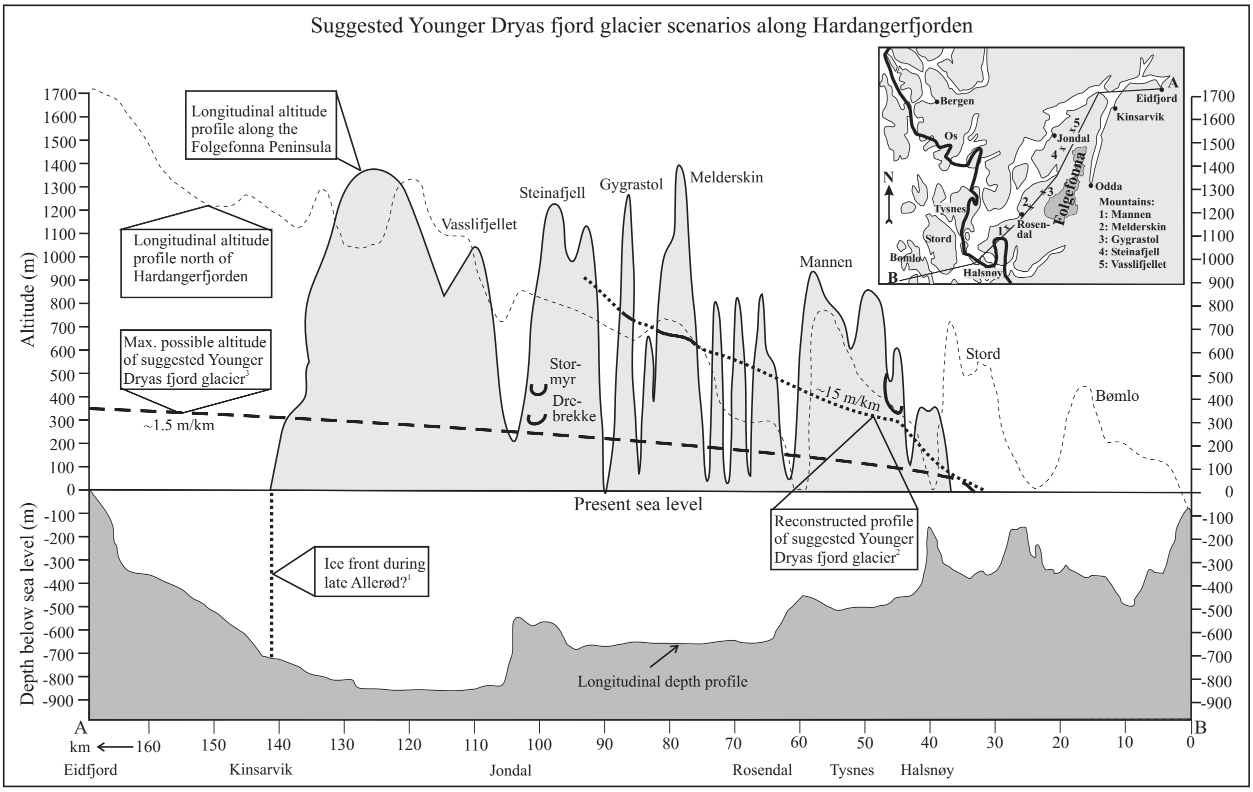

Figure 14 Suggested Younger Dryas fjord glacier scenarios along the Hardangerfjord modified from Follestad (1972). The upper dotted line shows the reconstructed Younger Dryas fjord glacier after Follestad (op. cit.), while the lower punctuated line marks the highest possible ice sheet / fjord glacier based on the Younger Dryas cirque glacier at Drebrekke in Jondal.

glaciers since c. 12.500 cal. yr BP (Fig. 7, Table 1). Bondevik and Mangerud (2002) dated the Younger Dryas glacier maximum to 11,700-11,600 cal. yr BP at Os just north of outer Hardangerfjorden (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 Hardangerfjorden showing a final deglaciation in late Allerød (Fig. 10) (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 Halsnøy in outer parts of Hardangerfjorden (Fig. 1) (e.g. Follestad, 1972; Holtedahl, 1975; Mangerud, 2000), the area is important for the ice-sheet configuration in western Norway.

At Drebrekke in Jondal (Fig. 1), two sets of marginal moraines and indications of a third formed by a low-altitude cirque glacier are mapped down to 290 m above the present sea level (Figs. 1, 5 & 6). The farm at the marginal moraines at Drebrekke has a history back to the 15th century (Kolltveit, 1953), and together with lichen observations and Schmidt-hammer rebound values, this suggests that no glacier formed at Drebrekke during the 'Little Ice Age' (Figs. 4a & 4b). At Kråkenes on Vågsøy, western Norway, Larsen *et al*. (1984) mapped a similar setting of two marginal moraines and indications of a third formed by a Younger Dryas cirque glacier close to sea level.

The vertical difference between the modern TP-ELA of ~1465 m at northern Folgefonna and the TPW-ELA of the lowest active local cirque glacier is about 425 m. If both ELAs are adjusted for a glacio-isostatic land uplift of 100 m (Fig. 1), the difference between the Younger Dryas TP-ELA of 1120 m at northern Folgefonna and the reconstructed TPW-ELA of 305 m asl. at Drebrekke, is 815 m.

The compiled Lateglacial and early-Holocene summer-temperature record from Kråkenes (Fig. 12) (Birks and Ammann, 2000; Brooks and Birks, 2000) 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. 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 was not enough to compensate for the high summer temperatures during the early-Holocene (Fig. 13).

Derived from the above discussion, the low-altitude cirque glaciers at Drebrekke and Stormyr in Jondal are suggested to have formed during the Younger Dryas. The regional implications for the reconstructed Scandinavian ice sheet in Hardanger as summarized by Mangerud (2000) are shown in Figure 14. The reconstructed northern Folgefonna and the cirque glacier at Drebrekke during the Younger Dryas demonstrate that Hardangerfjorden 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 Hardangerfjorden indicating a final deglaciation in late Allerød (Helle *et al.*, 1997). The suggested margin of the Younger Dryas Scandinavian ice sheet at Halsnøy in outer Hardangerfjorden (e.g. Follestad, 1972; Holtedahl, 1975; Mangerud, 2000) is poorly dated, 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 Hardangerfjorden most likely had a local origin in the Gullfjellet area on the Bergen Peninsula. As a consequence, the extent of the Younger Dryas glacier(s) in the Hardanger region was much less than previously suggested (e.g. Mangerud, 2000), and a major revision with implications for the Younger Dryas Scandinavian ice sheet in western Norway is therfore 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 Sollid, 1982; Sollid and Reite, 1983; Anda, 1984; Rye *et al.*, 1987).

The first direct evidence of climate-induced glacier advances after the Younger Dryas have previously been pre- 'Little Ice Age' moraines from the Erdalen Event readvance(s) at Jostedalsbreen, Grovabreen, Hardangerjøkulen 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 associated with two readvances was achieved at this glacier (Dahl *et al.*, op. cit.). The first Erdalen Event readvance took place between 10,100 and 10,050 cal. yr BP, while the second occurred close to 9700 cal. yr BP.

Based on rerouting of glacier meltwater across a local watershed in front of northern Folgefonna, three early-Holocene climate-induced glacier readvances are inferred from a consistent AMS radiocarbon dated lithostratigraphy from lakeVetlavatn (Fig. 7, Table 1). The first named 'Jondal Event 1' took place c. 11,150-11,050 cal. yr BP within the temperature drop during the PBO (Björck *et al.*, 1997). The second named 'Jondal Event 2' occurred c. 10,550-10,450 cal. yr BP, while the third is suggested to be an equivalent to the 'Erdalen Event 1' as described by Dahl *et al.* (2002) and took place c. 10,000-9000 cal. yr BP. This implies that especially early 'Preboreal stages' to some extent may have been influenced by the climatic induced readvances at high-lying glaciers during Jondal Event 1 and 2.

Comparison with ELA and winter precipitation records in western Norway

The Younger Dryas

Only 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 south-western 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 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 the estimation. By suggesting the winter precipitation as snow to be similar to the present values, Larsen *et al.* (op. cit.) attributed the ELA lowering of 700 m to be the result of a drop in summer temperature of c. 4.2°C only. 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 Storeloga 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 in the same order as the estimate of 335 m from northern Folgefonna (Fig. 15).

Based on a similar approach as 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 per cent during the suggested Younger Dryas at northern Folgefonna (Fig. 13), and may be explained

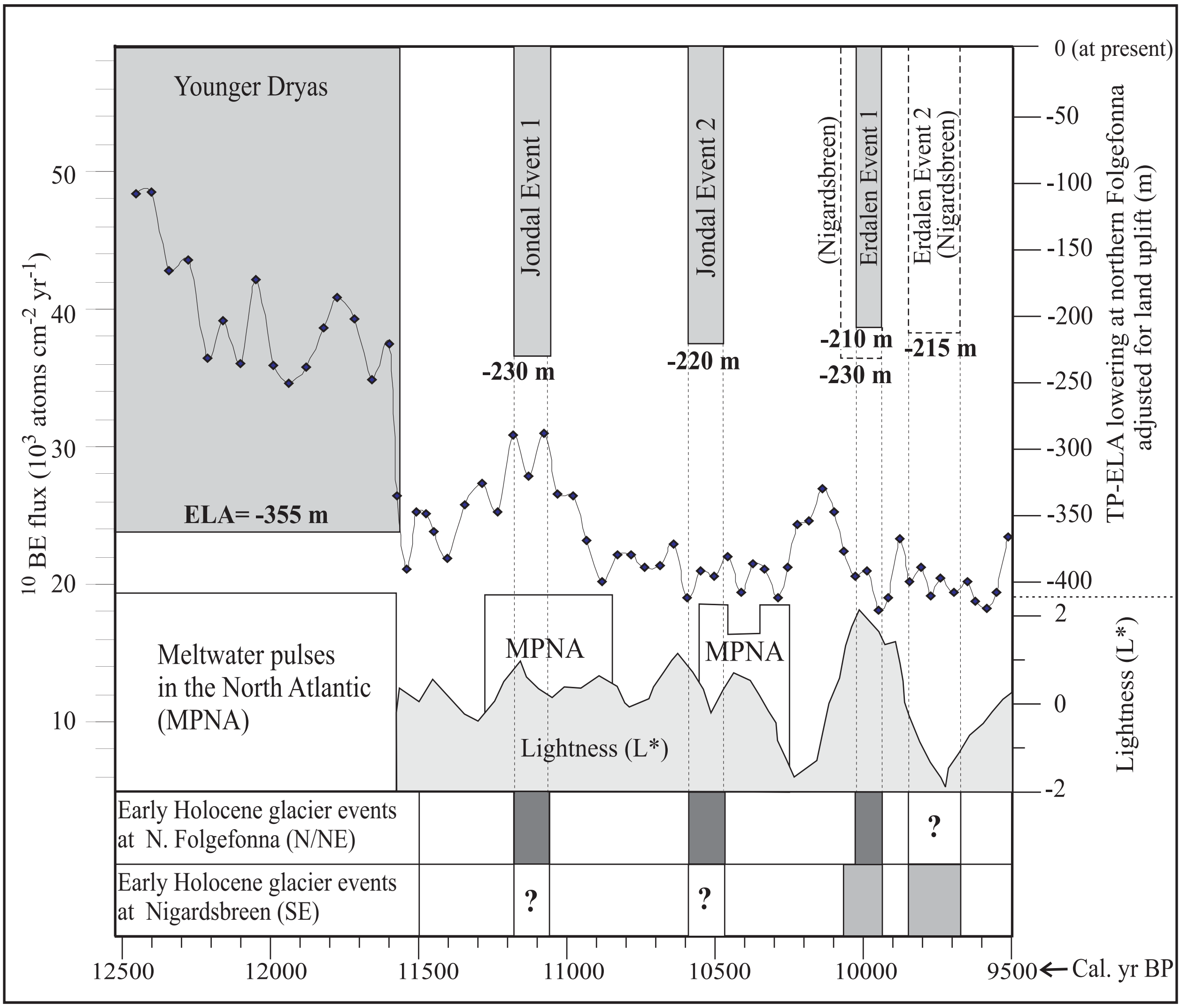

Figure 15 Glacier events at northern Folgefonna and at Nigardsbreen (Dahl et al., 2002) with corresponding ELA lowering estimates to the right, meltwater pulses in the North Atlantic (Clark et al., 2001), lightness (Chapman and Shackleton, 2000) with scale to the right and atmospheric beryllium fluxes measured in the GRIP ice core (Björck et al., 2001, and references therein) with scale to the left. The timing of the early-Holocene glacier events at northern Folgefonna and at Nigardsbreen are shown in the lower column.

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

The glacier readvance during the ‘Jondal Event 1’/ PBO (Björck *et al.*, 1997) with a TP-ELA lowering of about 230 m is primarily suggested to be the result of somewhat lower summer temperatures for about 100 years (Figs. 12, 13 and 15) (Brooks and Birks, 2000). No other climate induced glacier advances/ readvances has been demonstrated from western Norway during the PBO.

‘Jondal Event 2’

This climate-induced glacier readvance with a TP-ELA lowering of about 220 m is suggested to be the result of a marked increase in winter precipitation (Figs. 13 and 15). ‘Jondal Event 2’ may be contemporaneous with cirque glaciation recorded by Eikeland (Eikeland, 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’

The TP-ELA lowering of 210 m at northern Folgefonna during the suggested ’Erdalen Event 1’ is primarily suggested to be the result of a marked increase in winter precipitation (Figs. 13 and 15).

This is in agreement with the conclusions by Dahl *et al.* (2002) from Nigardsbreen, a southeastern outlet glacier from Jostedalsbreen. Compared with the estimates by Dahl and Nesje (1996), the calculated winter precipitation values during the ‘Erdalen Event 1’ may have been among the highest during the entire Holocene.

‘Erdalen Event 2’

No ‘Erdalen Event 2’ has been recorded at northern Folgefonna. At Nigardsbreen with a south-easterly aspect, however, this glacier (re)advance may primarily 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 whereas other sites have recorded the first or the second Erdalen Event glacier readvance (e.g. Dahl and Nesje, 1992; 1996a; Matthews *et al.*, 2000; Nesje *et al.*, 2001b). Why the 'Erdalen Event 2' is not recorded at northern Folgefonna is therefore poorly understood. However, aspect of the investigated outlet glacier(s) at northern Folgefonna and lack of a sensitive site may be of importance.

Atmosphere-ocean interaction during the Lateglacial and early-Holocene

Suggested to be deglaciated prior to the Younger Dryas and sensitive to northern Folgefonna at present, Vetlavatn is 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 suggested to be:

- Large fresh-water outbursts into the North Atlantic may explain (some) abrupt climatic deteriorations during this time span (e.g. Broecker *et al.*, 1989; Broecker *et al.*, 1990; Clark *et al.*, 2001; Fisher *et al.*, 2002; Teller *et al.*, 2002).
- Variations in solar and / or geomagnetic forcing may explain the observed climate instability, and have been studied by use of ^{10}Be and ^{14}C records from the Greenland ice cores as a direct signal of changes in the production rates of the cosmogenic radionuclides (Björck *et al.*, 2001, and references therein).
- Fluctuations in the thermohaline circulation 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 Figure 15, reconstructed records of fresh-water outbursts into the North Atlantic, solar and / or geomagnetic forcing and the production of NADW have been combined with Lateglacial and early-Holocene glacier fluctuations at northern Folgefonna.

Based on variations in ^{10}Be from Greenland ice cores, the input of solar energy was low during the Younger Dryas (Björck *et al.*, 2001, and references therein), and there was a major meltwater pulse associated with this cold spell in the North Atlantic (e.g. Broecker *et al.*, 1989; Broecker *et al.*, 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 (Björck *et al.*, 1998; 2001, and references therein). Hence, the mechanisms behind the rather cold and dry 'Jondal Event 1' are suggested 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 ^{10}Be was high during 'Jondal Event 2' (Björck *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, south westerly winds during winter time in western Norway. Based on modern instrumental records, these characteristica are associated with a positive North Atlantic Oscillation (NAO) mode in this region (e.g. Nesje *et al.*, 2000b, and references therein).

Predating the 'Jondal Event 2'and a North Atlantic meltwater pulse (Fig. 15), Björck *et al.* (2001) linked a cooling event at 10,300 cal. yr BP and one of the largest Holocene ^{10}Be flux peaks. Contemporaneous, or somewhat prior to this 10Be flux peak, a marked reduction in the thermohaline circulation of the North Atlantic occurred (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 mechanisms behind 'Erdalen Event 1' may be analogous to 'Jondal Event 2'.

The 'Erdalen Event 2' 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 distinct glacier readvance at Nigardsbreen, a south-easterly valley-outlet glacier to Jostedalsbreen (Dahl *et al.*, 2002) (Fig. 15). The reason for this lack of evidence from northern Folgefonna may be a different aspect than Nigardsbreen.

Conclusions

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

1) The ice cap northern Folgefonna is suggested to have been isolated from the Scandinavian ice sheet during late Allerød and the entire Younger Dryas. This contradicts the previously presented model (e.g. Mangerud, 2000) where the Folgefonna Peninsula is suggested to be a main source of glacier ice to fill 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 a poly-thermal to a temperate temperature regime during this transition due to the sediments in lake Vetlavatn.

2) Based on the radiocarbon dated lithostratigraphy from lake Vetlavatn, 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 may have existed for the last time during the Younger Dryas. The existence of a cirque glacier in this topographical setting give a maximum altitude for the Scandinavian ice sheet during the suggested Younger Dryas which is well below the proposed model by Mangerud (2000) (Fig. 14).

3) The 'Jondal Event 1' is a climatic induced glacial readvance dated to 11,200 cal. yr BP, and with a TP-ELA lowering of c. 230 m. The event is suggested to be contemporaneous with the temperature drop during the Preboreal Oscillation (e.g. Björck *et al.*, 1997).

4) The climatically induced 'Jondal Event 2' occurred c. 10,550-10,350 cal. yr BP, and had a TP-ELA lowering of about 220 m. 'Jondal Event 2' is suggested to be the first Holocene glacier readvance / advance initiated by an increase in winter precipitation (Figs. 13 and 15).

5) An 'Erdalen Event 1' glacier readvance with a TP-ELA lowering of 210 m is suggested to have taken place at northern Folgefonna c. 10,000-9,850 cal. yr BP. The glacier readvance is primarily suggested to be the result of a marked increase in winter precipitation (Figs. 13 and 15), and the estimated values may have been 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) Among several proposed hypotheses, the climate-induced early-Holocene glacier advances / readvances at northern Folgefonna are discussed in the context of large fresh-water outbursts to the North Atlantic, variations in solar and / or geomagnetic forcing and by fluctuations in the thermohaline circulation of the North Atlantic (see discussion for references):

- 'Jondal Event 1' is closely related to a low the 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, south-westerly winds during winter time in western Norway equivalent to a positive North Atlantic Oscillation (NAO) mode based on instrumental data in this region (e.g. Nesje *et al.*, 2000b, and references therein).
- 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. Whereas 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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