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Holocene mean July temperature and winter precipitation in western Norway inferred from palynological and glaciological lake-sediment proxies

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Abstract: Reconstructions of mean July temperature (T_{jul}) and winter precipitation (P_w) for the last 11/500 years on the Folgefonna peninsula are presented. T_{jul} was reconstructed using pollen–climate transfer functions and P_w was reconstructed based on the exponential relationship between mean solid winter precipitation and ablation-season temperature at the equilibrium-line altitude (ELA) with a reconstructed former ELA, using T_{jul} as the proxy for ablation-season temperature. The reconstructions from the Folgefonna peninsula suggest that the early Holocene was relatively cool and dry until *c.* 8000 cal. yr BP, followed by a warm and humid mid-Holocene until *c.* 4000 cal. yr BP with inferred T_{jul} above 12°C and P_w reaching as high as 225% of the present day. Subsequent to *c.* 4000 cal. yr BP a reduction is seen in both inferred T_{jul} and P_w with large fluctuations during the last 500 years. In addition, new calculations of P_w from two glaciers (Hardangerjøkulen and Jostedalsbreen) in southern Norway are presented. The results show that P_w varied in phase at all glaciers, probably as a response to the same climate forcing factor. During the early Holocene a major shift is suggested between winds from the west and the east.

Key words: Lake sediments, pollen, transfer functions, summer temperature, ELA, winter precipitation, Preboreal Oscillation, Folgefonna, Holocene.

Introduction

Lake systems respond to changes in the physical, biological and chemical environment within the lake, but changes affecting the environment in the lake catchment are also captured by lakes (Battarbee, 2000). Lake sediments provide important archives for biological, chemical and physical proxies derived from the lake and from its surroundings, all responding to changes in the environment, including changes in climate. Lake sediments and their contained proxies can thus provide continuous and high-resolution reconstructions of past climatic conditions (e.g., Barnekow, 1999; Birks and Ammann, 2000; Seppä and Birks, 2001; Dahl *et al.*, 2002; Hammarlund *et al.*, 2002; Nesje *et al.*, 2000a). Using a pollen–climate transfer function, aspects of past climate, particularly mean July temperature (T_{jul}), can be reconstructed on the basis of pollen preserved in lake sediments. Lakes situated at ecotonal boundaries, such as the treeline, are well suited for climate reconstructions as small climate changes can cause large biotic changes (MacDonald *et al.*, 1993; Körner, 1998). The two lakes used here for studying biological proxies are situated close to the present-day treeline formed by *Pinus sylvestris* or *Betula pubescens.* The presence of plant macrofossils in lake sediments are believed to show the presence of the species in the catchment area. With modern ecological knowledge about the species, tolerances to climate, past climatic conditions can

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also be inferred. The presence of macrofossils can thus be used as a validation of the reconstructions based on the pollen content in the lake sediments (H.H. Birks, 2003; Birks and Birks, 2000; 2003).

Small plateau glaciers are also sensitive to climate change. Glacier size is mainly dependent on summer temperature (mean ablation-season temperature) and winter precipitation. On small plateau glaciers such as northern Folgefonna the input of wind-blown dry snow can be ignored and the equilibrium-line altitude (ELA) can be expressed as temperature-precipitation ELA (TP-ELA) (Dahl and Nesje, 1992). Sediments in lakes located downstream from glaciers can be used to obtain records of glacier variations (e.g., Karlén, 1976; Dahl *et al.*, 2003). The reconstructed T_{jul} can be used as a proxy for summer temperature to reconstruct winter precipitation (P_w) through time when the former ELA is known, as there is an established relationship between ELA, winter precipitation and summer temperature (Liestøl in Sissons, 1979; Sutherland, 1984).

A high correlation between decadal variations in the North Atlantic Oscillation (NAO) (Hurrell, 1995) and glacier mass balance has been demonstrated in different areas in northern Europe (Nesje *et al.*, 2000b; Reichert *et al.*, 2001; Six *et al.*, 2001). The dominant factor is the strong relationship between winter precipitation and NAO, and these two factors are highly correlated with the mass balance of maritime glaciers in southern Norway. A positive NAO mode gives high amounts of P_w over maritime glaciers in Scandinavia and reduced P_w for glaciers in the European Alps (Six *et al.*, 2001). Reconstructions of Holocene P_w may reflect periods with prevailing mild and wet winter conditions (positive NAO mode) and periods with prevailing cold and dry winters (negative NAO mode) or periods with stronger effect of high-pressure fields over Russia (Shabbar *et al.*, 2001), thereby indicating broad-scale Holocene variability in the atmospheric winter circulation over NW Europe.

Several climatic oscillations, when glaciers in Norway expanded, have been recorded during the Holocene in Scandinavia, and the most pronounced occurred in the early Holocene; the Preboreal Oscillation (PBO) (Björck *et al.*, 1997) or Jondal Event 1 as it is termed for northern Folgefonna by Bakke *et al.* (2005a), the Erdalen event at 9700 cal. yr BP (Dahl *et al.*, 2002; Bakke *et al.*, 2005b), and the Finse event at $\sim$8200 (8500–7900) cal. yr BP (e.g., Klitgaard-Kristensen *et al.*, 1998; Nesje and Dahl, 2001; Nesje *et al.*, 2001). Another pronounced glacial event occurred in the later part of the Holocene – 'the Little Ice Age' (LIA) (AD $\sim$1550–1920) caused by cooling and increased P_w (Grove, 1988; Nesje and Dahl, 2003). During the Holocene thermal optimum temperatures were almost 2°C higher than at present and many glaciers disappeared completely or were greatly reduced (e.g., Dahl and Nesje, 1994; 1996; Nesje *et al.*, 2000a; 2001; Nesje, 2002; Bakke *et al.*, 2005b). Similarly treelines reached their maximum elevation during the Holocene thermal optimum (Aas and Faarlund, 1988).

In this paper we present new reconstructions of T_{jul} from two sites in western Norway and glacier fluctuations and inferred P_w for northern Folgefonna during the last 11 500 years by combining biological and geological proxies from lake sediments and reconstructed ELA variation (Bakke *et al.*, 2005b). The reconstruction of P_w from northern Folgefonna is the first P_w reconstruction to cover the entire Holocene in this area. These reconstructions are further compared to reconstructions of P_w at two other glaciers, Hardangerjøkulen and Jostedalsbreen (Figure 1) in southern Norway based on existing ELA data (Dahl and Nesje, 1996; Nesje *et al.*, 2000a; Nesje *et al.*, 2001), and the new T_{jul} reconstruction from Vestre Øykjamyrtjørn.

Figure 1 Map indicating the location of the lakes studied and the distribution of glaciers (shaded) in southern Norway.

Study area

Sediment cores from five different lakes have been used. Pollen and plant macrofossils were analysed from Trettetjørn and Vestre Øykjamyrtjørn. For analyses of glacier variations, sediments from the proglacial lakes Vetlavatn, Dravladalsvatn and Vassdalsvatn have been used. The positions of all lakes and glaciers discussed in this paper are shown in Figure 1.

Vestre Øykjamyrtjørn

The nonglacial lake Vestre Øykjamyrtjørn (59°4′N, 6°00′E) close to the coast near Matre, Sunnhordland, in western Norway, is located *c.* 45 km southwest of the glacier Folgefonna. The lake lies at 570 m a.s.l. and has a maximum water depth of 8 m. Granitic rocks dominate the catchment bedrock (Askvik, 1995). The lake is situated just above the present-day treeline formed by *Betula pubescens* and *Alnus incana* within the oceanic part of the boreonemoral vegetation zone (Moen, 1998). Present-day climatic conditions are estimated by interpolation of meteorological data from the closest meteorological stations, taking into account site location, altitude (0.57°C per 100 m) and distance from the sea. This interpolation procedure estimates a highly oceanic climate at the site with a present-day T_{jul} of 11.0°C, January temperature (T_{jan}) of –1.4°C, and annual precipitation (P_{ann}) of 3070 mm (A. Odland, personal communication).

Trettetjørn

Trettetjørn (60°43′N, 7°00′E) is situated in the low-alpine vegetation zone (Moen, 1998) at 810 m a.s.l. in the Upsete valley on the western side of the Hardangervidda plateau. The lake is within the present-day treeline formed by *Betula pubescens*, and scattered birch trees are present in the hillsides surrounding the lake. The maximum water depth is 7.5 m. The catchment bedrock is dominated by gabbro, with some areas of sandstone and phyllite. Interpolation for the present-day climate indicate an oceanic climate with T_{jul} of 10.7°C, T_{jan} of −5.5°C and P_{ann} of 1800 mm yr^{-1} (A. Odland, personal communication).

Proglacial lakes

The proglacial lakes used in this study are all situated within the same area (60°14′N, 6°25′E) north of the glacier northern Folgefonna (Figure 1). Vetlavatn, situated at 915 m a.s.l. received glacial meltwater when the outlet glacier Jordalsbreen reached beyond a local bedrock threshold. In periods when the glacier was behind this threshold, organic sediments were deposited in the lake. Vassdalsvatn, at 490 m a.s.l., is the seventh lake downstream from northern Folgefonna along the present meltwater stream and receives input of glacial meltwater at present. This lake is believed to provide a sensitive record of glacier variations when the glacier is present and when it had completely melted away. The third proglacial lake, Dravladalsvatn, at 938 m a.s.l., receives glacial meltwater when northern Folgefonna is present. The present-day climatic conditions at sea level in Jondal are oceanic with a mean summer temperature (May to September) of 12.7°C (Klimaavdelingen, 1993). For a detailed description of these sites, see Bakke *et al.* (2005a; 2005b).

Methods

Coring

All cores were collected with a 110 mm diameter modified piston corer (Nesje, 1992) either from the lake ice in winter or from a raft in summer.

Pollen and plant macrofossil analysis

0.5 cm^3 subsamples for pollen were extracted from the cores from Vestre Øykjamyrtjørn and Trettetjørn, and prepared using standard methods (acetolysis, HF) (Fægri and Iversen, 1989) and mounted in glycerine. At least 500 terrestrial pollen grains and spores were identified to the lowest possible taxonomic level using keys (Fægri and Iversen, 1989; Moore *et al.*, 1991; Punt *et al.*, 1976–95) and an extensive modern pollen reference collection at the Department of Biology, University of Bergen. Macrofossils were analysed from the same cores. Samples with known volume were washed through a sieve with mesh diameter of 125 μm, soaked in water and 10% KOH for a few minutes to dissolve the gyttja, and sieved again through the same sieve (Birks, 2001) until the water was clear. Macrofossils were identified and counted at 12 × magnification under a stereo-microscope. Numbers of macrofossils are calculated for sediment volume of 100 cm^3 for Vestre Øykjamyrtjørn and 25 cm^3 for Trettetjørn. Pollen and macrofossil diagrams were drawn using TILIA and TILIA GRAPH (Grimm, 1990). Plant nomenclature follows Lid and Lid (1994).

Stratigraphic changes in the composition of pollen assemblages were detected using optimal partitioning zonation using a sum-of-squares criterion (Birks and Gordon, 1985). The number of pollen zones was determined by comparison with the broken-stick model (Bennett, 1996; Birks, 1998).

Loss-on-ignition

For loss-on-ignition (LOI) from Vestre Øykjamyrtjørn and Trettetjørn dry weight was determined after drying overnight at 105°C. The samples were then ignited at 550°C for six hours and then put in a desiccator for cooling to room temperature and weighed (Bengtsson and Enell, 1986). LOI is calculated as a percentage of dry weight. From Vetlavatn, Dravladalsvatn and Vassdalsvatn LOI analyses were performed according to Heiri *et al.* (2001).

Chronology

From Vestre Øykjamyrtjørn 11 AMS dates were obtained from terrestrial plant macrofossils covering both the Lateglacial and the Holocene. Chronology is presented as calibrated years before present (cal. yr BP), where BP is AD 1950 (Table 1). From Trettetjørn nine AMS dates were obtained on both bulk sediments and terrestrial plant macrofossils. The basal bulk date is clearly too old, probably due to phyllite in the basal minerogenic-rich part of the core, causing a 'hard water' error, and this date is therefore rejected. These dates were calibrated using CALIB 4.3, method A, and the bidecadal INTCAL98 data set (Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). Age-depth modelling was performed using a weighted regression procedure in the framework of generalized additive models (Heegaard, 2003; Heegaard *et al.*, 2005) and ages below the lowest radiocarbon dates were estimated by extrapolation of the fitted model.

From Vetlavatn and Vassdalsvatn 19 AMS dates were obtained on both bulk sediments and terrestrial plant macrofossils. The bedrock at both sites is dominated by Precambrian granitic gneiss which is not believed to cause any significant hard-water error on the dates (e.g., Moore *et al.*, 1998; Barnekow, 1999). From Vetlavatn and Vassdalsvatn dates were calibrated as above but the age-depth models are based on linear interpolation (Bakke *et al.*, 2005b).

Proglacial lakes, ELA and terminal moraines

Estimates of former glacier ELAs are based on observations of modern analogues in accordance with Dahl *et al.* (2003). Aerial photographs and field observations were combined to produce glacial geomorphological maps. Calculations of ELA at the plateau glacier are made by using an accumulation area ratio (AAR) of 0.7 (Dahl and Nesje, 1996). The calculation of the area distribution was carried out electronically by using the vector-based GIS program (MapInfo 6.0 at N-50 map datum).

Physical sedimentological parameters that reflect glacier activity in the catchment were measured in the sediments of the proglacial lakes. These include magnetic susceptibility, grain size measured using a Micromeretics Sedigraph 5100 (X-ray determination), wet and dry bulk density, and water content (Menounos, 1997).

For a full description and an explanation of the methods, as well as a complete presentation of data, see Bakke *et al.* (2005b).

Reconstructions of mean July temperature

For reconstructions of mean July temperature (T_{jul}), a modern calibration data set for pollen and climate was used. This includes surface sediments from 191 lakes distributed in Norway and northern Sweden crossing large temperature and precipitation gradients (H.J.B. Birks and S.M. Peglar, unpublished data). Modern mean July temperature values are estimated for each of the 191 lakes from modern climate data (1961–90 normal period) from nearby meteorological stations

Table 1 Radiocarbon dates from the sites investigated, with laboratory number, sample depth, material dated, ^{14}C age BP and calibrated age BP

Locality	Lab. no.	Depth (cm)	Material dated	Age (^{14}C yr BP)	Age (cal. yr BP) (1 sd)
Vestre Øykjamyrtjørn	Poz-801	34–35	Plant macrofossils	235 ± 45	141–444
	Poz-805	82–83	Plant macrofossils	1530 ± 30	1348–1472
	Poz-803	130–131	Plant macrofossils	2830 ± 40	2888–2984
	Poz-802	178–179	Plant macrofossils	4590 ± 45	5238–5380
	Poz-804	201–202	Plant macrofossils	5930 ± 50	6658–6832
	Poz-799	217–218	Plant macrofossils	6880 ± 50	7622–7740
	Poz-800	227–228	Plant macrofossils	7630 ± 55	8386–8428
	Poz-806	241–242	Plant macrofossils	7990 ± 55	8741–9025
	Poz-813	302–303	Plant macrofossils	10 070 ± 50	11 323–11 885
	Poz-811	332–333	Plant macrofossils	10 730 ± 60	12 720–13 008
	Poz-1162	354–356	Plant macrofossils	11 170 ± 60	13 068–13 228
Trettetjørn	Poz-807	28.5–29.5	Bulk sediments	1150 ± 50	960–1156
	Tua-3513A	55.5–56	Bulk sediments	1545 ± 30	1352–1474
	Tua-3514A	93.5–94	Bulk sediments	2620 ± 35	2742–2758
	Tua-3515A	133.5–134	Bulk sediments	3625 ± 40	3939–3951
	Poz-808	168.5–169	Bulk sediments	4520 ± 40	5028–5280
	Beta-164122	203.5–204	*Betula* macrofossils	5260 ± 40	5877–6105
	Tua-3516A	225.5–226	Bulk sediments	5880 ± 40	6655–6741
	Tua-3517A	251.5–252	Bulk sediments	7645 ± 60	8378–8442
	Beta-164121	269.5–270	Bulk sediments	11 680 ± 60	13497–13847
Vetlavatn, core I	Tua-13603A	15	Bulk sediments	6785 ± 160	7934–7468
	Tua-13604A	20	Bulk sediments	7475 ± 30	8783–7789
	Tua-13605	33	Bulk sediments	7640 ± 135	8502–8315
	Tua-13606	46	Bulk sediments	8950 ± 145	10 034–9859
	Beta-115399	50	Bulk sediments	8840 ± 60	9920–9850
	Beta-115400	53	Bulk sediments	8990 ± 60	10 005–9940
	Beta-115401	58	Bulk sediments	9050 ± 60	10 035–9975
	Beta-115403	61.5	Bulk sediments	9660 ± 70	10 960–10 625
	Beta-115403	69.5	Bulk sediments	10 200 ± 80	12 155–11 680
Vetlavatn, core III	Beta-148430	110	Bulk sediments	9630 ± 60	11 160–10 690
	Beta-148431	118	Bulk sediments	10 250 ± 70	12 360–11 580
Vetlavatn, core IV	Beta-148424	23	Bulk sediments	2980 ± 40	3260–3000
	Beta-148425	118	Bulk sediments	8150 ± 50	9130–8990
	Beta-148426	136	Bulk sediments	9360 ± 60	10 670–10 270
	Beta-148427	138	Bulk sediments	9380 ± 60	10 690–10380
	Beta-148428	144	Bulk sediments	9830 ± 60	11 250–11130
	Beta-148429	148	Bulk sediments	10480 ± 40	12 820–12 080
Vassdalsvatn, core I	Beta-102930	28–31	Bulk sediments	1150 ± 70	1170–970
	Beta-102931	117–120	Bulk sediments	2280 ± 60	2350–2160
	Beta-102932	182–185	Bulk sediments	3370 ± 70	3690–3480
	Beta-102933	250–253	Bulk sediments	4270 ± 80	4965–4650
	Beta-102934	295–298	Bulk sediments	5200 ± 70	6170–8590
	Beta-102935	368–372	Bulk sediments	8260 ± 80	9415–9130
	Beta-102936	525–535	Bulk sediments	4330 ± 50	4965–4840
Vassdalsvatn, core II	Tua-13607	19	Bulk sediments	2100 ± 85	2295–1970
	Tua-13608	83–84	Bulk sediments	1900 ± 70	1920–1735
	Tua-13788A	77–79	Bulk sediments	2310 ± 60	2360–2160
	UtC-6691	123	Bulk sediments	2765 ± 45	2920–2785
	UtC-6692	138	Bulk sediments	3319 ± 40	3630–3475
	UtC-6693	142	Bulk sediments	3460 ± 60	3830–3640
	UtC-6694	147	Bulk sediments	3820 ± 50	4345–4100
	UtC-6695	171	Bulk sediments	6280 ± 60	7270–7030
Dravladalsvatn, core I	Poz-3175	1	Plant macrofossils	2060 ± 30	2060–1990
	Tua-3627A	24	Bulk sediments	2000 ± 40	1990–1920
	Tua-3628A	57	Plant macrofossils	2315 ± 45	2355–2305
	Poz-3176	72	Plant macrofossils	5530 ± 40	6390–6290
	Poz-3177	82	Bulk sediments	8090 ± 40	9220–9000
	Tua-3629A	88	Bulk sediments	8645 ± 70	9690–9540
Dravladalsvatn, core II	Poz-3178	1	Bulk sediments	2565 ± 30	2750–2550
	Tua-3640A	24	Bulk sediments	2320 ± 45	2360–2180
	Poz-3198	45	Bulk sediments	2315 ± 25	2350–2330
	Tua-3630	78	Plant macrofossils	1910 ± 45	1910–1745
	Tua-3631A	100	Bulk sediments	3215 ± 60	3475–3360
	Poz-3179	124	Bulk sediments	4675 ± 35	5465–5320
	Poz-3256	132	Bulk sediments	5050 ± 30	5890–5805
	Tua-3632A	151	Bulk sediments	6375 ± 70	7415–7250

by a standard interpolation and modelling procedures (A. Odland, unpublished data).

Pollen-climate transfer functions based on this calibration data set were developed using weighted-averaging partial least squares (WA-PLS) regression (ter Braak and Juggins, 1993). The resulting models have a good predictive ability as estimated by leave-one-out cross-validation (ter Braak and Juggins, 1993), with a root mean square error of prediction (RMSEP) of 1.03°C and r^2 between predicted and observed values of 0.54. For a full description of the method, see H.J.B. Birks (2003).

Reconstruction of winter precipitation

The equilibrium-line altitude (ELA) on a glacier is mainly controlled by precipitation as snow during the accumulation season and summer temperature during the ablation season. It has been demonstrated that there is an exponential relationship between mean ablation-season temperature **t** (1 May to 30 September) and winter accumulation **A** (1 October to 30 April) at the ELA of modern Norwegian glaciers (Liestøl in Sissons, 1979; Sutherland, 1984), which is expressed by the regression equation (Ballantyne, 1990):

$$A = 0.915\ e^{0.0339t}\ (r^2 = 0.989,\ P < 0.0001) \qquad (1)$$

where **A** is in metres water equivalent and **t** is in °C.

The reconstructed T_{jul} from both Trettetjørn and Vestre Øykjamyrtjørn are used as an independent proxy for summer temperature to calculate winter precipitation/accumulation at northern Folgefonna. The ELA variations at northern Folgefonna are presented in Bakke *et al.* (2005b). At Jostedalsbreen and Hardangerjøkulen only the Vestre Øykjamyrtjørn T_{jul} was used as a proxy for summer temperature to calculate P_w while the ELA data are based on data published by Dahl and Nesje (1996) and Nesje *et al.* (2001).

Correction factors for land uplift were calculated by the program SeaLevel Change Ver. 3.51 (Møller and Holmeslet, 1998) based on sea-level data and land-uplift isobases parallel to the west coast of Norway. For ages older than the model estimate the land uplift was based on Helle *et al.* (1997). Reconstructed ELA, T_{jul}, and P_w are corrected for land uplift, with a lapse rate of 0.6°C per 100 m altitude for T_{jul} (e.g., Sutherland, 1984; Dahl and Nesje, 1992).

Results

The presentation of the results is divided into two parts. First, the new inferred T_{jul} from Vestre Øykjamyrtjørn and Trettetjørn and the P_w for northern Folgefonna are presented. Secondly, the reconstructed P_w from northern Folgefonna is compared to the new reconstructions of P_w at Jostedalsbreen and Hardangerjøkulen.

Inferred T_{jul} and P_w at northern Folgefonna

Simplified pollen diagrams are presented in Figures 2 and 3, and inferred climate parameters are presented in Figure 4. The presentation and discussion of the inferred climate are divided into three major periods:

1) early Holocene from 11 500 to 8000 cal. yr BP (cool and dry);
2) mid-Holocene from *c.* 8000 to *c.* 4000 cal. yr BP (warm and wet);
3) late Holocene from *c.* 4000 cal. yr BP to the present (cooler and drier).

Early Holocene: 11 500–8000 cal. yr BP

The vegetation around both Vestre Øykjamyrtjørn and Trettetjørn was at this time dominated by open shrub vegetation, which was rapidly replaced by birch (*Betula pubescens*) and gradually by pine (*Pinus sylvestris*) as T_{jul} increased. At Vestre Øykjamyrtjørn, the T_{jul} was low in the earliest part of the Holocene, but rose rapidly from just above 7.5°C at 11 500 cal. yr BP reaching 12°C in the last part of this period with small peaks at 9850, 8900 and 8300 cal. yr BP. A drop in T_{jul} occurred between 11 300 and 11 130 cal. yr BP. Associated with this drop in temperature at Vestre Øykjamyrtjørn there was a drop in the LOI curve.

At Trettetjørn the sediments cover only the last 500 years of this time period (8500–8000 cal. yr BP) and inferred T_{jul} fluctuated below 12°C and reached 12°C just at the end of this phase. During these 500 years two cooler phases occurred, one at *c.* 8400 and another at *c.* 8200 cal. yr BP. The LOI rose from 5% to 30% during this period, suggesting more production of organic matter in the catchment and in the lake.

The ELA at northern Folgefonna fluctuated during this time period and was as low as 240 m below present at *c.* 11 200–11 050 cal. yr BP. Another drop in ELA occurred at 10 600 and at 10 000–9850 cal. yr BP. After 9800 cal. yr BP, ELA rose and at *c.* 9600 cal. yr BP it was higher than 1585 m a.s.l. in a period when the glacier was absent (see Bakke *et al.*, 2005b). The inferred P_w increased from 11 500 cal. yr BP and reached a sharp peak at *c.* 9800 cal. yr BP, with more than 200% winter precipitation compared to present (= 100%). After this peak, P_w based on the Vestre Øykjamyrtjørn T_{jul} decreased and two minor peaks occurred at 8900 and 8300 cal. yr BP. Based on the inferred T_{jul} from Trettetjørn, P_w at northern Folgefonna stayed above 100% with two lower peaks at 8460 and 8200 cal. yr BP. The inferred P_w during the period when the glacier was absent is an estimate of the maximum winter precipitation possible without a glacier being present.

Mid-Holocene: 8000–4000 cal. yr BP

Maximum values of pine pollen occurred during this time period at both Trettetjørn and Vestre Øykjamyrtjørn, and the macrofossils suggest that birch woodland was replaced by pine forest (Bjune, unpublished data). The inferred T_{jul} was above 12°C. Maximum T_{jul} values occurred in this period, reaching 14.0°C at Vestre Øykjamyrtjørn and 13.2°C at Trettetjørn, 1.4°C and 1.9°C higher than at present at Vestre Øykjamyrtjørn and Trettetjørn, respectively. At Trettetjørn T_{jul} was variable, with two short cooler phases around 6600 cal. yr BP and 5000 cal. yr BP.

The ELA continued to be as high as at the end of the previous phase, staying 120 m higher than at present at northern Folgefonna until *c.* 5200 cal. yr BP when the glacier was formed again. During this period there was no glacial meltwater input to the lakes. Subsequently a marked ELA drop was inferred until 4800 cal. yr BP, when it started to rise again, reaching higher altitudes than at present (see Bakke *et al.*, 2005b). In general, the inferred P_w increased throughout the whole period, but rather large oscillations occurred. Maximum P_w values occurred at *c.* 5200 and 4700 cal. yr BP, reaching 190% of the present value based on Vestre Øykjamyrtjørn's T_{jul} and 225% based on Trettetjørn's T_{jul}. Lower values of P_w occurred when T_{jul} dropped at 6600 and 5000 cal. yr BP.

Late Holocene: 4000 cal. yr BP to present

The last 4000 years were characterized by a decrease in inferred T_{jul}. At Trettetjørn, T_{jul} reached as low as 9°C, whereas at

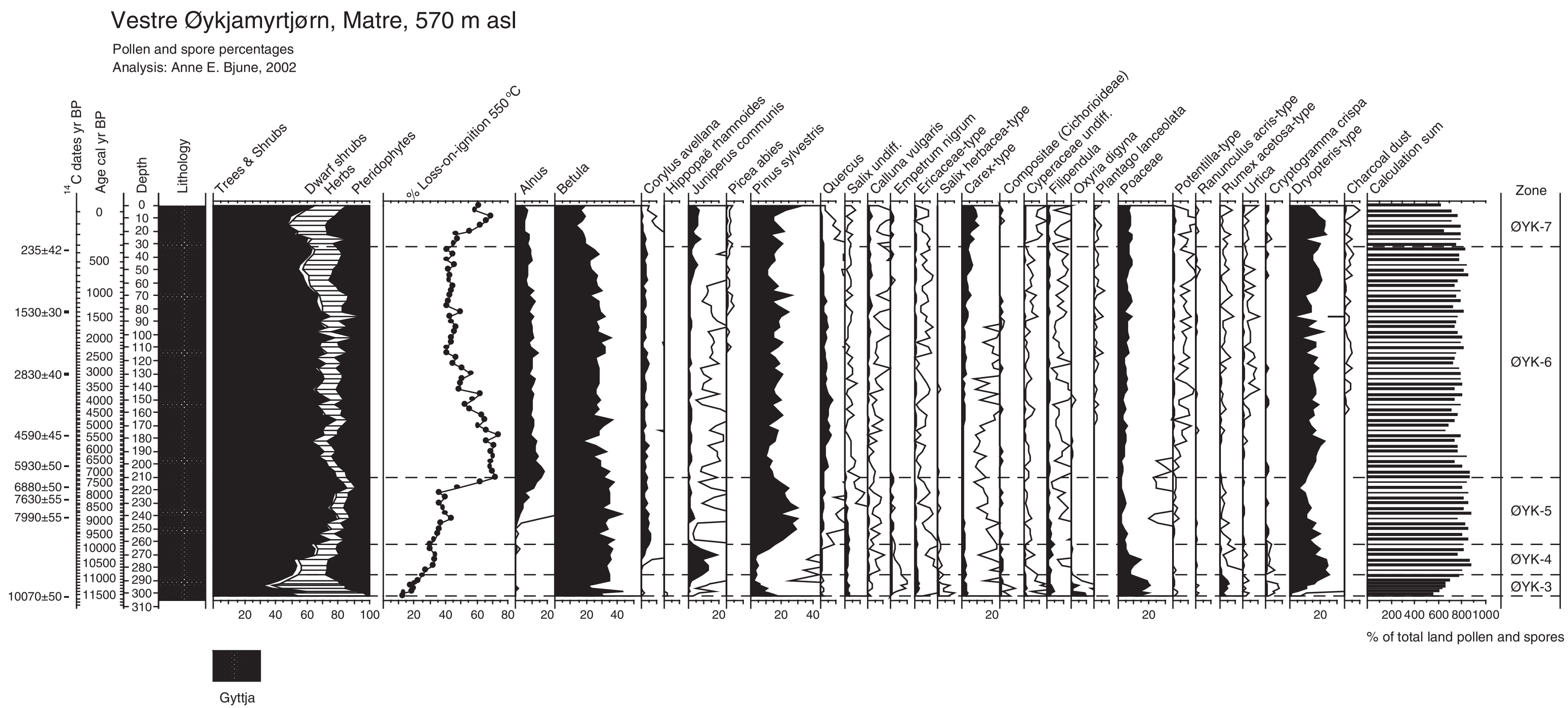

Figure 2 Simplified percentage pollen diagram from Vestre Øykjamyrtjørn. The data are presented on a depth basis with a calibrated age scale, and the hollow silhouettes denote a 10× exaggeration of the percentage values. The pollen zones are shown in the right-hand column. LOI is shown on the left.

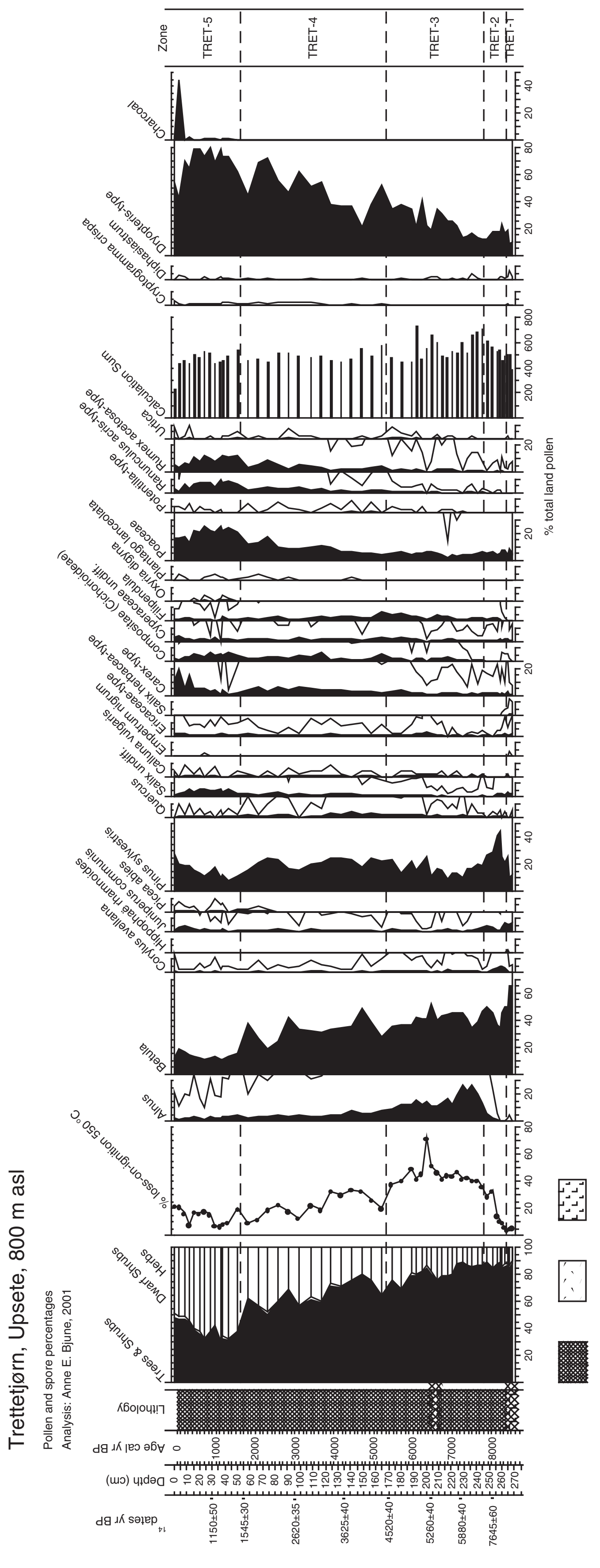

Figure 3 Simplified percentage pollen diagram from Trettetjørn. The data are presented on a depth basis with a calibrated age scale, and the hollow silhouettes denote a 10× exaggeration of the percentage values. The pollen zones are shown in the right-hand column. LOI is shown on the left.

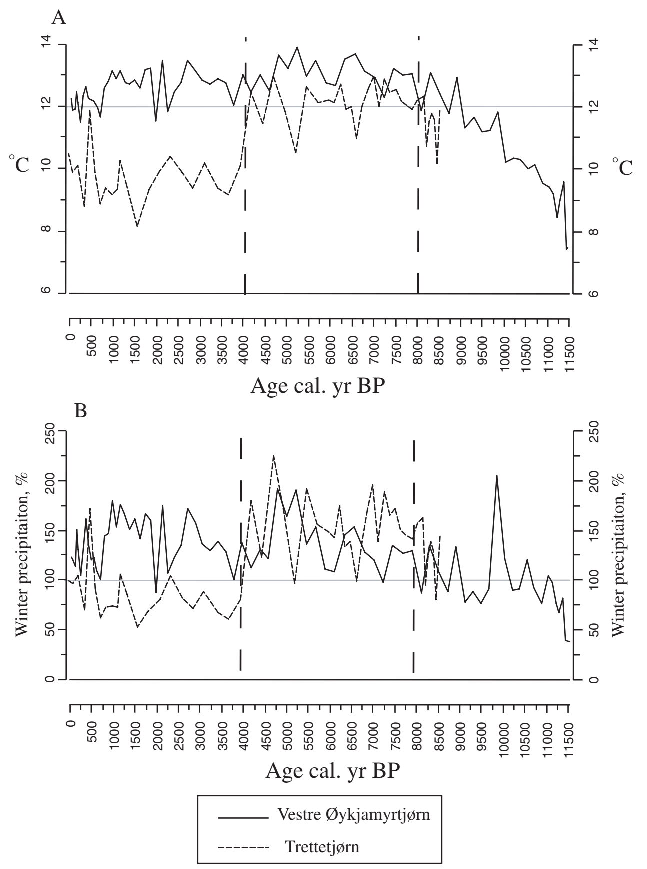

Figure 4 Climate reconstructions presented on a calibrated age scale. (A) T_{jul} reconstructed at Vestre Øykjamyrtjørn and at Trettetjørn with a dotted reference line at 12°C. (B) P_w from northern Folgefonna based on (A). P_w is expressed as a percentage of the 1961–90 normal (dotted line).

Vestre Øykjamyrtjørn T_{jul} stayed around 12°C. Pine forest disappeared from Trettetjørn, and was gradually replaced by birch woodland as a response to a cooler and wetter climate. At Vestre Øykjamyrtjørn, however, pine was present until *c.* 700 cal. yr BP (Bjune, unpublished data).

The ELA at northern Folgefonna fluctuated, but the general trend was a decrease in ELA as the glacier advanced. The lowest ELA occurred during the 'Little Ice Age' which represented the largest glacier extent at northern Folgefonna, with an ELA 105 m below the present-day ELA. A sharp rise in the ELA occurred after the 1930s (see Bakke *et al.*, 2005b).

P_w decreased in this period based on the inferred T_{jul} from the Trettetjørn pollen data, with P_w at northern Folgefonna reaching as low as 52% of the present. By using the inferred T_{jul} from Vestre Øykjamyrtjørn, P_w was higher but still variable throughout this period. The largest discrepancies between the two P_w reconstructions occurred during this period. Between 700 and 330 cal. yr BP, P_w increased abruptly to more than 140% based on the T_{jul} reconstruction from Trettetjørn. Using Vestre Øykjamyrtjørn's T_{jul}, P_w increased again from 700 cal. yr BP after a short drop between *c.* 950 and 700 cal. yr BP, from 180% to the same amount as the present day.

Validation of inferred T_{jul}

To validate pollen-based climate reconstructions, the macrofossils found in the sediments can be used (Birks and Birks, 2003). In Figure 5, *Pinus sylvestris* macrofossil data from Trettetjørn and Vestre Øykjamyrtjørn are presented together with the inferred T_{jul} from the two lakes. At Trettetjørn several pine macrofossils were found in the period from 7800 to 4400 cal. yr BP, and Vestre Øykjamyrtjørn from 9300 to 700 cal. yr BP. In the time periods when pine macrofossils were abundant, the inferred T_{jul} based on the pollen stratigraphy was above 101–12°C.

Winter precipitation

The new inferred P_w data from Jostedalsbreen and Hardangerjøkulen using T_{jul} from Vestre Øykjamyrtjørn are presented in Figure 6 together with the P_w curve from northern Folgefonna.

All the curves follow the same pattern but the absolute values differ. In general P_w increased from 11 500 cal. yr BP and a peak occurred at all glaciers at 9800 cal. yr BP, with the highest values at northern Folgefonna reaching 205% of the present day. From 9800 to 9100 cal. yr, P_w decreased at all sites. From 9100 to 6000 cal. yr BP, inferred P_w fluctuated and peaks occurred at 8900, 8400–8300, 7900, 7700 and 6500 cal. yr BP. At 6500 cal. yr BP, maximum Holocene P_w values occurred, with the highest P_w at Hardangerjøkulen, reaching 177% of the present. Minimum P_w values occur at 8700, 8100, 7300 and 6000 cal. yr BP.

After 6000 cal. yr BP, P_w increased at all glaciers until 4400 cal. yr BP, when P_w decreased until 3800 cal. yr BP. From 3800 cal. yr BP, a sharp rise in P_w occurred until 2700 cal. yr BP with rather similar amounts of precipitation at all sites. After 2700 cal. yr BP P_w varied and peaks occurred at 2100, 1900–1700, 1300, 1000, 400 and 200 cal. yr BP. The highest P_w values occurred at Jostedalsbreen. Minimum P_w values occurred at 2000, 1500, 1200, 700, 300 and 100 cal. yr BP.

Discussion

July temperature during the Holocene

At the end of the Younger Dryas (YD) and in the early Holocene, the inferred T_{jul} at Vestre Øykjamyrtjørn rose from 8.5°C to 10.5°C between 11 000 and 10 000 cal. yr BP. This temperature rise is comparable with the increase found at Kråkenes based on pollen (Birks and Ammann, 2000; Birks *et al.*, 2000) and chironomids (Brooks and Birks, 2000), as well as diatoms in the Norwegian Sea (Birks and Koç, 2002) from the period from the YD into the early Holocene. The rapid increase in temperature allowed birch to establish at Vestre Øykjamyrtjørn and pine expanded from *c.* 9300 cal. yr BP (Bjune, unpublished data). Higher than present Northern Hemisphere solar radiation in summer time would have occurred during the early Holocene (Berger, 1978) suggesting higher temperatures on land and warmer ocean water. In the Lateglacial and early Holocene, there was, however, a regional climatic effect due to the presence of the Scandinavian ice sheet.

In the early Holocene, until *c.* 8500 cal. yr BP, a more oceanic climate prevailed, as indicated by the low T_{jul} and high annual precipitation reconstructed here and at other sites. This period was probably characterized by stronger-than-present zonal circulation (Seppä and Birks, 2001). Higher lake levels occurred in northern and northeastern Finland (Eronen *et al.*, 1999; Korhola and Rautio, 2002). Expanding glaciers in western Norway (Nesje *et al.*, 2001) suggest a more humid climate and a stronger flow of moist Atlantic air over Fennoscandia until about 9000 cal. yr BP (Hammarlund *et al.*, 2003).

At *c.* 8200 cal. yr BP a decline in pine and a rise in *Juniperus* pollen occurred at Toskaljavri in northern Finland (Seppä and Birks, 2002) corresponding with changes in the North Atlantic

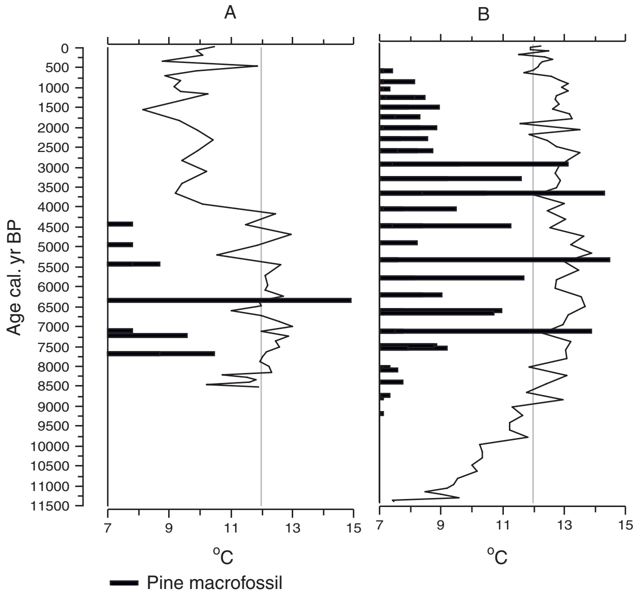

Figure 5 The inferred T_{jul} and the presence of pine macrofossils at (A) Trettetjørn and (B) Vestre Øykjamyrtjørn. A reference line is added at 12°C.

circulation system (Alley *et al.*, 1997; Klitgaard-Kristensen *et al.*, 1998) as a response to a short cooling event, probably triggered by the drainage of the Laurentide ice lakes in Canada (Barber *et al.*, 1999). Klitgaard-Kristensen *et al.* (1998) suggested an approximate 2°C drop in sea-surface temperature corresponding with a decrease in tree-ring width in Germany reflecting shorter or cooler growing seasons. Inferred sea-surface temperature (SST) based on foraminifera suggests *c.* 3°C cooling in the Norwegian Sea during the 'Finse event' (Risebrobakken *et al.*, 2003). Changes in the surface-ocean circulation also affected the atmospheric temperature. A lowering of T_{jul} of ~1°C occurred at Trettetjørn around 8200 cal. yr BP, but not at Vestre Øykjamyrtjørn. A decrease in *Betula* pollen percentages at Trettetjørn suggests a lower inferred T_{jul}, whereas at Vestre Øykjamyrtjørn no comparable changes can be traced in the pollen diagram. Lower summer temperature led to glacier readvance of many glaciers in southern Norway and the event was termed the 'Finse event' (Dahl and Nesje, 1996; Nesje *et al.*, 2001). This event has, however, not been recorded at northern Folgefonna, probably due to the altitude and the topography at northern Folgefonna. During the 'Finse event' the lowering of the ELA did not cross the altitude of instantaneous glaciation at this site (Bakke *et al.*, 2005a; 2005b).

After this short cooling event, maximum July temperatures were reconstructed at Toskaljavri in northern Finland between 8300 and 6500 cal. yr BP, representing the Holocene Thermal Maximum, with inferred T_{jul} around 12°C (Seppä and Birks, 2002). In Abisko in northern Sweden, the mid-Holocene warm (Thermal Maximum) period was about 1.5–2.0°C warmer than at present (Barnekow, 1999; Bigler *et al.,* 2002). Similar temperatures occurred at Trettetjørn, with maximum T_{jul} from *c.* 8000 cal. yr BP to 4200 cal. yr BP with temperatures 1.5–1.9°C higher than at present. At Vestre Øykjamyrtjørn, T_{jul} was 0.6–1.5°C higher than at present from *c.* 8500 to 700 cal. yr BP. At Trettetjørn, the higher T_{jul} was probably a result of its more continental location than Vestre Øykjamyrtjørn and of local effects leading to a warmer climate in a closed valley than on an open mountain plateau. A higher portion of long-distance transported pollen at Vestre Øykjamyrtjørn than at Trettetjørn may have led to higher than expected T_{jul}. The COHMAP (1988) model estimates at 9000 and 6000 cal. yr BP indicate stronger westerlies from the Atlantic to the Eurasian continent, resulting in temperatures 2–4°C higher than at present due to increased solar insolation. Diatom inferred SST from the Norwegian Sea suggest 4°C warmer than at present as warm waters passed along the coast (Birks and Koç, 2002). Their reconstructions are warmer than the local reconstructions presented here.

Subsequent to 6000 cal. yr BP, a gradual decrease in the westerlies and lower temperatures is suggested as an effect of the reduction of ice sheets and lower insolation at high latitudes (COHMAP, 1988). Magny and Haas (2004) gives several reasons for a cooler and wetter climate between 5600

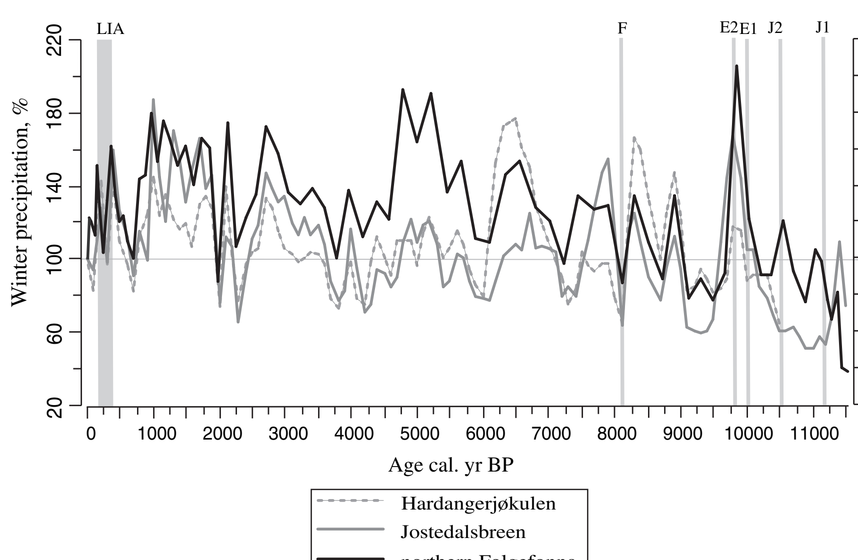

Figure 6 Holocene variations in winter precipitation in% compared to the present day calculated from Jostedalsbreen, Hardangerjøkulen and northern Folgefonna based on the T_{jul} from Vestre Øykjamyrtjørn. 100% = 1961–90 normal. Some of the glacial events mentioned in the text are indicated by grey bar:, LIA = 'Little Ice Age', F = Finse event; E1 = Erdalen event 1; E2 = Erdalen event 2; J1 = Jondal event 1; J2 = Jondal event 2 (see also Bakke *et al.*, 2005b).

and 5000 cal. yr BP, including orbital forcing, changes in ocean circulation, and changes in solar activity. Decreasing temperatures were also reconstructed at Abisko, where the inferred T_{jul} decreased 0.8–1.5°C during the last 6000 years (Bigler *et al.*, 2002). In addition to the terrestrial evidence, these estimates are supported by diatom-inferred SST in the Norwegian Sea (Koç *et al.*, 1993). At Trettetjørn, a sharp decline in inferred T_{jul} was observed after 4000 cal. yr BP. At Vestre Øykjamyrtjørn the inferred T_{jul} stayed around 12°C until the present day. At Vestre Øykjamyrtjørn pine persisted longer, suggesting warmer summers and less precipitation, whereas at Trettetjørn the vegetation became more open in the late Holocene. This was probably due to lower temperatures and increased precipitation as seen by the rise in fern spores. On a regional scale, a climate shift is observed after 4500 cal. yr BP, with cooler summers and more precipitation giving higher lake levels (Hammarlund *et al.*, 2003) and glacial readvances (Dahl and Nesje, 1996; Nesje *et al.*, 2000a; 2001; Bakke *et al.*, 2005a; 2005b).

Validation of reconstructed T_{jul}

Summer temperature is probably the most important factor for the establishment and growth of *Pinus sylvestris* (Bartholin and Karlén, 1983; Briffa *et al.*, 1988; Hicks, 2001). Helland (1912) and Vorren *et al.* (1996) proposed that the 12°C July isotherm limits the distribution of *Pinus sylvestris* in Norway. At both Trettetjørn and Vestre Øykjamyrtjørn the inferred T_{jul} is 12°C or higher at the same time as pine macrofossils, such as needles and budscales, are abundant in the sediments. This suggests that the inferred T_{jul} are valid at both sites during this time period and can thus be used as a basis for reconstructing winter precipitation in conjunction with reconstructed glacial ELA values.

Holocene winter precipitation at northern Folgefonna

Previously winter precipitation has been reconstructed for Hardangerjøkulen by using variations in pine tree limits based on pine megafossils as a proxy for summer temperature (Dahl and Nesje, 1996), at Jostedalsbreen by using reconstructions of T_{jul} based on chironomid assemblages in lake sediments from Finse (Nesje *et al.*, 2001), and at northern Folgefonna by using summer temperatures inferred from plant macrofossils and chironomids (Bakke *et al.*, 2005a). By using pollen data validated with plant macrofossils as a proxy for T_{jul} when reconstructing $P_{w,}$ the problem of lakewater temperature being chilled by glacial meltwater input as seen in some of the inferred T_{jul} based on chironomids in lake sediments is avoided (Brooks and Birks, 2000; Velle *et al.*, 2004).

One of the most prominent glacier events during the Holocene was the Preboreal Oscillation (PBO) that occurred between 11 300 and 11 150 cal. yr BP (Björck *et al.*, 1997). This cooling event can also be traced in pollen diagrams. In Germany, a decrease in pine and an increase in *Juniperus*, *Empetrum* and herb pollen occurred (Behre, 1966). In Scandinavia, the pioneer flora was still dominant, and stratigraphical changes are not so obvious. In southwestern Norway, Paus (1989a; 1989b) found traces of the PBO in pollen diagrams as a reduction in pollen concentration. At Vestre Øykjamyrtjørn, a short fluctuation with lower values of *Betula* pollen and an increase in *Vaccinium*-type, Poaceae and herb pollen in general is recorded between 11 300 and 11 050 cal. yr BP, giving a decrease in T_{jul}. The glacier advance termed 'Jondal event 1' at northern Folgefonna corresponds to the PBO and is suggested to have been a response to lower summer temperature and hence a 230 m lower ELA (Brooks and Birks, 2000; Bakke *et al.*, 2005a). Estimates based on marine diatoms suggest that the SST in the Norwegian Sea decreased by 1°C during the PBO (Birks and Koç, 2002). The next event, the 'Jondal event 2' was, according to Bakke *et al.* (2005a) response to increased P_w. This event is also recorded in the inferred P_w presented here. No change in T_{jul} was observed at that time.

Following the PBO, the Erdalen event is believed to be a response to increased P_w with an increase to 170% compared with the 1961–90 normal period at northern Folgefonna. At northern Folgefonna, only the first Erdalen event is recognized, while ELA rose rapidly after the Erdalen event 2, dated to 10 000–9850 cal. yr BP by Bakke *et al.* (2005a), similar to the development at Hardangerjøkulen (Dahl and Nesje, 1996) and Jostedalsbreen (Dahl *et al.*, 2002). At Hardangerjøkulen, this ELA increase was followed by a gradual decline during the Finse event (*c.* 8500–8300 cal. yr BP), whereas the Finse event is not recorded at northern Folgefonna. During the Finse event winter precipitation is estimated to have been 175% higher than at present and the mean summer temperature was 1.35°C higher than today (Dahl and Nesje, 1996). According to the inferred T_{jul} from Trettetjørn, the summers were cooler during the Finse event. Seppä and Birks (2002) suggested that this was an oceanic event, and hence a larger temperature difference is expected at the coast than inland. At Vestre Øykjamyrtjørn, no temperature changes have been detected, whereas at the more inland Trettetjørn the summers were cooler. The signal in the pollen record is weak, probably due to the insensitivity of vegetation as the sites were not located close to an ecotonal boundary at that time. In addition, the response time may have been too slow since the Finse event was mostly a response to increased precipitation and not so much to summer temperature which is the main climatic factor controlling subalpine vegetation (Körner, 1998).

After the culmination of the Erdalen event, the northern Folgefonna glacier disappeared and the input of glacial meltwater into the lakes ceased (Bakke *et al.*, 2005b). The maximum estimates of P_w suggest that the winters had more precipitation than at present, but the warm summers prevented a large glacier forming at northern Folgefonna until *c.* 5200 cal. yr BP. A warmer climate may have also caused P_w to fall as rain and not as snow. Subsequent to 5200 cal. yr BP, however, a decline in ELA below the present day altitude and an increase in inferred P_w are observed, suggesting higher glacier activity until the present-day. A wetter, more maritime climate in the later part of the Holocene caused lowering of the ELAs and readvance of many glaciers in Norway (e.g., Dahl and Nesje, 1996; Nesje *et al.*, 2000a; 2001; Lie *et al.*, 2004) as well as in the Alps (Magny and Haas, 2004). The late-Holocene glacial readvance also corresponds to cooler inferred temperatures in the southeastern Norwegian Sea (Andersson *et al.*, 2003). A lowering of the pine treeline and an increase in the birch treeline altitude occurred in most of Fennoscandia at that time due to a wetter and cooler climate (e.g., Aas and Faarlund, 1988; Seppä and Birks, 2001; 2002; Barnett *et al.*, 2001; Bjune *et al.*, 2004). At Abisko, Barnekow (1999) suggested increased precipitation and lower growing-season temperatures during the last 4500 years.

Until *c.* 4000 cal. yr BP, P_w reconstructed from the two T_{jul} curves follows the same pattern and have similar values. After *c.* 4000 cal. yr BP, however, a large discrepancy occurs between the two curves, possibly due to topographical differences giving more precipitation at Trettetjørn.

Climate changes during the last millennium were dominated by the 'Mediaeval Warm Period' (MWP) and the 'Little Ice Age' (LIA). At northern Folgefonna both glacial growth and decay are recorded during the MWP as a response to increased precipitation due to unstable westerlies (Bakke *et al.*, 2005b). The MWP was followed by three glacier readvances during the LIA at northern Folgefonna at AD 1750, 1870 and 1930 (Bakke *et al.*, 2005b) caused by increased P_w and lower T_{jul}. Cooler climates are also supported by data from the Norwegian Sea (e.g., Andersson *et al.*, 2003). According to Nesje and Dahl (2003), the LIA was mainly due to increased P_w with a positive NAO weather mode as confirmed at northern Folgefonna.

Regional climate – all glaciers

The reconstructed P_w from all the three glaciers (northern Folgefonna, Hardangerjøkulen and Jostedalsbreen) show large variations throughout the Holocene. Most of these variations occurred at the same time but with different magnitude, indicating similar P_w patterns over southern Norway during the Holocene. All of them are situated in an oceanic climate and are affected mainly by changes in the westerlies. The relative mild climate in northern latitudes is due to the heat transport driven by the North Atlantic thermohaline and atmospheric circulation advecting warm surface waters from the subtropical Atlantic (Manabe and Stouffer, 1999). Changes in P_w during the Holocene may reflect fluctuations between periods with prevailing mild and wet winter conditions (+NAO index weather mode) and periods with prevailing cold and dry winters (−NAO index weather mode) and thus different inputs of snow on the glaciers during the accumulation season. The higher inferred P_w in the mid-Holocene at northern Folgefonna reflects its more maritime position than the other glaciers. A lower correlation between NAO and winter precipitation are found by Uvo (2003) on leeward sides of mountains and in central parts of Norway and a high correlation on the southwestern coast. A high correlation between the Holocene P_w and NAO is evident from Nesje *et al.* (2000b). During the early Holocene, inferred P_w was highest at the most oceanic site, northern Folgfonna, suggesting a dominance of westerly winds. During short periods P_w was higher at Hardangerjøkulen, suggesting that the dominant wind direction was then from the east, giving high amounts of precipitation at Hardangerjøkulen.

Conclusions

Changes in the Holocene climate in southern Norway have been reconstructed on the basis of evidence from lake sediments such as pollen, plant macrofossils, sediment characteristics and redundant additional moraine data. The results clearly indicate three phases.

The early Holocene, from 11 500 to 8000 cal. yr BP, was characterized by low T_{jul} and low P_w at northern Folgefonna. The mid-Holocene, from *c.* 8000 to 4000 cal. yr BP, was warmer with maximum T_{jul} reaching 13°C at Vestre Øykjamyrtjørn and high P_w values at northern Folgefonna. The later part of the Holocene, from *c.* 4000 cal. yr BP until the present, was cooler and drier at northern Folgefonna than the previous period. During this period glacier advances are recorded. A similar development of P_w was inferred at all glaciers presented in this study. The observed changes in P_w at the three glaciers may have been related to changes in a NAO-like weather mode over the north Atlantic. The work shows promising results when biological and geological proxies are integrated. The results presented how biological and geological data can be combined to infer long-term Holocene variations in winter precipitation.

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