

## Rapid Communication

# A major widespread climatic change around 5300 cal. yr BP at the time of the Alpine Iceman

MICHEL MAGNY<sup>1\*</sup> and JEAN NICOLAS HAAS<sup>2</sup>

<sup>1</sup> Laboratoire de Chrono-Ecologie, Faculté des Sciences et Techniques, 16 route de Gray, 25 030 Besançon, France

<sup>2</sup> University of Innsbruck, Department of Botany, Division of Palynology, Systematics and Geobotany, Sternwartestraße 15, 6020 Innsbruck, Austria

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**ABSTRACT:** Palaeoenvironmental and archaeological data from Arbon Bleiche, Lake Constance (Switzerland) give evidence of a rapid rise in lake-level dated by tree-ring and radiocarbon to 5320 cal. yr BP. This rise event was the latest in a series of three successive episodes of higher lake-level between 5550 and 5300 cal. yr BP coinciding with glacier advance and tree-limit decline in the Alps. This west-central European climate change may have favoured the quick burial and the preservation of the Alpine Iceman recently found in the Tyrolean Alps. It has possible equivalents in many records from various regions in both hemispheres dating to 5600–5000 cal. yr BP and corresponds to global cooling and contrasting patterns of hydrological changes. This major mid-Holocene climate event marks the Hypsithermal/Neoglaciation transition possibly resulting from a combination of different factors including orbital forcing, changes in ocean circulation and variations in solar activity. Copyright © 2004 John Wiley & Sons, Ltd.



**KEYWORDS:** mid-Holocene; climate change; interhemispheric linkages; solar activity; orbital forcing; ocean circulation.

## Introduction

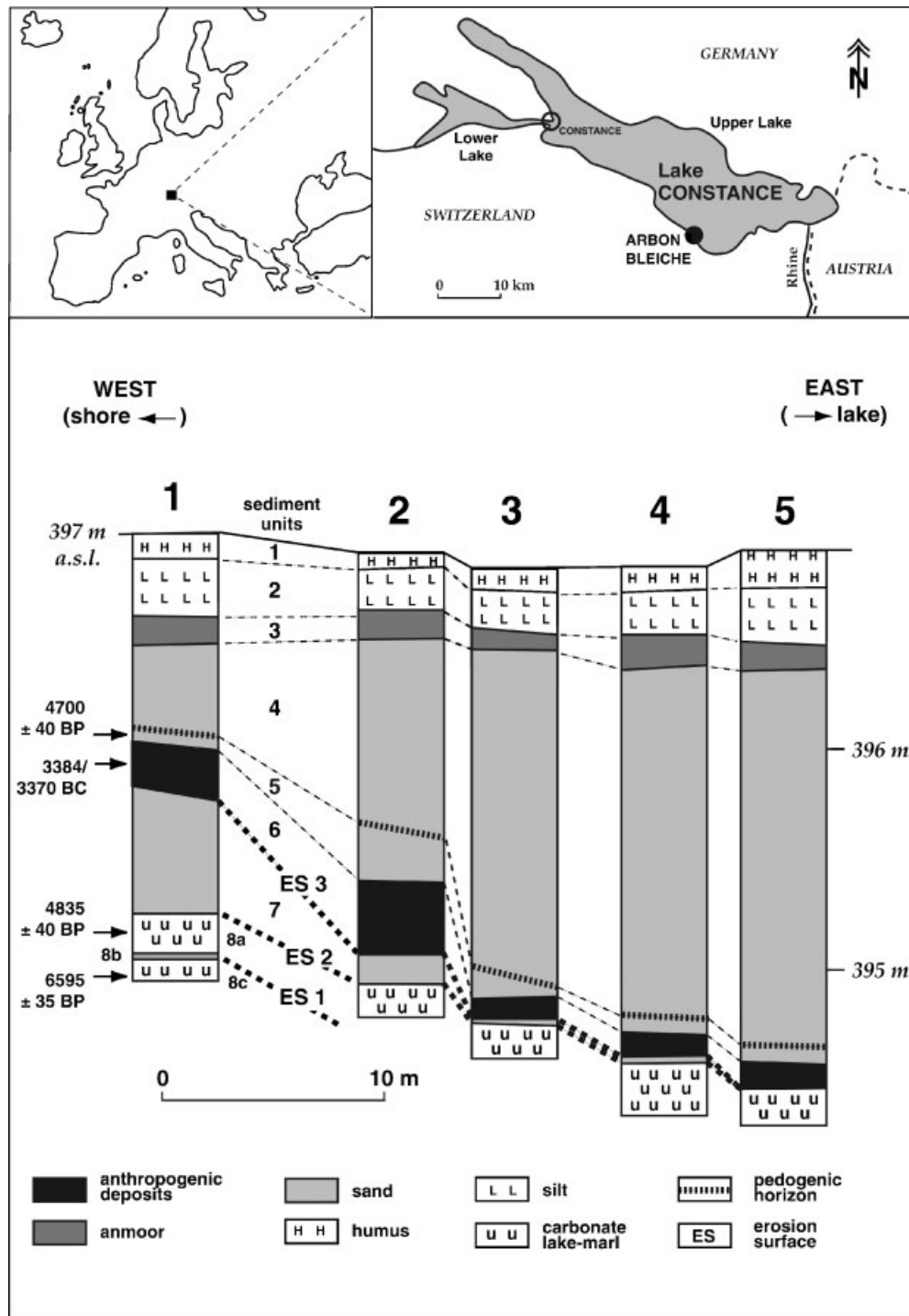
From several points of view, the Alpine Iceman found in September 1991 in the Tyrolean Alps is the most exciting European archaeological discovery in recent years (Höpfel *et al.*, 1992). Radiocarbon dated to 5320–5050 cal. yr BP (Kutschera and Müller, 2003), he appears to be the oldest well preserved pre-historic body ever discovered in Europe, even older than the Egyptian royal mummies. It has been hypothesised that the striking preservation of this Neolithic man and his equipment resulted from a quick burial below snow and ice cover owing to rapid climate cooling (Baroni and Ombelli, 1996). This paper presents palaeoenvironmental and archaeological evidence of an abrupt climate change at 5550–5300 cal. yr BP at Arbon Bleiche, Lake Constance (Switzerland), i.e. ca. 110 km west of the Tyrolean Alps. Cooler and wetter conditions associated with this climatic oscillation may actually have favoured the rapid burial of the Alpine Iceman. Moreover, climatic changes possibly correlative to this event can be observed in

many palaeoclimatic records from both hemispheres. This suggests a more global significance of the climate oscillation recorded at Arbon Bleiche that was responsible for the preservation of the Alpine Iceman, and allows increasing understanding of the mechanisms and underlying forcing factors of this mid-Holocene climatic reversal.

## The Arbon Bleiche record in west-central Europe

The site of Arbon Bleiche (47.30° N, 9.25° E, 397 m a.s.l.) is located on the southeastern shore of Lake Constance (Fig. 1). This lake has the second largest surface area of all European peri-Alpine lakes. The main inflow is the Alpine River Rhine draining an area of more than 6100 km<sup>2</sup> in the Alps. Archaeological investigations recently revealed remains of a Neolithic lake-shore village established in the former shallow bay of Arbon Bleiche, which was dendrochronologically dated to 5334–5320 cal. yr BP (Leuzinger, 2000). Figure 1 presents the sediment sequence observed in the investigation area. Palaeoenvironmental studies have focused on the reconstruction of lake-level and vegetation cover before, during and just after the neolithic settlement. The results have been described

\*Correspondence to: Michel Magny, Laboratoire de Chrono-Ecologie, Faculté des Sciences et Techniques, 16 route de Gray, 25 030 Besançon, France.  
E-mail: michel.magny@univ-fcomte.fr



**Figure 1** Upper panel: Geographical location of the site of Arbon Bleiche, Lake Constance (Switzerland). Lower panel: the sediment sequence of Arbon Bleiche

extensively elsewhere (Haas and Magny, in press). The present paper deals only with data obtained from units 8 to 5 at the base of the sediment sequence (Fig. 1), which documents the period around 5600–5200 cal. yr BP.

Unit 8 is composed of carbonate lake marl and divided into two subunits, 8a and 8c, by a thin sand layer (subunit 8b) where the presence of beach pebbles marks an erosion surface (ES1) responsible for a sediment hiatus in agreement with the radiocarbon dates. The transition between units 8 and 7 coincides with a second erosion surface (ES2) marked by a sharp change in sediment composition, the presence of beach pebbles and the pollen stratigraphy (Table 1). Unit 7 is a sand layer 1 to

60 cm thick. It is missing in the eastern part of the site as a result of erosion: erosion surface (ES3). Unit 6 is a 5 to 40 cm thick archaeological layer mainly composed of anthropogenic organic material. Unit 5 is a 10 to 30 cm thick sand layer containing remains resulting from the destruction of the Neolithic houses. The contact between units 5 and 4 is marked by a pedogenic horizon.

The chronology is based on (i) AMS radiocarbon dates from terrestrial plant macrofossils and (ii) tree-ring dates from wooden piles used by prehistoric people for dwelling construction. The lake-level fluctuations were reconstructed using a specific sedimentological method (Magny, 1992, 1998) in addition to

**Table 1** Changes in lake-level and vegetation cover reconstructed from the sediment sequence of Arbon Bleiche (Switzerland). Note that the death of the Alpine Iceman is radiocarbon-dated to 5320–5050 cal. yr BP (Kutschera and Müller, 2003), i.e. close to the sudden rise in lake-level in Arbon Bleiche at 5320 cal. yr BP

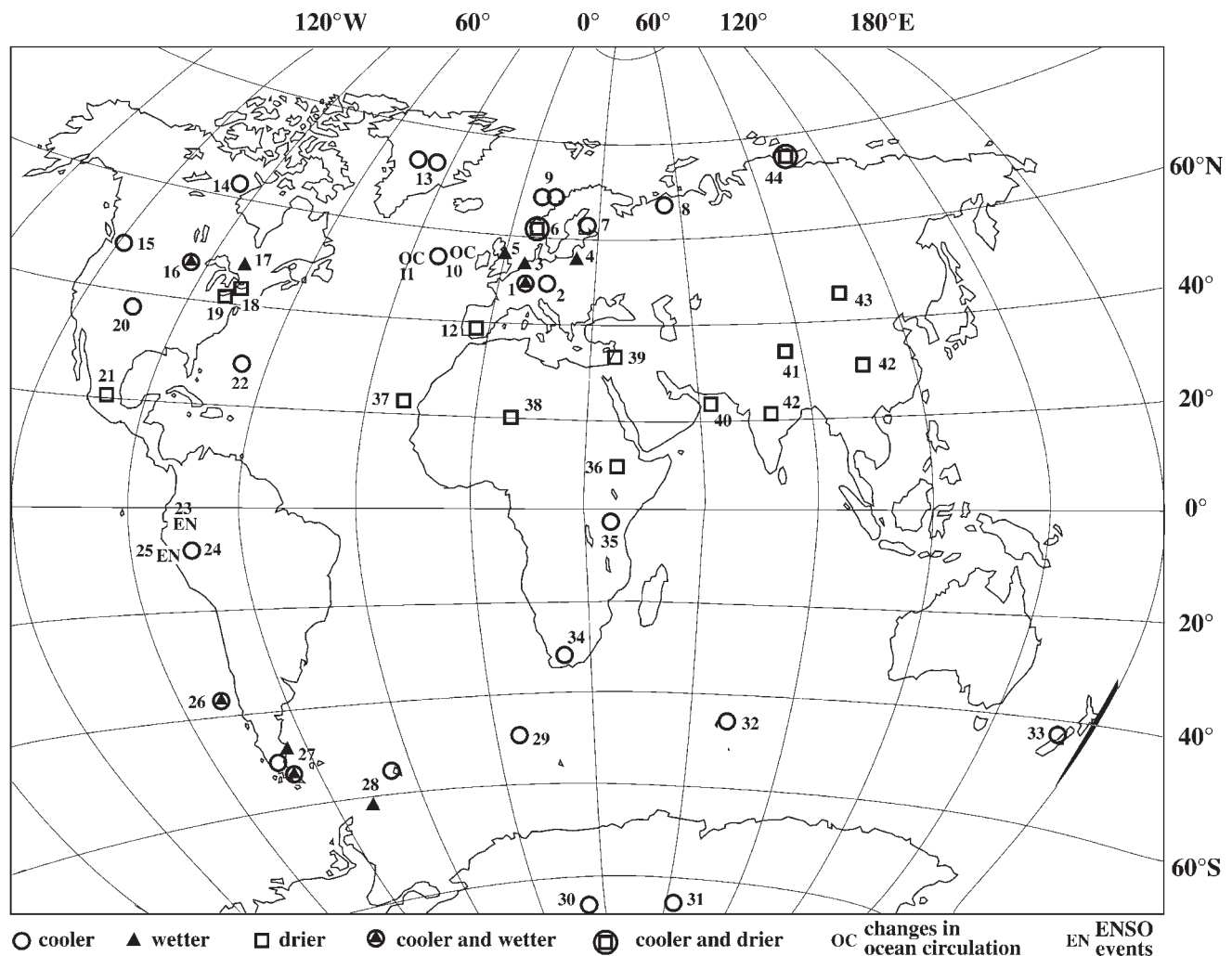
Soil/erosion surface	Sediment units	Lithology	Ages	Lake level	Pollen zones
Pedogenic horizon	4	Sand		High Low	
	5	Sand	4700 ± 40 <sup>14</sup> C yr BP, i.e. 5583–5317 cal. yr BP (VERA 2486)	High	Subboreal (rising values of <i>Fagus</i> , <i>Abies</i> , <i>Picea</i> and <i>Ulmus</i> decline)
Erosion surface 3	6	Anthropogenic organic deposits	5334–5320 cal. yr BP (Zürich Laboratory)	Low	
	7	Sand	ca. 5440 cal. yr BP (interpolated age)	High Low	
Erosion surface 2	8a	Carbonate lake-marl	4835 ± 40 <sup>14</sup> C yr BP, i.e. 5602–5492 cal. yr BP (VERA 1701)	High	Younger Atlantic ( <i>Quercetum mixtum</i> dominance, <i>Ulmus</i> > 5%)
	8b	Sand		Low	
Erosion surface 1	8c	Carbonate lake-marl	6595 ± 35 <sup>14</sup> C yr BP, i.e. 7560–7432 cal. yr BP (VERA 1703)	High	

changes in sediment texture and geometry of the sediment layers (Digerfeldt, 1988). Erosion surfaces 1 to 3 correspond to three phases of low lake-level, each followed by a phase of higher lake-level conditions responsible for the deposition of units 8a, 7 and 5 (Table 1). Morphotypes of carbonate concretions and shells of aquatic molluscs found in units 8a, 7 and 5 support this interpretation (Haas and Magny, in press). Thus, the lowering marked by ES3 favoured the installation of the neolithic village on the southeastern shore of Lake Constance, tree-ring dated to 5334–5320 cal. yr BP. Immediately afterwards, dated to 4700 ± 40 yr BP (i.e. 5583–5317 cal. yr BP), the deposition of unit 5 corresponds to a rapid rise in lake-level, which caused the village to be abandoned. This rise was the latest in a series of three successive episodes of higher lake-level, the first (unit 8a) occurring at 4835 ± 40 yr BP (i.e. 5602–5492 cal. yr BP) and the second (unit 7) at ca. 5440 cal. yr BP (interpolated age). Regarding the history of the vegetation cover, the transition from the Younger Atlantic to the Subboreal pollen zones occurred after the deposition of unit 8a (Table 1).

The changes in climatic conditions at 5600–5300 cal. yr BP, as recorded at Arbon Bleiche by vegetation and lake-level data, appear to be fully consistent with (i) a regional phase of higher lake-level dated to 5650–5200 cal. yr BP by radiocarbon and dendrochronology (Magny, 2004), and (ii) cooler conditions in the Alps indicated by glacier advance at ca. 5450–5000 cal. yr BP (Patzelt, 1977), tree-limit decline at ca. 5600–5200 cal. yr BP and changes in vegetation cover at 5600–5000 cal. yr BP (Schmidt *et al.*, 2002). The development of cooler and wetter climate conditions at that time in the Alps may explain the quick burial and preservation of the Alpine Iceman as hypothesised by Baroni and Orbelli (1996). More than 40 AMS radiocarbon dates (Kutschera and Müller, 2003) indicate that the death of the Alpine Iceman occurred at 5320–5050 cal. yr BP, i.e. close to the abrupt climate variation recorded by a sudden rise in lake-level in Arbon Bleiche at 5320 cal. yr BP. Furthermore, the 5600–5000 cal. yr BP climate reversal recognised in west-central Europe coincides with maximum values in the atmospheric <sup>14</sup>C content marked by three successive peaks at 5600, 5450 and 5300 cal. yr BP, i.e. close to the ages of the three successive episodes of higher lake-level reconstructed at Arbon Bleiche. This supports the hypothesis of an abrupt climate change forced by varying solar activity (Haas and Magny, in press).

## A major widespread climate reversal at 5600–5000 cal. yr BP

Mid-Holocene climatic reversal has been recorded by several authors and Fig. 2 presents a map of possibly correlative events in various regions in both hemispheres (based on selected data listed on Table 2). Bearing in mind the difficulties of assessing the exact temporal relationships owing to differences in dating accuracy and sample temporal resolution, it can be observed that most of the events fall in the 5600–5000 cal. yr BP time window and provide evidence for a generally prevailing climate cooling at that time, as shown by changes in vegetation cover (Heikkikä and Seppä, 2003), glacier advance (Benedict, 1973; Patzelt, 1977; Wenzens, 1999), decline in tree limit in mountains (Bortenschlager, 1977; Rochefort *et al.*, 1994), increasing permafrost and retreating timberline at high latitudes (Payette *et al.*, 2002; Väiliranta *et al.*, 2003), cooler sea-surface temperatures (Calvo *et al.*, 2002; Lamy *et al.*, 2002), or ice-sheet isotope records at the poles and in the tropics (Dahl-Jensen *et al.*, 1998; Masson *et al.*, 2000; Thompson *et al.*, 2002). For example, the cooling has been assessed at 1–1.5°C for mean summer temperature in the European Alps (Bortenschlager, 1977; Haas *et al.*, 1998), 0.75°C for mean annual temperature in Finland (Heikkikä and Seppä, 2003), 1–2°C for mean annual temperature in southern Africa (Jerardino, 1995), more than 1°C for sea-surface temperature (SST) in the Nordic Seas (Calvo *et al.*, 2002; Risebrobakken *et al.*, 2003), 0.6°C for SST off Chile (Lamy *et al.*, 2002), and 1.5°C in Greenland (Dahl-Jensen *et al.*, 1998). In addition, as suggested by Fig. 2, the 5600–5000 cal. yr BP period coincided with drier conditions in central Asia (Morrill *et al.*, 2003), in the northern part of Africa (Damnati, 2000; Chalié and Gasse, 2002; deMenocal *et al.*, 2000), in eastern North America (Kirby *et al.*, 2002), in Central America (Street-Perrott and Perrott, 1990), in the southern Mediterranean region (Carrion, 2002; Bar-Matthews *et al.*, 1999; Arz *et al.*, 2003) and at high latitudes (Nesje *et al.*, 2001; Andreev *et al.*, 2003). Figure 2 also suggests that, at the same time, wetter conditions prevailed over intermediate latitudes between ca. 40° and 60° latitudes in west-central Europe (Starkel, 1991; Langdon *et al.*, 2003; Blaauw *et al.*, 2004; Magny, 2004) and South America (Steig, 1999; Lamy *et al.*, 2002; Noon *et al.*, 2003).



**Figure 2** World-wide climatic change at 5600–5000 cal. yr BP according to the multiproxy records of study sites mentioned in Table 2

Such contrasting patterns of hydrological changes, in addition to a global temperature cooling, appear to be consistent with changes in the atmospheric methane content, which shows an inverse trend to increase from 5200 cal. yr BP in relation with the higher-/lower-latitude  $\text{CH}_4$  emission ratio (Blunier *et al.*, 1995). Moreover, these hydrological changes reflect a weakening of the African and Asian monsoon linked to cooler SST and a weaker thermal contrast between landmass and adjacent oceans (Damnati, 2000; Morrill *et al.*, 2003). They also suggest (i) a reinforcement and a migration of westerlies toward lower latitudes in response to a stronger thermal gradient between high and low latitudes (Magny *et al.*, 2001; Mullins and Halfman, 2001; Lamy *et al.*, 2002), and (ii) the establishment of modern El Niño periodicity in relation to the onset of a steeper zonal SST gradient over the tropical Pacific Ocean (Rodbell *et al.*, 1999).

Among potential causes of the climate reversal at 5600–5000 cal. yr BP, orbital forcing, changes in ocean circulation and variations in solar activity appear to be possible candidates. As indicated above, the 5600–5000 cal. yr BP event is placed just at the abrupt inversion in the interglacial trend of atmospheric methane values (Blunier *et al.*, 1995) and various other records show an abrupt climate oscillation at 5600–5000 cal. yr BP close to the beginning of a long-term climate reversal toward cooling (e.g. Calvo *et al.*, 2002; Dahl-Jensen *et al.*, 1998; Hodell *et al.*, 2001). This corresponds to the rapid

mid-Holocene transition from the Hypsithermal to the Neoglaciation (Steig, 1999). Despite apparent contradiction between progressive insolation changes and abruptness of events in many records at 5600–5000 cal. yr BP, model experiments have shown the ability of gradual insolation forcing to produce abrupt climatic oscillations owing to the non-linear sensitivity of the climate system when crossing threshold values (deMenocal *et al.*, 2000; Hodell *et al.*, 2001; Kirby *et al.*, 2002). However, some records also show a more progressive mid-Holocene climatic transition in response to orbitally driven changes in summer insolation. Thus, the ENSO frequency increased progressively as early as ca. 7000 cal. yr BP before the modern periodicity was established at ca. 5000 cal. yr BP (Rodbell *et al.*, 1999). Similarly, lake-level records from the Tibetan Plateau provide examples showing that the climate drying associated with the weakening of the Asian monsoon and the decrease in summer insolation began as early as 6900–6300 cal. yr BP (Gasse *et al.*, 1991), although a synthesis of multiple regional records also suggests an abrupt change at ca. 5000 cal. yr BP (Morrill *et al.*, 2003). The Asian monsoon and ENSO also have been considered as interacting systems affected by changes in insolation (Morrill *et al.*, 2003), and Schmittner *et al.* (2000) have pointed to the possible significance of the amplitude of ENSO events for the strength of the North Atlantic thermohaline circulation.

**Table 2** Non-exhaustive list for records of world-wide climatic change at 5600–5000 cal. yr BP. The site numbers are those indicated on Fig. 2. Note that site numbers may refer to several study sites

Site number	Site	Climatic signal	Age (cal. yr BP)	References
1	Arbon-Bleiche, Lake Constance (Switzerland)	Wetter	5550–5300	Haas and Magny, in press
1	Swiss Plateau and Alps	Cooler and wetter	5100	Haas <i>et al.</i> , 1998
1	Jura and Pre-Alps (France), Swiss Plateau	Wetter	5650–5200	Magny, 2004
2	Nieder Tauern (Austria)	Cooler and wetter	5200	Schmidt <i>et al.</i> , 2002
2	Rotmoos (Austria)	Cooler	5600–5200	Bortenschlager, 1977
2	Alps (Austria)	Cooler	5450–5000	Patzelt, 1977
3	The Netherlands	Wetter	5650, 5550, 5400	Blaauw <i>et al.</i> , 2004
4	Poland	Wetter	ca. 5500	Starkel, 1991
5	Pentland Hills (Scotland)	Wetter	5300	Langdon <i>et al.</i> , 2003
6	Jostedalbreen region (Norway)	Cooler and drier	ca. 5000	Nesje <i>et al.</i> , 2001
7	Finland	Cooler	5200	Heikkikä and Seppä, 2003
8	East-European Russian Arctic	Cooler	ca. 5600	Väliranta <i>et al.</i> , 2003
9	Nordic Seas	Cooler	5200	Risebrobakken <i>et al.</i> , 2003
9	Norwegian Sea	Cooler	5500	Calvo <i>et al.</i> , 2002
10	Feni Drift (North Atlantic Ocean)	Change in ocean circulation	5100	Oppo <i>et al.</i> , 2003
10	Subpolar North Atlantic Ocean	IRD	5400	Bond <i>et al.</i> , 2001
11	Gardar Drift (North Atlantic Ocean)	Change in ocean circulation	5300	Bianchi and McCave, 1999
12	Lake Siles (Spain)	Drier	5200	Carrión, 2002
13	GRIP core (Greenland)	CH <sub>4</sub> increase	5200	Blunier <i>et al.</i> , 1995
13	GRIP core (Greenland)	Cooler	5300	Dahl-Jensen <i>et al.</i> , 1998
13	GISP2	Higher Polar Circulation Index	5000	Mayewski <i>et al.</i> , 1997
14	Treeline (Canada)	Cooler	ca. 5800/5500	Lamb, 1977; Payette <i>et al.</i> , 2002
15	Western North America (USA)	Cooler	ca. 5700	Rocheport <i>et al.</i> , 1994
16	Elk Lake (USA)	Cooler and wetter	5400–4800	Bradbury <i>et al.</i> , 1993
17	Shepherd Lake (Canada)	Wetter	5550–5300	Haas and McAndrews, 2000
18	Owasko Lake (USA)	Drier	5300	Mullins and Halfman, 2001
19	Fayetteville Green Lake (USA)	Drier	5200	Kirby <i>et al.</i> , 2002
20	Colorado Front Range (USA)	Cooler	ca. 5200	Benedict, 1973
21	Lakes Chiconahuapan and Chalco, Mexico	Drier	ca. 5700–5100	Street-Perrott and Perrott, 1990
22	Sargasso Sea (North Atlantic Ocean)	Cooler	5000	Keigwin, 1996
23	Ecuador	Modern El Niño periodicity	5000	Rodbell <i>et al.</i> , 1999
24	Huascaran ice sheet	Cooler	5200	Thompson <i>et al.</i> , 1995
25	Peruvian coast	Cooler, modern ENSO onset	ca. 5800	Sandweiss <i>et al.</i> , 2001
26	Southern Chile shelf	Cooler, lower salinity	5500	Lamy <i>et al.</i> , 2002
27	Southern Andes (Argentina)	Cooler	5050–4800	Wenzens, 1999
27	Tierra del Fuego (Argentina)	Cooler and wetter	5700	Heusser, 1998
27	Southern Patagonia	Wetter	5000	Steig, 1999
28	South Georgia (Southern Ocean)	Cooler	5200	Rosqvist and Schuber, 2003
28	Signy Island, maritime Antarctica	Cooler and wetter	5300–5000	Noon <i>et al.</i> , 2003
29	South Atlantic sector	Cooler, sea-ice advance, IRD	5500–5200	Hodell <i>et al.</i> , 2001
30	Taylor Dome	Cooler	5500	Steig <i>et al.</i> , 1998
31	Antarctica ice sheet	Cooler	5000	Masson <i>et al.</i> , 2000
32	Kerguelen	Cooler	ca. 5700	Porter, 2000; Young and Schofield, 1973
33	New Zealand	Cooler	5300–5000	Porter, 2000
34	Cango Caves (South Africa)	Cooler	5300–4850	Jerardino, 1995
35	Kilimanjaro ice sheet	Cooler	5200	Thompson <i>et al.</i> , 2002
36	Lake Abiyata (Ethiopia)	Drier	After 5400	Chalié and Gasse, 2002
37	Off Cap Blanc (Mauritania)	Drier	5500	deMenocal <i>et al.</i> , 2000
38	Lakes of Northern Hemisphere of Africa	Drier	5700–5500	Damnati, 2000
38	Southern Sahara	Drier	5700–5500	Vernet and Faure, 2000
39	Soreq Cave (Israel)	Drier	5200	Bar-Matthews <i>et al.</i> , 1999; Arz <i>et al.</i> , 2003
40	Arabian Sea	Drier	5500	Sirocko <i>et al.</i> , 1993
41	Sumxi Co (Tibet Plateau)	Drier	ca. 5450–5000	Gasse <i>et al.</i> , 1991
42	Asian summer monsoon area	Colder and/or drier	ca. 5000–4500	Morrill <i>et al.</i> , 2003
43	Lakes of Mongolia	Drier	ca. 5200	Fowell <i>et al.</i> , 2003
44	Taymyr Peninsula (Arctic Russia)	Colder and drier	5200	Andreev <i>et al.</i> , 2003

IRD, ice-rafted debris.

Changes in ocean circulation are regarded as other good candidates for provoking rapid climate variations (Broecker, 1992). Several records listed in Table 2 suggest a weakening of the thermohaline circulation (Keigwin, 1996; Bianchi and McCave, 1999; Oppo *et al.*, 2003), a latitudinal shift of the

Antarctic Circumpolar Current (Lamy *et al.*, 2002), or possible expansions of polar waters into the Humboldt and Benguela Currents (Jerardino, 1995) during the 5600–5000 cal. yr BP period. This may result from an intrinsic ocean instability or bipolar seesaw (Maslin *et al.*, 2001). However, in the case of the

5600–5000 cal. yr BP event, such a bipolar seesaw appears to be ruled out as suggested by a concomitant cooling of both hemispheres (Fig. 2).

Variations in solar activity also appear to have been responsible for successive climate oscillations punctuating the whole Holocene (Denton and Karlén, 1973; Magny, 1993a; van Geel *et al.*, 1996; Bond *et al.*, 2001; Blaauw *et al.*, 2004). They may account for the abruptness, the relative short duration (e.g. Bar-Matthews *et al.*, 1999; Thompson *et al.*, 2002) and the global extension of the 5600–5000 cal. yr BP event (Fig. 2), which coincided with a period of weaker solar activity as indicated by a 5600–5200 cal. yr BP maximum in the atmospheric  $^{14}\text{C}$  content (Stuiver *et al.*, 1998). Model experiments developed by Gooose *et al.* (2002) have shown how variations in solar irradiance may trigger a reduction in the thermohaline circulation quite similar in magnitude, direction and spatial pattern of climate anomalies to those resulting from, for instance, freshwater outbursts from proglacial lakes during the last deglaciation. Furthermore, timberline retreat in North America (Payette *et al.*, 2002; Nichols, 1967, cited by Lamb, 1977), increasing permafrost in the east European Russian Arctic (Väliranta *et al.*, 2003), extension of sea-ice and/or IRD events in North and South Atlantic sectors (Bond *et al.*, 2001; Hodell *et al.*, 2001), higher values of Polar Circulation Index above Greenland (Mayewski *et al.*, 1997), and displacement of westerlies to lower latitudes (Magny, 1993b; Magny *et al.*, 2001; Lamy *et al.*, 2002) suggest an extension of the polar cell in both hemispheres, fully in agreement with the scenarios proposed by van Geel and Renssen (1998) to explain a possible sun–climate link.

In summary, far from a straightforward understanding, the 5600–5000 cal. yr BP event offers an example characteristic of the complexity of Holocene climate oscillations which may have resulted from a combination of multiple, non-exclusive factors. It still seems difficult to distinguish between high- or low-latitude climate control in the mechanisms involved in this event (Hodell *et al.*, 2001; Lamy *et al.*, 2002; Leuschner and Sirocko, 2003). Problems with sampling resolution and dating accuracy complicate the debate, in addition to (i) the abruptness of this event, which requires records with high temporal resolution, and (ii) the specificity and the sensitivity of available markers that give either a direct or indirect picture of climate change. Moreover, the Arbon Bleiche record clearly shows that, in certain regions, the mid-Holocene climate reversal appears to be characterised by intermediate warm spells (Fig. 1 and Table 1) within the distinct succession of strong cooling episodes (maxima at ca. 5550, 5450 and 5300 cal. yr BP), probably in relation to a solar forcing. Finally, although the onset of Neoglaciation favoured snow accumulation and glacier advance in the Tyrolean Alps and, as a result, the excellent preservation of the Alpine Iceman, the changes in palaeoenvironmental conditions induced by this mid-Holocene climate reversal may have led, via a more or less complex causal network, to substantial perturbations within human societies, as suggested by changes in cultural development in central Europe (Arbogast *et al.*, 1996; Berglund, 2003; Magny, 2004), strong variations in human settlement patterns (Vernet and Faure, 2000) and by a rapid development of hierarchical societies in the overpopulated Nile valley and Mesopotamia (Sirocko *et al.*, 1993) as well as in South America (Sandweiss *et al.*, 2001).

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