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# Rapid climate change during the early Holocene in western Europe and Greenland

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**Abstract:** Based on microfacies analyses of seasonally laminated varved sediments from lake Holzmaar, Germany, we report evidence of decadal- to century-scale climate variability during the early Holocene. The shifts in climate are documented in the thickness variations and changes in the composition of the varves in response to subtle shifts in limnological conditions. The close similarity between the Holzmaar varve record and the GRIP oxygen isotope record during 7.4–9.0 calendar (cal.) ka suggests that the high frequency climatic variations in both regions were controlled by the same mechanism. Our more detailed studies covering the central 409-yr period (~7.846–8.255 cal. ka, encompassing the 8.2 ka event) document for the first time, on a seasonal scale, the changing precipitation regimes in western Europe during these climate shifts. We show (i) that winters were drier and summers shorter and cooler in western Europe during colder periods in Greenland, (ii) in contrast to the present-day climate in the Holzmaar region, summer rains were clearly reduced during the early Holocene, and (iii) the climate not only changed rapidly (< 5 years) but recurring drier events were common during the studied period. In the Holzmaar record, the 8.2 ka event is the most prominent and longest of a series of short-term climatic oscillations.

**Key words:** Palaeoclimate, varve microfacies, Holocene, 8.2 ka event, western Europe, Greenland.

## Introduction

Ice core (O'Brien *et al.*, 1995; Alley *et al.*, 1997), marine (Bond *et al.*, 1997) and lake sediment (Stager and Mayewski, 1997; von Grafenstein *et al.*, 1998; Snowball *et al.*, 2002; Magny *et al.*, 2003a) records provide evidence of early and mid-Holocene climate variability. The most prominent event was a cooling event around 8.2 ka in Greenland (O'Brien *et al.*, 1995) which has been variously attributed to the collapse of Laurentide ice sheets (Barber *et al.*, 1999) or multiple smaller influxes of fresh water (Alley *et al.*, 1997). Various archives testify to the widespread impact of this event – annual temperature decrease in central and eastern Europe (eg, von Grafenstein *et al.*, 1998; Magny *et al.*, 2003a; Veski *et al.*, 2004), expansion of the drought-sensitive vegetation in Central Europe (Tinner and Lotter, 2001), dryness in western Ireland (Baldini *et al.*, 2002) and weaker monsoons (Gasse, 2000; Gupta *et al.*, 2003). Investigations into the internal structure of the 8.2 ka event and the smaller decadal scale $\delta^{18}O$ fluctuations preceding and following the 8.2 ka event (Nesje and Dahl, 2001; Magny *et al.*, 2003a) have been constrained by the limited number of archives with time resolution comparable with the Greenland ice cores. For such a study, high-resolution climate archives and an environmentally sensitive proxy with rapid response time (seasonal or annual) are needed. Here we present an early Holocene varve thickness record from the varve and AMS $^{14}C$ dated lake Holzmaar (50°7′N, 6°53′E) sequence in Germany (Zolitschka *et al.*, 2000). The seasonal diatom and clastic sublaminae comprising a varve contain a high-resolution record of palaeoclimate changes in western Europe. Using microfacies analyses we have, for the first time, reconstructed a continuous record of decadal- and centennial-scale climate instability and its seasonal impact in western Europe during the period ~7.846–8.255 cal. ka.

## Study area and methodology

The location of the study area is shown in Figure 1a. The region receives an average annual precipitation of ~730 mm

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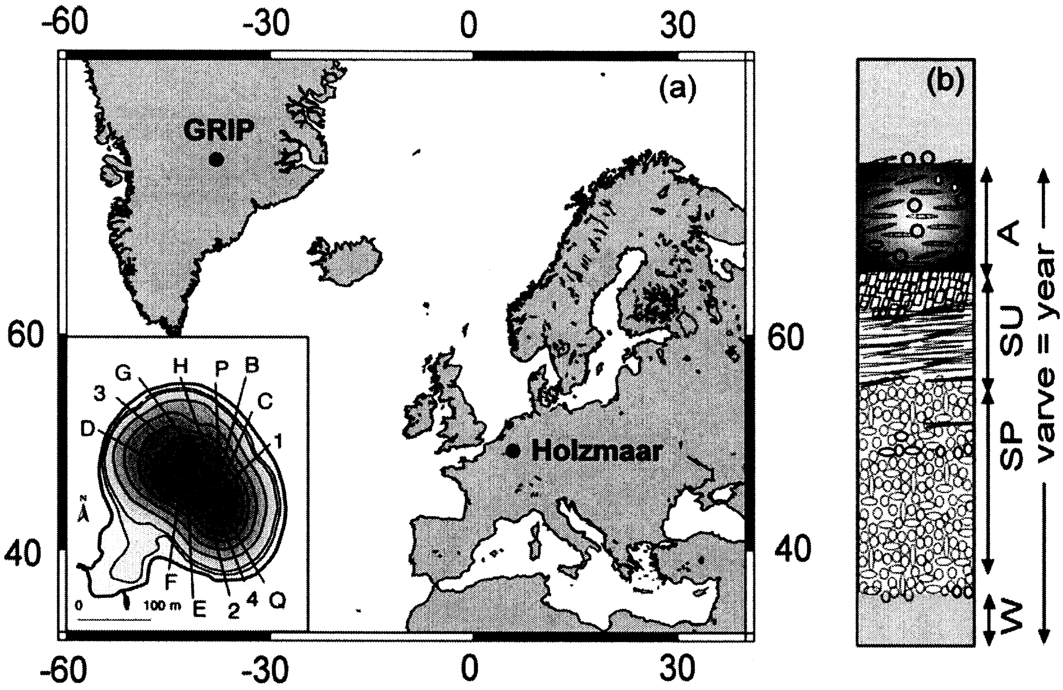

**Figure 1** (a) Site map showing the location of the GRIP core and the lake Holzmaar. The location of various cores used to build the varve chronology are shown in the inset. (b) Schematic representation of a Holzmaar varve. W (winter): clays; SP (spring): *Stephanodiscus* sp.; SU (summer): *Asterionella formosa* with calcite rhombs in late summer; A (autumn): *Cyclotella* sp. and benthic species in disseminated organic matter

(Deutscher Wetterdienst) in association with cyclones of Atlantic origin whose tracks are steered by the subtropical jet stream. The precipitation is equally distributed in winter and summer with minima occurring in spring and autumn. Lake Holzmaar presently has a maximum depth of 20 m and mesotrophic to eutrophic nutrient conditions. The lake is dimictic and holomictic and seasonal anoxic conditions exist below a water depth of 15 m (Scharf and Oehms, 1992). The demonstrated sensitivity of lake Holzmaar as a proxy recorder of major climatic changes (Zolitschka *et al.*, 2000) makes it suitable for high-resolution studies. Recent studies in the Holzmaar have linked variations in diatom assemblages to changes in nutrient ratios resulting from precipitation-induced inflow and varying lake circulation patterns (Baier *et al.*, 2004).

The core sediments are well laminated except in the upper section where the quality of lamination is, with some exceptions, very poor. Therefore we began the counting in the older and clearly varved part of the cores. The three composite cores (HZM-1, 2, 3, HZM-B, C and HZM-4) from Holzmaar were correlated using the Ulmener Maar Tephra (UMT) and micromarker layers (diatom blooms or turbidite events found every 1–3 cm in all cores) and a floating chronology was established by varve counting in all three composite cores. The varve counting in all the cores (S. Prasad, unpublished data) yielded a cumulative difference of less than 2% during $\sim$11–3 cal. ka. We have anchored the floating varve chronology to the published radiocarbon dates on organic matter (Hajdas *et al.*, 1995). Thus, while the boundary of the time interval discussed below might have an uncertainty of ±120 years (one standard deviation) inherent in $^{14}$C age determination, the duration of the individual events can be expressed as varve years.

The varve thickness measurements have been made on four cores by different observers and show a correlation coefficient of 0.86 (significant at 99.9% confidence level). A typical Holzmaar varve sequence for the early Holocene (Figure 1b) comprises dark clays deposited during the winter, overlain by the spring blooms of *Stephanodiscus* sp. These are commonly succeeded by *Asterionella formosa* during summer. Overlying the *A. formosa*, at times, are calcite crystals that are formed during late summer. Topping this sequence are the autumn sublaminae comprising *Cyclotella* sp., disseminated organic matter and benthic species. With their rapid response time (days to weeks), diatoms are ideally suited for studying the seasonal impact of climate change.

The Si/P ratios exert a major influence on the productivity of *Stephanodiscus* sp. and *A. formosa* (Kilham *et al.*, 1986; Bradbury and Dieterich-Rurup, 1993; Kilham *et al.*, 1996). The input of silica in lake Holzmaar is from precipitation-induced inflow (Lücke, 1997). Since clay is also brought in at the same time as Si by the inflow, an indication of changes in Si input can be derived from the thickness variations in clay sublaminae deposited during winter. The early spring *Stephanodiscus* sp. can grow successfully under low Si/P ratios and low light (Kilham *et al.*, 1986; Bradbury and Dieterich-Rurup, 1993). High fluxes of this diatom would reflect the climatic and limnologic factors that promote low Si/P ratios, ie, (i) a reduction in input of Si, possibly from reduced winter precipitation, (ii) an increase in phosphorus release from sediments resulting from reduced flushing of the lake (and increased residence time of lake waters) during drier periods (Rippey *et al.*, 1997), coupled with enhanced and deep spring water circulation that lowers the Si/P values in the photic zone where the *Stephanodiscus* sp. grows (Baier *et al.*, 2004). *Asterionella formosa* has high optimum Si/P requirements (van Donk and Kilham, 1990; Kilham *et al.*, 1996). Therefore limnologic and climatic factors (eg, wet winters and/or reduced water circulation) that increase the Si/P ratios would favour the dominance of *A. formosa*. Calcite polyhedra are formed during late summer because of calcium carbonate supersaturation of the surface water induced by enhanced summer biological productivity in the lake waters (Hsü and McKenzie, 1985; Rippey *et al.*, 1997). Their preservation depends on water chemistry and temperature (the solubility of calcite increases with decreasing temperature). In the time period discussed in this study, diatoms and organic matter usually occur as a mixture during the autumn season. Since it is not possible to assess the relative content of diatoms and organic matter they have not been used here as a climate proxy for the autumn.

## Results and discussion

The varve thickness measurements from lake Holzmaar (see eg, core 1, Figure 2a) indicate decadal- to century-scale variability between 7.4 and 9.0 cal. ka. These oscillations have been defined in terms of varve microfacies changes and labelled as HZ-1 to HZ-6. The longest of these events (HZ-3, characterized by increased varve thickness) has a thickness maximum at 8057 ± 120 years. If the oxygen isotope data from GRIP and GISP2 are compared according to their stratigraphic position, a chronological discrepancy of ~100 years is observed between the two, yielding an average age of 8170 ± 50 years for the peak of the 8.2 ka cold event in the Greenland record. Within the uncertainties of dating in both the records, the timing of the increased varve thickness in Holzmaar during the HZ-3 event is in agreement with the cold period observed in Greenland during the 8.2 ka event. The $\delta^{18}O$ record in the Greenland ice cores is believed to reflect mainly palaeotemperature changes (Jouzel *et al.*, 1997). Additional decadal-scale fluctuations in the GRIP $\delta^{18}O$ record (a range of up to ~2.5‰ from the beginning to the climax of the event), preceding and following the 8.2 ka event (Figure 2), also correlate with decadal-scale changes in varve thickness in the Holzmaar data (HZ-1, 2, 4, 5, 6) confirming the wider occurrence of these fluctuations. The close correspondence shown by two independently derived records, even on a decadal-scale, demonstrates that the climatic changes in western Europe and Greenland followed a similar pattern between 7.4 and 9.0 cal. ka. An expanded polar influence during the period under consideration has been inferred from high dust and sea salt concentrations reported in Greenland

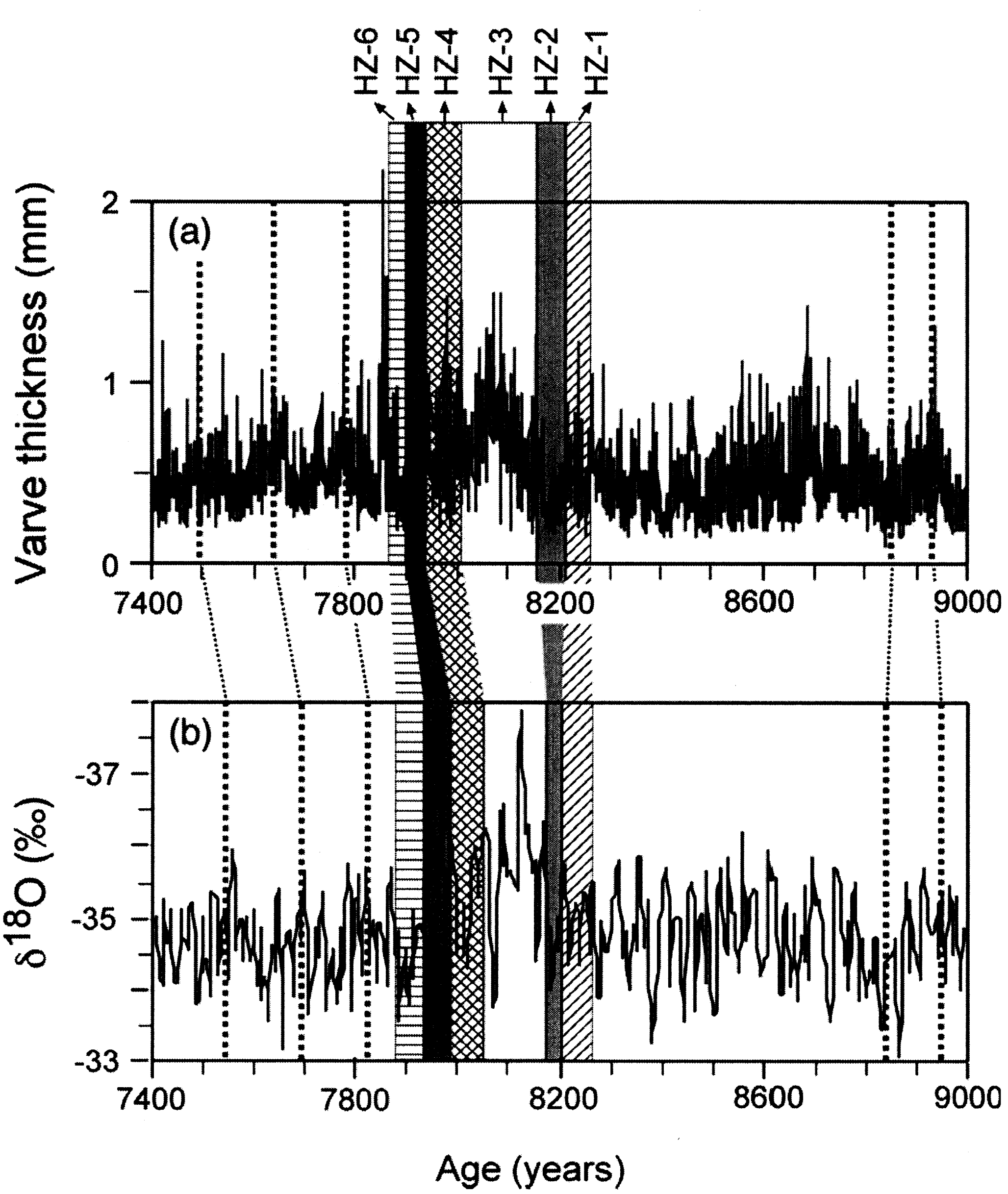

**Figure 2** A comparison of the varve thickness measurements (a) from Holzmaar (core HZM-1) with the GRIP oxygen isotope data (b). The varve curve has been smoothed using a five-point moving mean for comparison with the GRIP $\delta^{18}O$ data, which has a resolution of about 5 years in this time interval. The events studied in detail in the Holzmaar cores are labelled as HZ events. An increase in varve thickness is observed during colder fluctuations in the GRIP $\delta^{18}O$ record. The dashed lines indicate additional events that have been correlated in both the records

cores (O'Brien *et al.*, 1995), which could explain the close similarity between the Holzmaar and the Greenland record.

To investigate the seasonal changes in the western European climate during the short-term climate events (HZ-1 to HZ-6) the seasonal sublaminae in Holzmaar sediments were studied in detail in core HZM-4. The results were confirmed by spot checks in cores HZM-1 and HZM-3. To evaluate intra-annual shifts in the relative dominance of seasonal diatoms, an indicator of changes in the nutrient balance, the thickness of seasonal sublaminae are shown as percentages of total varve thickness (Figure 3). The clays (Figure 3a) reflect the winter precipitation-induced inflow and hence are an indicator of Si input into the lake. We have ruled out any role for vegetation changes in influencing the input of clays into the lake since they are unlikely to explain the unequivocal variations in clay input that occur over a period of 2–3 years in the Holzmaar record (Figure 3a). The variation in clay content can be a result of a qualitative change in either the strength or frequency of winter precipitation. We are inclined towards the latter explanation because stronger floods would show a grain size shift towards coarser silt and sand, as has been observed during the Boreal oscillation in lake Holzmaar (Brathauer *et al.*, 1999). Detailed microscope examination of thin sections for the HZ events did not indicate the presence of coarser grain sizes. The interpretation of decreased winter precipitation during periods of low clay content is further supported by

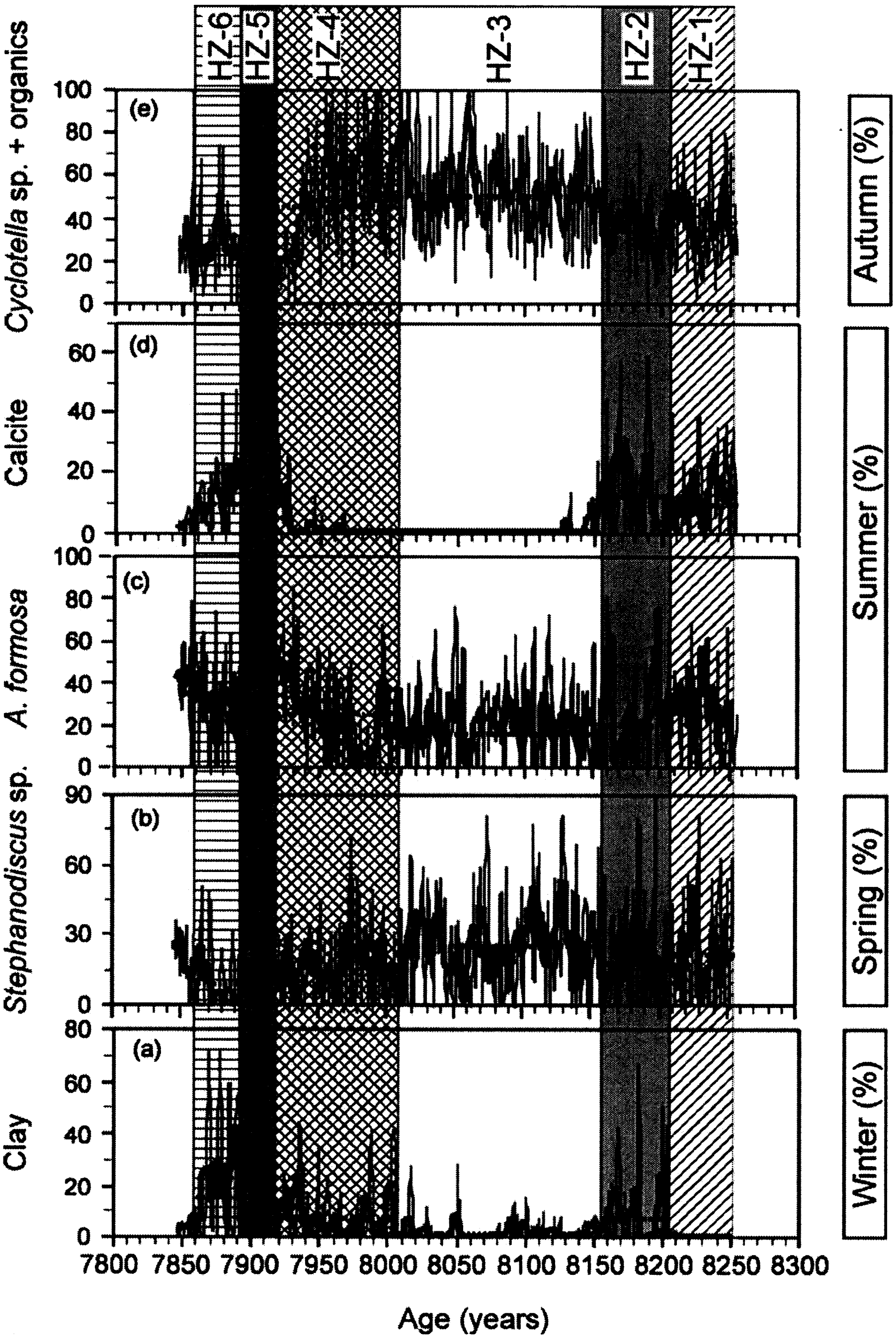

**Figure 3** The seasonal sublaminae thickness from core HZM-4, expressed as percentages of total varve thickness, for the HZ events identified in Figure 2. Note that the age is based on counted varves anchored to calibrated radiocarbon dates on organic matter, and the duration of events can be expressed in terms of varve years. A five-point moving mean is also shown. The dashed line indicates the event average. The 8.2 ka event (HZ-3), characterized by lower winter precipitation and cooler summers, was preceded and followed by other short-term climatic fluctuations

the absence of spring snowmelt layers that form only if sufficient amounts of snow were to have accumulated during winter. Our evidence for drier climate during the 8.2 ka event is in agreement with the evidence from other sites in northern Europe (Nesje and Dahl, 2001; Baldini *et al.*, 2002).

Winter precipitation seems to have varied significantly during the early Holocene (Figure 3a), with drier climate during events HZ-1, 3 and 5. During these drier events the spring *Stephanodiscus* sp. also showed an increase, indicating lower Si/P in the epilimnion. We attribute these changes to reduced Si input and enhanced water circulation promoting P transport from the hypolimnion to the epilimnion, reducing the Si/P in the latter. Indeed, evidence from the North Atlantic indicates stronger winds during the period 8–8.4 cal. ka (Alley *et al.*, 1997). During the wetter periods (HZ-2, 4 and 6) increased Si input from winter inflow favours the blooming of *A. formosa* in the succeeding summer (Figure 3c). Even though the nutritional requirements of *A. formosa* are different from *Stephanodiscus* sp. (higher Si/P ratios as opposed to low Si/P needed for *Stephanodiscus*), no significant correlation between the two is observed in Figure 3. This is related to the broader range (Bradbury and Dieterich-Rurup, 1993) of Si/P tolerated by *A. formosa* compared with *Stephanodiscus* sp. The calcite (Figure 3d) is completely absent for 233 years during events HZ-3 and 4, which could be indicative of (i) lowered summer productivity, either because of reduced influx of Si, and/or a shorter growing season that resulted in no calcite being formed, or (ii) dissolution of calcite. While the summer productivity during HZ-3 and HZ-4 is lower, it is presently not possible to state conclusively that no calcite was formed. However, there is independent evidence for cooler summers during the 8.2 ka event from Norway (Nesje and Dahl, 2001) and eastern France (Magny *et al.*, 2003a). Therefore, we believe that cooler waters promoted the solubility of any calcite that might have formed during events HZ-3 and HZ-4 in the Holzmaar. Interestingly, no clay sublaminae were deposited during the summer for the entire 409-yr period subjected to detailed seasonal investigations. This clearly points to reduced or absent summer rains during the studied interval, in contrast to the present-day climate.

A comparison of Figures 2 and 3 indicates that the colder periods (depleted $\delta^{18}O$) in the Greenland record are marked by drier winters in Holzmaar (HZ-1, 3 and 5). The increase in varve thickness during these drier periods is largely due to an increase in the contribution from the spring sublaminae. The longest event, HZ-3 with drier winters and possibly shorter and cooler summers, lasted for ~147 years and correlates with the 8.2 ka cold event in Greenland (O'Brien *et al.*, 1995; Stager and Mayewski, 1997). The occurrence of dry seasons in Holzmaar during the 8.2 ka event is consistent with the geochemical evidence from speleothems in Ireland (Baldini *et al.*, 2002). However, there seems to be a disagreement between this evidence for apparent drier climate in Holzmaar and the expansion of drought-sensitive vegetation in southern Germany and Switzerland that could be interpreted as indicating wetter conditions (Tinner and Lotter, 2001) during the 8.2 ka event. One potential mechanism that could reconcile these apparently conflicting results would involve the southward migration of the wetter westerly winds during this event in response to changes in the latitudinal thermal gradient, as proposed by Magny *et al.* (2003b). We also note that while the warming in the Greenland ice core record is accompanied by the return of winter rains in the Holzmaar record (HZ-3, Figure 3), the colder summers persisted for an additional 86 years, as indicated by the absence of calcite.

Short-term climate variability appears to have been a common feature of the climate for the time period shown in Figure 3. There is also evidence from lake Annecy (Magny *et al.*, 2003a) and Norwegian lakes (Nesje and Dahl, 2001) of short-term climate fluctuations that correlate with the events HZ-2, 3, 4 and 5 in lake Holzmaar. The total duration of the period HZ-1 to HZ-6 is 396 yr in core HZM-4 compared to ~389 yr for the correlated events in the GRIP core. The durations of the smaller events show differences in both the records (Table 1). These could possibly be attributable to (i) the sampling resolution and smoothing window used in the GRIP core, and/or (ii) differing response time of the proxies – ice cores versus lake sediments. However, the Holzmaar data (Figure 3) do indicate that the precipitation changes during the onset and termination of the 8.2 ka, and other short duration events, took place over a period of less than five years.

What triggered the decadal- and centennial-scale instability during the period around 8.2 cal. ka? Until now it is the 8.2 ka event that has received most of the attention. A change in the thermohaline circulation, either resulting from a large influx of freshwater from the drainage of Laurentide lakes resulting from the collapse of ice sheets (Barber *et al.*, 1999; Clark *et al.*, 2001; Teller *et al.*, 2002) or multiple smaller influxes of freshwater (Alley *et al.*, 1997), may have played a major role in causing the 8.2 ka event. Within one standard deviation, the timing of the collapse of the Laurentide ice sheets (8.16–8.74 cal. ka) does lie within the age range of the 8.2 ka event (Barber *et al.*, 1999). This collapse is considered to have been either a single (Barber *et al.*, 1999) or a two-step process (Teller *et al.*, 2002). In either case it leaves unexplained the smaller decadal-scale drier events that preceded and followed the 8.2 ka event. We speculate that the following mechanisms, either singly or in combination, might have been responsible for the short-term climate instability – (i) multiple smaller fluxes of freshwater in the North Atlantic (Alley *et al.*, 1997), which continued until the final melting of the ice sheet, (ii) a major reorganization of the atmospheric circulation in response to marked changes in land, water and glacial ice boundaries in the circum-Atlantic following the massive water influx from the Laurentide lakes (Dean *et al.*, 2002), and/or (iii) solar variability (Nesje and Dahl, 2001; Magny, 2003). A detailed comparison with the North Atlantic must await the availability of high-resolution data from the oceans. Also, while our data do have seasonal resolution, the errors in the boundaries of our time interval (±120 yr) do not, at this stage, permit a rigorous comparison with the $\Delta^{14}C$ from tree rings, considered to be largely a proxy for solar activity (Stuiver and Braziunas, 1993).

The Holzmaar data highlight the importance of complementing the ice core and ocean records with high-resolution continental archives for investigating the seasonal impact of short-term climate variability. It also demonstrates that the

**Table 1** A comparison of the duration of events in Holzmaar and the GRIP ice core

| Events | Duration HZM-4 (yr) | Duration GRIP (yr) |
|---|---|---|
| HG-1 | 51 | 59 |
| HG-2 | 53 | 31 |
| HG-3 | 147 | 148 |
| HG-4 | 86 | 42 |
| HG-5 | 29 | 54 |
| HG-6 | 30 | 55 |
| Total | 396 | 389 |

decadal-scale climate fluctuations observed in the GRIP record also occurred in western Europe. The seasonal data indicate that the winters were drier, and the summers drier and cooler during the 8.2 ka event in western Europe. While the Greenland ice core record indicates cooler temperatures for ~148 years during the 8.2 ka event, the seasonal record from Holzmaar indicates that cooler summers in western Europe persisted for an additional 86 years.

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