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Replicated proxy-climate signals over the last 2000 yr from two distant UK peat bogs: new evidence for regional palaeoclimate teleconnections

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Abstract

Ombrotrophic peat is an established source of proxy-climate data but previous records have been produced by different methods and have been difficult to compare. High-resolution plant macrofossil analysis has been applied to a lowland raised bog at Fallahogy, Northern Ireland, and a montane blanket bog, Moine Mhor in the Cairngorms, Scotland. Although the bogs are 300 km apart and differ floristically, the results demonstrate parallel responses to climatic forcing, especially that of the Little Ice Age. This approach provides a powerful tool for reconstructing proxy-climate records wherever suitable peat deposits exist. In contrast to the ocean and ice core records these proxies are from a terrestrial source, and related to climate changes on land over most of the Holocene. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

The peat stratigraphy of ombrotrophic bogs, those which have accumulated peat above the groundwater table and become rain-fed, has been established as a source of proxy-climate data for some time (Aaby, 1976; Barber, 1981; White et al., 1994; Van Geel et al., 1996; Chambers et al., 1997) and indeed the lighter (unhumified) and darker (humified) layers which reflect wetter and drier conditions, respectively, in such bogs were one of the earliest means used to subdivide the Holocene (Godwin, 1975, pp. 51–55). The development of Quadrat and Leaf Count macrofossil analyses (Barber et al., 1994a) and the application of Weighted Averages Ordination (WAO), to transform the raw macrofossil counts of the taxon abundances into a single line graph of the climate proxy, bog surface wetness, has been used with some success (Dupont, 1986; Barber et al., 1994a). There is an element of subjectivity in this procedure, in that the indicator values, usually ranging from 1 to 8 (Dupont, 1986), are chosen to reflect the position of a taxon with respect to average water-level. However, the field data used to support these indicator values are neither extensive nor unequivocal, and of course the results are also dependent on the taxa present, which complicate comparisons between bogs that differ floristically.

A more objective technique of multivariate analysis, Detrended Correspondence Analysis (DCA), was applied to data from Bolton Fell Moss, Cumbria. Both WAO (Barber et al., 1994a) and DCA (Barber et al., 1994b) showed that the data possessed coherent and robust structure, and the variations in the data were interpreted as being related to the bog water table and through that to climate. As part of a wider programme of research into climate change over the last 2000 yr (Battarbee et al., 1996; Barber et al., 1999), it was decided to compare the proxy-climate records of two distant peat bogs, one lowland and one montane, carefully chosen as relatively intact sites. The present vegetation and climate of the sites, Fallahogy Bog in Northern Ireland and Moine Mhor in the Cairngorm Mountains of Scotland, are quite different but it was intended that their proxy-climate records would be compared once the data had been subjected to DCA.

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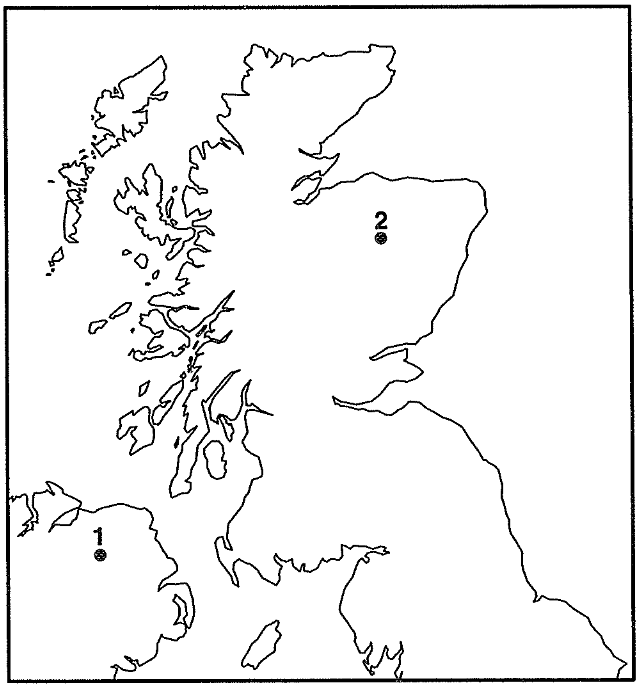
2. Sites and methods

At Fallahogy bog, Northern Ireland (latitude: 54°45′N, longitude: 06°36′W; Irish grid reference G075925; altitude 46 m; see Fig. 1), three cores were taken for preliminary plant macrofossil analyses, all of which replicated the main features of species change at the site. Quantitative macrofossil analyses were then performed on one of the cores using contiguous 1 cm samples for the top 60 cm, with counts every 2 cm below this to 160 cm. These analyses covered the last two millennia of peat accumulation and the species assemblages were dominated by *Sphagnum* bog mosses which react sensitively to climatically driven water table changes (Barber et al., 1994b).

At Moine Mhor (latitude: 57°02′N, longitude: 04°10′W; UK National Grid Reference NN892952, see Fig. 1) an area of water-shedding blanket bog at 920 m altitude in the western Cairngorms of Highland Scotland was cored and found to contain a series of bands of lighter and darker peat, replicatable over a plot of 20 × 30 m. These variations were confirmed by laboratory determinations of humification and bulk density. Blanket bogs normally produce a slowly accumulating homogeneous and well-humified type of peat, often with the plant remains completely broken down. At Moine Mhor, however, there is remarkable preservation of abundant macrofossils, presumably due to the sub-arctic climate. The macrofossils mirror the humification and bulk density with alternations of *Sphagnum*-rich and *Racomitrium*-dominated peat, representing relatively wet and dry periods, respectively. Tallis (1995) noted that although *Racomitrium* is an oceanic species requiring high humidity, its presence also denoted a relatively dry bog surface. These macrofossils were counted as contiguous 1 cm samples on a 60 cm peat monolith, covering the last 2000 yrs. The full macrofossil and humification data, and the palaeoecology of both sites, will be presented elsewhere.



1 Fallahogy Bog
2 Moine Mhor

Fig. 1. Map to show location of Fallahogy Bog, Northern Ireland and Moine Mhor, Scotland.

3. Chronology

Considerable effort was expended to ensure that the chronology of both profiles was as accurate and precise as possible. Forty bulk radiocarbon assays, 20 per site, were obtained from the NERC Radiocarbon Laboratory, but unfortunately the uppermost five dates from 30 to 43 cm at Fallahogy could not be used, being contaminated by bomb carbon which is thought to have penetrated into the peat via root channels following a fire in the 1960s. There were also reversals in the dating profiles (3 from Fallahogy and 2 from Moine Mhor) and these dates were not used in the age/depth models. The remaining dates (12 from Fallahogy and 18 from Moine Mhor) were calibrated using CALIB version 3.0 (Stuiver and Reimer, 1993). They were not re-calibrated using the more recent CALIB version 4 bearing in mind the comments of Stuiver and van der Plicht (1998) concerning the fact that the differences between the 1986, 1993 and the 1998 calibrations amount to no more than 15 radiocarbon years. The OXCAL calibration programme (V2.18; Bronk Ramsey, 1995) was also used to produce probability plots of each date, and the ages plotted in Figs. 2 and 3 are the best estimates from a consideration of all these data — in most cases the plotted date is the mid-point of the 2σ range. The uppermost peats, where the calibrated radiocarbon dates give imprecise results, were also dated using pollen/landuse correlations by comparing the pollen stratigraphy of the Fallahogy profile with previous work by Hall (1994) and by comparing the record of spheroidal carbonaceous fly-ash particles (SCP) in both profiles with the chronology established by Rose et al. (1995).

These data, when plotted as age/depth graphs (Figs. 2 and 3) show peat accumulation rates of about 10 yrs/cm at Fallahogy and 33 yrs / cm at Moine Mhor, both values in accord with many other such estimates. A fourth-order polynomial trendline was fitted to the graphs, giving r^2 values of 0.99 and 0.98, respectively. A volcanic ash (tephra) layer was also identified at each site, and shown to be contemporaneous (AD 920 and 940) by the age/depth model developed by the other methods. Unfortunately, the shards of this tephra were rather small, the particle size distribution peaking at 35 μm, and

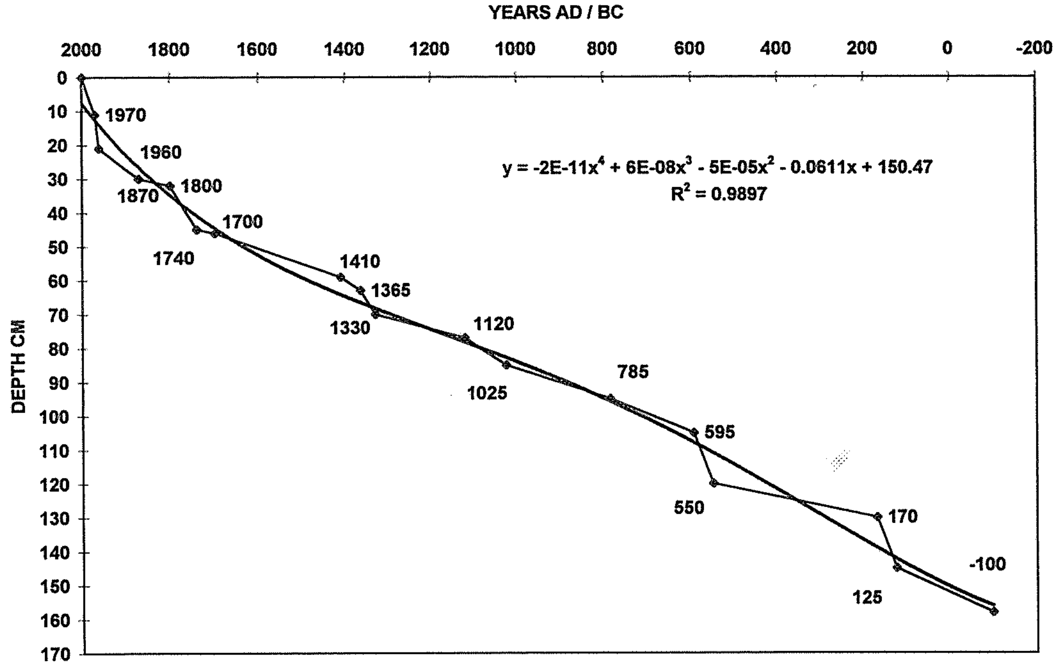


Fig. 2. Age/depth diagram for Fallahogy. All are calibrated radiocarbon ages, except for 1970, 1960 and 1870, which are based on the SCP chronology, and 1800 and 1700, which are based on pollen/landuse correlations (see text for details).

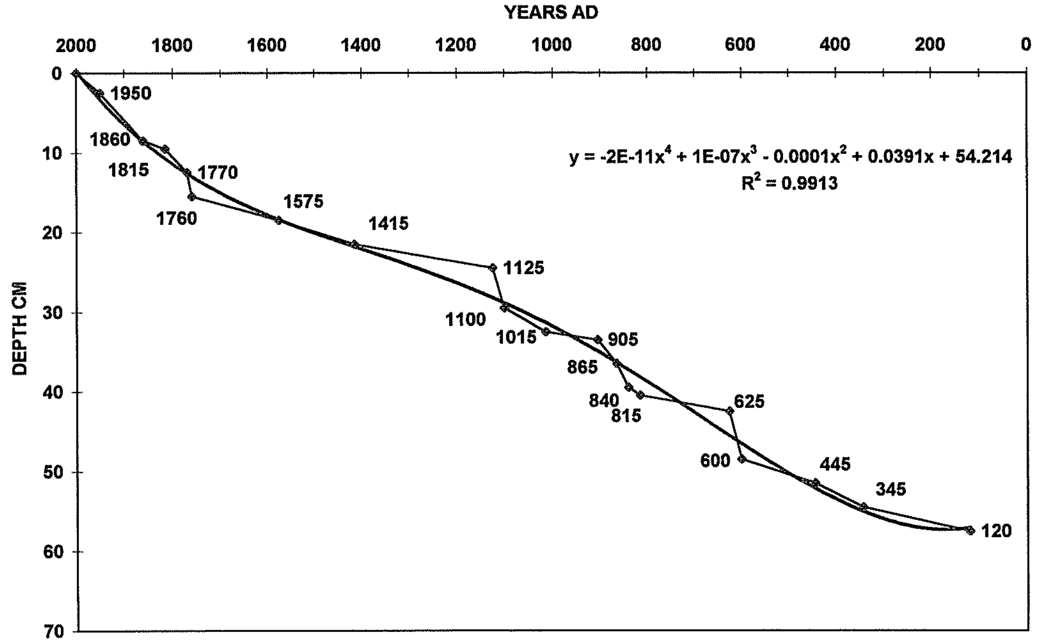


Fig. 3. Age/depth diagram for Moine Mhor. All are radiocarbon ages, except for 1950 and 1860, which are based on the SCP chronology. The 1815 age point is both a radiocarbon date, and an independent SCP date (see text for details).

because of this we have not been able to geochemically type these as yet, though further efforts will be made. It may be the same tephra previously identified in Northern Irish bogs and dated to cal. AD 860 ± 20 (Pilcher et al., 1996). The dates in Fig. 5 are derived from the age/depth models and denote significant points of change in the raw macrofossil data.

4. The link to documented climate

Climatic parameters of significance for the bog habitats were reconstructed at the remote sites by analysing and comparing north British records with other European instrumental records for temperature and precipitation. This was approached through splicing, homogenisation and time-series analysis of monthly averaged data, and the use of filtering techniques to identify and to assess the spatial and temporal coherence of temperature and precipitation records between sites. The Edinburgh temperature series, which extends back to January 1764, was analysed and compared with the Central England (Manley) series and the Netherlands (de Bilt) series. Such comparisons demonstrated that the air-temperature over the British Isles displays a high spatial and temporal coherence whereas the opposite was true for precipitation. The remote site reconstructions were made via a multiple regression procedure in which recent climate records from a local station, close to the field site, were regressed against air-temperature data from long reference sites, such as Edinburgh. The regression coefficients were then used to retrodict temperature at the local station. Finally, the retrodictions were combined with estimates of the local change of temperature with elevation in order to build up an estimate of the monthly changes of temperature at the field sites. Interpolation techniques and empirical relationships (Shaw, 1983) were used to convert the reconstructed air-temperatures into other climatic parameters such as evaporation and the length of the growing-season.

Fig. 4a shows a smoothed record (decadal averages) of evaporation changes for the bog at Fallahogy. Such changes, on a rain-fed bog, must be one of the most important factors affecting bog growth in this lowland environment and the 10-yr averages show the climate variations at about the same resolution as the peat samples. At 920 m altitude in the Cairngorm Mountains the length of the growing season, as shown in Fig. 4b, will be one of the most important factors in the growth of peat on Moine Mhor, since little or no growth takes place during the montane winter. The decadal averages for both climate parameters reconstructed here show very similar trends. The duration of the growing-season clearly depends on the lateness/earlyness of the spring and autumn. Evaporation is dominated by the integrated summer warmth, and is insensitive to extreme winter cold. The low temperatures of the period around AD 1700 are well shown and since then the main climatic trend has been a gradual rise in air-temperature, with no abrupt changes but with significant decadal fluctuations.

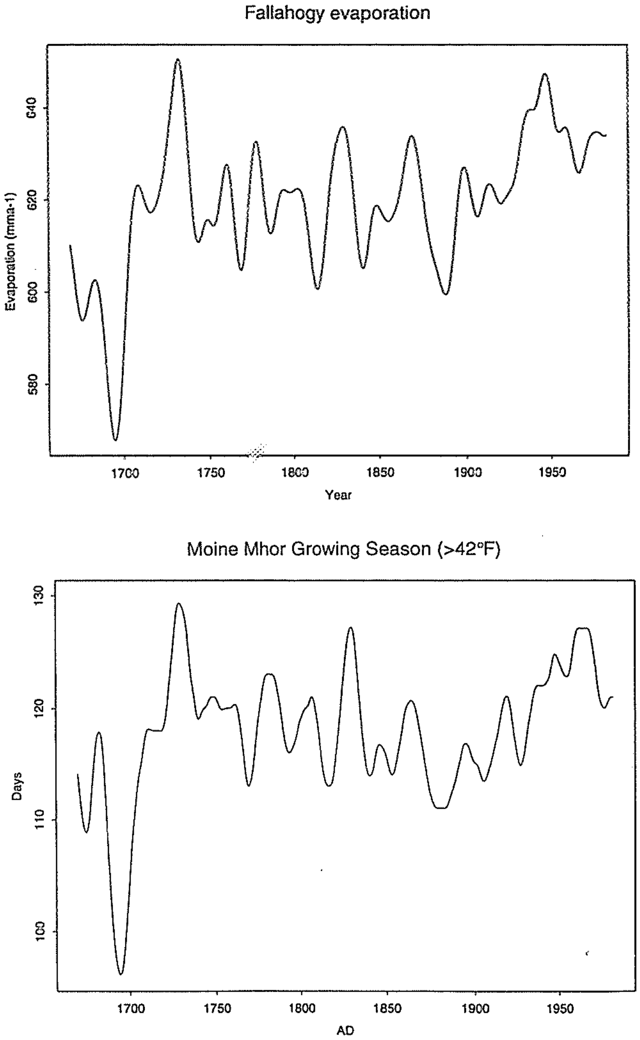


Fig. 4. (a) Evaporation reconstruction for Fallahogy bog. Thornthwaite's method (Shaw, 1983) was used to convert monthly mean air-temperature reconstructions into evaporation, using Armagh Observatory as the local transfer site. The resulting time-series was then smoothed using a 10 yr filter. (b) Duration of growth season (mean air temperatures over 42°F/6°C) at Moine Mhor. Monthly mean air temperatures were reconstructed using Braemar as the local transfer site. The number of days with mean air temperatures over 42°F were found by interpolation and the time-series smoothed with a 10 yr filter.

5. The proxy-climate signal

Both sets of macrofossil data were subjected to Detrended Correspondence Analysis (DCA) using the computer program CANOCO (ter Braak, 1987). This technique identifies the principal axes of variability within the macrofossil sample taxa proportions. In both cases discussed here the first axis accounts for a substantial proportion of the dataset variability and the position of the taxa along the axis indicates that axis 1 represents a bog surface wetness gradient. As these are ombrotrophic (precipitation-fed) bogs this index is therefore a proxy-record of atmospheric conditions, and gives a dramatic picture of climatically driven oscillations in the macrofossil assemblages (Fig. 5). The major change in both records is between AD 1650 and 1850, when open water pools dominated by aquatic bog-mosses formed on the bog surface at Fallahogy, and the surface of Moine Mhor was dominated by *Sphagnum* bog moss, producing peat of low humification and bulk density. This was the last pulse of the Little Ice Age and is contemporaneous within the limits of the dating methods. There is a good correlation between the beginning of this event and the

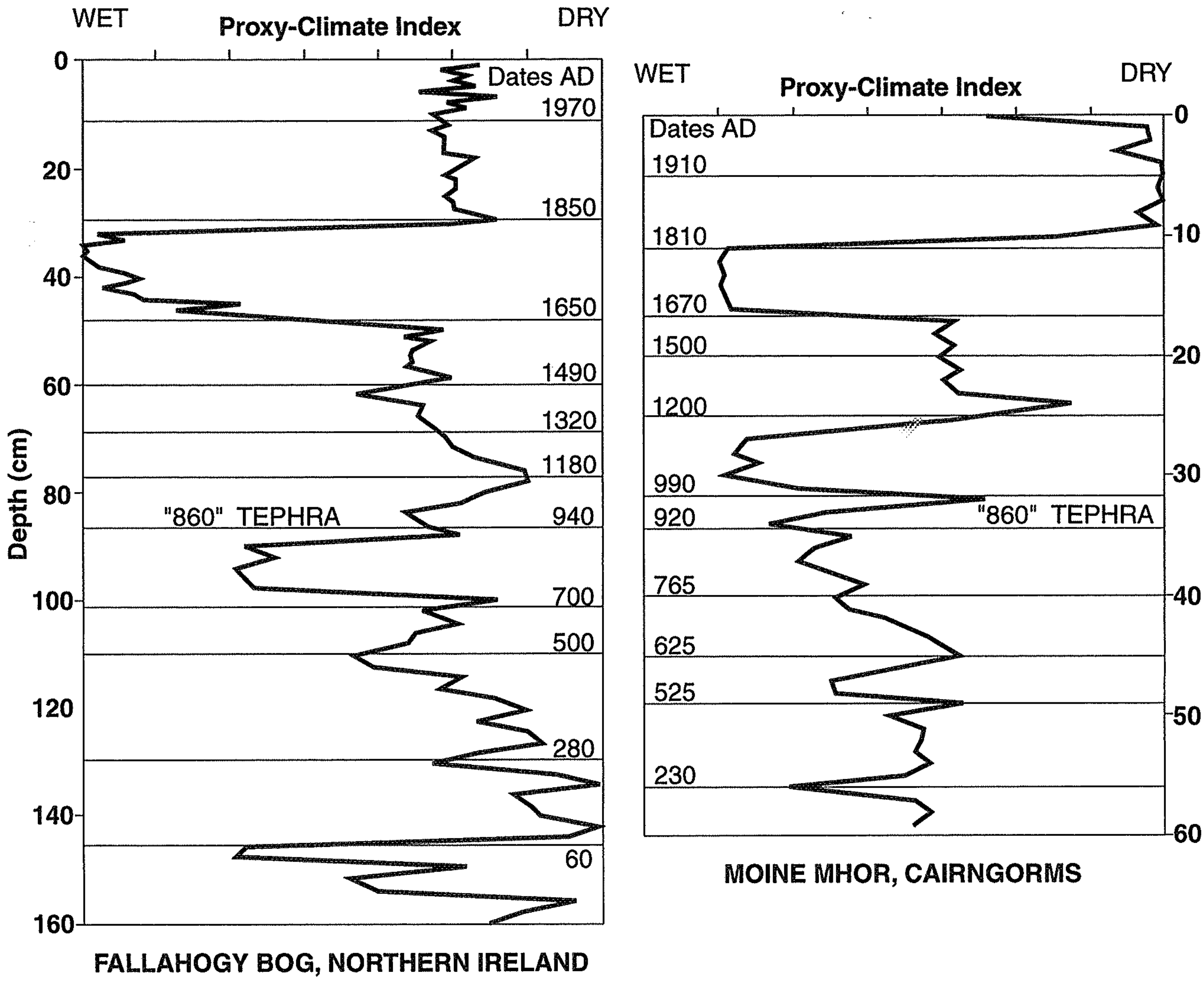


Fig. 5. Proxy-climate indices (DCA axis 1 scores) plotted against depth for Fallahogy Bog and Moine Mhor. Individual sample scores on this axis indicate the relative wetness of the growing surface. The dates AD are derived from the age/depth models (Figs. 1 and 2) and mark significant points of change in the raw macrofossil data.

severe downturn in the evaporation figures calculated for Fallahogy, and the growing season length calculated for Moine Mhor (Fig. 4). It is interesting to note that once initiated the wet conditions at both sites (a pool at Fallahogy and *Sphagnum* peat at Moine Mhor) continued to exist through the period of reconstructed higher evaporation/longer growing season at around AD 1740, indicating some degree of inertia in the bogs' response to higher air temperatures. The later part of the record, up to the present bog surfaces, also agrees with documented climate in showing no abrupt changes.

That both bogs, separated by over 300 km in distance and almost 900 m in altitude, and with different species composition, showed such a similar response in the Little Ice Age indicates that this is most probably a response to the spatially and temporally coherent temperature changes, rather than the incoherent rainfall fluctuations. The data also confirm the conclusion reached from other peat stratigraphic sequences (Barber, 1981; Chambers et al., 1997) — that the Little Ice Age is the coolest period of the last 2000 yr. It is possible that where the two records are in accord elsewhere in Fig. 5, such as the dry peaks ca. AD 1200 and the wet phases ca. AD 230/280, then the bogs were responding to a temperature signal, but where they are out of phase then they may have been responding to non-coherent rainfall regimes. For example, the relatively wet conditions on Moine Mhor between AD 990–1200 were unexpected and may point to higher rainfall in the mountains during the Medieval Warm Period.

6. Implications for future work

Both sites demonstrate striking changes in response to climatic forcing over the last 2000 yr. The linking of the records of these two bogs via DCA is a notable advance. The addition of other proxies which are being developed rapidly, such as the analysis of humification (Blackford and Chambers, 1995; Chambers et al., 1997) and of testate amoebae (Woodland et al., 1998; Charman et al., 1999), and the development of more precise radiocarbon chronologies through "wiggle match dating" (Van Geel et al., 1996 , p. 457), are clearly the way ahead. The analysis of contiguous 0.5 – 1 cm samples can give a high-resolution record which, since many bogs became ombrotrophic from about 7500 yr ago, would yield a record for the greater part of the Holocene (Hughes et al., 2000). The implications of this are far-reaching and reinforce the view that the remaining raised and blanket bogs of Eurasia and the Americas contain a valuable archive of past climates. A major effort to expand the number of proxy-climate records, using standardised methods (Barber et al., 1998), from raised and blanket bogs is needed, since it is clear that a strong signal exists, over and above any "ecological noise". Such records, using in addition other complementary proxy-data such as tree-rings (Luckman et al., 1997), glacial advances (Evison et al., 1996), and lake-level changes (Starkel et al., 1996), would give secure *terrestrial* proxy-climate frameworks at local and regional scales, which would also have significance for interpreting past changes in other terrestrial ecosystems and in past human agriculture. Work is now underway at two sites in Cumbria to test the hypothesis that the peat record is temperature driven, by comparing a chironomid-based proxy temperature record from a lake (Brooks et al., 1997; Lotter et al., 1999; Olander et al., 1999), with an effective precipitation record from a nearby peat bog (Barber and Langdon, in progress). It is hoped that this will allow us to achieve a greater understanding of climatic forcing mechanisms, to tune the Climate Response Model established from the same area (Barber et al., 1994b), and to take an important step towards providing quantitative data for the climate modelling community.

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