The Holocene 13,1 (2003) pp. 139–145

The 'Little Ice Age' – only temperature?

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Received 21 January 2002; revised manuscript accepted 7 May 2002

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Abstract: Understanding the climate of the last few centuries, including the 'Little Ice Age', may help us better understand modern-day natural climate variability and make climate predictions. The conventional view of the climate development during the last millennium has been that it followed the simple sequence of a 'Mediaeval Warm Period', a cool 'Little Ice Age' followed by warming in the later part of the nineteenth century and during the twentieth century. This view was mainly based on evidence from western Europe and the North Atlantic region. Recent research has, however, challenged this rather simple sequence of climate development in the recent past. Data presented here indicate that the rapid glacier advance in the early eighteenth century in southern Norway was mainly due to increased winter precipitation: mild, wet winters due to prevailing 'positive North Atlantic Oscillation (NAO) weather mode' in the first half of the eighteenth century; and not only lower summer temperatures. A comparison of recent mass-balance records and 'Little Ice Age' glacier fluctuations in southern Norway and the European Alps suggests that the asynchronous 'Little Ice Age' maxima in the two regions may be attributed to multidecadal trends in the north–south dipole NAO pattern.

Key words: 'Little Ice Age', glacier variations, North Atlantic Oscillation, NAO, Norway, European Alps.

Introduction

The conventional perception of the climate development during the last millennium has been that it followed the simple sequence of a 'Mediaeval Warm Period' (MWP), a cool 'Little Ice Age' (LIA) followed by global warming since the latter part of the nineteenth century and especially in the latter part of the twentieth century. The climate development during the MWP and the LIA was mainly based on Lamb (1963; 1965; 1977) on evidence from western Europe and the North Atlantic region (e.g., Bradley, 2000). Recent research has, however, challenged this sequence of climate development in the recent past.

Lamb (1965; 1977) defined the 'Mediaeval Period' (MP) as a period of high temperatures during the eleventh to thirteenth centuries. In a review of a range of palaeoclimatic data, Hughes and Diaz (1994), however, found no clear evidence for a long-lasting, globally uniform, warm epoch in the MP. Crowley and Lowery (2000) did not find any support either for higher global or hemispheric mean temperatures in the MP compared to the twentieth century. There were, however, significant precipitation anomalies during the MP. Many areas, especially in the USA, experienced drought episodes far beyond the range recorded during the period of instrumental records (e.g., Stine, 1994).

Numerous studies have demonstrated cooler climate and advancing glaciers subsequent to the MP – a period termed the 'Little Ice Age' (e.g., Grove, 1988). Due to regional differences in the climate development, it has, however, been difficult to define the 'initiation' (Grove, 2001) and 'termination' of the 'Little Ice Age'. Traditionally, AD 1550–1850 has been applied for the duration of the LIA (Jones and Bradley, 1992), but glacier-front variations and temperature records from Scandinavia indicate that the 'Little Ice Age' lasted until ~AD 1920. There is, however, evidence of significant cooling prior to AD 1550, at AD 1450, or even AD 1250 (Grove and Switsur, 1994; Luckman, 1994). Records of glacier variations show that most Scandinavian glaciers reached their LIA maximum during the mid-eighteenth century. There is, however, evidence that outlet glaciers from Folgefonna, a maritime glacier in western Norway, reached their LIA maximum position in the 1890s, or even as late as around 1940 (Tvede, 1973; Tvede and Liestøl, 1977). In the Alps, the majority of glaciers reached the maximum LIA position in the mid-nineteenth century (e.g., Grove, 1988).

The objective of this paper is to assess what climatic factors caused the extensive glacier advance during the first half of the eighteenth century in southern Norway and to discuss why the 'Little Ice Age' glacier maxima did not occur simultaneously in Scandinavia and in the European Alps.

The 'Little Ice Age'

During the Holocene, a number of abrupt and widespread climatic variations are recorded around the world (e.g., Lockwood, 2001). In the North Atlantic region, it has been claimed that these changes have an approximate 1500 (1470 ± 500)-yr periodicity (Bond *et al.*, 1997; Campbell *et al.*, 1998). The most recent cold

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10.1191/0959683603hl603fa

period in these 1500-yr cycles may have been the 'Little Ice Age' (Lockwood, 2001). A Northern Hemisphere temperature reconstruction indicates an irregular temperature decline from AD 1000 to 1850 of about 0.2°C with a subsequent warming of approximately 0.8°C (Mann *et al.*, 1999). Apparently, there was a series of post-Mediaeval cool periods with widespread climatic cooling after approximately AD 1200. Century-scale variability in the temperature series may be related to variations in solar irradiance and volcanic eruptions (Lean *et al.,* 1995; Mann *et al.,* 1998; Crowley, 2000). The climatic variations during the 'Little Ice Age' caused worldwide growth of glaciers, but the evidence from Scandinavia and the European Alps is best documented (Grove, 1988; Lowell, 2000).

Estimates of Northern Hemisphere mean annual temperature for the last millennium (Mann *et al.,* 1999; Crowley and Lowery, 2000) do not show a marked LIA cooling, but rather a gradual temperature decline during the first half of the last millennium. It is also evident that there was significant regional temperature variations during the LIA. Several temperature data sets obtained from different archives (tree rings, corals, varved sediments, ice cores, glaciers, historical records, etc.) show that some regions were warm while others were cold, and *vice versa.* Most of the reconstructed climatic changes have been linked to external forcing factors (e.g., solar activity, volcanic eruptions) in combination with internal ocean-atmosphere interactions (Crowley and Kim, 1996; Mann *et al.*, 1998). Since these forcing factors, together with 'greenhouse' gases, are suggested by the Third Assessment IPCC Report, published in 2001, to play a role in future climatic variations, it is important to obtain better records of climatic change in the recent past and a better understanding of the relative contribution of these forcing factors.

The early eighteenth-century glacier advance of Nigardsbreen – summer temperature or winter precipitation?

Historic evidence shows that Nigardsbreen, an eastern outlet glacier from Jostedalsbreen in western Norway (46°39′ N, 8°37′ E), advanced 2800 m between AD 1710 and 1735 (Figure 1, upper panel), giving a mean annual advance rate of ~110 m. Between AD 1735 and the historically documented 'Little Ice Age' maximum in AD 1748, the glacier advanced 150 m. Subsequently, the lichenometrically and historically dated terminal moraines demonstrate the rate of retreat (Figure 1, lower panel). Annual frontal measurements of Nigardsbreen started in AD 1907. No annual frontal measurements were, however, carried out between AD 1964 and 1972, but the retreat in this period was photogrammetrically determined to be 515 m (Østrem *et al.*, 1977).

The question then arises whether the AD 1710–1748 glacier advance was mainly caused by lower summer temperatures or higher winter precipitation. A comparison between cumulative frontal fluctuation curves of Nigardsbreen and Briksdalsbreen, a western outlet glacier of Jostedalsbreen with a frontal timelag to net mass-balance perturbations of 3–4 years (Nesje *et al.,* 1995), suggests that the lag time of Nigardsbreen is ~20 years (Figure 2). A comparison between winter balance (Bw)/net balance (Bn) and the NAO index (Jones *et al.,* 1997, with later updates) show that the annual mass balance on Nigardsbreen since the early 1960s has been strongly controlled by the winter balance (Figure 3, upper panel). In the 1990s, there was a period of high winter precipitation (strongly positive NAO index; see below), giving both high Bw and positive Bn. This resulted in the largest glacier advance of Briksdalsbreen during the twentieth century, and possibly since the early eighteenth century. In the 1990s Briksdalsbreen advanced altogether approximately 320 m, with a maximum annual advance (in 1994) of 80 m (mean daily advance rate of ~20 cm!) (Figure 2, upper panel; Figure 3, lower panel). In the same timespan Nigardsbreen has become significantly thicker in its lower part and steeper in the front.

The North Atlantic Oscillation (NAO) and glacier mass balance

The North Atlantic Oscillation (NAO) is one of the major modes of climate variability in the North Atlantic region (e.g., Walker and Bliss, 1932; van Loon and Rogers, 1978; Kushnir and Wallace, 1989; Kushnir, 1994; Hurrell, 1995; Hurrell and van Loon, 1997). Atmospheric circulation during winter commonly displays a strong meridional (north–south) pressure contrast, with low pressure (cyclone) centred close to Iceland and high pressure (anticyclone) near the Azores. This pressure gradient drives mean surface winds and mid-latitude winter storms from west to east across the North Atlantic, bringing mild, moist air to NW Europe. Interannual atmospheric climate variability in NW Europe, especially over the British Isles and western Scandinavia, has mainly been attributed to the NAO, causing variations in winter weather over the NE North Atlantic and the adjacent land areas. A considerable impact of the NAO on regional winter precipitation has been observed. Positive NAO-index winters are related to above-normal precipitation over Iceland, the British Isles and Scandinavia, and below-normal precipitation over central and southern Europe, the Mediterranean region and NW Africa (van Loon and Rogers, 1978) (important for the winter mass balance on maritime glaciers in Scandinavia and for glaciers in the European Alps). A comparison between NAO and winter precipitation between AD 1864 and 1995 in western Norway shows that these are highly correlated (r = 0.77) (Hurrell, 1995). Variations in NAO are also reflected in the mass-balance records of Scandinavian glaciers (Nesje *et al.*, 2000; Reichert *et al.*, 2001; Six *et al.,* 2001); the highest correlation is with winter and net mass balance on the maritime Ålfotbreen in western Norway (r = 0.79 and 0.72, respectively, observation period AD 1963–2000). Reichert *et al.* (2001) inferred that precipitation is the dominant factor (1.6 times higher than the impact of temperature) for the relationship (r = 0.60) between net mass balance on Nigardsbreen and the NAO index (observation period AD 1962–2000). For Nigardsbreen and Rhônegletscher (46°37′ N, 8°24′ E, Switzerland) they also found a high correlation (r = 0.55) and anticorrelation (r = -0.64), respectively, between decadal variations in the NAO index and in glacier mass-balance model experiments.

Observed or reconstructed glacier fluctuations provide important information on natural climatic variations as a result of changes in the mass and energy balance at the earth's surface. Variations in glacier mass balance (e.g., Paterson, 1994) is the direct reaction of a glacier to climatic variations. On valley and cirque glaciers, variations in glacier length are the indirect, filtered and commonly enhanced response. Available mass-balance records are, however, relatively short compared to the longer records of glacier-length variations. A high correlation between decadal variations in the NAO and glacier mass balance in Europe has been demonstrated (Nesje *et al.,* 2000; Reichert *et al.,* 2001; Six *et al.*, 2001), the dominant factor being the strong relationship between winter precipitation associated with the NAO. A positive NAO phase means enhanced winter precipitation for maritime glaciers in Scandinavia and reduced winter precipitation on glaciers in the European Alps (Reichert *et al.,* 2001). This internal climate-system mechanism explains observed strong positive mass balance on maritime glaciers in western Scandinavia and partly (also due to high summer temperatures) strong negative mass balance of glaciers in the European Alps.

Winter (DJFM) air temperature in Bergen (western Norway) shows a high correlation (r ~ 0.8) with central England (T. Fure-

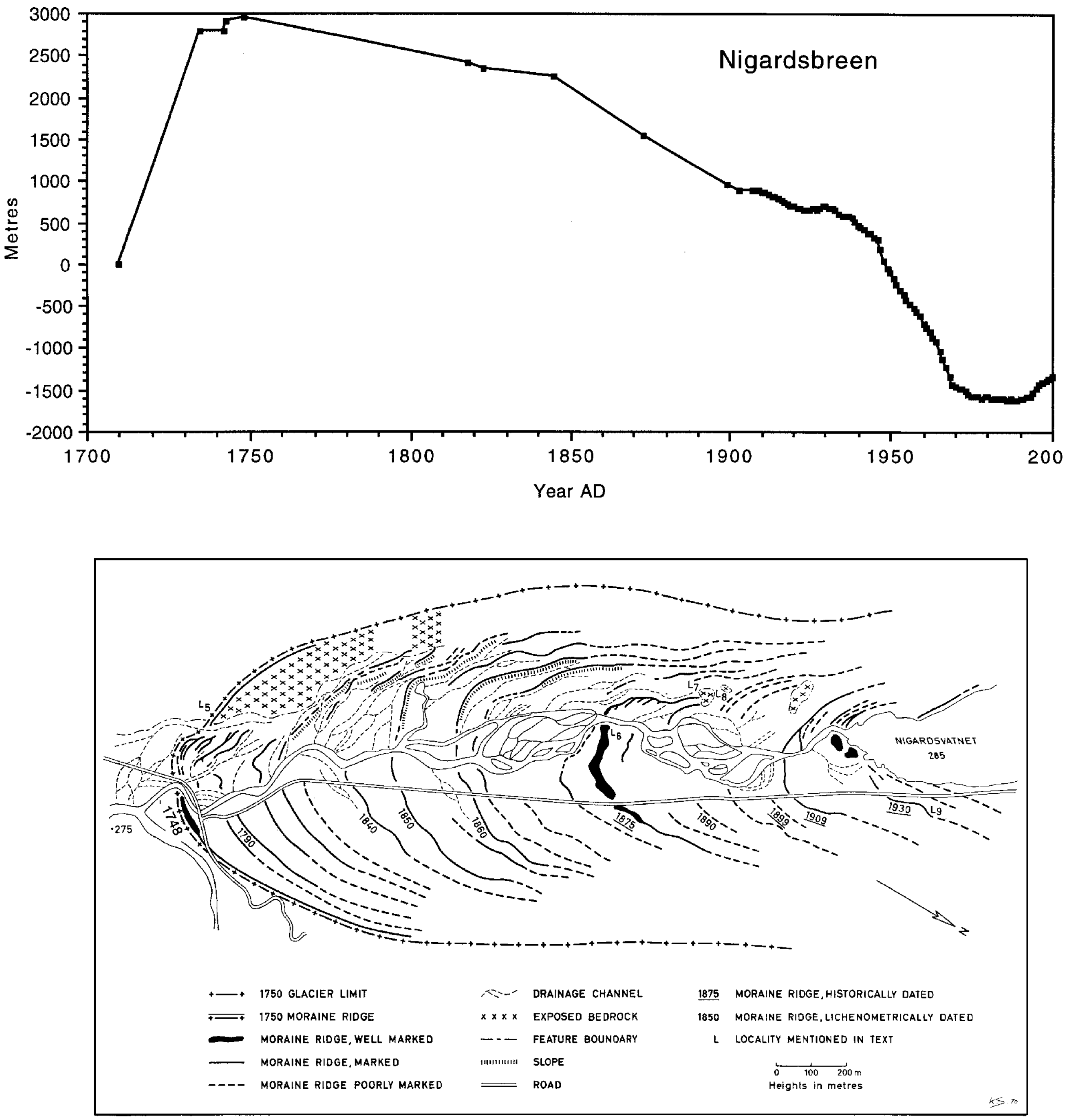

Figure 1 Upper panel: historically reported and measured frontal variations of Nigardsbreen. Adapted from Østrem *et al.* (1977) with later updates by NVE, Section for Glacier and Snow. Lower panel: the Nigardsbreen glacier foreland with historically dated marginal moraines. From Andersen and Sollid (1971) with permission of the authors.

vik, personal communication). The 95 and 99% confidence levels are at 0.27 and 0.35 correlation. This means that a central-England temperature series (Manley, 1974; Parker *et al.,* 1992; with later updates by the Hadley Centre), going back to AD 1659, can be used to test whether the significant early eighteenth-century glacier advance in western Norway may have been caused by summer temperature and/or winter precipitation. The cold winters in the late seventeenth and early eighteenth centuries when the Dutch canals were frozen (e.g., Grove, 1988) are evident in the the central-England temperature record (Figure 4, upper panel). Standardized central-England mean December–March temperatures show strong coherence (r = 0.72) with the winter (D–M) NAO index by Jones *et al.* (1997, with later updates; Figure 4, middle panel), indicating that the standardized December–March central-England temperature record may be used to indicate variations in the NAO weather mode over England and western Norway back to the initiation of the central-England temperature series in AD 1659 (Manley, 1974; Figure 4, lower panel). Neither the central-England summer (May–September) temperature record (Manley, 1974; Parker *et al.*, 1992; with later updates by the Hadley Centre; the correlation between summer temperature in Bergen and central England is ~0.5; the 95 and 99% confidence levels are at 0.27 and 0.35 correlation; T. Furevik, personal communication; Figure 5, upper panel), nor a July–August temperature reconstruction from tree rings in eastern Norway (Kalela-Brundin, 1999; Figure 5, middle panel), nor a 'northern' chronology average of normalized mean tree-ring density anomalies (Briffa, 2000; Figure 5, lower panel), indicate that the early eighteenth century summers were sufficiently cold to explain the rapid early eighteenth-century glacier advance recorded in western Norway. Instead, the three

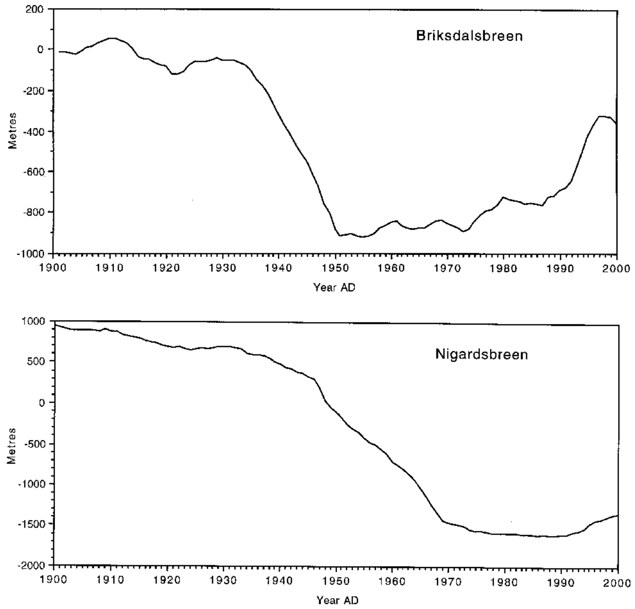

Figure 2 Cumulative frontal variations of Briksdalsbreen (upper panel) and Nigardsbreen (lower panel) in the twentieth century (data: Østrem *et al.,* 1977, and NVE, Section for Glacier and Snow).

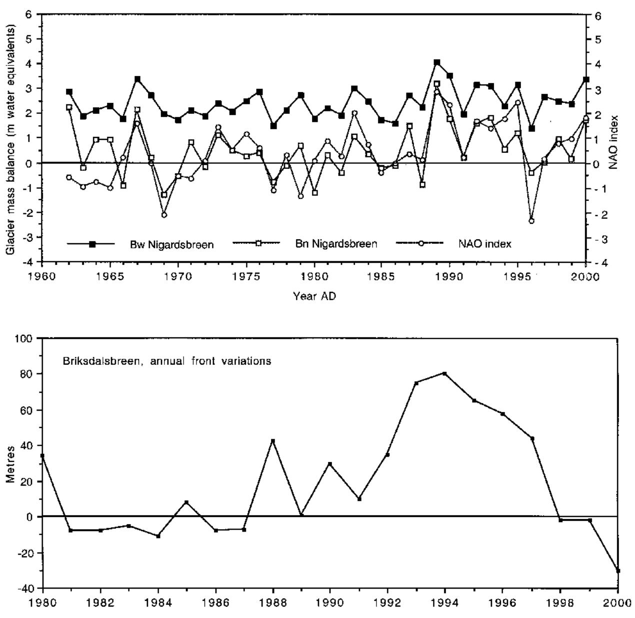

Figure 3 Upper panel: winter balance (Bw) and net balance (Bn) for Nigardsbreen (Kjøllmoen, 1998, with later updates by NVE, Section for Glacier and Snow), and the NAO December–March index (Jones *et al.,* 1997, with later updates) between AD 1962 and 2000. Lower panel: annual frontal variations of Briksdalsbreen, a western outlet glacier from Jostedalsbreen, between AD 1980 and 2000 (data: NVE, Section for Glacier and Snow).

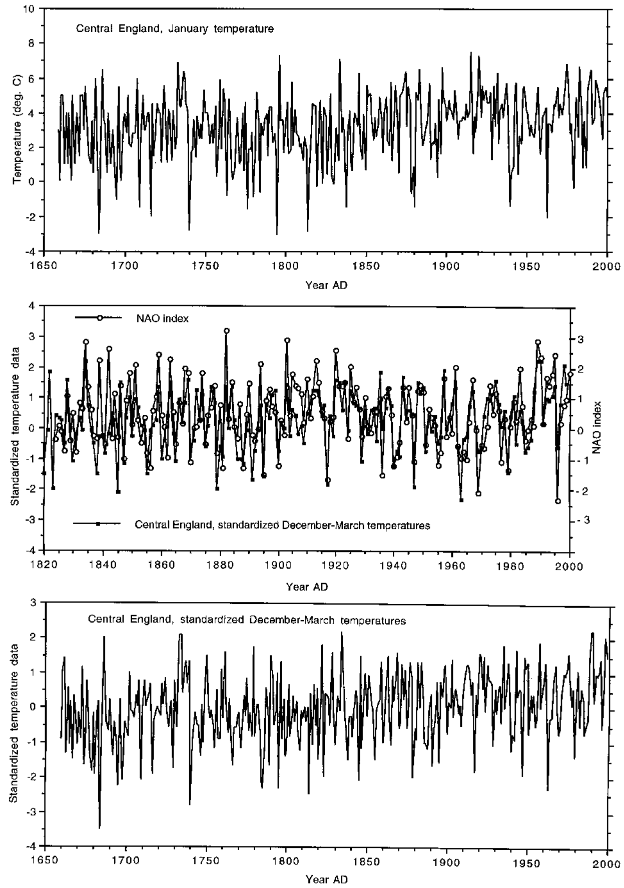

Figure 4 Upper panel: the central England mean January temperature record between AD 1659 and 2000 (Manley, 1974; Parker *et al.,* 1992; with later updates by the Hadley Centre). Middle panel: the December–March NAO index (Jones *et al.,* 1997, with later updates) plotted versus standardized central-England mean December–March temperatures for the period AD 1820–2000 (Manley, 1974; Parker *et al.,* 1992; with later updates by the Hadley Centre). Lower panel: standardized central-England mean December–March temperatures for the period AD 1659–2000.

records indicate a general summer-temperature *rise* in the first part of the eighteenth century. A similar trend is seen in northern Fennoscandian pine chronologies in the first part of the eighteenth century (Briffa *et al.,* 1988; 1992; Eronen *et al.,* 1999) and in a Northern Hemisphere (14 chronologies) tree-ring-based temperature reconstruction (Esper *et al.,* 2002). Four tree-ring chronologies from coastal northern Norway (Kirschhefer, 2001) show that the summers in the first half of the eighteenth century were not especially cold. The central-England winter (October–April) temperature record (Manley, 1974; Parker *et al.,* 1992; with later updates by the Hadley Centre), on the other hand, indicates a significant rise in winter temperatures (indicating mild and humid winters; positive 'NAO weather mode') in NW Europe in the first half of the eighteenth century (between 1690 and 1740 mean ~2°C; Figure 6). A similar pattern is also indicated by a reconstruction of winter (December–February) temperatures from three European sites (central England, Holland and Zürich) for the period AD 1684–1783 (Ingram *et al.,* 1978), reconstructed winter temperatures at De Bilt, Holland, inferred from historical records of canal freezing (van den Dool *et al.,* 1978) and a reconstruction of the NAO index back to AD 1429 (Glueck and Stockton, 2001) and AD 1500 (Luterbacher *et al.,* 2002). The NAO index of Luterbacher *et al.* (2002) included, however, the central-England temperature data. A reconstruction of winter temperature in Tallin, Estonia, also indicates an increasing winter-temperature trend in the southern Baltic region during the first half of the eighteenth century (Tarand and Nordli, 2001). This is further supported by an increase in the number of historically reported incidents of major physical hazards (e.g., snow avalanches and river floods), especially between AD 1650 and 1750, leading to tax reduction for farms in the vicinity to the glaciers Jostedalsbreen and Folgefonna in western Norway (Grove and Battagel, 1983; Nesje, 1994).

Why did the LIA glacier maxima in Scandinavia and the European Alps not occur simultaneously?

Maritime glaciers in Scandinavia experienced a significant increase in winter and net balance in the 1990s due to increased

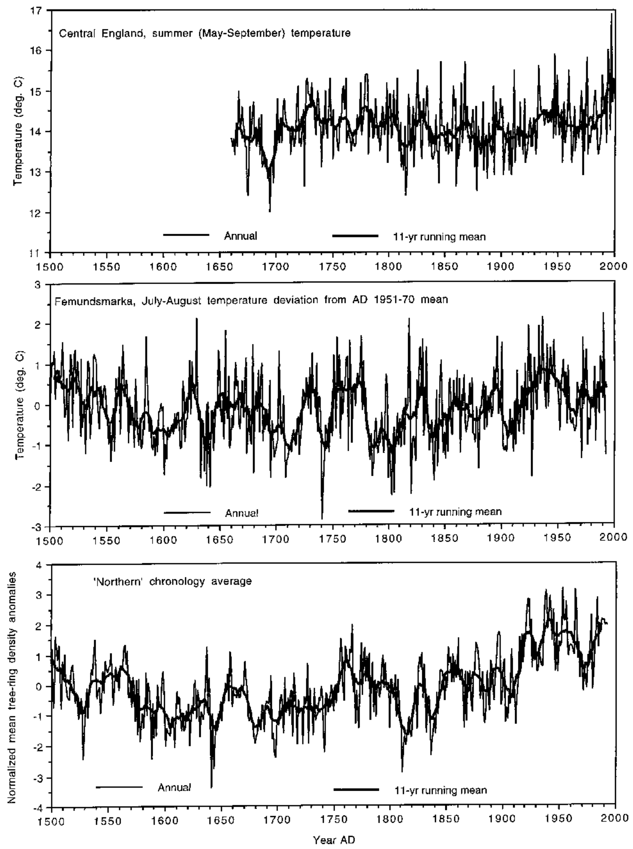

Figure 5 Upper panel: central-England summer (May–September) temperature record (Manley, 1974; Parker *et al.*, 1992; with later updates by the Hadley Centre). Middle panel: July–August temperature deviation from the 1951–70 mean reconstructed from tree rings, Femundsmarka, eastern Norway (Kalela-Brundin, 1999). Lower panel: 'northern' chronology average of normalized mean tree-ring density anomalies (standard deviation) (adapted from Briffa, 2000).

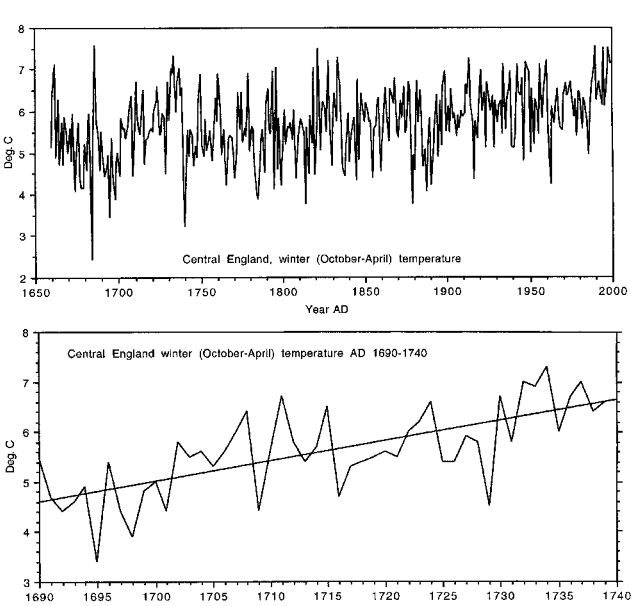

Figure 6 The central-England winter (October–April) temperature record (Manley, 1974; Parker *et al.,* 1992; with later updates by the Hadley Centre) for the period AD 1659–2000 (upper panel) and for the period AD 1690–1740 (lower panel).

winter precipitation associated with prevailing positive NAO index (Nesje *et al.*, 2000; Reichert *et al.*, 2001) which caused annual frontal-advance rates unprecedented since the 'Little Ice Age'. Glaciers in the European Alps, on the other hand, have lost approximately 30–40% of their surface area and about 50% of their volume since the 'Little Ice Age' maximum around the mid-nineteenth century. Since 1980 the glaciers have lost in the order of 10–20% of their volume (Haeberli and Beniston, 1998) because the average mass-balance value has been strongly negative (Haeberli *et al.,* 1999). This can partly be attributed to the generally strong positive phase of the NAO during this period (Reichert *et al.,* 2001) and a general positive temperature trend in this region during the 1980s and 1990s (Beniston *et al.,* 1994a, 1994b). The pressure field is well correlated with the NAO index for distinct periods of the twentieth century (1931–50 and 1971–90) and is almost decorrelated from the NAO index for the other decades (Beniston *et al.,* 1994b). The mass loss on the glaciers in the Alps over the last decades due to reduced winter precipitation (prevailing positive NAO index) are therefore superimposed on the temperature variations.

A glacier mass-balance record (AD 1949–1999; Figure 7) from the Sarennes glacier (45°07′ N, 6°10′ E) in the French Alps (data from World Glacier Monitoring Service (WGMS)), shows that the net balance of the Sarrennes glacier is anticorrelated with the NAO index (positive net mass balance in negative NAO index years, and *vice versa*) and with the glacier mass balance in western Norway, reflecting the general NAO influence on winter climates of different parts of Europe (e.g., Hurrell, 1995; Nesje *et al.*, 2000; Reichert *et al.*, 2001; Six *et al.,* 2001). An unexplained paradox has been that the LIA glacier maxima in Scandinavia and the Alps were not contemporaneous. Might the NAO pattern also explain why the LIA maxima in southern Norway and the Alps are asynchronous? In order to test this, the historic record of glacier-front variations and a simulation of frontal variations based on meteorological data from adjacent sites of Unterer Grindelwaldgletscher, Switzerland (data from WGMS and Schmeits and Oerlemans, 1997), which is representative for the historic glacier variations in the western Alps (Mont Blanc Massif), were used (Figure 8, upper and middle panels). A comparison with the central-England December–March temperature record (11-yr running mean) (Figure 8, lower panel) shows that the two records are in general anticorrelated, i.e., that Unterer Grindelwaldgletscher was in an advanced position when the winter temperatures over England were low, and *vice versa*, which is in accordance with the modern NAO north–south dipole pattern in Europe (Reichert *et al.,* 2001; Six *et al.,* 2001). A winter-precipitation index for the northern Swiss Alpine foreland between AD 1550 and 1995 (Pfister, 1995; Wanner *et al.,* 2000) shows that the early eighteenth century period of significant glacier growth in Scandinavia was characterized by a decreasing winter-precipitation trend. Climatic variability over the last 600 years in the northwest-

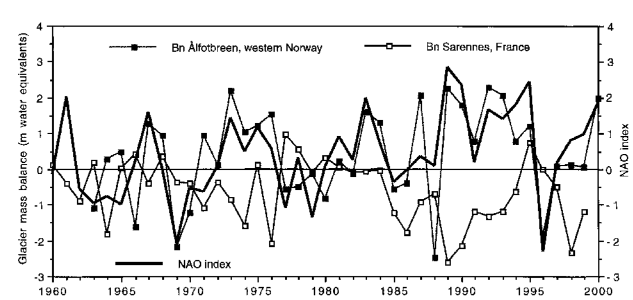

Figure 7 Records of net mass balance between AD 1960 and 1999 from Sarennes glacier in the French Alps and Ålfotbreen in western Norway (data from World Glacier Monitoring Service) plotted versus the December–March NAO index (Jones *et al.*, 1997, with later updates).

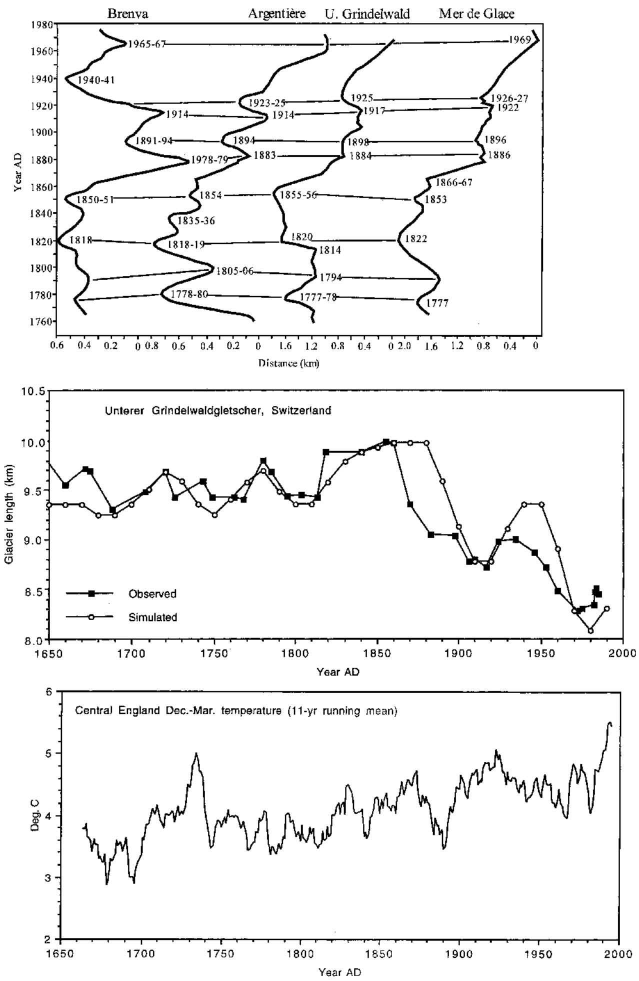

Figure 8 Upper panel: historic variations of four glaciers in the western Alps (Mont Blanc Massif; adapted from Grove, 1988). Middle panel: historic record of glacier-front variations and a simulation of frontal variations of Unterer Grindelwaldgletscher in Switzerland based on meteorological data from adjacent sites of Unterer Grindelwaldgletscher (adapted from Schmeits and Oerlemans, 1997). Lower panel: the central-England December–March temperature (11-yr running mean) record (Manley, 1974; Parker *et al.,* 1992; with later updates by the Hadley Centre).

ern Alps in France, as reconstructed from terrigenous sedimentation in Lake Le Bourget, indicates a strong link with the NAO (Chapron *et al.,* 2002). The asynchronous behaviour of LIA glacier variations in Scandinavia and the European Alps may thus mainly be explained by this NAO pattern in NW Europe.

Conclusions

Until recently, and mainly based on evidence from western Europe and the North Atlantic region, the conventional view of the climate development during the last millennium has been that it followed the simple sequence of a warm Mediaeval period, then a cool 'Little Ice Age', followed by global warming. However, climate reconstructions obtained recently have challenged this rather simple sequence of climate development. The central-England temperature record going back to the late 1650s indicates that the rapid glacier advance which is historically documented in the early eighteenth century in western Norway may be explained mainly by increased winter precipitation (mild and humid) due to prevailing 'positive NAO weather mode' in the first half of the eighteenth century. Lower summer temperatures alone cannot explain such a significant glacier advance over a few decades. A comparison of records from southern Norway and the European Alps of annual mass-balance data and records of 'Little Ice Age' glacier fluctuations may indicate that the asynchronous LIA pattern in the two regions may be attributed to multidecadal trends in the NAO.

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