THE 'LITTLE ICE AGE': RE-EVALUATION OF AN EVOLVING CONCEPT

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Matthews, J.A. and Briffa, K.R., 2005: The 'Little Ice Age': re-evaluation of an evolving concept. *Geogr. Ann.,* 87 A (1): 17–36.

ABSTRACT. This review focuses on the development of the 'Little Ice Age' as a glaciological and climatic concept, and evaluates its current usefulness in the light of new data on the glacier and climatic variations of the last millennium and of the Holocene. *'Little Ice Age' glacierization* occurred over about 650 years and can be defined most precisely in the European Alps (*c.* AD 1300–1950) when extended glaciers were larger than before or since. *'Little Ice Age' climate* is defined as a shorter time interval of about 330 years (*c.* AD 1570–1900) when Northern Hemisphere summer temperatures (land areas north of 20°N) fell significantly below the AD 1961–1990 mean. This climatic definition overlaps the times when the Alpine glaciers attained their latest two highstands (AD 1650 and 1850). It is emphasized, however, that 'Little Ice Age' glacierization was highly dependent on winter precipitation and that 'Little Ice Age' climate was not simply a matter of summer temperatures. Both the glacier-centred and the climate-centred concepts necessarily encompass considerable spatial and temporal variability, which are investigated using maps of mean summer temperature variations over the Northern Hemisphere at 30-year intervals from AD 1571 to 1900. *'Little Ice Age'-type events* occurred earlier in the Holocene as exemplified by at least seven glacier expansion episodes that have been identified in southern Norway. Such events provide a broader context and renewed relevance for the 'Little Ice Age', which may be viewed as a 'modern analogue' for the earlier events; and the likelihood that similar events will occur in the future has implications for climatic change in the twenty-first century. It is concluded that the concept of a 'Little Ice Age' will remain useful only by (1) continuing to incorporate the temporal and spatial complexities of glacier and climatic variations as they become better known, and (2) by reflecting improved understanding of the Earth–atmosphere–ocean system and its forcing factors through the interaction of palaeoclimatic reconstruction with climate modelling.

Key words: Little Ice Age, climate, glaciers, glacierization, decadal variability, last millennium, Holocene

A controversial term

The term 'little ice age' was coined by Matthes (1939, p. 520) with reference to the phenomenon of glacier regrowth or recrudescence in the Sierra Nevada, California, following their melting away in the Hypsithermal of the early Holocene. The moraines on which Matthes based his initial concept have been described more recently as a product of 'neoglaciation' (Porter and Denton 1967) and the term 'Little Ice Age' now generally refers only to the latest glacier expansion episode of the late Holocene. In her most recent, authoritative review, Grove (2004, p. 1) defines this as beginning in the thirteenth or fourteenth century and culminating between the mid-sixteenth and mid-nineteenth centuries.

Although it would be a relatively simple matter to continue to define the 'Little Ice Age' exclusively in terms of glacier variations, as proposed by Grove, that proposition has been rendered impractical by further changes to the original usage of the term (Ogilvie and Jónsson 2001). As was also the case with the term 'Ice Age', use of 'Little Ice Age', almost from the start, became associated with a climate different from today, and especially with a 'cold period' (e.g. Lamb 1965, 1977). Hence, the concept of the 'Little Ice Age' has moved on and today 'Little Ice Age' climate is often the focus of discussion, rather than 'Little Ice Age' glacierization. This has, however, created confusion to the extent that, at least in terms of climate, several commentators consider the term is inappropriate (Landsberg 1985), should be used cautiously (Bradley and Jones 1992a, b), should be allowed to disappear from use (Ogilvie and Jónsson 2001), or should be avoided because of limited utility (Jones and Mann 2004). Most recently the concept has been stretched to include earlier 'Little Ice Ages' (as in the title of the second edition of Grove's book), which we suggest would be more appropriately termed 'Little Ice Age'-type events.

In addition to the need for clarification of terminology, a re-evaluation of the concept of a 'Little Ice Age' is considered timely for two reasons. First, new information from historical and proxy sources relating to both glacier and climatic variability during the interval normally associated with the 'Little Ice Age' is increasingly becoming available. This allows an up-to-date assessment of the characteristics of the 'Little Ice Age' as both a glaciological and a climatic concept. Second, increasing knowledge of the character of 'Little Ice Age'-type events earlier in the Holocene, and the rapid development in reconstructing parallel histories of climatic forcings (such as solar irradiance changes and volcanic frequency) has broadened the context in which investigations of the 'Little Ice Age' take place. It is no longer viewed merely as a unique phase in the history of glaciers and climate, but can now be regarded as a fundamental test case for understanding the century- to millennial-scale events affecting the Earth–atmosphere–ocean system over the Holocene. Better understanding of the context, characteristics and physical mechanisms that shaped this event is thus relevant to assessing the nature of future trends in climate, especially those likely to be experienced during the twenty-first century.

'Little Ice Age' glacierization

The expanded state of glaciers, relative to today, during the last few hundred years is an incontrovertible fact. Grove's (2004) summary of the data available worldwide shows that glaciers on all continents, from the tropics to the polar regions, were characterized by glacier expansion and subsequent retreat. However, beyond the European Alps, and to a lesser degree in Scandinavia and North America, data on the precise timing of variations in glacier size during this broad time interval are still patchy. Consequently, several controversial issues remain, including: (1) the timing of the onset (and end) of the 'Little Ice Age'; (2) the amplitude and timing of glacier variations within the 'Little Ice Age'; (3) the degree of synchroneity between glaciers from the different regions; and (4) the attribution of cause(s) in terms of large-scale climate forcing.

Onset and highstands

The onset question was specifically addressed by Grove (2001a, 2001b). Her analysis was couched as a test of the hypothesis, attributed to Porter (1981a, 1986), that the 'Little Ice Age' began in the thirteenth century AD. Her generalized conclusion was that the 'Little Ice Age' glacier expansion was initiated before the early-fourteenth century in the regions around the North Atlantic (Grove 2001a) and that elsewhere glaciers were advancing between the twelfth and fourteenth centuries (Grove 2001b). In almost all regions, however, the evidence is based on radiocarbon dating rather than the more precise evidence of historical sources or dendroglaciology. Radiocarbon dating is normally of no better accuracy than ±100 years with 95% confidence (±2 standard deviations), which may not differentiate the particular century in which a glacier advance occurred. Greatest reliance must therefore be placed on the geographically restricted evidence available from the European Alps, where the historical sources are sufficient in quality and quantity to answer not only the question of onset but also questions about when the 'Little Ice Age' glaciers reached their maximum extent and what amplitude of glacier variations occurred within the 'Little Ice Age' period. The broad picture has been known for some time (e.g. Le Roy Ladurie 1971) but recent research has revealed much further detail (e.g. Zumbühl and Holzhauser 1988; Holzhauser and Zumbühl 1996).

Figure 1 shows the history of the Grosser Aletsch Glacier over the last 3000 years (Holzhauser 1997). Several aspects of this curve are critical when using it to define the 'Little Ice Age' in the Swiss Alps. First, the three glacier highstands of *c.* AD 1350, 1650 and 1850 were remarkably similar in extent. Second, previous glacier maxima, including those in the third, seventh, ninth and twelfth centuries, were less extensive. Third, the size of the glacier during the retreat phases between the 'Little Ice Age' highstands was much greater than in the earlier retreat phases. Despite the evidence of continuous variation in glacier size throughout the last 3000 years, therefore, these aspects support the notion of a step-change towards a distinctly more glacierized region at the end of the twelfth century, and so marking the onset of the central European 'Little Ice Age'. This step-change has also been interpreted as marking the end of the 'Mediaeval Warm Period', and a similar pattern and timing is supported on a centennial timescale by the somewhat less complete records from other Alpine glaciers (Holzhauser 1997; Holzhauser and Zumbühl, 2003). There are, however, some differences between glaciers on shorter timescales. It must nev-

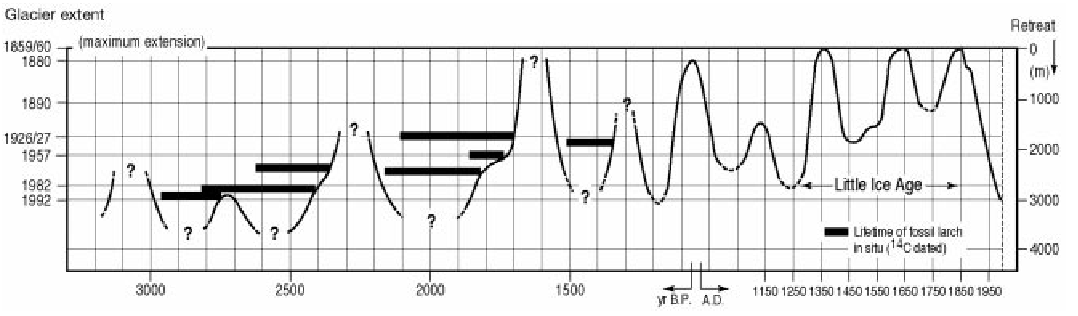

Fig. 1. Variations in the size of the Grosser Aletsch Glacier, Swiss Alps, over the last 3000 years based on documentary and proxy evidence (after Holzhauser 1997).

ertheless be concluded that, even in the Swiss Alps, differences between the glacier variations during the ‘Little Ice Age’ and those before the ‘Little Ice Age’ were a matter of degree rather than of kind.

Synchroneity or asynchroneity?

In Scandinavia (e.g. Karlén 1988; Matthews 1991, 1997; Nesje and Rye 1993; Karlén *et al.* 1995) and North America (e.g. Osborn and Luckman 1988; Luckman 2000; Calkin *et al.* 2001) there is a lack of comparable, detailed information on the timing of the onset of the ‘Little Ice Age’ glacier expansion despite convincing evidence of both its existence and the timing of particular advances and/or highstands, especially the later ones. The synchroneity question is therefore best considered in relation to whether glacier highstands were synchronous, rather than whether the onset of the ‘Little Ice Age’ was synchronous.

Several authors have addressed the question in this way, from Bray (1974), to Porter (1981b, 1986) and Grove (2004), but data comparability becomes a major problem in relation to inter-regional comparisons. According to Grove (2004, p. 560) there is a ‘striking consistency in the timing of the main advances’ worldwide (but she identified some exceptions). Porter (1981b) recognized synchroneity of recent advances between most regions of the Northern Hemisphere identifying four phases of glacier advance between the late-nineteenth and the late-twentieth centuries. He distinguished a different pattern in the Southern Hemisphere, which was attributed to independence of volcanic forcing in the two hemispheres. Porter’s (1981b) analysis is important because it shows that even over the last century or so, when relatively reliable data based on observation and measurement are available, most synchronous phases were of the order of 20 years’ duration: any attempt to identify shorter phases leads to the disappearance of the apparent synchroneity. This should not be a surprise, because even in a single region subject to similar climatic variability, glaciers can still exhibit differences in behaviour showing leads and lags in response as a result of situation and geometry. Indeed, to expect any greater synchroneity than that identified by Porter would be unrealistic. Similar arguments apply when considering glacier behaviour earlier in the ‘Little Ice Age’ and the ‘Little Ice Age’ glacier expansion as a whole.

Termination

As rates of glacier recession increased substantially and tended to accelerate following the last highstand of the nineteenth century, some authorities have suggested that ‘Little Ice Age’ glacierization ended by the beginning of the twentieth century (Dyurgerov and Meier 2000; Bradley *et al.* 2003). This conclusion may be questioned, however, because most glaciers had not yet shrunk to their pre-‘Little Ice Age’ size (see, for example, Fig. 1). Judged by this criterion, the mid-twentieth century provides a more appropriate end point in terms of visible response, though perhaps to an earlier change in forcing. However, relatively small glacier advances continue to interrupt the major retreat that occurred during the twentieth century (e.g. Patzelt 1985; Nesje *et al.* 1995).

‘Little Ice Age’ climate

The time interval from about AD 1550 to 1850 has commonly been used to define the period characterized by a ‘Little Ice Age’ climate (Bradley and Jones 1992a, b). This corresponds with what Ogilvie and Jónsson (2001) have called the ‘orthodox’ or 'classical' climatological definition of Lamb (1977), Flohn and Fantechi (1984) and others. Although glaciological and climatic concepts of the 'Little Ice Age' should not be regarded as synonymous, the classical definition encompasses the last two of the three Alpine glacier highstands shown in Fig. 1. Furthermore, some climatologists recognize a longer time interval, which comes closer to agreement with the concept of 'Little Ice Age' glacierization provided above (e.g. Jones and Mann 2004). Yet others point out that there were narrower time windows, within the classical period, in which climate was relatively severe, including Lamb's (1963, 1966, p. 463) so-called 'pessimum' from AD 1550 to 1700. Definitions are more difficult from the climatic point of view, however, because temporal and spatial variability in climate is greater than that of glaciers. This is probably the main cause of the greater dissatisfaction with the concept of a 'Little Ice Age' climate which, as expressed by Landsberg (1985, p. 62), 'was not uniformly cold in space or time'.

High-resolution reconstructions

High-resolution reconstructions of past climate using both instrumental and proxy sources have provided more information on 'Little Ice Age' climate but have also identified new problems to be resolved. The concept of a distinctive 'Little Ice Age' climate seems to have survived despite initial scepticism within the palaeoclimate community. First, there is the issue of the apparent absence of an uninterrupted, centuries-long cold phase following a similar, uninterrupted, centuries-long 'Mediaeval Warm Period' (*cf*. Hughes and Diaz 1994; Broecker 2001). Williams and Wigley (1983) were able to discern three main climatic episodes – the 'Little Ice Age', the 'Mediaeval Warm Period', and an earlier cold period between the eighth and tenth centuries – using simple, graphical comparisons of various records of 'summer temperature' from around the Northern Hemisphere. Likewise, a detailed dendroclimatological reconstruction of northern Fennoscandinavian summer temperatures designed to preserve low-frequency variability by Briffa *et al.* (1990, 1992) detected a two-centuries-long cold period (late-sixteenth to mid-eighteenth century) that lies within the classical climatic definition of the 'Little Ice Age' given above.

Some oxygen-isotope and melt-layer records from Greenland and Canadian ice cores record a 'Little Ice Age' of similar duration (Fisher and Koerner 2003). The Devon, Agassiz, Camp Century and North GRIP ice cores all have a 'Little Ice Age' – 'Mediaeval Warm Period' couple, but the Summit and Dye-3 cores do not. Different reconstructions do tend, however, to show differences in the number, severity and duration of 'Little Ice Age' cold periods. This was demonstrated effectively by Overpeck *et al.* (1997) using 29 complementary records sensitive to air temperature in the Arctic, derived from lake sediments, trees, glaciers and marine sediments.

Numerical approaches to the production of Northern Hemisphere surface temperature anomalies using annually resolved data covering up to the last 1000 years have been attempted with increasing sophistication since the 1990s (Bradley and Jones 1993; Barnett *et al.* 1996; Jones *et al.* 1998; Mann *et al.* 1998, 1999; Briffa 2000; Crowley and Lowery 2000; Briffa *et al.* 2001; Cook *et al.* 2004a). These continue to show an average Northern Hemisphere 'Little Ice Age' climatic signal but a less clearly defined 'Mediaeval Warm Period'. Warm conditions relative to the 1000-year mean are apparent in the longer reconstructions but those represent a predominantly northern, high-latitude warmth in the tenth and early-eleventh centuries (Briffa 2000; Crowley and Lowery 2000; Esper *et al.* 2002), which is not a clear, persistent deviation from the long-term mean.

In their reconstruction, covering the last 600 years and based on selected tree-ring density series mainly from high-latitude land areas (Fig. 2), Briffa *et al.* (2001) demonstrate a distinct 'Little Ice Age' climate from about AD 1570 to 1900 when Northern Hemisphere summer temperatures (April to September) fell significantly below the AD 1961–1990 mean. However, whereas in western North America summers were cool throughout much of the seventeenth and eighteenth centuries, the evidence suggests that it was significantly cooler in the early-nineteeth century (LaMarche 1974; Cook *et al.* 2002; Luckman and Wilson 2005). Thus, although there are still differences to be resolved between the different data sets and approaches, and further improvements to such reconstructions can be anticipated, it would appear that there is a tenable statistical basis for belief in at least the main phase of the 'Little Ice Age' as at least a hemispherical cold period. Figure 2 shows that, in terms of summer temperature, most of the seventeenth century was of the order of 0.5°C below the 1961–1990 mean. The question of whether the event was global

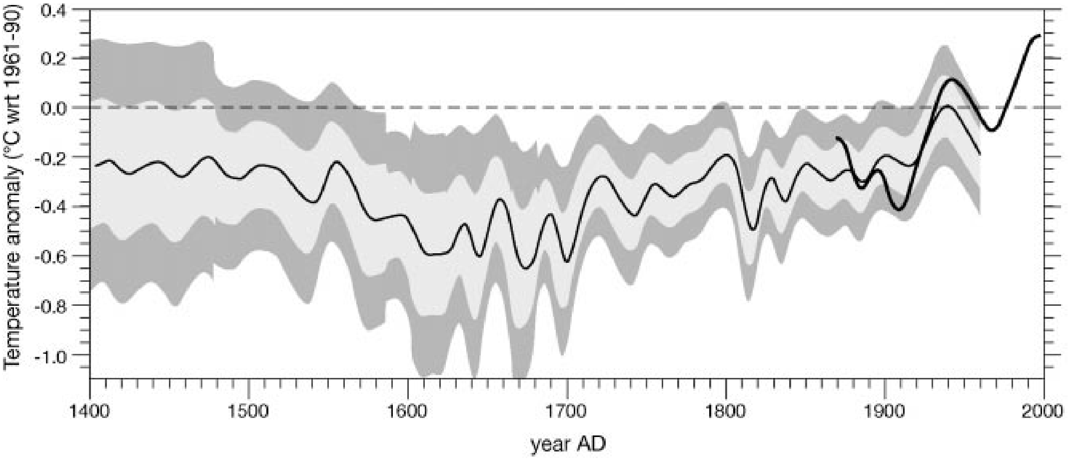

Fig. 2. Tree-ring density reconstruction of Northern Hemisphere (land areas north of 20°N) summer temperature (April to September) since AD 1400 (thin continuous line). Units are °C anomalies with reference to the 1961–1990 mean (dashed line). Shaded areas show 68% and 95% confidence intervals. Instrumental temperatures (thick line) are also shown (after Briffa *et al.* 2001).

remains more open, although Kreutz *et al.* (1997) have argued strongly for a synchronous onset to the 'Little Ice Age' based on a shift to enhanced meridional circulation around AD 1400 detected in ice cores from both Siple Dome, Antarctica, and central Greenland. More recent temperature reconstructions from Tasmania and New Zealand (Cook *et al.* 2000, 2002) also indicate cool Austral summers in the late-sixteenth and early-seventeenth centuries.

Regional heterogeneity and 'Little Ice Age' geography

The second major issue raised by the large number of high-resolution climatic reconstructions is how to deal with regional heterogeneity in the palaeoclimatic record. The compilation of hemispherical or global 'averages' is only one approach, which is designed to express underlying climate forcing and often assumes that all the individual reconstructions represent the same climate population; an alternative approach is to acknowledge that geography matters! Jones *et al.* (1998) demonstrated, using 17 reconstructions representing temperature changes during various seasons of the year since the mid-seventeenth century, that they may actually exhibit relatively low spatial cohesion. Similarly, the heterogeneity exhibited by the appearance or non-appearance of a 'Little Ice Age' signal in ice-core data is real and not merely a function of noise (Fisher and Koerner 2003). Extensive hemisphere-wide dendroclimatic investigations by Briffa *et al.* (2002a, b) show that spatial coherence of temperature change over the last 600 years was usually sub-hemispherical in scale. Indeed, the temperature trend in one region of the hemisphere may be the opposite of that in another region, and explicable with reference to persistent patterns in the general circulation of the atmosphere. Uninformed averaging of such data would mask marked global climatic changes. If the full potential of 'Little Ice Age' climatic reconstruction is to be realized in terms of atmospheric and oceanic circulation patterns, then the aim must be more fully to recognize, quantify and preserve the spatial dimension of climatic variability. Hence mapping of climatic changes becomes extremely important as demonstrated, for example, by Lamb (1979), Pfister *et al.* (1998), Fisher (2002) and Briffa *et al.* (2002a, b).

Spatial variation in 'Little Ice Age' climate is illustrated in Fig. 3A, which shows mean summer temperature (April–September) anomalies from the AD 1961–1990 mean for the 330 years from AD 1571–1900 over the Northern Hemisphere based on annually resolved dendroclimatic reconstructions. In effect, Fig. 3A can be viewed as an average of the maps for individual years published in Briffa *et al.* (2002b), modified to retain slightly more long-term climatic variability (Osborn *et al.* submitted). This allows important generalizations to be made.

– Almost all areas of the Northern Hemisphere for which data are available show average 'Little Ice

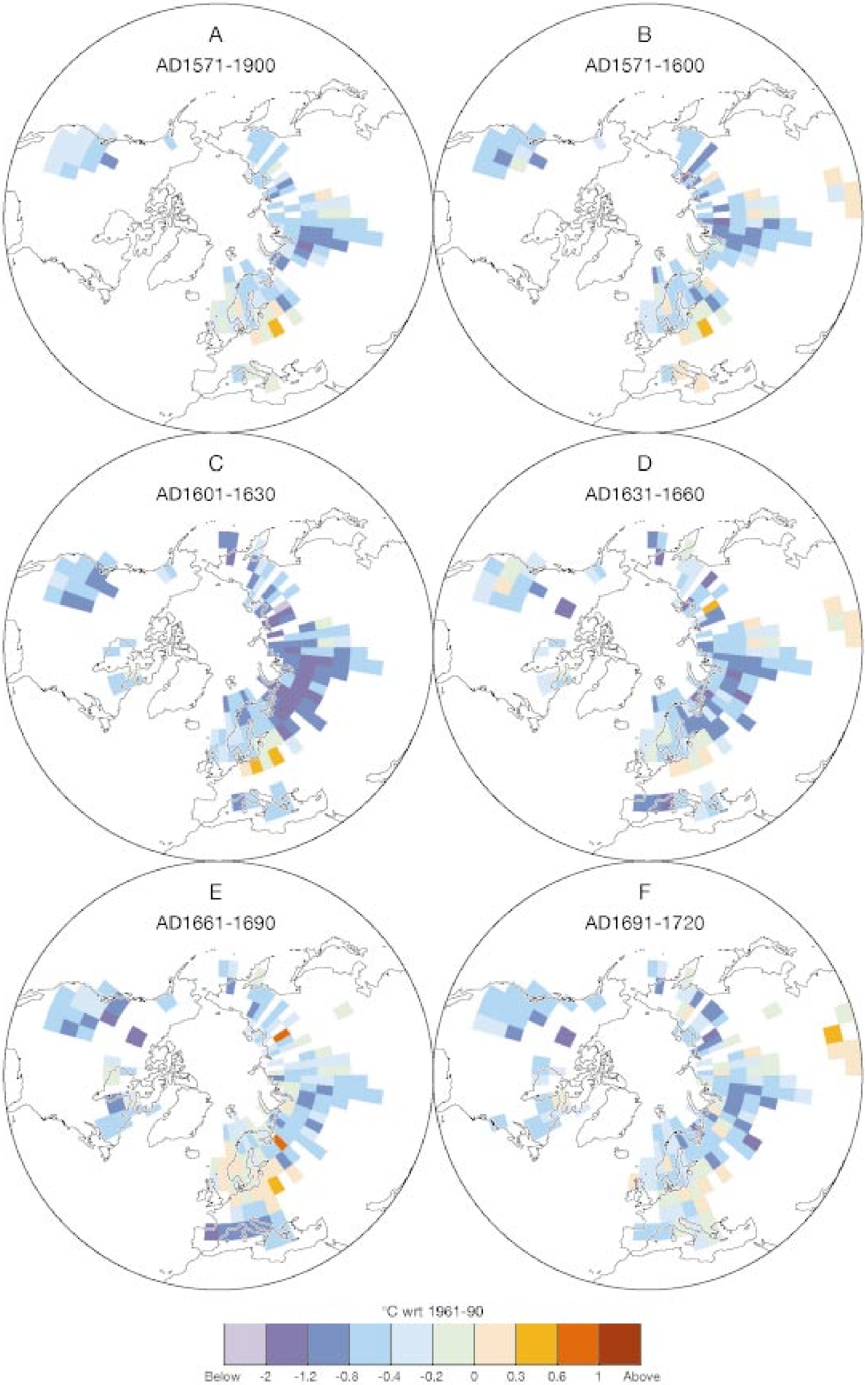

Fig. 3. Geography of 'Little Ice Age' climate. (A) Patterns of summer temperature (°C anomalies from the AD 1961–1990 mean) over the Northern Hemisphere from AD 1571 to 1900 derived from a tree-ring density network. (B–L) Similar maps for 30-year time intervals within the 'Little Ice Age'. Coloured areas show the individual grid boxes for which data are available.

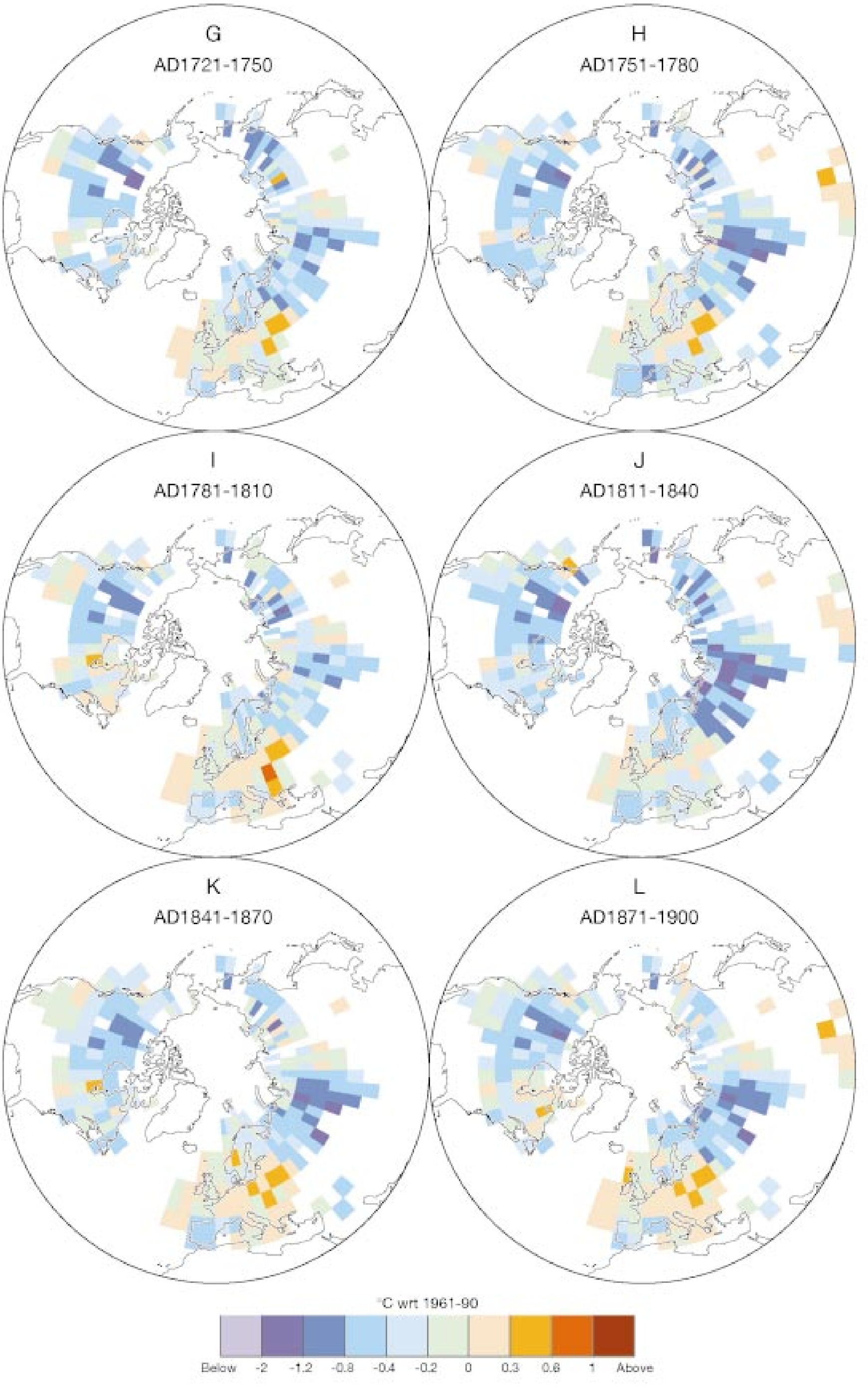

Fig. 3. *Continued*.

Age' temperatures that are 0.0–2.0°C below the 1961–1990 mean. The data therefore again indicate a 'Little Ice Age' climate that was at least hemispherical in extent.
– The few areas where the temperature anomalies are shown to be only slightly below, or even above (–0.2 to +1.0°C), the 1961–1990 mean are mostly located in Europe. The 'Little Ice Age' summer-cold signal was not, therefore, everywhere apparent and had a geography.
– The largest negative temperature anomalies (>0.8°C) are in northwest-central Asia. Thus, the 'Little Ice Age' was clearly not merely, or even mainly, a European phenomenon.

Temporal variability concealed by the AD 1571–1990 mean is revealed by the 30-year time slices shown in Fig. 3B–L. Notable features of these spatial and temporal patterns include the following.

– Large negative anomalies (>0.8°C) are more prevalent during the interval 1601–1630 than at any other time, especially in northwest Asia. Much of the remainder of the seventeenth century also appears to have been relatively cold, in line with Lamb's 'pessimum' period.
– The positive anomalies are most apparent during the eighteenth and nineteenth centuries in central and eastern Europe, suggesting an early end to a relatively weak 'Little Ice Age' in these areas of Europe. However, 1811–1840 was relatively cold, especially across northern Asia.
– An antiphase relationship between northern and southern Europe (the latter including the region from the Iberian Peninsula to Greece) seems to exist for all time slices. This may indicate a summer manifestation of the North Atlantic Oscillation throughout the 'Little Ice Age' period (see Bradley *et al.* (2003) and below).
– The seventeenth century appears to have been the coldest century of the 'Little Ice Age' in North America, although this data set is relatively sparse for central and eastern areas of the continent (but also see Luckman 1996; Jacoby *et al.* 1996).
– For the eighteenth and nineteenth centuries at least, northwestern North America was apparently in phase with northwest Asia. This dominant pattern suggests persistent positions of long waves (Rossby waves) at the hemispheric scale throughout the 'Little Ice Age' (cf. Briffa *et al.* 2002b).

Not only summer temperature!

Whereas the above discussion concerns only summer temperature, it is important not to underestimate the other aspects of climate. This raises a third major issue in the discussion of 'Little Ice Age' climate, namely the overemphasis on summer temperature. Temperature, especially summer-temperature, data are the most widely available, and it has been argued that temperature is the most important variable in the field of climate-change detection (e.g. Santer *et al.* 1996), but these reasons are not definitive when considering the fundamentals of 'Little Ice Age' climate. Where questions of seasonality, extremes and precipitation change have been addressed, significant variations have been found in time and space (e.g. Pfister 1992a; Luterbacher *et al.* 2001, 2004; Nesje and Dahl 2003a). Cold winters, for example, seem to have been an even more characteristic feature of the 'Little Ice Age' climate than cool summers (cf. Manley 1974; Lamb 1985; Pfister 1992b; van Engelen *et al.* 2001; Jones *et al.* 2003; Luterbacher *et al.* 2004).

Considerably less geographical information exists for defining detailed patterns of precipitation change over wide areas during 'Little Ice Age' times. It is certainly difficult to recognize any persistent, ubiquitous anomaly coincident with the seventeenth- and eighteenth-century cold. In North America there are records of precipitation and drought that are both extensive spatially and continuous in time (e.g. Cook *et al.* 1997, 2004b; Bradley *et al.* 2003), which indicate widespread moisture limitation in the late-sixteenth century and relative excess in the early-seventeenth century. More disjunct evidence from parts of Europe indicates a variety of patterns, such as relative wetness in the UK during the seventeenth century (Barber *et al.* 2004), an increase in atmospheric humidity in the Swiss Jura and in northwestern Spain since the fourteenth century (Martínez-Cortizas *et al.* 1999; Roos-Barraclough *et al.* 2004), and generally cool and dry conditions overall in Switzerland during the seventeenth and eighteenth centuries, especially in winter and spring (Pfister 1992c) when Czech lands experienced cool and somewhat wetter conditions (Brázdil 1996).

Complexity in the glacier–climate relationship

Differentiation of the local, regional, hemispherical and global response of glaciers to climate variability during the 'Little Ice Age' is no easy task.

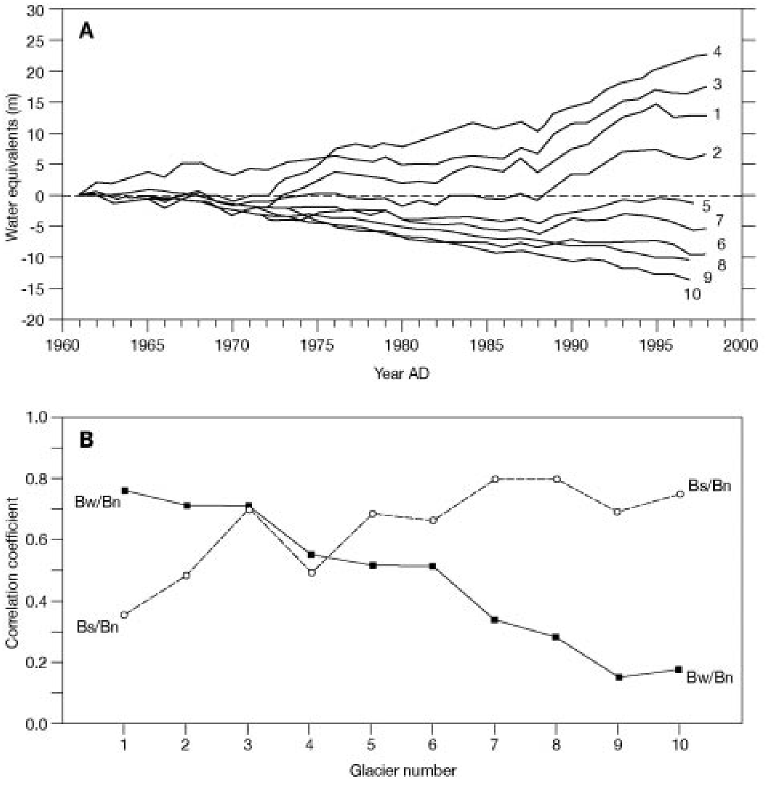

Fig. 4. (A) Cumulative net mass balance variations on Scandinavian (northern and southern Norway, Svalbard and northern Sweden) glaciers since AD 1960. (B) Correlation coefficients between net balance (Bn) and summer balance (Bs) or winter balance (Bw) for Scandinavian glaciers (numbered as above in terms of increasing continentality) (after Kjøllmoen 1998; Nesje and Dahl 2000).

1, Ålfotbreen;
2, Hardangerjøkulen;
3, Nigardsbreen;
4, Engabreen;
5, Storglaciären;
6, Storbreen;
7, Hellstugubreen;
8, Gråsubreen;
9, Midtre Lovénbreen;
10, Austre Brøgerbreen.

Glaciers respond to variations in both summer temperature and winter precipitation as expressed in the mass balance (Porter 1981a; Nesje and Dahl 2000, 2003b). The response is cumulative, in that it depends on the climate of a number of previous years, and is non-linear. Glacier response time – the lag between a climatic change and an advance or retreat at the glacier snout – varies with glacier size; it commonly takes 15–60 years for changes in mass in the accumulation zone to reach the snout of maritime temperate glaciers (Johanesson *et al.* 1989). There may be a more immediate reaction to climate at the glacier snout in some situations, however. At the low-altitude outlet glaciers of the Jostedalsbreen ice cap in southern Norway, for example, Bickerton and Matthews (1993) showed that general glacier retreat following the 'Little Ice Age' maximum was interrupted by short-term glacier advances. Glaciers of different size advanced synchronously after runs of cool summers with glacier advances occurring about 5 years after summer-temperature minima. Though regional groups of glaciers may respond to climate in a broadly similar manner, they also exhibit individualistic behaviour, especially as a result of the influence of non-climatic factors such as glacier size, topography, debris cover and calving. Glacier variations therefore integrate more than one climatic element, and smooth out the extremes of annual variability in climate, and may respond on different timescales.

These aspects of the glacier–climate relationship clarify why there can be no one-to-one agreement between the glaciological and the climatic concepts of a 'Little Ice Age'. On the one hand, glacier variations (e.g. Fig. 1) provide a complex record of climate; on the other hand, it is simplistic to expect the hemispherical mean summer temperature (Fig. 2) either to correlate closely with or to provide a complete explanation of glacier variations. One would expect, however, clearer patterns to emerge at the regional scale. This is illustrated well by the climatic controls on glacier variations

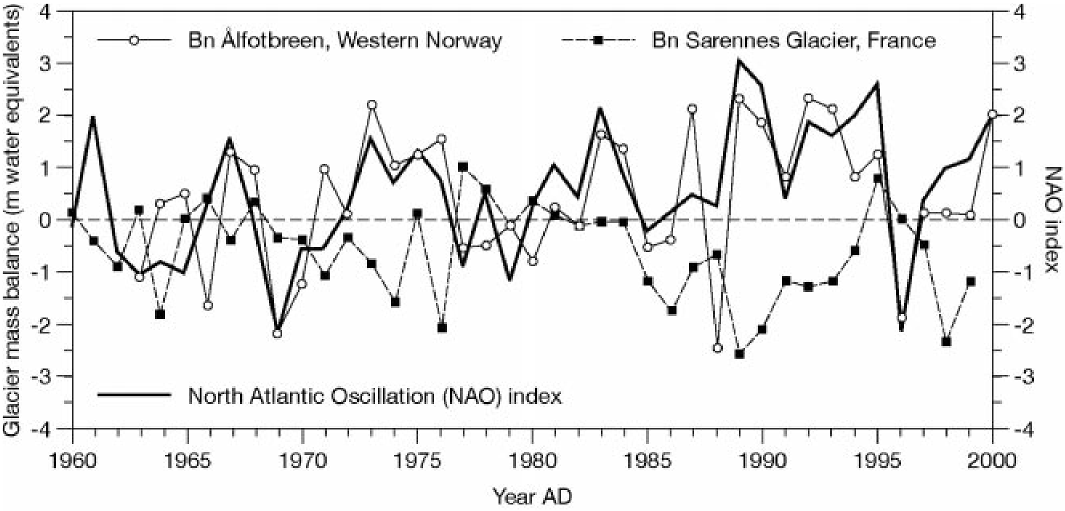

Fig. 5. Variations in the annual net mass balance of Ålfotbreen, western Norway (open circles), and the Sarennes Glacier, southeastern France (filled squares), related to the North Atlantic Oscillation Index (thick line) since AD 1960 (after Nesje and Dahl 2003b).

within Scandinavia and some recent differences in glacier behaviour between Scandinavia and the European Alps. Figure 4A shows that, over the last half of the twentieth century, the main difference between monitored Scandinavian glaciers was the increase in volume of the maritime glaciers (e.g. Engabreen and Ålfotbreen) when the more continental, inland glaciers (e.g. Austre Brøgerbreen and Gråsubreen) decreased (Kjøllmoen 1998; Nesje and Dahl 2000; see also Pohjola and Rogers 1997). The increase in volume and hence in the cumulative net balance of the maritime glaciers was a response to the high winter balance, especially in the 1990s when, for almost all years, the net balance was positive. This is demonstrated in Fig. 4B, which shows the varying correlation coefficients between net balance (Bn) and winter balance (Bw) or summer balance (Bs) for glaciers on the continentality gradient. It would be expected, therefore, that the importance of winter precipitation (relative to summer temperature) in explaining frontal variations of the glaciers would increase from east to west across southern Norway, and there is evidence to support this proposition from the twentieth century (Nesje 1989; Nesje *et al.* 1995), and over the longer time interval since the 'Little Ice Age' maximum of the mid-eighteenth century (Matthews 2005).

Nesje and Dahl (2003a) have argued that enhanced winter precipitation rather than low summer temperature also accounts for the difference in timing of the 'Little Ice Age' glacier maximum in southern Norway compared with the Alps. The three Alpine glacier highstands described in Fig. 1 have not been detected in Scandinavia where, in southern Norway at least, a simple mid-eighteenth-century glacier maximum is characteristic (see also Grove 1985). Nesje and Dahl (2003a) demonstrate that summer temperature was insufficiently cold to explain the scale of the regional early-eighteenth-century glacier advance in southern Norway. They also show that regional precipitation patterns are implicated in differences of behaviour between Ålfotbreen, western Norway, and the Sarennes Glacier, southeastern France, which are related to the **North Atlantic Oscillation** (**NAO**) in Fig. 5. Winter precipitation in western Norway between AD 1865 and 1995 is highly correlated ($r = +0.77$) with the NAO Index (Hurrell 1995). Being a maritime glacier, the net balance of Ålfotbreen is highly correlated with the NAO Index (Nesje *et al.* 2000a; see also Reichert *et al.* 2001; Six *et al.* 2001), which is consistent with the dominant effect of the winter balance discussed above. The antiphase relationship shown in Fig. 5 between the net balance of the Sarennes Glacier and both the net balance of Ålfotbreen and the NAO Index, reflects the observation that positive-NAO-Index winters signify above-normal precipitation over Iceland, the British Isles and Scandinavia, while below-normal precipitation is received in central and southern Europe and the Mediterranean region (van Loon and Rogers

1978). The importance of winter precipitation to glacier variations earlier in the Holocene is further highlighted below.

‘Little Ice Age’-type events

Various ‘Little Ice Age’-type glaciological and climatic events occurred on century to millennial timescales during the Holocene. This has been demonstrated by many proxy data sets. From marine sources, recent examples include the North Atlantic ‘ice-rafting’ events of Bond *et al.* (1997, 2001), ‘monsoon’ events in the Indian Ocean (Gupta *et al.* 2003), and ‘isotopic’ events on the North Atlantic Shelf (Castañeda *et al.* 2004). Terrestrial sources include the central European ‘cool periods’ defined on the basis of pollen analysis by Haas *et al.* (1998), lake-level fluctuations in Africa (Gasse 2000), and ‘wet shifts’ recorded in peatlands (Hughes *et al.* 2000; Barber *et al.* 2004). Although these and similar events have been called ‘Little Ice Ages’ by Grove (2004) and others, use of the plural of ‘Little Ice Age’ in this way overemphasizes their similarity, perhaps before ‘Little Ice Age’-type events are understood well enough to decide whether they exhibit differences that are significant.

Recognition of ‘Little Ice Age’-type events is important for the ‘Little Ice Age’ concept for several reasons. First, it identifies the fact that glacier and climatic variations of moderate scale have interrupted the Holocene, an interval of geological time that only a few proxies still suggest is characterized by aberrant stability (cf. Dansgaard *et al.* 1993). Second, it suggests that the ‘Little Ice Age’ may be employed as a ‘modern analogue’ in the interpretation of the earlier events about which far less is known. Third, it indicates that information about a general class of events may shed light on the ‘Little Ice Age’ itself and the future. This is particularly true in relation to the identification of the cause(s) of the ‘Little Ice Age’ and of specific climatic forcing factors.

Holocene glacier variations

Scandinavian glacier and climatic variations can again be used to elucidate the nature of these ‘Little Ice Age’-type events. In the context of glacier variations, most ‘Little Ice Age’-type events could be termed Neoglacial events, though the appropriateness of this term for events before or during the Hypsithermal or ‘Climatic Optimum’ is debatable. In southern Norway, relatively complete records of century- to millennial-scale Holocene glacier variations have been reconstructed from two types of distal sedimentary sequences, downstream of glaciers: first, glaciolacustrine sequences (e.g. Karlén and Matthews 1992; Matthews and Karlén 1992; Matthews *et al.* 2000; Nesje *et al.* 2000b, 2001; Dahl *et al.* 2003); second, glaciofluvial sediments from stream-bank mires subject to episodic overbank deposition of suspended sediment (e.g. Nesje and Dahl 1991; Nesje *et al.* 1991; Dahl and Nesje 1994, 1996; Matthews *et al.* 2005). These reconstructions, which owe much to Karlén’s (1976, 1981) pioneering work on the glaciolacustrine approach in northern Sweden, complement each other and are more appropriate than moraine stratigraphic studies where large ‘Little Ice Age’ glacier advances were destructive of the evidence of earlier events.

The results of a detailed reconstruction using the glaciofluvial approach are shown in Fig. 6, further details of which are given in Matthews *et al.* (2005). Glacier extent is here based on the evidence of multiple sedimentological indicators (weight loss on ignition, mean grain size, grain-size fractions, bulk density, moisture content and magnetic susceptibility). Seven ‘Little Ice Age’-type glacier expansion episodes have been identified. Apart from the late-Preboreal Erdal Event (see also, Dahl *et al.* 2002), the ‘Little Ice Age’ advance was the most extensive of the Holocene. Climatic reconstruction is summarized in Fig. 7. Figure 1Bshows the **equilibrium-line altitude** (**ELA**), corrected for land uplift, derived from the glaciological evidence alone using the **accumulation-area ratio** (**AAR**) method. Figure 1 A is an independent summer temperature curve estimated from a pollen-based proxy (Bjune *et al*. 2005). Figure 1 C is the reconstructed winter precipitation curve derived by substituting values from the upper two curves in the ‘Liestøl equation’, which relates mean ablation-season temperature (May to September) to winter accumulation (October to April) at the equilibrium line of Norwegian glaciers (Sutherland 1984; Ballantyne 1989; Dahl and Nesje 1996; Nesje and Dahl 2000). This equation is the key to understanding the climate of the ‘Little Ice Age’-type events because it enables both summer temperature and winter precipitation to be examined, and hence permits a test of the hypothesis (often assumed to be true) that the glacier variations are primarily if not wholly a response to relatively cool summer temperatures. Figure 7 also enables comparisons between the ‘Little Ice Age’

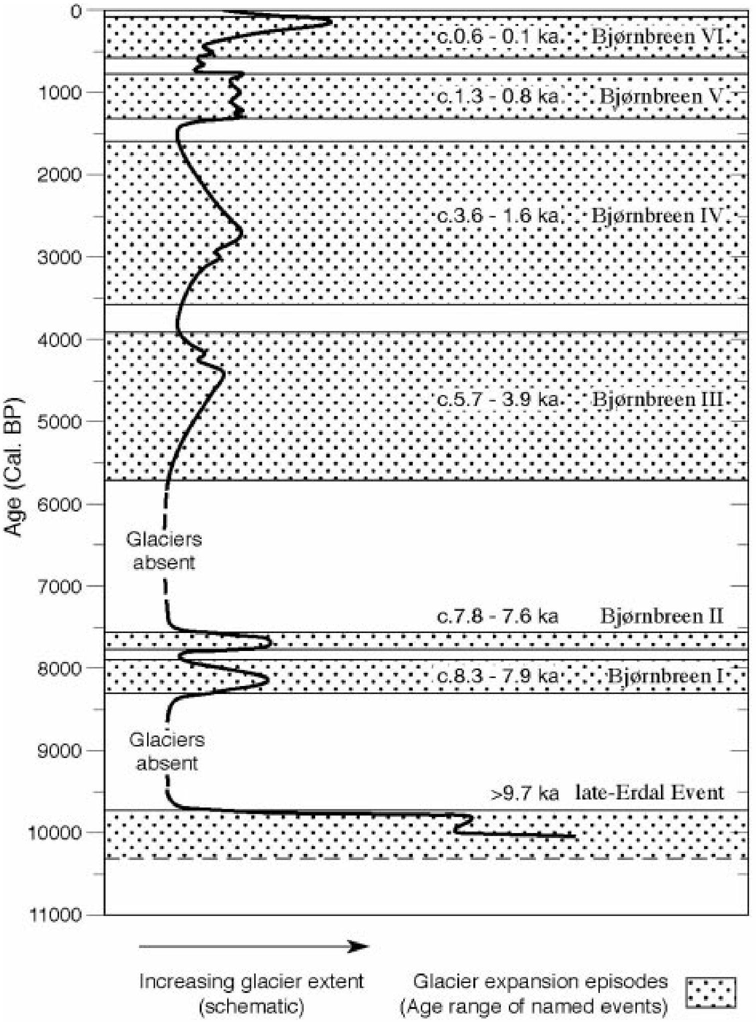

Fig. 6. Holocene history of Bjørnbreen, Jotunheimen, southern Norway, reconstructed from sedimentary evidence in glaciofluvial stream-bank mires. Shaded bands indicate radiocarbon-dated and named 'Little Ice Age'-type events. Bjørnbreen VI is equivalent to the 'Little Ice Age'. Bjørnbreen III corresponds with the Finse Event in Norway (after Matthews *et al.* 2005).

and the earlier 'Little Ice Age'-type events from both glaciological and climatic standpoints.

Accepting limitations to the accuracy of the ELA and temperature reconstruction, and the partial dependence of the precipitation reconstruction on the reconstructed ELA, several general implications can be drawn from the pattern and timing of the events shown in Fig. 7.

– The magnitude, duration and abruptness of the events vary considerably. Whereas the two events around 8000 cal. years BP (Bjørndalen I and II) were only slightly less extensive glacier advances than that of the 'Little Ice Age' event (Bjørndalen VI) and lasted for 250–500 years, the mid- to late-Holocene, Bjørndalen III and IV events were much less extensive and had durations of 1600–2000 years. It is not correct, therefore, to designate all these events as 'abrupt climatic events'.
– Bjørnbreen appears to have been absent for much of the early Holocene, from about 9700 to 8300 and from about 7600 to 5700 cal. years BP. Although there are problems with detecting the presence of very small glaciers, this contrasts with the later Holocene when the glaciers were probably continuously present and the frequency of events increased. This pattern is consistent with a climatic model that emphasizes an early-Holocene Hypsithermal or 'Climatic Optimum' followed by a late-Holocene climatic deterioration, possibly driven by underlying orbital forc-

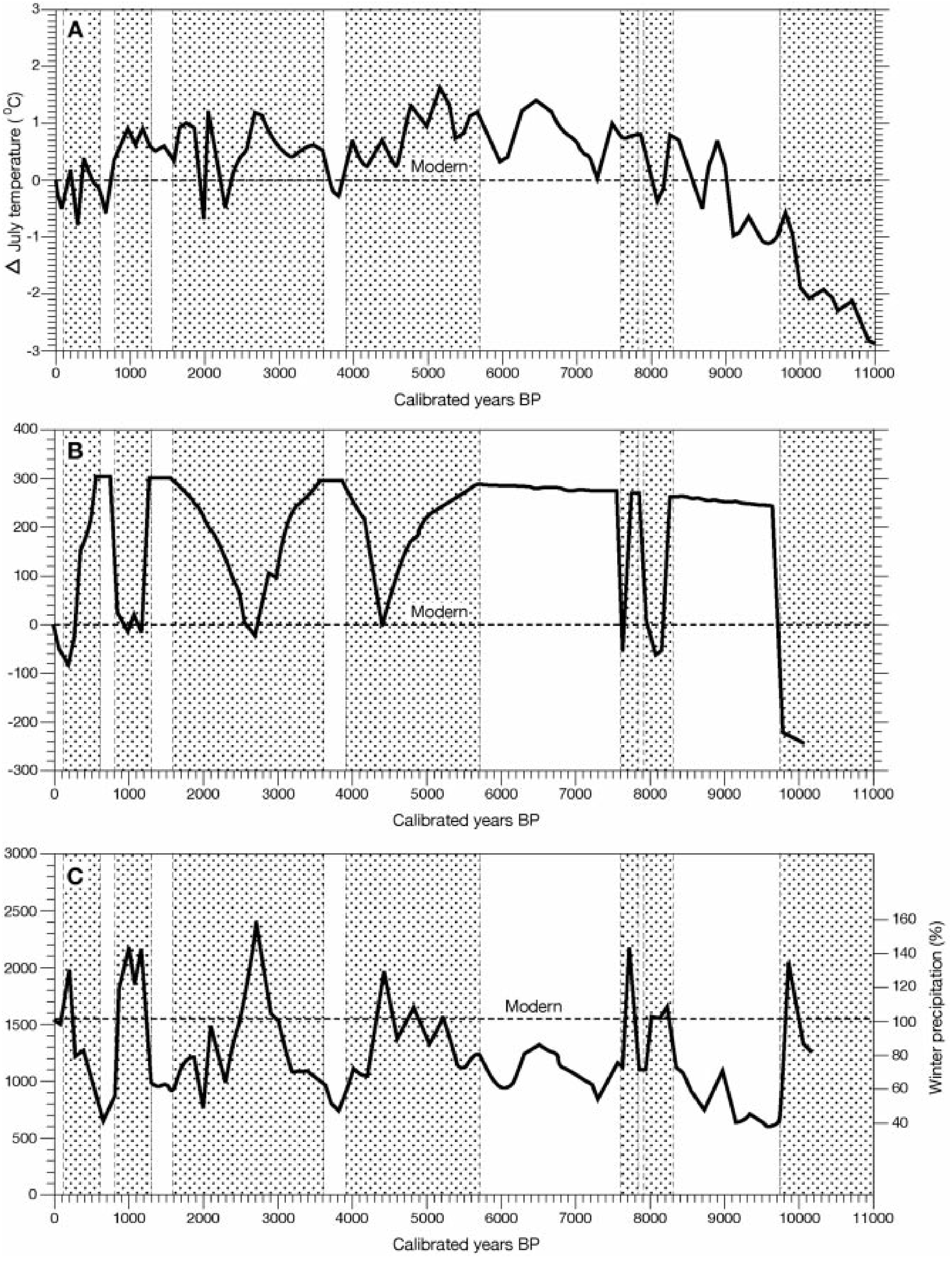

Fig. 7. Holocene climatic variations (relative to modern values) associated with ‘Little Ice Age‘-type events (shaded bands) at Bjørnbreen, Jotunheimen, southern Norway. (A) Mean July temperatures from an independent pollen-based proxy. (B) Variations in the equilibrium-line altitude (ELA) of Bjørnbreen. (C) reconstructed winter precipitation variations at the ELA (after Matthews *et al.* 2005).

ing (cf. Matthews 1991; Nesje and Kvamme 1991; Matthews and Karlén 1992).
- The record suggests that winter precipitation may have been more important than summer temperature as a cause of the 'Little Ice Age'-type events in most cases, although the 'Little Ice Age' itself corresponded with low summer temperatures *combined with* high winter precipitation.
- Finally, these events are episodic but not necessarily periodic. At first sight, the average frequency of *c*.1400 years would appear to relate to the 1400–1600-year periodicity identified in other types of data from the North Atlantic region and beyond (e.g. Bond *et al.* 1997, 2001; Stuiver *et al.* 1997; Campbell *et al.* 1998; Bianchi and McCave 1999; Chapman and Shackleton 2000; Gupta *et al.* 2003) but the variability of the events and their timing suggest a strong non-periodic element.

Holocene dendroclimatology

A second example relates to dendroclimatology in northern Eurasia, which provides further detail and insights into the regional and perhaps wider-scale prescience of 'Little Ice Age' climate in a temporal context of up to 1000 years. At a hemispherical scale, various tree-ring reconstructions indicate persistently cool summers over extratropical northern lands throughout much of the thirteenth century (Briffa 2000; Esper *et al.* 2002; Luckman and Wilson 2005) and this is seen right across northern Europe and western Siberia (Grudd *et al.* 2002; Helama *et al.* 2002; Naurzbraev *et al.* 2002; Snowball *et al.* 2004) where very long temperature-sensitive chronologies are available in a way that preserves multi-century climate variability. It is clear that persistent cool phases are a frequent characteristic of high-latitude summer climate. Robust tree-ring evidence for cold summer conditions in Fennoscandia shows multiple periods (*c.* 4030–3940 BC, 3750–3690 BC, 2470–2400 BC, 2120–2020 BC, 1610–1480 BC and 150–20 BC) that could be considered as indicative of 'Little Ice Age'-type events. Not until many further high-resolution and precisely dated reconstructions become available, with better geographical coverage, will it be possible to gauge the synchrony and global significance of such events and to explore their likely causes.

The variable nature of 'Little Ice Age'-type climatic events, the non-periodic element and the geographical patterns emerging at both regional and hemispherical scales all suggest the interaction of several forcing factors. A detailed discussion of these factors will not be attempted here but it is clear that solar variability and volcanic forcing are strong candidates, possibly moderated or amplified by the natural dynamic behaviour of the Earth–atmosphere–ocean system, including changes in the ocean thermohaline circulation (cf. Cronin 1999; Crowley 2000; Bradley 2003; Bradley *et al.* 2003; Grove 2004).

Forcing factors and palaeodata–climate model interaction

To distinguish the effects of different influences, external or internal to the climate system, and to identify their global to local expression in terms of temperature and precipitation variability, we must ultimately depend on a combination of palaeodata with climate model analyses. Simple correlative exercises can provide empirical evidence of linkages between potential forcings and deduced climate anomalies (e.g. Porter 1981b; Briffa *et al.* 1998). This is, however, only a starting point for building an understanding of: (1) the complex roles of individual and combined forcings; (2) the lags and feedbacks that operate as their influence is registered in different terrestrial and marine archives; (3) the geographical patterns of climate; and, subsequently (4) glacier behaviour that may well be seen on different timescales.

If the concepts of the 'Little Ice Age' and of 'Little Ice Age'-type events are to be meaningful, they must be understood in terms of the causes, forcing factors and dynamic mechanisms that distinguish them from other Holocene climatic states. At present, the history of volcanic forcing in terms of both total radiative forcing of the climate system and the detailed spatial distribution of aerosols is highly uncertain, as it must be deduced from imprecisely dated, somewhat crude measurements of ice acidity, mostly from high-latitude ice cores (Porter 1981b; Robock 2000). Similarly, the magnitude and distribution of energy associated with changing solar irradiance over recent millennia is difficult to estimate because direct irradiance measurements are only decades long and indirect records based on cosmogenic isotopes in ice and tree-rings (or shorter records of sunspot numbers) are not consistent or straightforward to interpret (Lean 2000; Bard *et al.* 2000; Robertson *et al.* 2001). Nevertheless, it is likely that the period AD

1600–1900 contained intervals of slightly lower irradiance and a higher frequency of large volcanic eruptions (Briffa *et al.* 1998; Crowley 2000; Bertrand *et al.* 2002) compared with the most recent century. What evidence exists does not indicate any significant reduction in the meridional overturning circulation of the North Atlantic at this time (Bianchi and McCave 1999; van der Schrier and Barkmeijer 2005). Many models, of varying complexity and forced by somewhat different histories of volcanic and solar changes, provide a reasonable consensus, at least to the qualitative scale of hemispheric cooling during this time period, and suggest the primary role of volcanic forcing (Crowley 2000; Jones and Mann 2004; Foukal *et al.* 2004). Much remains to be done, however, in improving our understanding of the forcings, and validating and diagnosing the output of coupled climate models, before we can say to what extent the ‘Little Ice Age’ was unusual and explicable in terms of climate variability and consequent modelled glacier response (cf. Raper *et al.* 1996; Reichert *et al.* 2001; Webber and Oerlemans 2003).

Relevance to future climate

Because ‘natural’ century- to millennial-scale climatic variations occurred repeatedly during the Holocene we can confidently expect similar events to influence the course of future climate change. Furthermore, detection of an anthropogenic greenhouse-gas ‘signal’ has to take account of the ‘noise’ introduced by ‘Little Ice Age’-type events. In other words, they form part of natural climatic variability in the Earth–atmosphere–ocean system, which provides the base-line against which the significance of anthropogenic effects can be measured. It was possible, until recently, to interpret the warming that occurred in the twentieth century as merely recovery from the ‘Little Ice Age’. However, the demonstration that the enhanced summer temperatures over the last few decades have been unprecedented in terms of those experienced during the last millennium (e.g. Fig. 2) is convincing evidence that the anthropogenic signal has indeed exceeded the natural background.

Conclusion: a complex and adaptable concept

Standing in front of an extant glacier, it is very difficult for a glacial geomorphologist not to be convinced of the existence of the ‘Little Ice Age’ when he or she can see the morphostratigraphic evidence of the moraines (commonly in the form of extensive walls of sediment looming above). Similarly, the geoecologist can see the limited soil development and relatively sparse vegetation that testify to the short period of time that has elapsed since the ice retreated from the glacier foreland (see, for example, Matthews 1992). The dates of the moraines, the extent of the recent glacier retreat and the timescale of vegetation succession demonstrate that glaciers were considerably larger in the recent past than they are today. In addition, there is the historical evidence of the people who lived close to the glaciers and bear witness to the former extent of the glaciers. Later research has established that climate-related changes in glacier mass balance must have been responsible for this glacier-centred concept of the ‘Little Ice Age’. Beyond this, however, the controversy starts.

This paper has examined the various controversies that revolve around the ‘Little Ice Age’ as a glaciological and climatic concept, and the extension of the concept to ‘Little Ice Age’-type events earlier in the Holocene. The changing use of the term, the increase in evidence relating to the complexity of glacier variations over recent centuries (including the precise timing of the onset, maxima and termination of ‘Little Ice Age’ glacierization in different regions), the doubts of climatologists and palaeoclimatologists over the inherent variability of climate (especially over the existence of a prolonged, centuries-long cold period and the lack of global synchroneity) have all led to the concept of a ‘Little Ice Age’ being questioned. Yet the concept has proved remarkably resilient as annually resolved reconstructions have lengthened and their confidence intervals have narrowed. A climate-centred ‘Little Ice Age’ concept continues, therefore, to have meaning for an ever-widening range of proxy data sets from tree-rings to ice cores, speleothems and borehole temperatures.

The concept has only survived by its being adapted to increasing knowledge and understanding of climatic variability and of spatial variation in the Earth–atmosphere–ocean system, which no longer lead us to expect a ‘Little Ice Age’ that is an uninterrupted, globally synchronous, cold period, characterized only by (summer) temperature. Those who would continue to criticize the term ‘Little Ice Age’, used in the climatic sense, should contemplate not only the nature of climatic variability but also the geography of climatic change. The ‘Little Ice Age’ concept has become more complex as the details (including temporal- and spatial-scale relations) of climate change have become better known. The classical concept of Lamb and others is, however, still recognizable in current usage. Indeed, we show here, for the first time in map form, that the majority of the Northern Hemisphere experienced a relatively low mean summer temperature for more than three centuries (AD 1570 to 1900), and that the 'Little Ice Age' was not merely or even mainly a European phenomenon. Using 30-year time-slices, we also demonstrate the extent to which smaller-scale, systematic climatic changes in turn exibited large-scale geographical patterns.

Alongside these developments, the concept of 'Little Ice Age'-type events has gained momentum, provided a broader context, and given renewed relevance to the 'Little Ice Age' which, as Cronin (1999, 301 p.) has described, is 'prototypical of a distinct genre of climatic variability'. The main challenges today are: (1) to refine our understanding of the temporal and spatial patterns, and (2) to understand the forcing factors and mechanisms that caused 'Little Ice Age'-type events during the Holocene. Both will require much more research at the interface between high-resolution reconstructions from proxy data and climatic modelling. Thus, Holocene glacier and climatic events on century to millennial timescales are currently one of the most important foci of palaeoclimatic research. This vitality arises not only from their fundamental scientific importance, but also from their impact on the recent history and imminent future of humans on Earth.

Acknowledgements

Both authors wish to acknowledge the seminal influence of Wibjörn Karlén on their research careers. In J.A.M.'s case this has ranged from lively discussions on the radiocarbon dating of palaeosols to lake-coring expeditions and joint publications on the Holocene glaciers of southern Norway and Mount Kenya. K.R.B. acknowledges the inspiration and practical collaboration which led to the development of the Tornaträsk multimillennial tree-ring chronology and temperature reconstructions. K.R.B. also acknowledges support from the European Commission (EVK2-CT-2002-00160,SO@P) and the UK Natural Environment Research Council (RAPID Climate Change programme). J.A.M.'s research at Bjørnbreen was supported by Natural Environment Research Council Grant GR3/9691 and by the Jotunheimen Research Trust. We also thank Tim Osborn for producing Fig. 3 and Anne Hormes for constructive comments on the manuscript.

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Manuscript received October 2004, revised and accepted December 2004.