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Lake isotope records of the 8200-year cooling event in western Ireland: Comparison with model simulations

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ABSTRACT

The early Holocene cooling, which occurred around 8200 calendar years before present, was a prominent abrupt event around the north Atlantic region. Here, we investigate the timing, duration, magnitude and regional coherence of the event as expressed in carbonate oxygen-isotope records from three lakes on northwest Europe's Atlantic margin in western Ireland, namely Loch Avolla, Loch Gealáin and Lough Corrib. An abrupt negative oxygen-isotope excursion lasted about 200 years. Comparison of records from three sites suggests that the excursion was primarily the result of a reduction of the oxygen-isotope values of precipitation, which was likely caused by lowered air temperatures, possibly coupled with a change in atmospheric circulation. Comparison of records from two of the lakes (Loch Avolla and Loch Gealáin), which have differing bathymetries, further suggests a reduction in evaporative loss of lake water during the cooling episode. Comparison of climate model experiments with lake-sediment isotope data indicates that effective moisture may have increased along this part of the northeast Atlantic seaboard during the 8200-year climatic event, as lower evaporation compensated for reduced precipitation.

1. Introduction

The early Holocene cooling event that occurred around 8200 years BP has become a major research focus for palaeoclimatologists concerned with rapid climate change. The abrupt event, which is most clearly recognized in Greenland ice cores, is associated with widespread cooling in the middle and high northern latitudes and a reduction in tropical and subtropical moisture (Alley et al., 1997; Alley and Ágústsdóttir, 2005; Morrill and Jacobsen, 2005). In the ocean, surface cooling of the North Atlantic (Kleiven et al., 2008) and reduction in deep water flow speed (Ellison et al., 2006) are consistent with a slowdown of Atlantic Meridional Overturning Circulation (AMOC). The primary trigger for the 8200 year cooling is thought to be the catastrophic drainage of glacial Lakes Agassiz and Ojibway; large water bodies that accumulated over North America to the south of the waning Laurentide ice sheet during the late glacial and early Holocene (Barber et al., 1999). A large flux, up to 5 Sv over <1 year, of cold and fresh meltwater was routed through the Hudson Strait into the North Atlantic, via the Labrador Sea, 8470 ± 300 years BP (Teller et al., 2002). Although there is some evidence to suggest that the freshwater outburst occurred in two discrete events rather than as a single episode (Clarke et al., 2004; Hillaire-Marcel et al., 2007), it is clear that a large amount of fresh water was discharged into the North Atlantic over a very short time prior to 8000 years ago. Whilst freshwater forcing is seen as the major trigger for the 8200-

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year climatic event, other factors, including reduced solar output (e.g. Bond et al., 2001) and feedback effects, for example through changes to sea-ice distribution (e.g Rohling and Pälike, 2005), may also have played a role. Rohling and Pälike (2005) argued that a sharp (i.e. brief, large amplitude) climatic event in the near-field (i.e. circum-North Atlantic) region was superimposed on a broader-scale (i.e. longer and more subdued) cooling event and suggested that whereas the former was a direct response to the drainage of Lake Agassiz, the latter was not. They further suggested that the sharp event was largely a winter signal, whereas the broader event relates to summer conditions, although not all records support this conclusion (e.g. Marshall et al., 2007).

Oxygen-isotope records from both marine and non-marine archives provide an excellent basis for investigating geographical patterns of the 8200-year event that can be compared with ice cores. Daley et al. (2011) mapped $\delta^{18}O$ values in terrestrial archives, including lake-sediment and speleothem carbonate, and peat-bog cellulose, around the North Atlantic region. They showed that a primary negative excursion in most archives lasted between 110 and 200 years. Timing of the event clustered between 8500 and 8250 yr BP, and the authors concluded that minor age differences between records were the result of dating uncertainties. Despite some contrast in the interpretation of the $\delta^{18}O$ records from different archives, all provide first-order evidence for a sharp reduction in the oxygen-isotope composition of precipitation ($\delta^{18}O_p$). The amplitude of this negative excursion decreases from Labrador, in Canada, through Greenland and then across western Europe from Ireland through to Estonia. This geographical pattern is consistent with attenuation of the amplitude of the $\delta^{18}O_p$ excursion with distance from the meltwater source and in broad agreement with the results of simulations with the isotope-enabled GCM HadCM3 (e.g. Tindall and Valdes, 2011).

In contrast to the northern hemisphere tropics and subtropics, where an abrupt dry event is clearly seen around 8200 years BP (Street-Perrott and Roberts, 1983; Gasse, 2000), much less is known about the mid-latitude hydrological response to early Holocene cooling. Alley et al. (1997) suggested that cooling was associated with drying over some parts of the northern mid-latitudes, while Magny et al. (2003) argued that Europe showed geographical variations in response, with dry conditions north of 50° N and south of 43° N, coupled with increased effective moisture (precipitation minus evaporation, or P−E) in the intervening areas. Evidence from Ireland (e.g. Baldini et al., 2002, 2007; Ghilardi and O'Connell, 2013; Molloy and O'Connell, 2014; O'Connell et al., 2014) and southern England (e.g. Rousseau et al., 1998; Garnett et al., 2004) was used to support the inference of dry conditions in these areas at the time. In contrast, findings from southern Scandinavia (Hammarlund et al., 2005) point to an increase in effective moisture during the cooling event: such an increase may have resulted from decreased evaporation and/or increased rainfall. Hammarlund et al. (2005) argued that increased effective moisture in southern Sweden resulted from drier winters coupled with cooler, wetter summers, suggesting that seasonality is important in explaining patterns of change.

The uniqueness of the 8200-year event in the Holocene is such that it provides an ideal test for coupled climate models used to predict future climate change. It has therefore been the focus of numerous modelling studies (Bauer et al., 2004; Meissner and Clark, 2006; Renssen et al., 2002, 2001; Wagner et al., 2013) including those that simulate proxies for past $\delta^{18}O$ values in rainfall (LeGrande and Schmidt, 2008; LeGrande et al., 2006; Tindall and Valdes, 2011). Model experiments generally have difficulty in replicating the duration of the 8200-year event using only the forcing from the Agassiz–Ojibway lakes and additional forcing from the melting ice sheets is normally required to capture the timing and duration (Meissner and Clark, 2006; Wagner et al., 2013). However the amplitude and geographical pattern of the event is reasonably simulated by using only the Agassiz–Ojibway lake forcing (Tindall and Valdes, 2011) and can be reliably compared with geological data (Daley et al., 2011).

In this paper, we evaluate changes in hydrology during the 8200-year event in western Ireland by examining $\delta^{18}O$ records from three carbonate lakes. Given the proximity of the three sites, they are expected to fall under the same $\delta^{18}O_p$ and temperature regime during the early Holocene. However, the three lake basins have contrasting morphologies and hydrologies, and so will likely have responded differently to changes in effective moisture. By comparing the oxygen-isotope records from the three basins, and drawing on additional non-isotope climate proxies, we undertake semi-quantitative reconstruction of changes in effective moisture during the 8200 year event in order to contribute to our understanding of hydrological change during this interval. Because western Ireland lies on the Atlantic margin of Europe, it would be expected to have experienced a relatively large amplitude isotope oscillation during the 8200 year event and is therefore ideal for such investigations. Despite a very good spatial correlation between $\delta^{18}O_p$ and climate (Dansgaard, 1964), the relationship between temporal $\delta^{18}O_p$ anomalies and temporal climate anomalies is less clear and the two are not always regionally coherent (Tindall and Haywood, 2015). This means that a modelling study that incorporates $\delta^{18}O$ tracers can be an invaluable tool to relate proxy records of $\delta^{18}O$ to climate. This paper therefore makes use of previous modelling work (Tindall and Valdes, 2011) in order to address questions about the climate, and in particular the effective moisture, that are consistent with the $\delta^{18}O$ signal recorded in the lake sediments.

2. Site descriptions, materials and methods

2.1. Site description

This study is based on early Holocene lake-sediment cores from Loch Avolla, Loch Gealáin and Lough Corrib (Fig. 1). Loch Avolla and Loch Gealáin are located in the Burren, Co. Clare, an internationally important karst region in western Ireland. Loch Gealáin occupies a depression in the lowlands immediately to the south-west of Mullach Mór, a hill that that defines the south-western edge of the Burren plateau. Loch Gealáin (sometimes referred to as Gortlecka) consists of a permanent lake (maximum recorded depth is 13 m; seasonal variation ca. 3 m; permanent open-water area: 12 ha) with

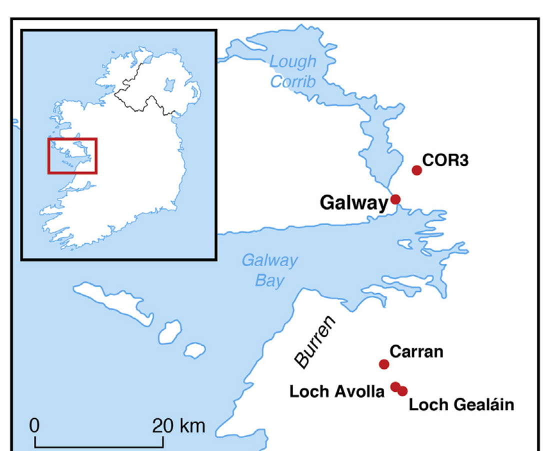

Fig. 1. Location of the core sites and other localities mentioned in the text.

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thick marl benches on the southern side where the sediment core was recovered. The adjoining area to the west is a turlough, i.e. a non-permanent lake that dries out more or less completely in dry weather, mainly during summer. Around the lake, bare but jointed limestone pavement, shattered limestone and thin patchy drift cover support mainly species-rich open herbaceous vegetation and occasional patches of hazel scrub. There is also a small patch of semi-mature tall-canopy woodland. Loch Avolla lies 1.7 km north-west of Loch Gealáin in a rather deep, sheltered depression surrounded by pastures on thin drift and hazel scrub where soil cover is insufficient to support pasture. Thinly vegetated and often bare limestone dominates in the surrounding plateau area. This small lake (permanent open water: <0.5 ha) lies at c. 90 m a.s.l. and is ca. 6 m deep in summer, although the lake levels oscillate considerably. When lake levels are high, a wetland fringe ca. 20–50 m wide around the lake is flooded. Groundwater tracing experiments confirm that the two lakes are linked by a common groundwater hydrological system (Drew, 1988).

Lough Corrib is a large lake located north of Galway Bay. The coring site is where the thickest sediments were recorded along a 5.5 km-long transect that stretched north-east from close to the mouth of the Clare river north-east towards Claregalway. Today, the area consists largely of extensive cutover bog that, where reclaimed, supports wet pasture. A remnant of the original raised bog survives as Addergoole Bog (ca. 44 ha). Until about the mid Holocene, the area was a large bay in the southern Corrib basin (Bingham, 2011). The underlying bedrock is Carboniferous limestone (Holland and Sanders, 2009), which is also the bedrock of the large eastern catchment of the lower Corrib basin drained by the Clare and Clegg rivers. Karstic features are common including underground river systems and many turloughs (Sheehy Skeffington et al., 2006).

The climate of western Ireland is distinctly oceanic, with mild winters and cool summers. Frontal systems from the Atlantic bring heavy rainfall and strong south to south-westerly winds (www.met.ie). At the National University of Ireland Galway (NUIG) campus in Galway city for the period 1966–2005 (Gaffney, 2006), mean annual air temperature was 10.3 °C and mean monthly air temperatures for January and July were 5.8 °C and 15.6 °C, respectively. Mean annual rainfall was 1189 mm with, on average, 228 rain days ($\geq$1 mm precipitation). The mean seasonal rainfall was 341 mm and 252 mm (winter and summer, respectively). Total sunshine hours averaged 179 in May (sunniest month) and 39 in December (month with least sun). These statistics are regarded as indicative of the climate in the study area though there is undoubtedly considerable spatial variation; e.g. in the Burren uplands annual precipitation can reach 1750 mm (Drew and Daly, 1993) and, in the north-western Corrib catchment, annual rainfall may exceed 2000 mm (www.met.ie).

Rainfall at Carran (Fig. 1), which lies at 130 m a.s.l. in the central southern Burren, has a weighted $\delta^{18}O_p$ value of −6.01‰ from monthly measurements for the period June 2004–December 2005, and arithmetic mean $\delta^{18}O_p$ value of -6.03 ± 1.63 (1σ) for the calendar year 2005. This is consistent with the long-term weighted value (from over three decades of monthly measurements) of −5.54‰ (arithmetic mean = -5.2 ± 1.57‰), at the GNIP (Global Network of Isotopes in Precipitation) station, Valentia, which lies close to sea-level near the Atlantic Ocean in south-western Ireland. Lake-water isotope measurements ($\delta^{18}O_w$) from Loch Gealáin in the period corresponding to the measurements from Carran had a mean $\delta^{18}O_w$ value -5.08 ± 0.61‰ (1σ), indicative of moderate evaporative enrichment of the lake water. The $\delta^{18}O_w$ values from Loch Avolla (mean = −6.4‰) are closer to those of the rainfall suggesting less evaporative enrichment. However, measurements are too few to draw firm conclusions. We have no values for $\delta^{18}O_w$ for Lough Corrib. Diefendorf and Patterson (2005) present $\delta^{18}O_w$ data derived from surface waters taken from numerous lakes and rivers, mainly in western Ireland including the Burren. Their results, with which the data reported here are consistent, suggest that slight evaporative enrichment has affected many waterbodies.

2.2. Methods

The three sites were cored as part of wider investigations into late glacial and Holocene environmental change in western Ireland. At Loch Avolla parallel cores LA2A and LA2B, recovered at the southwestern margin of the lake (53°0.3′ N, 9°2.7′ W; 88 m a.s.l.) using a Livingstone corer in March 2002, revealed 6.35 m of marl overlain by 1 m of peat and underlain by late-glacial clay. At Loch Gealáin, core MLM8 was recovered in June 2004 from the exposed marl shelf at the southern side near the margin of the permanent lake (52° 59.918′ N, 9° 01.359 W′, 30 m a.s.l.) using an Usinger piston corer (Mingram et al., 2007). The sedimentary sequence at the coring site consisted of, from bottom to top, ca. 25 cm of marl with a dark silt/clay on top (presumed to relate to the Bølling/Allerød and Younger Dryas, respectively), followed by fine silty light-grey marl (953–442 m) and then coarser marl (to 133 cm). Above this was fen peat (recorded in a parallel core, MLM7) with ca. 5 cm of marl at the top of the sequence, which is assumed to be recently formed. Core COR3 was recovered in October 2003 using an Usinger pistor corer from the infilled basin that once formed part of lower Lough Corrib (see above; 53°20.849′ N, 9°0.125′ W, 15 m a.s.l.). At the base, sediments that date to the Late-glacial were recovered (911–1071 cm). Marl, mainly fine and cream-coloured, containing abundant intact shells and laminated in parts was recorded between 911 cm and 191 cm. Above this lay poorly humified peat with abundant remains of *Eriophorum* and *Phragmites*. Several metres of peat are 'missing' as a result of peat cutting, presumably early and mid last century.

The chronology is based on AMS ^{14}C dates derived from terrestrial plant macrofossils for LA2B and MLM8. The dates were calibrated using IntCal13 (Reimer et al., 2013) and age-depth modelling performed using Clam 2.2 (Blaauw, 2010) (Fig. 2). Insufficient plant macrofossils were recovered for dating from COR3, but well-dated palynological events that are clearly expressed provide a satisfactory chronology in the absence of radiocarbon dates (Fig. 2).

We use the ratio of *Betula* to *Corylus* pollen as a palynological marker for the cooling event to refine the correlation of the early Holocene. These taxa are particularly useful in that *Corylus*, as a thermophile, is particularly sensitive to cooling, while *Betula* (presumably the tree birch species, *B. pubescens*), tolerates cold conditions, and so its pollen frequency relative to *Corylus* is expected to increase (see Ghilardi and O'Connell, 2013; Molloy and O'Connell, 2014).

Oxygen-isotope analyses of material from all three cores were undertaken at the Bloomsbury Environmental Isotope Facility (BEIF) in University College London (UCL). Bulk sediment samples were treated with 'chlorox' to remove organic matter and sieved though a 125 μm sieve in order to remove shell material and so isolate the fine fraction that is assumed to be endogenic. The fine fraction was then analysed using a ThermoFinnigan Delta Plus XP mass spectrometer connected to a GasBench. Oxygen-isotope values are reported in standard delta notation relative to the VPDB standard, with 1σ uncertainty of 0.08‰ based on 24 measurements of NBS19 during the period of sample analysis.

Oxygen isotope ratios of 2.5 mL water samples were measured by standard CO_2 equilibration (Epstein and Mayeda, 1953; Horita and Kendall, 2004) at 25 °C for 48 h in a constant temperature bath. After equilibration the CO_2 was recovered cryogenically and

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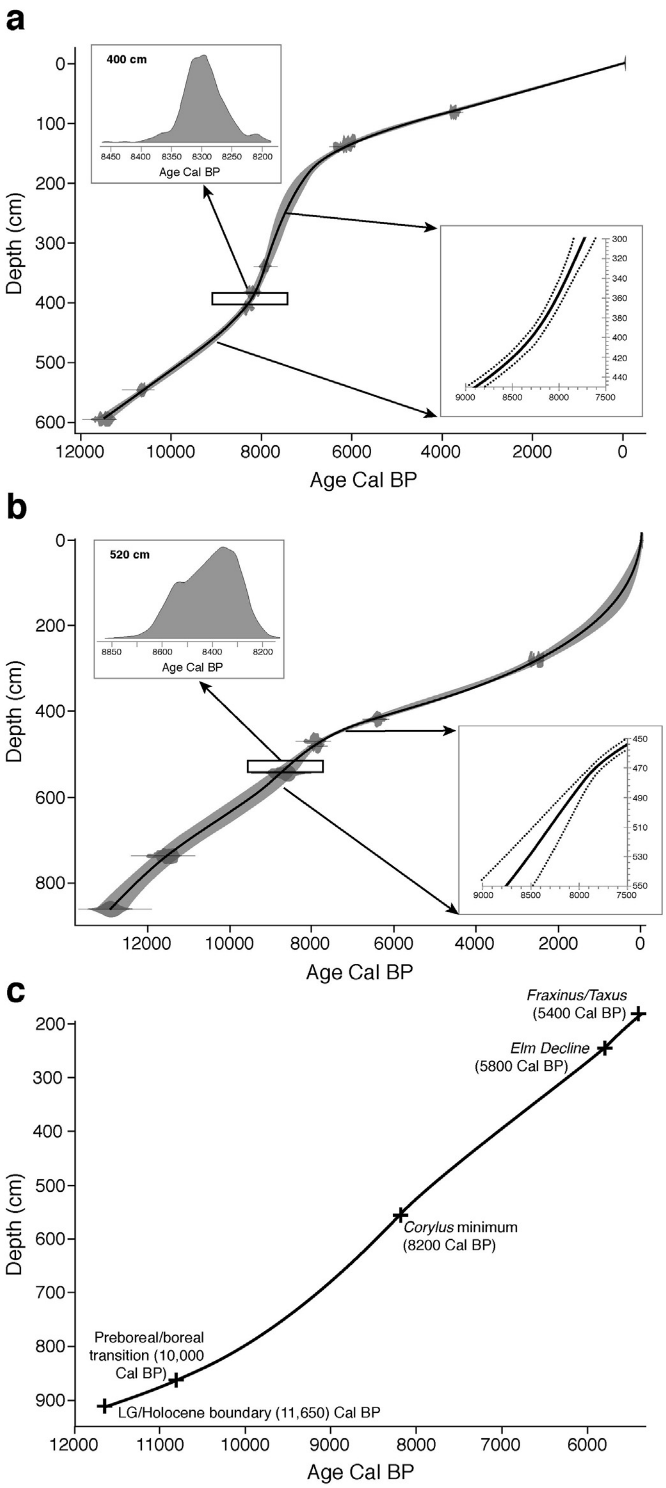

Fig. 2. Age-depth relationships for (a) Loch Gealáin core MLM8 and (b) Loch Avolla core LA2B, based on radiocarbon dates. (c) Lough Corrib core COR3. Events of well-established age that are clearly expressed and shown above include the late-glacial/Holocene transition, the Preboreal/Boreal transition (sharp early Holocene rise in *Corylus*), a substantial decline in *Corylus* at the 8.2 kyr, the mid-Holocene Elm Decline, and the *Fraxinus* and *Taxus* curves). The datapoints are well describe by a 4th order polynomial, AGE $=$ 0.000000046 Depth^4 $-$0.000086653 Depth^3 $+$ 0.0564689201 Depth^2$-$7.4261168482 Depth $+$ 5352.955, where age is in calendar years BP and depth is in cm.

analysed using a VG SIRA 10 mass spectrometer at the University of Liverpool. Isotope ratios are reported in standard delta (δ) notation in per mil (‰) relative to VSMOW (Coplen, 1988). Analytical precision based on replicate analysis of a standard laboratory water (Liverpool Tap Water) was ±0.04‰ (1σ).

2.3. Model simulations

The model simulations that are compared to the lake-sediment data in this paper are presented in Tindall and Valdes (2011), but they are also briefly described here for completeness. The model used for these simulations is the HadCM3 GCM (Gordon et al., 2000; Pope et al., 2000) with isotope tracers included (Tindall et al., 2009). HadCM3 has resolution of 3.75° $\times$ 2.5° with 19 vertical levels in the atmosphere, and 1.25° $\times$ 1.25° with 20 vertical levels in the ocean. This resolution is clearly too coarse to explain similarities and differences between the sites here, as there is only one model gridbox to represent the whole of Ireland. However, it does provide information about general patterns over the North Atlantic region and how the site data could relate to the wider climate system.

The 8200-year simulations were started from a background climate, which was intended to represent 9000 yr BP and had orbital variability (Berger, 1978), trace gases (EPICA-community-members 2014) and ice sheets (Peltier, 2004) appropriate to this time. The freshwater forcing (meltwater pulse, or MWP) added to represent the final drainage of the Lake Agassiz was 5 Sv for 1 year, which is at the upper limit of what was plausible (Clarke et al., 2004), and had a δ^{18}O value of $-$30‰. A total of nine simulations of the 8200-year event are included here, which differ by location of freshwater input or the initial AMOC state (see Tindall and Valdes, 2011 for more details). This paper will predominantly focus on the mean response from these nine simulations, although the range of values provides information about the uncertainties of the modelled response.

3. Results

3.1. Lake-sediment records

All three records show distinct, ~centennial-scale negative excursions in δ^{18}O values in the early Holocene (Fig. 3). In LA2B, average δ^{18}O values prior to the excursion, from ~8900 to 8500 cal yr BP, were ~$-$5.4‰. The negative excursion, which reached a minimum δ^{18}O of $-$6.1‰, lasted from 8490 to 8380 cal yr BP, after which values returned to an average of about $-$5.4‰. The δ^{18}O record in MLM8 is more noisy, although shows broadly similar characteristics. In the period before the excursion, from ~8900 to 8400 cal yr BP, values were ~$-$5.1‰ although highly variable. The negative excursion, which reached a minimum δ^{18}O of $-$6.1‰, lasted from 8400 to about 8200 cal yr BP, after which values returned to an average of about $-$5.4‰. In COR3, although the negative excursion is present, it barely exceeds the background variability. The COR3 stable-isotope record is also shorter than the records from MLM8 and LA2B, although all three records share some common features. In the period before the excursion in COR3, from ~8700 to 8300 cal yr BP, δ^{18}O values are around $-$5‰. During the negative excursion, from ~8300 to 8160‰, they fall to $-$5.8 ‰ before rising to $-$5‰ after the event. In all three records, there is evidence for two negative phases to the excursion, which are separated by slightly more positive δ^{18}O values.

Differences in the age of the negative excursion are likely to be the result of dating uncertainties rather than time-transgressive behaviour of the isotope records between these neighbouring sites. This is supported by the occurrence of a peak in the ratio of *Betula* to *Corylus* close to the minimum δ^{18}O value in each core. We note that the minimum δ^{18}O value COR3 is slightly higher than that in both LA2B and MLM8.

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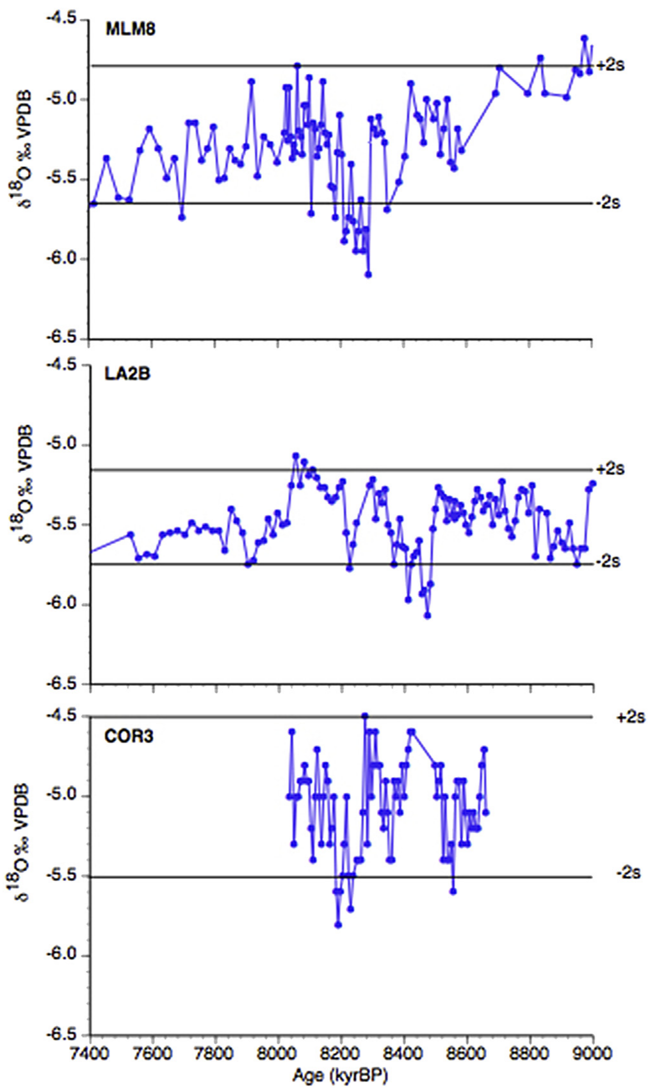

Fig. 3. Oxygen isotope profiles for MLM8, LA2B and COR3 versus calendar age. Each sequence is plotted against its own independent age scale. The ±2 σ values represent the variability in oxygen-isotope values for the period before and after the negative excursion.

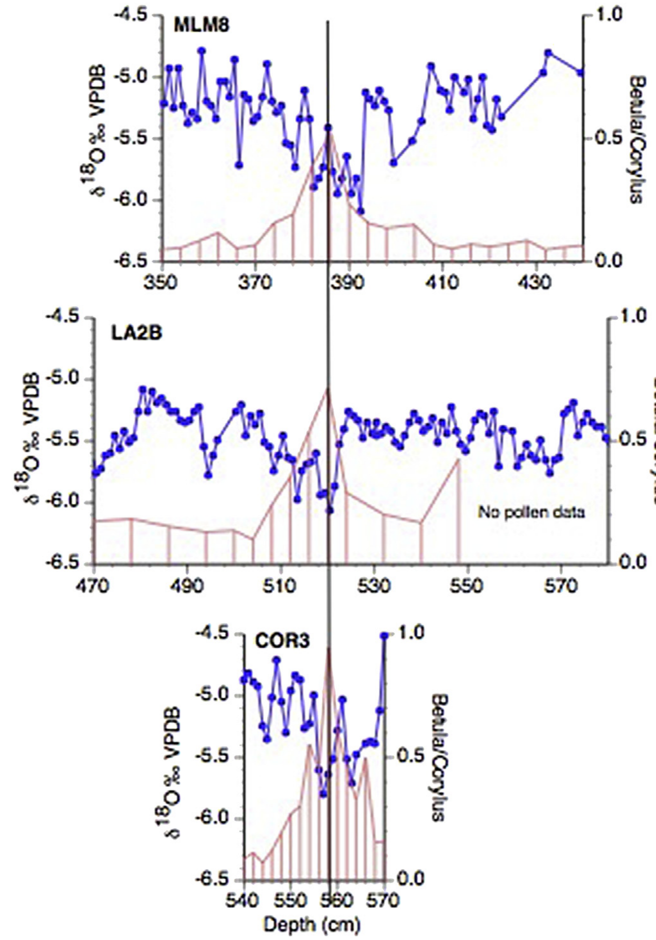

Fig. 4. Oxygen isotope profiles and *Betula*/*Corylus* pollen ratio values for MLM8, LA2B and COR3. The grey vertical line marks the peak in the *Betula*/*Corylus* ratio, which is assumed to be an age-equivalent marker. Data are plotted against depth (cm).

3.2. Model results

The temporal structure of the event over Ireland as modelled by HadCM3 is shown in Fig. 5, for $\delta^{18}O_p$, temperature and precipitation. In all cases a 20 year backward moving average has been applied, since the temporal resolution of the lake-sediment data is ~20 years, and applying this averaging should facilitate a better model – data comparison. However the application of this moving average does obscure the extremely sharp initial cooling seen in the model results (which lasted <1 year). This initial (<1 year) response showed an ensemble mean reduction of about 2‰ in $\delta^{18}O_p$ and a cooling of 2.3 °C, but with no apparent change in ensemble mean precipitation amount. The first decade after the initial cooling showed a substantial recovery towards background early Holocene conditions, with $\delta^{18}O_p$ showing a 65% recovery and temperature showing a ~75% recovery. However the background mean state was not reached until ~50 years after the MWP for $\delta^{18}O_p$ or ~100 years after the MWP for temperature. We also note that the average response does not occur in any single ensemble member, with most individual ensemble members having a much noisier pattern of recovery. For example, an initial temperature drop of ~2.5 °C with a decadal scale full recovery to the control temperature followed by a secondary (or even tertiary) drop in temperature of 1 °C is common, as is a relatively smooth recovery to the control state over several decades. Although there is no clear precipitation signal in the ensemble average at this location, there is a precipitation reduction in individual ensemble members and at other locations close to the site; hence the modelling does not preclude a reduction in precipitation at this site. The 20-year average response shows a reduction in $\delta^{18}O_p$ value and temperature of −0.8‰ and −0.7 °C, respectively. It is asymmetrical in both fields, with the cooling occurring more quickly than the recovery, although the recovery in temperature occurs more slowly than the recovery in $\delta^{18}O_p$.

4. Interpretation and discussion

4.1. Carbonate isotope records

The three isotope records can be synchronized biostratigraphically by aligning the peaks in the Betula/*Corylus* ratio (Fig. 4), and put onto a common timescale assuming synchronicity of the $\delta^{18}O_c$ minima. Their $\delta^{18}O$ records can then be superimposed and compared directly (Fig. 6). This reveals an extremely close similarity between the records in terms of both the event duration and the shape of the records. All sites show an abrupt fall in $\delta^{18}O$ values, marking the onset of the 8200-year event, followed by a

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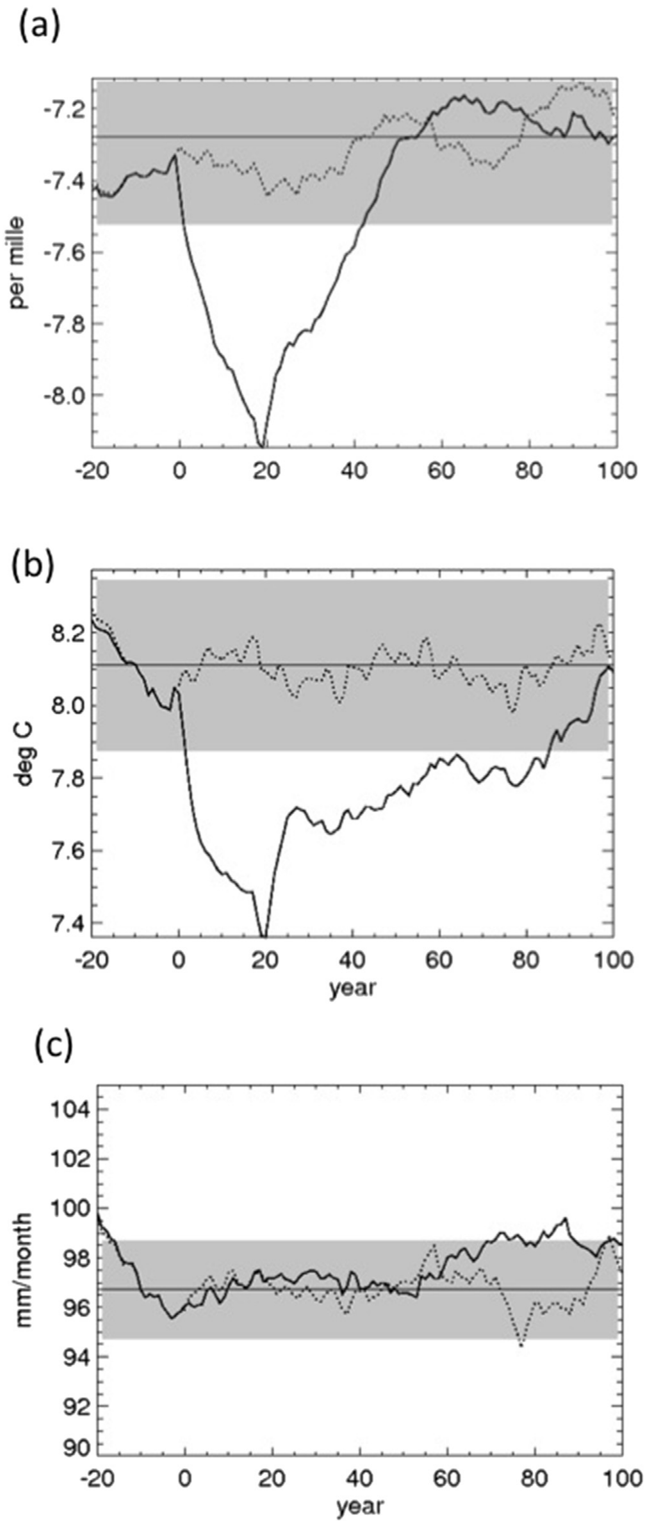

Fig. 5. The structure of the 8.2 ka event in the 8.2 ka modelled ensemble average for the gridbox centred on 52.5 N, 7.5 W. (a) $\delta^{18}O_p$ (b) temperature (c) precipitation. The solid line shows the ensemble average from the experiments, which incorporates the drainage of Lake Agassiz at year 0, with data smoothed using a 20 year backward moving average. The dotted line is a corresponding average from the control run and shows the variability that would be expected without the Lake Agassiz drainage. The straight horizontal line shows the average from the control run and the shaded area is the region that is within 1 standard deviation of the control mean. Note that time runs from left to right on the x-axes.

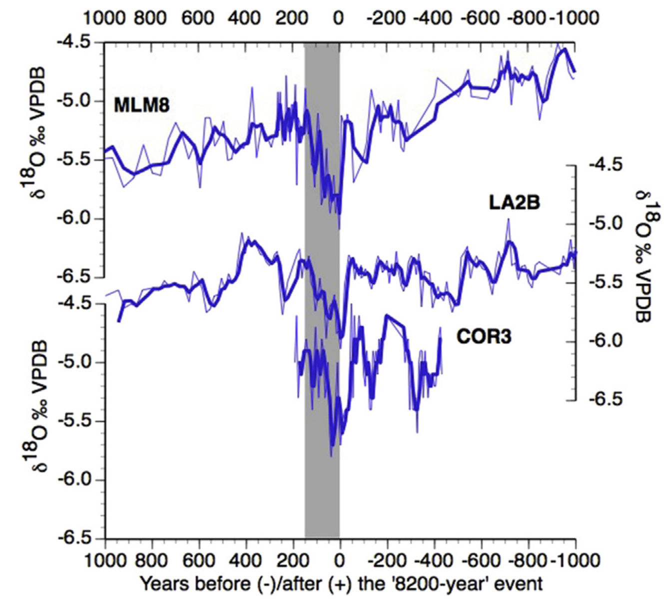

Fig. 6. Oxygen-isotope profiles for MLM8, LA2B and COR3 on a 'common' timescale. On the assumption that the negative $\delta^{18}O_c$ excursions at the two sites are contemporaneous, year zero is taken to be the minimum $\delta^{18}O_c$ for each profile. For each sequence, faint line joins the individual datapoints, heavy line is a 3-point moving average. Note that time runs from right to left on the x-axis.

more gradual recovery to pre-disturbance levels. The similarity of the records from Loch Avolla and Lough Gealáin is not surprising given that the two lake systems are hydrologically connected via the groundwater system in the eastern Burren, but the replication gives confidence that their sedimentary records are robust and representative of regional hydrological changes. The similarity of these two records with that from Lough Corrib, which is some distance away and hydrologically very different, adds further confidence to the view that the records are regionally representative. Another highly significant feature of the comparison between the LA2B and MLM8 is that both sequences reach the same $\delta^{18}O_c$ minimum value, −6.1‰, during the isotope excursion. This in turn implies that the two lake water isotope systems are unlikely to have been affected by any evaporative effects at this time. By contrast, immediately prior to and, to a lesser degree, after the 8200-year event, Loch Gealáin shows $\delta^{18}O$ values that are ^{18}O-enriched by ~0.2‰ relative to Loch Avolla, implying a small evaporative effect in the former lake, as is also the case today. Loch Avolla, by contrast, shows no evidence of evaporative effects on the lake isotope hydrology either at the present-day or (by inference) during the early Holocene. The minimum $\delta^{18}O$ value in COR3 during this event is slightly less negative than that at the other two sites, implying slight evaporative enrichment of Lough Corrib even during the cold phase, lower water temperatures (and hence greater fractionation of ^{18}O between calcite and water), differences in the hydrological system leading to elevated $\delta^{18}O$ in lake water, or a combination of all of these. We also note that both before and after the negative excursion, $\delta^{18}O$ values in COR3 are closer to those in MLM8 than in LA2B, suggesting that Lough Corrib waters were slightly evaporated throughout the early Holocene.

4.2. Reconstruction of $\delta^{18}O_p$

The oxygen-isotope value of calcite precipitated in a lake is a function of the temperature and isotopic composition of the water at the time of precipitation, together with any disequilibrium effects. If we can assume that the lake-sediment calcite in our material precipitated in isotopic equilibrium and are able to estimate temperature changes during the 8200-year event, it should be possible to calculate the change in the isotopic composition of lake water that accompanied the cooling episode. Furthermore, using the arguments above for the lack of evaporative enrichment of Loch Avolla during the early Holocene, and of both Loch Avolla and Loch Gealáin during the 8200-year cooling interval, we can use reconstructed $\delta^{18}O_w$ values as an approximation for the isotopic composition of precipitation and this value can then be compared with the model results.

It is reasonable to assume that the calcite was precipitated in oxygen-isotope equilibrium, based on studies in similar lakes in the mid-latitudes (e.g. Marshall et al., 2007). We have no proxies for temperature depression during the 8200-year event from our sites, but the modelled temperature reduction is ~−0.7 °C so a decline of this order may have accompanied the average measured decline of −0.9‰ in $\delta^{18}O_c$ (Fig. 6). If so, and assuming isotopic equilibrium in accordance with Kim and O'Neil (1997), the corresponding change in $\delta^{18}O_w$ (and by inference $\delta^{18}O_p$) would have been −0.9 to −1.2‰, averaging −1.1‰ across the three records. Both variables show somewhat smaller changes than those recorded at Hawes Water, Lancashire, where Marshall et al. (2007) reported a ~1.6 °C decline in average temperature of the warmest month (estimated by the chironomid transfer function technique), and inferred a ~1.3‰ decrease in $\delta^{18}O_p$. Whether these differences reflect real contrasts between the two sites, or are largely a function of the differing approaches to the calculation, is unclear, but propagation of estimated uncertainties for the chironomid-based temperatures in Marshall et al. (2007) gives an overlap at 1σ with our best estimate for $\delta^{18}O_w$.

4.3. Model simulations and data − model comparisons

The maximum amplitude of change in $\delta^{18}O_p$ values during the modelled cooling event (−0.8‰; Fig. 5a) and that inferred from the lake-sediment data (~−0.9‰) are in fairly good agreement. However, the duration of the modelled event (~50 years in $\delta^{18}O_p$ or ~100 years in temperature) is shorter than that in the lake-sediment data (between 100 and 200 years). The model response is also too short when compared with other palaeoclimatic data (e.g. Daley et al., 2011) and is likely explained by the non-inclusion of background forcing from the melting ice sheets in these simulations (Wagner et al., 2013). Moreover, there is some evidence for two asynchronous phases in meltwater release (Teller et al., 2002), whereas the model experiments include only one. However, there is good agreement between the depiction of the internal structure of the isotope excursion by the model and lake sediment data, in that both show the event to be non-symmetrical, with the cooling occurring more rapidly than the recovery. The modelled $\delta^{18}O_p$ response (Fig. 5a) and modelled temperature response (Fig. 5b) to the MWP support the suggestion that the majority of the $\delta^{18}O_c$ oscillation is the result of changes in $\delta^{18}O_p$ at the time, while the ~−0.7 °C change in modelled temperature would have the effect of reducing the amplitude of $\delta^{18}O_p$ that is seen in $\delta^{18}O_c$ by <0.2‰.

Because there is good agreement between model and data over Ireland, it is useful to explore the modelled response further to ascertain possible climate patterns that are consistent with the palaeoclimatic data. Fig. 7 shows the average response across the nine simulations for the 20 years immediately following the MWP. These results are only indicative, however, because there are differences in the exact location of the response and the amplitude of the response in each of the simulations, despite the fact that the forcing conditions for the simulations were very similar. However, all simulations agree that there is a reduction in temperature, $\delta^{18}O_p$, precipitation amount and evaporation, in the vicinity of the study sites. The reduction in evaporation is larger than the reduction in precipitation, such that the effective moisture increased. However, because both fields are quite noisy it would be consistent with the modelling if some data sites were to show no increase in effective moisture. The model also suggests that the relationship between temperature and $\delta^{18}O_p$ is not simple. For example it is clear that the $\delta^{18}O_p$ anomaly is much the same over the region north of the UK as it is over France, whereas the temperature anomalies are different, so that the slope $d(\delta^{18}O_{p)}/dT$ is much smaller in the north than the south. Several modelling studies suggest that temporal $\delta^{18}O_p$ is indicative of regional temperature change and has only a weak correlation with local temperature change (Schmidt et al., 2007; Tindall and Haywood, 2015, Sime et al., 2009).

4.4. Pollen records

In addition to contributing to biostratigraphical correlation between our three study sites, the pollen data provide information about palaeoenvironment during the 8200-year event. Here we provide brief details based on the pollen data for each site. Further details on the records from COR3 and MLM8 are provided in Bingham (2011) and Feeser (2009), respectively.

Pollen data for all three sites indicate a woodland perturbation during the early Holocene characterised by reduced *Corylus* repsentation and an increase in *Betula*. An opening-up of the woodland structure is also indicated by increased NAP representation in MLM8 (not shown here), expressed mainly as elevated Poaceae and *Pteridium* values, the latter a fern that is normally favoured by woodland disturbance and opening-up of the canopy. As *Corylus*, in comparison to *Betula*, is the more thermophilous species this might suggest a shift towards cooler climatic conditions or increased continentality with increased seasonality and decreased precipitation. Evidence for a contemporaneous change in within-lake conditions in Loch Gealáin (MLM) supports such a shift in climate. Increased representation of *Botryococcus* and Characeae oogonia, slightly lower organic carbon values and the occurrence of plate-like carbonate morphotypes with lower water conditions at the lake-inward edge of the littoral platform of marl lakes (Magny et al., 2003), all point to generally lower lake levels (Feeser, 2009). This contrasts with our inference drawn from the stable isotope data, of *increased* effective moisture.

4.5. Discussion

The −0.9‰ shift in $\delta^{18}O_p$ during the 8200-year event inferred from the carbonate isotope records agrees well with the shift seen in the model runs (−0.8‰) and is very consistent with geographical patterns presented in Daley et al. (2011): moreover, the results from the three sites studied here are very coherent. Note also the pattern of change, with a very sharp initial fall in $\delta^{18}O$ followed by a more gradual return to pre-decline values, is consistent between model runs and lake-sediment data. The reduction in temperature indicated in the model results also agrees qualitatively with pollen data that provide evidence for abrupt reduction in temperature during the 8200-year event. Two-phases of cooling separated by amelioration, as seen in the highest-resolution pollen record from MLM8 (Feeser, 2009; but not illustrated here) may also be present in the stable-isotope data.

In a detailed study of recent, event-based, $\delta^{18}O_p$ records from Dublin, Baldini et al. (2010) found that air mass history, related to atmospheric circulation, had a strong influence on the isotopic composition of precipitation, and warned against simplistic interpretation of palaeo-$\delta^{18}O_p$ records in terms of either temperature or precipitation amount. In combination therefore, our results provide some support for a shift in atmospheric circulation during the

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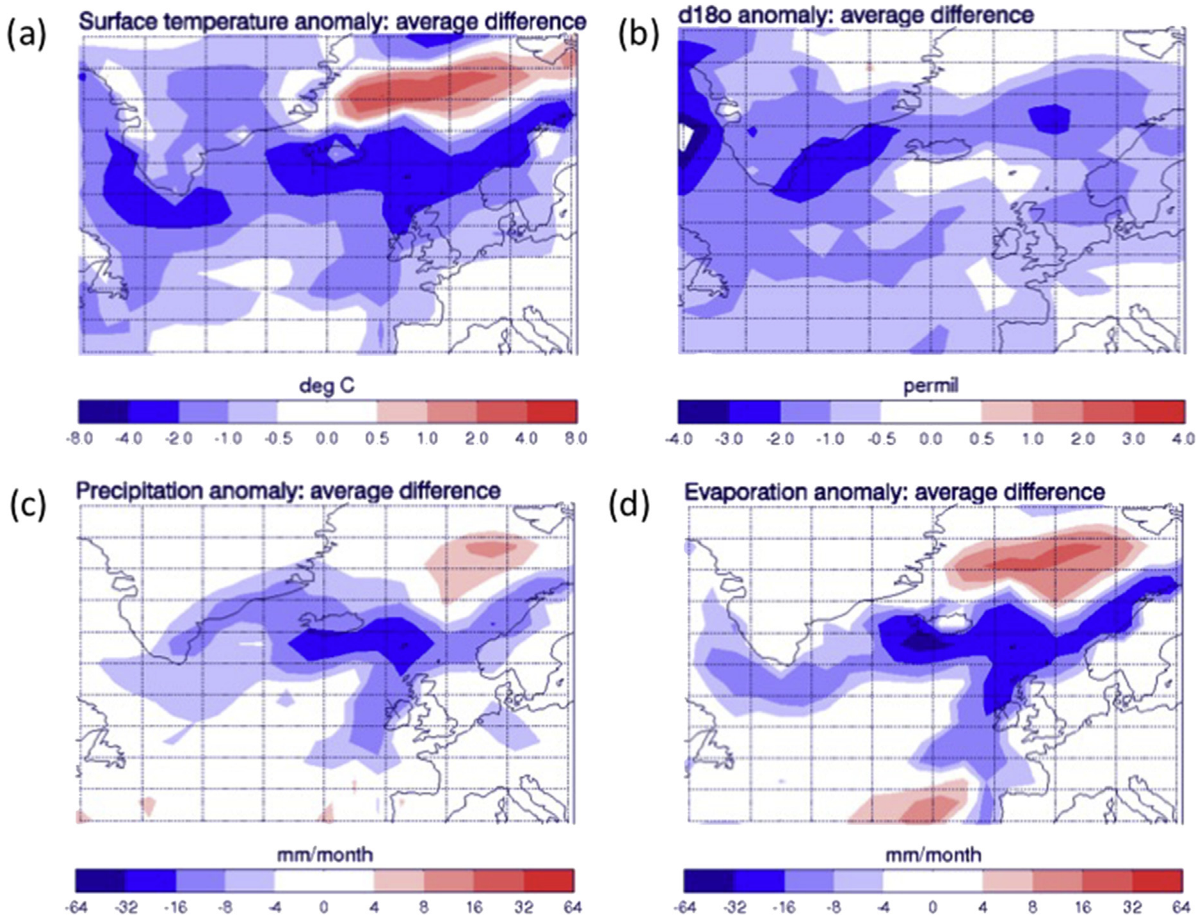

Fig. 7. Ensemble average climate anomalies in the vicinity of the lake-sediment sites in western Ireland for the 20 years following the meltwater pulse.

8200-year event, which was accompanied both by a cooling and a reduction in precipitation.

Convergence of the $\delta^{18}O_c$ values for MLM8 and LA2B (and to a lesser extent COR3) during the cooling implies reduction in evaporation, which is consistent with the cooling. Modelling results presented here as well as other records from Ireland and from NW Europe lend support to the idea of reduced precipitation during the cooling event, although this appears to have been over-ridden by decreased temperatures and hence decreased evaporation. However, the apparent fall in lake level of Loch Gealáin during the cooling event, as suggested by the carbonate mineralogy and pollen data, does not support an increase in effective moisture.

5. Conclusions

Oxygen-isotope records from three sites in western Ireland show a negative excursion in $\delta^{18}O_c$ values during the early Holocene, coincident with the 8200-year cooling event. This negative excursion is best explained by a transient reduction in $\delta^{18}O_p$ values. Although it was likely accompanied by both a cooling and a reduction in precipitation (as suggested by the pollen data and evident in the model results), changes in $\delta^{18}O_p$ values are probably explained as much by a change in atmospheric circulation during the early Holocene as by a direct response to reduced atmospheric temperature. The asymmetrical temporal structure of the event, with rapid onset and more gradual recovery, is apparent both within the lake-sediment data and the model simulations. However, the oscillation within the model simulations seems rather too short compared with the data presented in this paper and with published records (e.g. Daley et al., 2011), probably the result of background forcing being omitted from the model runs. Previous studies have suggested changes in atmospheric circulation during the 8200-year event and stable-isotope records provide sensitive tracers for such changes, especially when coupled with evidence from proxies for temperature or precipitation. Future work should focus on enhancing our understanding of such changes in atmospheric circulation as well as developing lake-based models for specific sites in order to better constrain the carbonate oxygen-isotope records.

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