Environmental change during the Allerød and Younger Dryas reconstructed from Swiss tree-ring data

MATTHIAS SCHAUB, KLAUS FELIX KAISER, DAVID CHARLES FRANK, ULF BÜNTGEN, BERND KROMER AND SAHRA TALAMO

BOREAS

Schaub, M., Kaiser, K. F., Frank, D. C., Büntgen, U., Kromer, B., Talamo, S. 2008 (February): Environmental change during the Allerød and Younger Dryas reconstructed from Swiss tree-ring data. *Boreas*, Vol. 37, pp. 74–86. 10.1111/j.1502-3885.2007.00004.x. ISSN 0300-9485.

Annually resolved tree-ring width variations and radiocarbon ages were measured from a collection of 120 Lateglacial pine stumps excavated on the Swiss Plateau. These data – representing the oldest absolutely dated wood samples worldwide – extend the absolute tree-ring chronology from Central Europe by 183 years back to 12 593 cal. yr BP (10 644 cal. yr BC). They also yield a 1420-year floating chronology covering the entire Allerød and the early Younger Dryas (14 170–12 750 cal. yr BP). Radiocarbon data suggest a 250-year jump in the ^{14}C reservoir correction around the time of the Allerød to Younger Dryas transition, although calendric dating of the floating chronology – by filling a ~150 year gap – is necessary for confirmation. Various subgroups, based on the year of germination, were used to assess temporal changes in growth characteristics along the Allerød to Younger Dryas transition. Comparison of these Lateglacial data with a reference data set of living and historic pines from the Swiss Valais (AD 940–2000) revealed differences in both growth trend and level. The generally slower Lateglacial growth was likely influenced by higher geomorphic activity and severe climatic conditions. After removal of the biological age-trend, a strong common signal found in the tree-ring data suggests some skill in estimating interannual to multidecadal Lateglacial climatic variations.

Matthias Schaub (e-mail: matthias.schaub@hispeed.ch), Klaus Felix Kaiser, Swiss Federal Research Institute WSL, Zuercherstrasse 111, CH-8903 Birmensdorf, Switzerland and Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zurich, Switzerland; David Charles Frank, Ulf Büntgen, Swiss Federal Research Institute WSL, Zuercherstrasse 111, CH-8903 Birmensdorf, Switzerland; Bernd Kromer, Sahra Talamo, Heidelberg Academy of Sciences, INF 229, D-69120 Heidelberg, Germany; received 27th November 2006, accepted 13th April 2007.

Various global climate models predict an anthropogenic forced rise in air temperatures of about 1.4 to 5.8°C by the end of the 21st century (e.g. Stainforth *et al.* 2005), whereas Holocene climate variability is reported to be relatively low (e.g. Mayewski *et al.* 2004). The last period of naturally forced large-scale climate change of a similar amplitude and rate is reported for the Lateglacial around 14 650 to 11 650 ice-core years BP (Rasmussen *et al.* 2006). This period represents the transition from the *Last Glacial Maximum (LGM)* to the early Holocene and was characterized by large and rapid changes in temperature and precipitation (Birks & Ammann 2000; Bard 2002; Denton *et al.* 2005; EPICA 2006, and references herein). The reconstructed range of Lateglacial decadal-scale swings in annual mean temperatures during the Allerød to Younger Dryas transition is quantified to be 3–6°C (Croope *et al.* 1998; Ammann *et al.* 2000; Lotter *et al.* 2000). Inferences on past environmental collapses or adaptations triggered by such rapid changes will increase our understanding necessary to anticipate future modifications of the Earth's climate system (IPCC 2001; NRC 2006). To assess and increase knowledge on such rapid Lateglacial to early Holocene climate fluctuations, well-dated proxy archives of high resolution are required.

For Central Europe, this Lateglacial episode of unstable climate conditions is reported from various archives of commonly lower resolution, i.e. decadal to centennial scale (Magny *et al.* 2006). Palaeoclimatic analyses of glaciological features such as snowline depressions (Maisch 1995), speleothems (Wurth *et al.* 2004), stratigraphic deposits in high-elevation firn fields (Wagenbach 1989) and lake sediments, particularly through the development of isotopic (Eicher 1979), pollen (Wick 2000), cladoceran (Lotter *et al.* 2000) and chironomid time series (Heiri & Lotter 2005), can reveal past variations in temperature. Such proxy data have the advantage of being fairly abundant and, at the same time, continuously extend into the last glacial period; however, there is a limitation (Petit *et al.* 1999). Since most of these archives are not highly resolved, they cannot be used independently to pinpoint rapid environmental changes of interannual scale, and in most cases not even within decadal precision. Dating uncertainties from standard measurement biases are further complicated in the case of radiocarbon-dating by plateaus or even reversals in the calibration curve (Reimer *et al.* 2004).

Annually resolved time series of radial tree-ring growth overcome such resolution problems, and thus are regarded as reliable evidence for a precise age

DOI 10.1111/j.1502-3885.2007.00004.x © 2007 The Authors, Journal compilation © 2007 The Boreas Collegium

determination and ^{14}C calibration (Reimer *et al.* 2004). In addition to the possibility of annual dating, measurements of tree-ring width (Fritts 1976), density (Schweingruber *et al.* 1979) and stable isotopes (e.g. Treydte *et al.* 2006) have been widely used to robustly reconstruct climatic variations during past centuries to millennia (Jones & Mann 2004). Some few studies have even used tree-ring data to reconstruct climate variability during the LGM to Holocene transition (Schaub *et al.* 2007), and 50 000 years ago mainly during the *Marine Isotope Stage 3* (MIS3) (Roig *et al.* 2001). Despite these advantages of tree-ring data, the preservation of environmental changes is complicated by an almost universal decrease of ring width and density with tree age (e.g. Fritts 1976). This so-called age trend can include some ecological forcing, but is mainly constant for a given species, site and region (Esper *et al.* 2003). In inferring climate-related variability, any age trend acts as a significant fraction of noise and therefore needs to be removed prior to any dendroclimatic interpretation. This technique is known as standardization or detrending (Fritts 1976). The ability to reconstruct low frequency fluctuations from tree-ring data sets, which are significantly longer than the mean of the individual measurement series, however, is particularly challenging (Briffa *et al.* 1992; Cook *et al.* 1995; Briffa *et al.* 1996; Esper *et al.* 2003). The preservation of such long-term trends depends on the design (i.e. sample replication and temporal distribution) of the data set used (Esper *et al.* 2003; Melvin 2004; Büntgen *et al.* 2005, 2006).

Over recent decades, work has continued on extending the absolutely dated ultra-long European tree-ring chronologies back in time (see references herein). The *Hohenheim Oak Chronology* (HOC), composed of more than 4000 oak samples from several river valleys in southern Germany, spans back to almost 10 000 cal. yr BP (Becker 1993). Corrections with respect to the chronology from Göttingen, spanning back to 9147 cal. yr BP (Leuschner 1992), and a combination of additional samples resulted in an extension back to 10 429 cal. yr BP (Spurk *et al.* 1998). A combination of the HOC and the *Preboreal Pine Chronology* (PPC; Friedrich *et al.* 2004), as well as the inclusion of new samples, further extended the calendar dated chronology back to 12 410 cal. yr BP, which corresponds to 10 461 yr BC (Friedrich *et al.* 2004). This compilation represents a worldwide unique data set developed by many researchers from different institutes and countries. Following a general rule in palaeoclimatology, the oldest part of the chronology is also the least robust, as the first 85 years consist of only 2 trees from Zurich-Wiedikon (hereafter abbreviated to ZHW1) (Kaiser 1993). ZHW1 has a 130-year overlap with the Cottbus chronology from eastern Germany (Spurk *et al.* 1999; Friedrich *et al.* 2004), which has been cross-dated to the PPC. We previously introduced some new tree-ring findings from Gaenziloo and Landikon near Zürich, Switzerland, developed some shorter chronologies and provided first interpretation (Schaub 2003; Schaub *et al.* 2005, 2007).

In addition to the absolutely dated tree-ring data, some floating (i.e. a continuous tree-ring time series perhaps linked approximately in time by radiocarbon-dating) Lateglacial chronologies from Daettnau, Switzerland (Fig. 1) were developed by Kaiser (1979, 1993). Other floating chronologies exist for Germany, northern Italy (Friedrich *et al.* 2001, 2004) and southeastern France (Miramont *et al.* 2000).

Here we seek to contribute to a more detailed understanding of environmental conditions during the Lateglacial to early Holocene episode by: (i) extending the

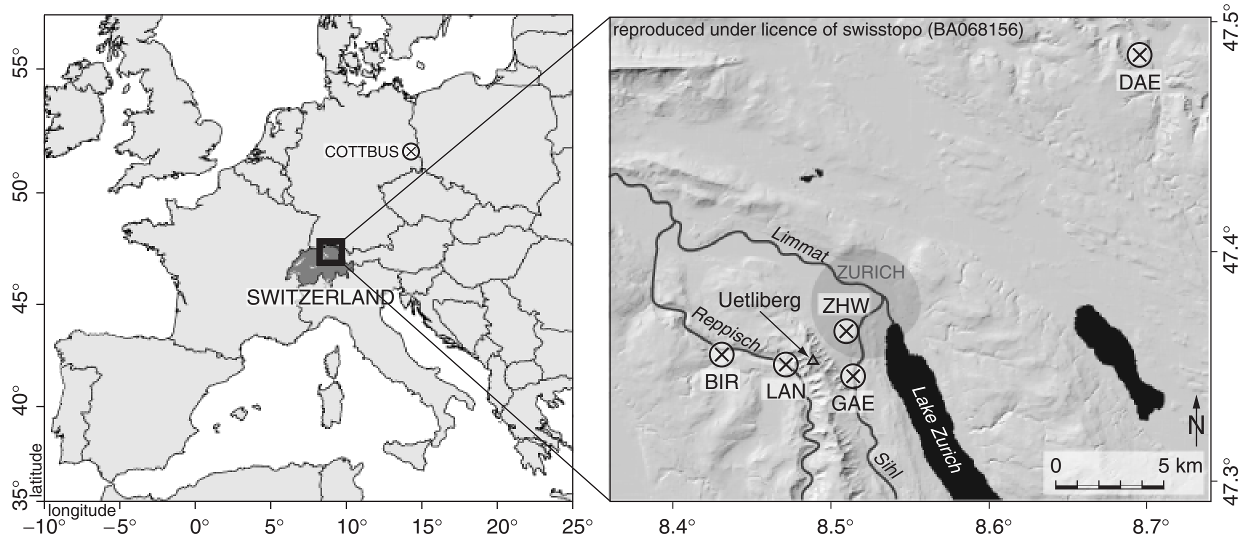

Fig. 1. Location of the original study sites Landikon (LAN), Gaenziloo (GAE), Birmensdorf (BIR) and Zurich-Wiedikon (ZHW) at the Uetliberg near Zurich, Switzerland, Daettnau (DAE) and Cottbus (see overview).

absolutely dated European pine chronology back to 12 593 cal. yr BP (10 644 cal. yr BC), (ii) improving the early radiocarbon calibration curve through new ^{14}C measurements, (iii) analysing pine growth-trend changes along the chronology, and (iv) reconstructing decadal-scale environmental fluctuations of the Allerød to early Holocene interval (~14 200–11 600 yr BP).

Data and methods

Geographical settings

The four study sites considered here, *Gaenziloo* (GAE), *Landikon* (LAN), *Zurich-Wiedikon* (ZHW) and Birmensdorf (BIR), are all located on the Swiss Plateau in the greater area of Zurich (Fig. 1). They are situated within a distance of 6 km from each other and between 430 and 500 m a.s.l. in the Sihl and Reppisch valleys on both slopes of the Uetliberg (873 m a.s.l.). Today, mean climatic conditions of this northern pre-Alpine region are classified as moderate (Veit 2002). During the last Ice Age, however, conditions were much more severe, and the Uetliberg was a nunatak, mainly composed of *upper freshwater molasse* (UFM), situated between the Linth–Rhine and Reuss glaciers (Schaub 2003; Schaub *et al.* 2007). The two canyon-like valleys were carved into the UFM as drainage channels by glacial meltwater at the transition into the Lateglacial. High-energy mass movements and landslides from the upper parts of the slopes filled these local channels after the meltwater pulse subsided. Subsequently, alluvial soil of clayey, silty and sandy sediments originating from the UFM bedrock were deposited by slower but more continuous geomorphic processes, allowing first herbages (e.g. true grasses, sedge and aster) and a pioneer vegetation (e.g. pine, birch, juniper, willow, sea buckthorn) to be reestablished from the valley bottom upwards along generally lower portions of the slopes. The re-forestation process, itself taking place during periods of lowered geomorphic activity, caused a further reduction in sedimentation rates. During such periods of relatively stable environmental conditions, adult trees were buried by continuous but varying sedimentation rates of predominantly loamy soil (Schaub *et al.* 2005). This continuous accumulation of water-saturated sediments most likely affected the formation and succession of even climax vegetation. In this regard, Kaiser (1993) and Schaub *et al.* (2007) described a clear relationship between the depth of tree root coverage and the timing of tree death.

During the past decade, various sites of Lateglacial pine stumps have been recovered from several construction sites within the greater area of Zurich (Kaiser 1993; Müller 2000). Owing to the prevailing ecological and geomorphological circumstances of these sites (e.g. slope decline, exposition, sedimentation processes), fossil pine stumps were excavated, but no macroremains such as trunks and branches were found. Similar results are reported from Finland, where pines were buried by aggrading sand (Hekkinen & Tikkanen 1987).

A pioneering study by Escher (1911) described various loam-pits located on both slopes of the Uetliberg near Zurich (Fig. 1) which were dated back to AD 1540. These pits included hundreds of upright standing *in situ* pine stumps with dimensions 50 to 150 cm in height and 20 to 50 cm in diameter (Grossmann 1934).

Sample collection, processing and radiocarbon-dating

Newly presented fossil pine (*Pinus sylvestris* L.) stumps derive from the GAE (n = 66) and LAN (n = 47) sites (Schaub *et al.* 2007), as well as from two sites previously described by Kaiser (1993), namely ZHW (n = 5) and BIR (n = 2). All sites are located close to the Uetliberg (Fig. 1). Trees were sampled by cutting disc cross-sections at different stump heights. The lowermost disc samples were taken just above the root system, thereby allowing determination of the trees' germination date, while higher disc samples were taken to obtain ring-width sequences less prone to any irregularities or eccentricities from root disturbances (Schaub *et al.* 2005, 2007). Annual variations in tree-ring width were measured on a Lintab measurement stage at 0.01 mm resolution using the program TSAP (Rinn 1996). Two radii were measured per disc, with two discs measured per tree. The four measurement series obtained per individual were then synchronized on a light-table, their dating checked using t-values (test for correlation significance) and the *Gleichläufigkeit* (Glk) parameter (for details, see Rinn 1996), and finally screened for missing rings using the program COFECHA (Holmes 1983). All four tree radii were averaged together, forming tree mean series which were subsequently averaged on a site-by-site basis into chronologies.

Additionally, the ^{14}C content of numerous wood samples was measured (Schaub *et al.* 2007), thereby facilitating initial tree-ring synchronization and providing data contributing to the absolutely dated radiocarbon calibration curve. Wood samples (mostly containing exactly 10 successive annual tree rings) were processed at the Heidelberg Radiocarbon Laboratory. These subsets were pretreated in a modified AAA procedure and combusted to CO_2 in a Parr bomb. CO_2 gas was purified and counted for 10 days in gas counters (Kromer & Münnich 1992). The variable content of ^{14}C in the atmosphere is preserved in the tree rings, but complicates the calibration of radiocarbon ages into calendar years. The IntCal04 reference data set is generated by tree-ring data (0.0–12.4 cal. kyr BP) and by data from marine records, such as corals and foraminifera (12.4–26.0 cal. kyr BP) (Reimer *et al.* 2004).

Fluctuations in atmospheric ^{14}C content allow floating series of radiocarbon dates to be 'wiggle-matched' to a reference data set (Ramsey *et al.* 2001). Floating chronologies of this study were dated relative to each other using ^{14}C data, with positions refined through wiggle-matching (Figs 2, 3). ^{14}C ages are given relative to AD 1950.

The high-precision ^{14}C ages are reliant on ring position determined in the chronology and are relative to the Cariaco ^{14}C data set (Hughen *et al.* 2000). The radiocarbon calibration data set (IntCal04) is based on marine radiocarbon data beyond 12 400 cal. yr BP (Reimer *et al.* 2004). Compared to the atmospheric ^{14}C level, the marine ^{14}C data from the Cariaco sediments or from corals, both originating from a mixed layer, depend on the rate of gas exchange (atmosphere–ocean) as well as on oceanic circulation (Kromer *et al.* 2004). In an attempt to account for such influences, a reservoir correction was applied. For terrestrial calibration, the marine ^{14}C ages were adjusted by 400 years in the Younger Dryas; prior to this time period, a correction of 650 years is used. See Kromer *et al.* (2004) and the discussion below for more details about possible shifts in the marine reservoir correction.

Growth-trend analyses

To understand tree growth as a function of time, i.e. to detect temporal changes in growth-trend behaviour from the Allerød to the Younger Dryas transition, the original data set of 120 mean measurement series was separated into 14 subgroups, referred to here as S1–S14 (Fig. 4A). This classification, based on the trees' germination date and considering pith offset estimations, resulted in a compromise between the number of possible subgroups and their individual replication. To ensure a robust calculation of the subgroups' specific growth-trend patterns, analyses were based on at least 24 radii from 6 or more trees. For each temporal subgroup (S1–S14), the individual series was aligned by its

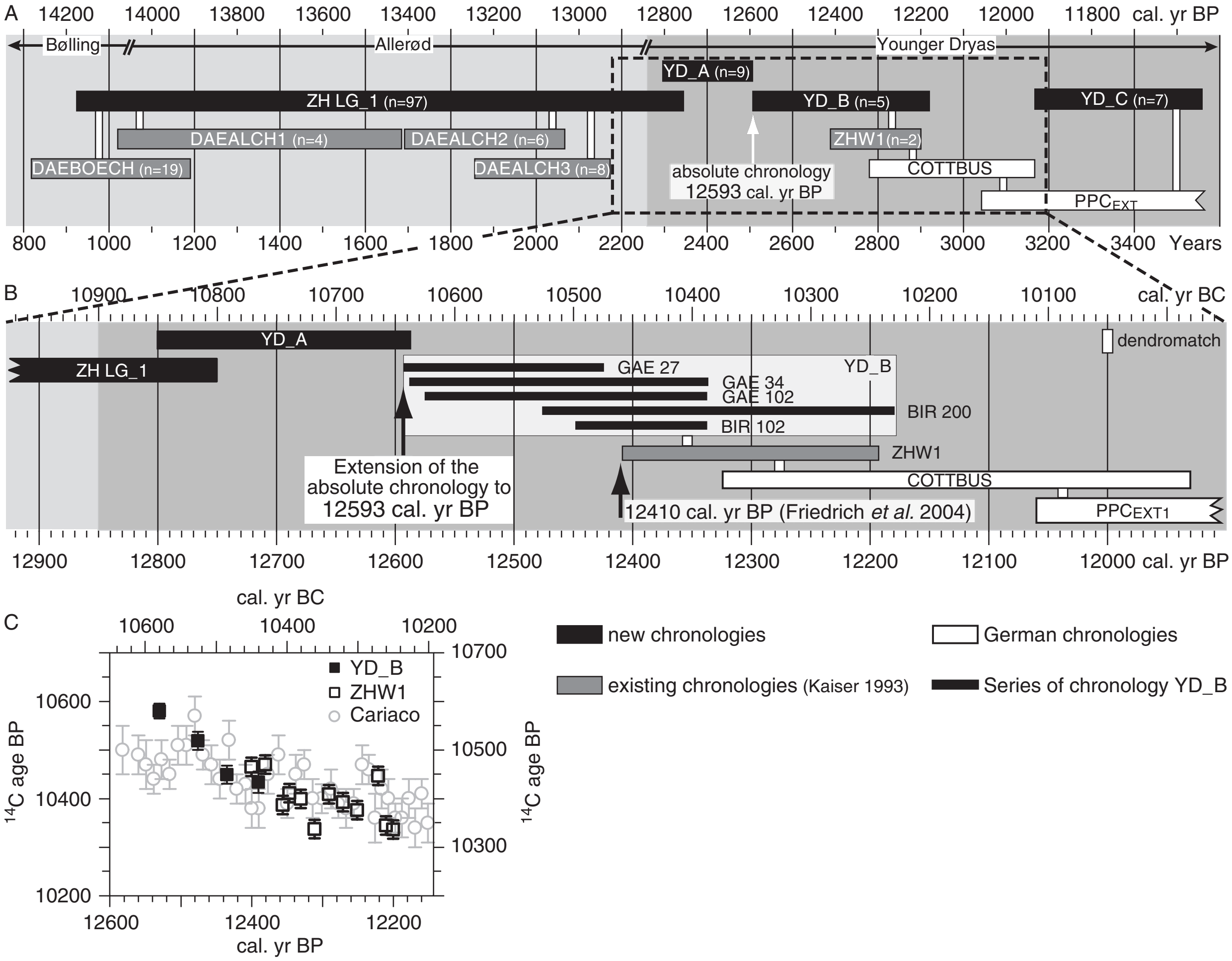

Fig. 2. A. Overview of the new (black), the existing Swiss (grey; Kaiser 1993) and the German (white; Friedrich *et al.* 2004) Lateglacial tree-ring chronologies. The replication is shown in parentheses and cross-dated chronologies are indicated by vertical white bars. B. The new extension of the absolute tree-ring chronology back to the year 12 593 cal. BP, based on the age determination of ZHW1 from Friedrich *et al.* (2004). C. ^{14}C ages of the new absolute chronology (YD_B (closed black squares), ZHW1 (open black squares)) in relation to the Cariaco reference data set (Hughen *et al.* 2000).

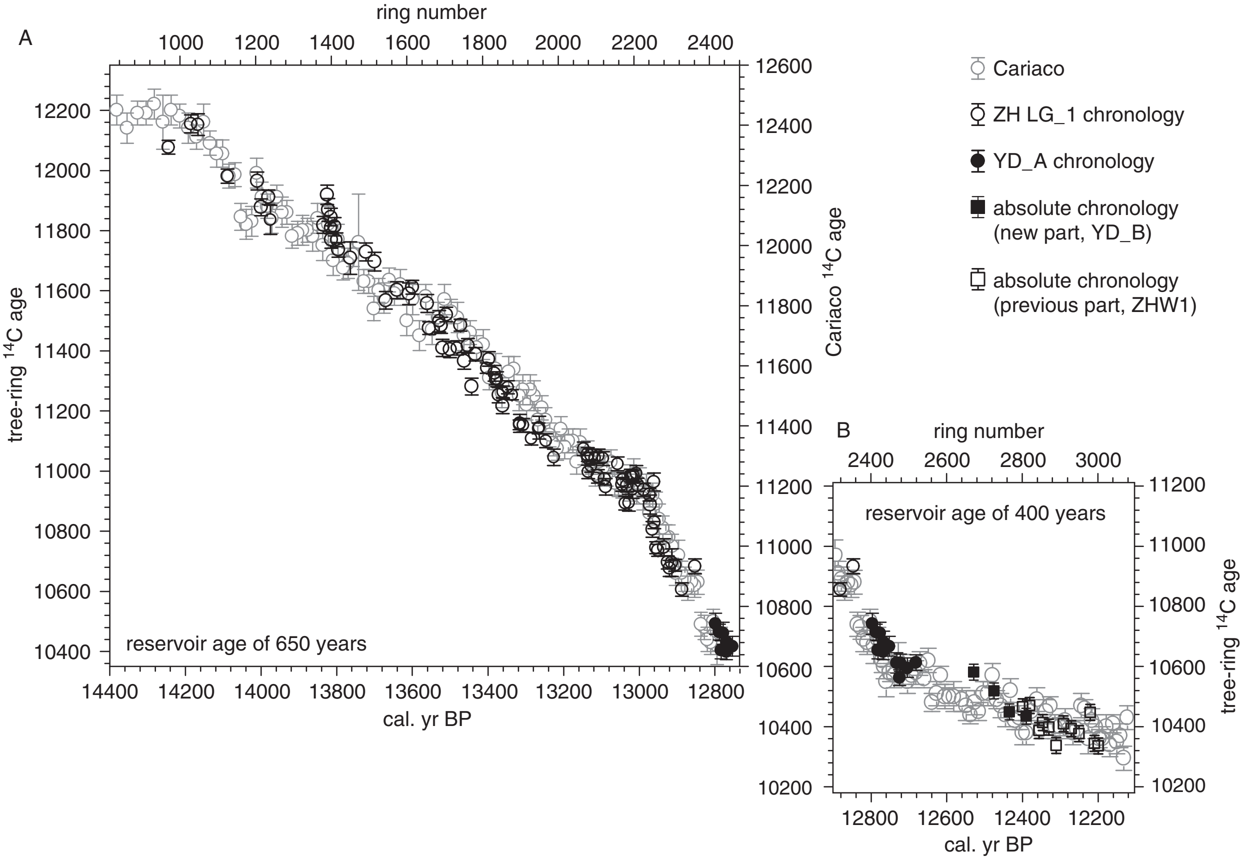

Fig. 3. ^{14}C ages of the new pine chronologies ZH LG_1 ((A), open black circles), YD_A ((B), closed black circles) and of the absolutely dated chronology YD_B ((B), squares). The ages are shown in relation to ring number (top scale), to Cariaco mixed-layer ^{14}C ages (open grey circles) (Hughen *et al.* 2000) and to cal. years BP (bottom scale). Vertical bars reflect the σ-error of the radiocarbon age determinations. The left (A) and right (B) vertical (^{14}C age) scales are related to the age of the tree-ring chronologies and the central vertical scale to those of the Cariaco data set.

cambial age; that is, aligned by its birthday rather than calendar year to assess the age-related trends. The arithmetic mean of the age-aligned series, the so-called *regional curve* (RC), describes the age-trend characteristic for a given subgroup (for details, see Esper *et al.* 2003).

To improve the robustness of such RCs, yet still provide insight into temporal changes of RC characteristics, six larger groups (G1–G6), each representing a different fragment of the Allerød to Younger Dryas transition, were created (Fig. 4B). *Mean segment length* (MSL) and *average growth rate* (AGR) calculated for each subgroup provide information on data composition through time. *Segment length* (SL) and *mean cambial age* (MCA) of the full data set including 120 trees are used to describe fluctuations in stand dynamics from the Allerød to Younger Dryas (Fig. 4C).

A more recent pine reference data set from the Swiss Alps was utilized for comparison between the Lateglacial growth-trend patterns and those observed over the past millennium (Fig. 4D). This compilation of 186 living and historic series spans the AD 940–2000 period. It was collected by M. Schmidhalter in the Swiss canton Valais, primarily in the Rhone valley ~1000 m a.s.l., and is generally representative of climate-sensitive pine growth within the greater Alpine region (Frank & Esper 2005a, b).

Environmental signal detection

To further detect environmental signals embedded within the raw measurement series, individual spline detrending was applied to systematically remove growth trends thought to be induced by non-climatic influences, such as ageing and/or site ecological effects (Fritts 1976). An adaptive power transformation was first applied to eliminate heteroscedastic behaviour of the raw tree-ring measurements (Cook & Peters 1997). To retain interannual to multidecadal scale variations, relatively stiff 300-year cubic smoothing splines (Cook & Peters 1981) were fitted to the power transformed series, and residuals between the measurements and splines were calculated. Note that even though the detrending technique applied here retains some mid-term fluctuations, the approach of individually fitting a spline to each series eliminates signals on wavelength longer than the series mean segment length (details in Cook *et al.* 1995). All detrended series were averaged to

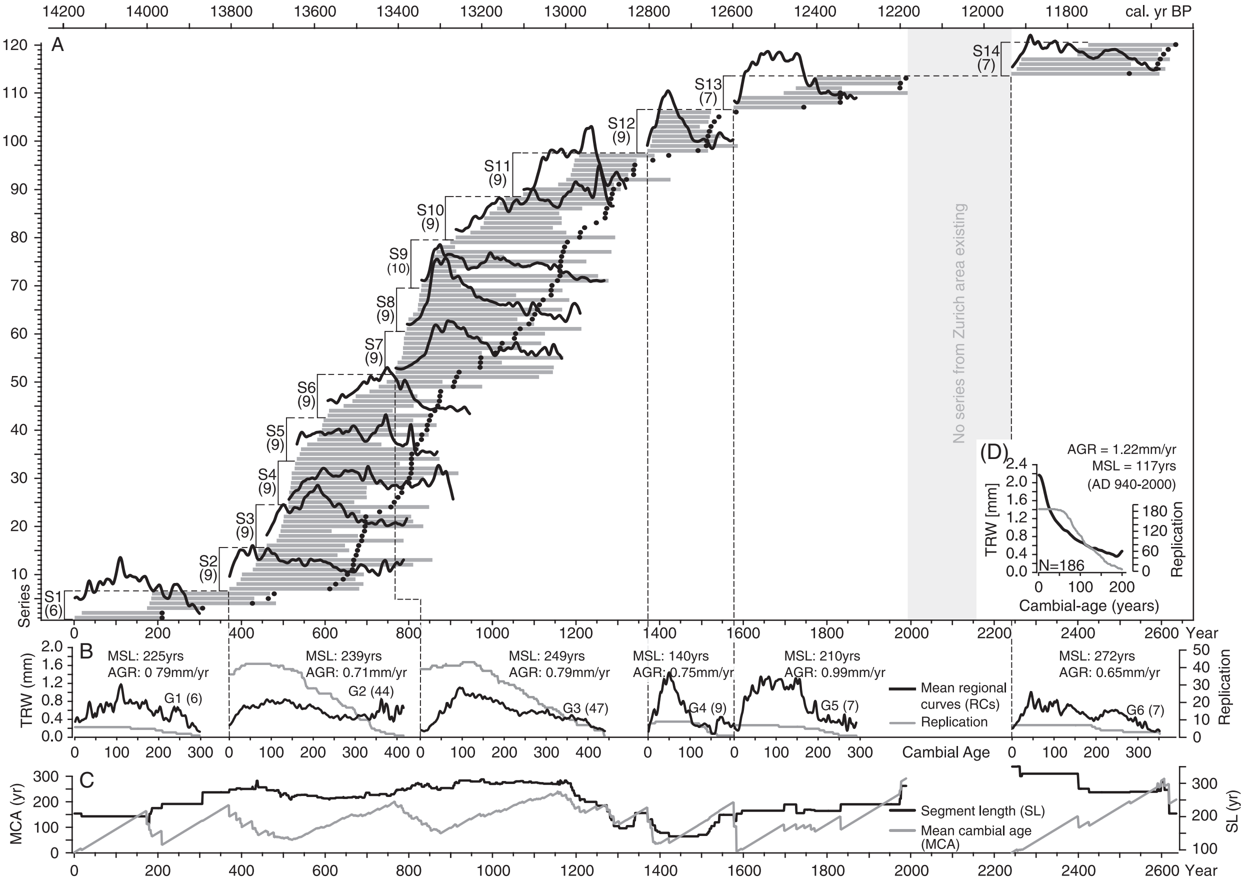

Fig. 4. A. Temporal distribution of the 120 Lateglacial pine series (horizontal grey bars) from Landikon, Gaenziloo, Birmensdorf and Zurich-Wiedikon. Black dots indicate the series distribution arranged by their outermost ring. The RCs of the 14 subgroups are indicated by black lines and 20 (10) year lowpass-filtered (A and B). B. S2 to S11 were divided into early (G2) and late (G3) Allerød subgroups, separated here by dashed lines. C. Mean cambial age (MCA) and segment length (SL) shown for each year along the entire data set. D. The RC of a recent reference data set.

form chronologies using a biweight robust mean (Cook 1985). The number of samples per year and the cross-correlation coefficient between all measurements were used for variance stabilization of the chronologies to avoid changes in variance related to changes in sample depth but not for changes in the inter-series correlation (Osborn *et al.* 1997). For signal strength assessment (Wigley *et al.* 1984; Cook & Kairiukstis 1990), the inter-series correlation (*Rbar*, $[\bar{r}]$) and the expressed population signal (*EPS*) were computed (Fig. 5). For detrending, chronology development and statistical analysis, we used the program ARSTAN (Cook 1985). For illustration, all chronologies were 20-year lowpass-filtered.

To understand the occurrence of external forcing as a function of time, i.e. to detect common growth variability from the Allerød to the Younger Dryas, we separated the original data set into subgroups S1–S14 (Fig. 5A). This classification was based on earlier decisions mentioned above. For each temporal subgroup (S1–S14), a so-called subchronology was then developed, and to provide a more robust picture of Lateglacial environmental variability (Fig. 5B), four well-replicated mean chronologies spanning differing time-windows were utilized (for details see below).

Results

Chronology development

Tree-ring series from Birmensdorf and Gaenziloo were successfully cross-dated with each other and their mean to the ZHW1 chronology. We refer to this new collection of 20 measurement series from 5 trees as the Younger Dryas B (YD_B) chronology (Fig. 2B). The YD_B chronology comprises 3 trees from Gaenziloo and 2 from Birmensdorf, and spans 412 years. The internal cross-dating of this material, both visually and statistically, was possible due to the strong common signal and long period of overlap. The mean *Gleichläufigkeit* (Glk) and the *t*-values after Baillie-Pilcher (t_{BP}) and Hollstein (t_H) of the YD_B chronology are 65.5%, 6.8 and 6.4 (for details, see Rinn 1996). Accordingly, the YD_B chronology extends the absolute tree-ring chronology by 183 years to 12 593 cal. yr BP

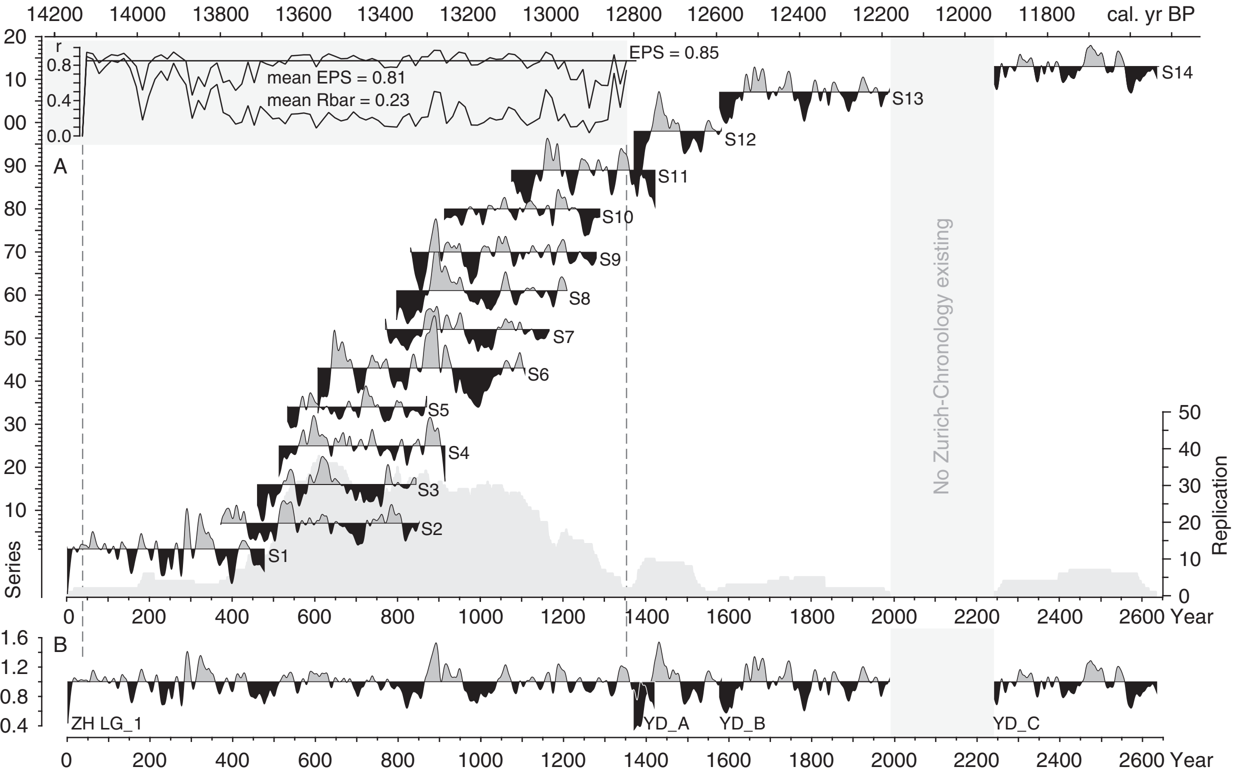

Fig. 5. A. 300-year spline chronologies of the 14 individual subgroups showing common signal strength. EPS and Rbar values were calculated over 30 years lagged by 50% (Wigley *et al.* 1984) and are shown for chronology ZH LG_1. B. 300-year spline chronology using all 120 series.

Table 1. Radiocarbon data and corresponding dendro-ages of the fossil samples of chronology YD_B.

Dendro sample ID	Subsample ring no.	Dendro-age (cal. yr BP)	^{14}C lab. ID	^{14}C age BP	Error (1 sigma)
G 27	59–68	12 535–12 526	Hd25008	10 579	33
G 102	95–104	12 480–12 471	Hd25006	10 518	26
G 27	148–167	12 446–12 427	Hd22000	10 449	29
G 34	193–202	12 395–12 386	Hd25067	10 433	25

(10 644 cal. yr BC). This dating is supported by high statistical agreement between the YD_B and ZHW1 chronologies (Glk = 62%, t_{BP} = 4.7 and t_H = 4.4) and independently confirmed by ^{14}C age determinations (see Fig. 3B). Thus, here we present the oldest absolutely dated wood samples worldwide.

Four samples taken from three different trees included in the YD_B chronology were further radiocarbon-dated (Table 1). Using the dendrochronlogical data and the known number of calendar years between different ^{14}C measurements, better estimates of the age may be obtained via wiggle-matching than are possible from non-cross-dated tree-ring material. Via wiggle-matching with the Cariaco calibration data set (Hughen *et al.* 2000), dating of the YD_B samples was estimated to lie within the time-window of approximately 12 600 to 12 400 cal. yr BP (Fig. 2C). The calibration curve displays various ^{14}C age plateaus and inversions during this time (Fig. 3), which complicates absolute dating in the absence of cross-dating. However, the radiocarbon data do provide independent support for the dendrochronologically determined position.

In addition to YD_B, two other chronologies (YD_A and YD_C) of Younger Dryas age were built. Both are wiggle-matched to the Cariaco reference data set. YD_A comprises nine trees from Gaenziloo. The 212-year-long data set is radiocarbon-dated to an age of approximately 12 800 to 12 600 cal. yr BP (Fig. 3). No other European terrestrial archive of annual resolution is available during this Lateglacial period. The oldest trees of YD_A germinated during the first portion of the Younger Dryas, which was characterized by the onset of generally colder conditions around 12 850 cal. yr BP (Rasmussen *et al.* 2006).

YD_C includes seven series from three different sites near the Uetliberg (LAN = 3, ZHW = 3, GAE = 1) and spans 393 years. It is dated by both radiocarbon ages and converted to a calendar year by tree-ring cross-dating to 11 930 to 11 538 cal. yr BP. This absolutely dated material extends into the Preboreal, which starts around 11 570 cal. yr BP (Friedrich *et al.* 1999) and provides additional evidence for environmental conditions during this time.

The longest currently existing Lateglacial tree-ring chronology (ZH LG_1) comprises 97 series from Gaenziloo (n = 53) and Landikon (n = 44). Even though this floating chronology cross-dates with the former chronologies DAEALCH1 to 3 and DAEBOECH, so far it is not calendrically dated (Fig. 2A). From this material, however, almost 100 radiocarbon ages from 42 different trees were obtained (Fig. 3A). Via wiggle-matching, ZH LG_1 fits within an age range of 12 150 to 10 610 ^{14}C yr BP, which is equal to approximately 14 170 to 12 750 cal. yr BP. In this period, the gradient of the Cariaco data set fits well to that of the tree rings, assuming a reservoir correction of 650 years (Kromer *et al.* 2004), although there is a short data gap (Fig. 4A).

Growth-trend patterns

The entire data set, comprising the ZH LG_1, YD_A, YD_B, ZHW1 and YD_C chronologies, has been dated to years BP either via cross-dating or approximately by wiggle-matching (Figs 2A, 3). The age-aligned series of the 14 subgroups displays the spreading of the Lateglacial forest because of the sampling technique used: pith age equal to germination age. Periods of high tree mortality (e.g. 13 500 cal. yr BP) and some high germination rates (e.g. 13 400–13 350 cal. yr BP) are revealed. Such periods provide clues to sedimentation activity and likely also to climatic variations.

Depending on their temporal position, the Lateglacial pine subgroups show RCs of different shape. Similar curve progressions and absolute growth values are detectable. The RC of subgroup S1 is similar to that of the mean Allerød RC previously presented in Schaub *et al.* (2007) showing an arched curve with trees reaching maximum radial growth after approximately 100 years, followed by a slow decrease. For the first part of the Allerød (13 800–13 400 cal. yr BP), the RCs tend to be more linear in nature. However, subgroups S7 to S9 are unique. For the first 70 years, they show a very steep juvenile growth increase and reach the highest values of absolute growth for any of the Allerød or Younger Dryas subgroup RCs. S10 and S11 are again of different shape with a moderate juvenile increase followed by an abrupt decrease at the year 12 900 cal. BP. The growth trend of the earliest Younger Dryas chronology (S12) is almost triangular in shape, with peak growth rates occurring at around 50 years.

To document Lateglacial tree-growth-trend changes more robustly (i.e. with sufficient sample size), the series was separated into six subgroups (G1–G6; Fig. 4B). Owing to increased replication, G2 and G3 possess a smoother appearance and show maximal values after about 100 years of juvenile growth. Maximal growth after 100 years is also found in G1 (Schaub *et al.* 2007). In contrast, chronologies as of early Younger Dryas reach highest growth rates already after about 50 years. Interestingly, the MSL remains relatively stable throughout the Allerød, but shows a minimum during the Allerød to Younger Dryas transition (Fig. 4B). MSL of all other series ranges between 272 and 210 years, whereas the series from G4 have an MSL of 140 years. AGR ranges from 0.65 to 0.79 mm/yr, but G5 shows a mean increment of almost 1.00 mm/yr. The germination of different populations is further indicated by the MCA curve with increased re-generation around years 14 000, 13 700 and 13 300 cal. yr BP.

The recent composite reference data set shows remarkable differences in growth behaviour compared to the Lateglacial material. The recent RC (Fig. 4) is close to the classical negative-exponential shape (e.g. Bräker 1981) also shown in other studies using large and fairly representative data sets of Holocene pine growth in northern Fennoscandia (Helama *et al.* 2005).

In addition to the shape of the age trend, differences are also observed in the absolute tree-ring widths. While the reference data set shows an AGR of 1.22 mm/yr (in relation to replication), the Lateglacial chronologies possess an overall mean of only 0.76 mm/yr. Maximum growth, which perhaps more closely reflects the productivity constraints on tree growth from all environmental conditions, is also distinctly lower in the Lateglacial series (1.4 mm/yr) compared with the more recent data set (2.25 mm/yr).

Environmental variability

Division of the data set composed of 120 series from primarily 2 sites into 14 subgroups allows the common signal in decadal-scale growth fluctuations to be tested. As the independent subgroups do not utilize any of the same material, it is likely that common variations reflect regional-scale environmental forcing. As mentioned above, we look at this environmental forcing after the age-related trend has been removed. During periods of overlap, the subgroups generally show high agreement for the timing of positive and negative growth anomalies. Positive anomalies are clearly detectable between the relative years 850 to 950 indicated by all the available subsets. Negative anomalies correspond well with each other (e.g. years 950 to 1050).

The currently oldest calendrically dated tree-ring chronology (YD_B; 12 593–12 182 cal. yr BP) denotes positive anomalies between 12 550 and 12 500 cal. yr BP. Furthermore, mostly negative growth anomalies of approximately 50 years in length are shown separated by shorter positive anomalies. Distinct negative and positive growth anomalies are also observed in the chronology YD_C (11 930 to 11 538 cal. yr BP). Positive (11 720 to 11 630) and negative (11 630–11 540 cal. yr BP) anomalies are particularly evident in the records of the past two centuries.

Subsets S1 to S11 (ZH LG_1) are summarized in Fig. 5B and, showing the full chronology, provide an overview of the anomalies during the Allerød and Younger Dryas period. The most distinctive positive departures are shown at positions 300, 900 and 1450 as well as about 12 500 and 11 900 cal. yr BP. Negative departures are revealed at positions 250, 450, 800, 1000 and during the Allerød to Younger Dryas transition (position 1350). Additional negative patterns are reported for the first 50 years of the absolutely dated chronology and for the 12 400 and 11 600 cal. yr BP periods.

The mean interseries correlation (Rbar; Fig. 5A) is 0.23 and is reasonably typical for between-tree correlations. EPS values (mean 0.81; Fig 5A) calculated for ZH LG_1 do not always fully meet the signal strength rules-of-thumb utilized in 'modern' dendroclimatology, indicating, as for most longer composite chronologies, that more samples would be useful in improving signal quality. The signal strength of this record is lowest towards both ends as replication tapers away. The Rbar and the EPS values of the composite reference data set are 0.16 and 0.69, respectively.

The first two centuries of Younger Dryas have positive anomalies between 1400 and 1500 (approximately 12 770–12 670 cal. yr BP) and are generally negative for the rest of the record. During a short period of estimated overlap between the ZH LG_1 and YD_A chronologies, which is at position 1370 to 1420, environmental signal agreement is evident.

Discussion

Chronology extension and radiocarbon-dating

Extension of the absolutely dated tree-ring chronology by 183 years is relevant for radiocarbon age determinations in generating the ^{14}C calibration curve. By taking into account the still sparsely and scattered locations of the little cross-datable wood material available for the Younger Dryas, key evidence for estimating environmental variability during that period can be obtained. In this context, the floating chronology YD_A (212 years) is important in closing prevailing data gaps. Radiocarbon high precision data indicate a small overlap of the two Younger Dryas chronologies YD_A and YD_B (Fig. 2). Tree-ring dating, however, remains insecure. In contrast, the wiggle-matching results show a clear overlap between ZH LG_1 and YD_A.

The currently longest Lateglacial chronology ZH LG_1 spans 1420 years and is wiggle-matched to the marine ^{14}C data set of Cariaco by the distinct slope in the course of the ^{14}C calibration curve, which is caused by a strong increase in the ^{14}C level at onset of the Younger Dryas (Fig. 2A). For the link, we assume that the ^{14}C rise is synchronous in the atmosphere and the oceanic mixed layer at the Cariaco site, i.e. supported by the short turnover time of approximately 8 years of ^{14}C with respect to atmosphere–ocean exchange. However, we can match the tree-ring based (terrestrial) ^{14}C data to the marine Cariaco data only if we assume an increased marine reservoir age of 650 years, rather than the commonly used 400 years. A possible explanation of such a change could be transient expansion of Atlantic intermediate water of Southern origin and retreat during the Younger Dryas (for discussion, see Kromer *et al.* 2004). For the mid-Younger Dryas tree-ring extension we can confirm the reservoir age of approximately 400 years; hence, the transition at the Cariaco site must have occurred within the time interval of the chronology gap in the early Younger Dryas.

Growth-trend shifts

The growth trend (RC) can be regarded as being primarily age-related and independent of climatic influences. As shown in the reference data set (Fig. 4D), the growth trend expected based on the modern analogue is a negative exponential decline. However, by computation and comparison of the RCs at different periods along the Allerød–Younger Dryas chronology, we determined that, depending on the time period, the shape of radial growth varies greatly. Maximum growth during the second part of the Allerød is significantly higher that of the first part, which seems to be more constant across biological age. These differences suggest strong influences from forcing mechanisms external to inherent age-related growth characteristics. The potential growth of these pines seems to be reduced by exogenous factors such as temperature, precipitation, competition and/or aggradation processes. This hypothesis is also supported by the average growth rates, which are about 40% lower compared to the modern pine analogue data set. However, in some periods, such as around 13 300 cal. yr BP, Lateglacial tree-growth (2 mm/yr) almost reaches the maximum rates of the recent chronology. With regard to the wide ecological amplitude of the Scots pines, and considering exogenous factors, precipitation and stand competition probably do not play a strong role as limiting factors. Sedimentation rates of 2.5 mm/yr during the Allerød and up to 7 mm/yr at the onset of the Younger Dryas are likely to be more dominant influences on tree growth (Schaub *et al.* 2007). On the slopes, the amount of erosion and consequently the amount of sedimentation at the slope bottom does not remain constant. Longer-term vegetation changes seem to be of primary importance, with reduced erosion as pioneer plants began to occupy higher and higher positions along the Uetliberg as ice retreated. Water abundance, controlled by heavy rainfall and melting snow, was also likely important in determining the seasonality and interannual changes in sedimentation rate.

The influence of aggradation affects the MSL directly. Scots pines die as soon as they are covered under approximately 1 m of soil, since they are unable to react by forming an adventitious root system (Kaiser 1993; Schweingruber 1996). At the Uetliberg, therefore, the segment length (SL) graph in Fig. 4D to some extent reflects the intensity of fine-grained sedimentation for 2000 years. At onset of the Younger Dryas around 12 850 cal. yr BP, a clear reduction in the SL is obtained. After a distinct depression of about 300 years, a recovery occurs during the second part of the Younger Dryas. Not only the SL, but also periods of high tree mortality (Fig. 4A, indicated by black dots, e.g. 13 500 and 13 000 cal. yr BP) provide temporarily high sedimentary activity. In contrast, high germination rates imply low aggradational activity as well as favorable climatic conditions.

Besides the above listed external forcing agents, temperature plays a decisive role in growth behaviour, especially during periods of lower sedimentation. Hence, detrended series probably possess a good proportion of climate-related variability, as evidenced by their common signal in Fig. 5 (Schaub *et al.* 2007). The AGR is strongly affected by the prevailing environmental conditions. Many archives suggest a temperature reduction of up to 3–6 °C for the Allerød to Younger Dryas transition (Croope *et al.* 1998; Ammann *et al.* 2000; Lotter *et al.* 2000). Instead of such an expected reduction in AGR, a growth increase is observed at the onset of the Younger Dryas (G5 in Fig. 4B). A reduction of this range does not seem congruous with the almost constant AGR. One possible explanation is that major environmental changes were largely restricted to the winter season and did not occur during the warmer vegetation period (see Denton *et al.* 2005; Lie & Paasche 2006).

Environmental variability and reconstruction uncertainties

Synchronous positive and negative decadal-scale fluctuations within independent subgroups were detected and demonstrate a generally common signal (Fig. 5). The high temporal accordance between subgroups, including samples from different sites and periods, is evidence of a regional-scale climatic signal. It is very likely that temperature is responsible for most of the observed variability, especially during longer periods of less geomorphic activity; an analogous situation today is how temperatures are the primary constraint on pine trees that form the recent northern tree line in Scandinavia (Grudd *et al.* 2002).

There is perhaps a slight tendency for subgroups to show more anomalous behaviour during the first and last decades in comparison to most other chronologies (e.g. years 600 to 650 and 750 to 850). This deviation probably reflects a reduced signal-to-noise ratio within the juvenile period, perhaps originating from relatively greater forest stands or geomorphic stress during the beginning of a tree's lifetime or insufficient removal of the age-related trend. More anomalous growth at the end of the subgroup chronologies could reflect noise, because the trees were stressed during burial. Sample replication is at its lowest at both the beginning and the end of the subgroups; therefore these periods contain less reliable information. Despite such potential complications, most of the subgroups usually display a high degree of coherency with each other (e.g. S9 and S10) independently of the exact timing of germination (e.g. S6 and S7).

The climatic progression shows fairly stable temperatures in the Bølling and during the first part of the Allerød, as reconstructed from oxygen isotopes ($\delta^{18}O$) in Greenland ice cores (e.g. GRIP: Johnsen *et al.* 2001). By contrast, abrupt and distinct changes are noted for the second part of the Allerød and the transition into the Lateglacial. Similar results are derived from the reconstruction using all data (Fig. 5B). The period of year 1 to 800 is mostly balanced and characterized by high-frequency variations of positive and negative anomalies. A first distinct environmental signal is detected at position 750 to 1050. Isochronally, the sediments of different Swiss lakes, such as the Gerzensee, show a strong reaction in oxygen isotope ratio (Eicher 1980). This so-called Gerzensee Deviation (also known as the Inner Allerød Cold Period, GI-1b) was most likely forced by the same impacts as the reaction in the tree-ring chronology, and is characterized by a ~4‰ decrease in the $\delta^{18}O$ values of glacial ice between 13 250 and 13 050 cal. yr BP (Mayewski *et al.* 1993). In contrast to the results discussed earlier, another period of distinct changes in the environmental reconstruction occurs during the time period after year 1400, i.e. when onset of the Younger Dryas is assumed.

Conclusions

Different Lateglacial chronologies, containing a total of 120 pine samples, were dated by tree-ring matches to the calendrically dated Preboreal Pine Chronology (PPC) or by wiggle-matching to the Cariaco reference data set to fall within the 14 170 to 11 538 cal. yr BP time frame. The new measurements from the Swiss Plateau extended the absolute chronology by 183 years back to 12 593 cal. yr BP. These tree-ring time series are currently the oldest calendrically dated series in the world.

The longest Lateglacial chronology (ZH LG_1) containing 1420 years was wiggle-matched to the 14 170 to 12 750 cal. yr BP period. Based on radiocarbon-dating, we estimate that the Younger Dryas chronology described here in YD_A falls within the approximately 150-year gap created by the ZH LG_1 and the absolutely dated chronology. However, reduced data availability has not yet permitted these chronologies to be linked. High-resolution evidence for environmental changes during the Allerød to Younger Dryas transition is provided by analysis of growth trend patterns along this 2400-year period within different temporal subgroups and also compared to recent tree growth. Environmental fluctuations are reconstructed for a predominant part of the Lateglacial. The development of these chronologies was supported by almost 100 radiocarbon age determinations, which also provide material to improve and extend the radiocarbon calibration data set.

In this study, we have drawn attention to the low number of tree finds at the onset of the Allerød as well as generally for onset of the Younger Dryas. Uncertainty within the calibrated radiocarbon data during plateaus in the radiocarbon calibration curve further complicates dating results. Besides these more general biases, local-scale influences, such as the sedimentation rate and ecological site conditions, can impact heavily on tree growth. Therefore, future research will need to consider (i) the improvement of dating techniques (e.g. tree-ring and radiocarbon); (ii) the update of existing and development of new local-scale to regional-scale Lateglacial chronologies (e.g. providing fossil tree-ring evidence from the greater Alpine region and other European areas). Such data should be derived exclusively from (iii) climate sensitive sites, with (iv) enough samples provided to allow detrending methods to be robustly applied, and (v) maximum density or stable isotope measurements being performed to add additional and independent parameters that will lead to a greater understanding of the rapid climatic fluctuations during the Lateglacial to Holocene transition.

Acknowledgements. – We thank the 'Tiefbauamt des Kantons Zürich' (O. Schnelli) for financial and technical support and H. Jäckli (Jäckli AG Zürich; Geologie-Geotechnik-Grundwasser) for administrative processing. The ^{14}C analyses were done within the German DEKLIM program (Federal Ministry of Education and Research). We also thank Dr. Fidel Roig and an anonymous reviewer for useful comments. M. Schmidhalter kindly provided recent and historic pine samples. U.B. and D.F. were supported by the Swiss National Science Foundation (EUROTRANS 200021-105663 and NCCR-Climate).

References

Ammann, B., Birks, H. J. B., Brooks, S. J., Eicher, U., von Grafenstein, U., Hofmann, W., Lemdahl, G., Schwander, J., Tobolski, K. & Wick, L. 2000: Quantification of biotic responses to rapid climatic changes around the Younger Dryas – a synthesis. *Palaeogeography, Palaeoclimatology, Palaeoecology 159*, 313–347.

Bard, E. 2002: Climate shock: Abrupt changes, over millennial time scales. *Physics Today 55*, 32–38.

Becker, B. 1993: An 11,000-year German oak and pine dendrochronology for radiocarbon calibration. *Radiocarbon 35*, 201–213.

Birks, H. H. & Ammann, B. 2000: Two terrestrial records of rapid climatic change during the glacial–Holocene transition (14,000–9,000 calendar years BP) from Europe. *Proceedings of the National Academy of Sciences of the United States of America 97*, 1390–1394.

Bräker, O. U. 1981: Der Alterstrend bei Jahrringdichten und Jahrringbreiten von Nadelhölzern und sein Ausgleich. *Mitteilungen der forstlichen Bundesversuchsanstalt Wien 142*, 75–102.

Briffa, K. R., Jones, P. D., Bartholin, T. S., Eckstein, D., Schweingruber, F. H., Karlén, W., Zetterberg, P. & Eronen, M. 1992: Fennoscandian summers from AD 500: Temperature changes on short and long timescales. *Climate Dynamics 7*, 111–119.

Briffa, K. R., Jones, P. D., Schweingruber, F. H., Karlén, W. & Shiyatov, S. G. 1996: Tree ring variables as proxy-climate indicators. Problems with low-frequency signals. *In* Jones, P. D., Bradley, R. S. & Jouzel, J. (eds.): *Climatic Variations and Forcing Mechanisms of the Last 2000 Years*, 9–41. Springer, Berlin.

Büntgen, U., Esper, J., Frank, D. C., Nicolussi, K. & Schmidhalter, M. 2005: A 1052-year tree-ring proxy of Alpine summer temperatures. *Climate Dynamics 25*, 141–153.

Büntgen, U., Frank, D. C., Nievergelt, D. & Esper, J. 2006: Alpine summer temperature variations, AD 755–2004. *Journal of Climate 19*, 5606–5623.

Cook, E. R. 1985 *A Time Series Analysis Approach to Tree-Ring Standardization*. Ph.D. dissertation, University of Arizona, 171 pp.

Cook, E. R., Briffa, K. R., Meko, D. M., Graybill, D. A. & Funkhouser, G. 1995: The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies. *The Holocene 5*, 229–237.

Cook, E. R. & Peters, K. 1981: The smoothing spline: A new approach to standardizing forest interior tree-ring width series for dendroclimatic studies. *Tree-Ring Bulletin 41*, 45–53.

Cook, E. R. & Peters, K. 1997: Calculating unbiased tree-ring indices for the study of climatic and environmental change. *The Holocene 7*, 361–370.

Cook, E. R. & Kairiukstis, L. A. 1990: *Methods of Dendrochronology. Applications in Environmental Science*, 394 pp. Kluwer Academic, Dordrecht.

Croope, G. R., Lemdahl, G., Lowe, J. J. & Walkling, A. 1998: Temperature gradients in Northern Europe during the Last-glacial–Holocene Transition (14–9 ^{14}C kyr BP) interpreted from coleopteran assemblages. *Journal of Quaternary Science 13*, 419–433.

Denton, G. H., Alley, R. B., Comer, G. C. & Broecker, W. S. 2005: The role of seasonality in abrupt climate change. *Quaternary Science Reviews 24*, 1159–1182.

Eicher, U. 1979 *Die $^{18}O/^{16}O$- und $^{13}C/^{12}C$-Isotopenverhältnisse in spätglazialen Süsswasserkarbonaten und ihr Zusammenhang mit den Ergebnissen der Pollenanalyse*. Ph.D. dissertation, University of Bern, 205 pp.

Eicher, U. 1980: Pollen- und Sauerstoffisotopenanalysen an den spätglazialen Profilen vom Gerzensee, Faulenseemoos und vom Regenmoos ob Boltigen. *Mitteilung der Naturforschenden Gesellschaft Bern 37*, 65–80.

EPICA 2006: One-to-one coupling of glacial climate variability in Greenland and Antarctica. *Nature 444*, 195–198.

Escher, K. 1911: *Chronik der ehemaligen Gemeinde Wiedikon und Aussersihl*. 224 pp. Orell Fuessli, Zürich.

Esper, J., Cook, E. R., Krusic, P. J., Peters, K. & Schweingruber, F. H. 2003: Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies. *Tree-Ring Research 59*, 81–98.

Frank, D. C. & Esper, J. 2005a: Characterization and climate response patterns of a high-elevation, multi-species tree-ring network for the European Alps. *Dendrochronologia 22*, 107–121.

Frank, D. C. & Esper, J. 2005b: Temperature reconstructions and comparisons with instrumental data from a tree-ring network for the European Alps. *International Journal of Climatology 25*, 1437–1454.

Friedrich, M., Kromer, B., Kaiser, K. F., Spurk, M., Hughen, K. A. & Johnsen, S. J. 2001: High-resolution climate signals in the Bølling–Allerød Interstadial (Greenland Interstadial 1) as reflected in European tree-ring chronologies compared to marine varves and ice-core records. *Quaternary Science Reviews 20*, 1223–1232.

Friedrich, M., Kromer, B., Spurk, H., Hofmann, J. & Kaiser, K. F. 1999: Paleo-environment and radiocarbon calibration as derived from Lateglacial/Early Holocene tree-ring chronologies. *Quaternary International 61*, 27–39.

Friedrich, M., Remmele, S., Kromer, B., Hofmann, J., Spurk, M., Kaiser, K. F., Orcel, C. & Küppers, M. 2004: The 12,460 year Hohenheim oak and pine tree-ring chronology from Central Europe – A unique annual record for radiocarbon calibration and paleo-environment reconstructions. *Radiocarbon 46*, 1111–1122.

Fritts, H. C. 1976: *Tree Rings and Climate*. 567 pp. Academic Press, New York.

Grossmann, H. 1934: Vorgeschichtliche Hölzer im Utolehm. *Schweizerische Zeitschrift für Forstwesen 4*, 116–120.

Grudd, H., Briffa, K. R., Karlen, W., Bartholin, T. S., Jones, P. D. & Kromer, B. 2002: A 7400-year tree-ring chronology in northern Swedish Lapland: Natural climatic variability expressed on annual to millennial timescales. *Holocene 12*, 657–665.

Heiri, O. & Lotter, A. F. 2005: Holocene and Lateglacial summer temperature reconstruction in the Swiss Alps based on fossil assemblages of aquatic organisms: A review. *Boreas 34*, 506–516.

Hekkinen, O. & Tikkanen, M. 1987: The Kalajoki dune field on the west coast of Finland. *Fennia 165*, 241–267.

Helama, S., Timonen, M., Lindholm, M., Meriläinen, J. & Eronen, M. 2005: Extracting long-period climate fluctuations from tree-ring chronologies over timescales of centuries to millennia. *International Journal of Climatology 25*, 1767–1779.

Holmes, R. L. 1983: Computer-assisted quality control in tree-ring dating and measurements. *Tree-Ring Bulletin 43*, 69–78.

Hughen, K. A., Southon, J. R., Lehman, S. J. & Overpeck, J. T. 2000: Synchronous radiocarbon and climate shifts during the last deglaciation. *Science 290*, 1951–1954.

IPCC 2001: *Climate Change 2001 – the Scientific Basis*. 944 pp. Cambridge University Press, Cambridge.

Johnsen, S. J., Dahl-Jensen, D., Gundestrup, N., Steffensen, J. P., Clausen, H. B., Miller, H., Masson-Delmotte, V., Sveinbjörnsdóttir, Á. E. & White, J. 2001: Oxygen isotope and paleotemperature records from six Greenland ice-core stations: Camp Century, Dye-3, GRIP, GISP2, Renland and NorthGRIP. *Journal of Quaternary Science 16*, 299–307.

Jones, P. D. & Mann, M. E. 2004: Climate over past millennia. *Reviews of Geophysics 42*, RG2002, doi: 10.1029/2003RG000143.

Kaiser, K. F. 1979: *Ein spätglazialer Wald im Dättnau bei Winterthur/Schweiz*. Ph.D. dissertation, University of Zurich, 90 pp.

Kaiser, K. F. 1993: *Beiträge zur Klimageschichte vom Hochglazial bis ins frühe Holozän, rekonstruiert mit Jahrringen und Molluskenschalen aus verschiedenen Vereisungsgebieten*. 206 pp. Ziegler Druck- und Verlags-AG, Winterthur.

Kromer, B., Friedrich, M., Hughen, K. A., Kaiser, K. F., Remmele, S., Schaub, M. & Talamo, S. 2004: Late Glacial ^{14}C ages from a floating, 1382-ring pine chronology. *Radiocarbon 46*, 1203–1209.

Kromer, B. & Münnich, K. O. 1992: CO_2 gas proportional counting in radiocarbon dating – review and perspective. *In* Taylor, R. E., Long, A. & Kra, R. S. (eds.): *Radiocarbon after Four Decades*, 184–197. Springer, New York.

Leuschner, H. H. 1992: Subfossil trees. *In* Bartholin, T. S., Berglund, B. E., Eckstein, D. & Schweingruber, F. H. (eds.): *Tree-rings and Environment. Proceedings of the International Dendrochronological Symposium*, 193–197. LUNDQUA Report 34, Ystad, Sweden.

Lie, O. & Paasche, O. 2006: How extreme was northern hemisphere seasonality during the Younger Dryas? *Quaternary Science Reviews 25*, 404–407.

Lotter, A. F., Birks, H. J. B., Eicher, U., Hofman, J., Schwander, J. & Wick, L. 2000: Younger Dryas and Allerod summer temperatures at Gerzensee (Switzerland) inferred from fossil pollen and cladoceran assemblages. *Palaeogeography, Palaeoclimatology, Palaeoecology 159*, 349–361.

Magny, M., Aalbersberg, G., Bégeot, C., Benoit-Ruffaldi, P., Bossuet, G., Disnar, J.-R., Heiri, O., Laggoun-Defarge, F., Mazier, F., Millet, L., Peyron, O., Vannière, B. & Walter-Simonnet, A.-V. 2006: Environmental and climatic changes in the Jura mountains (eastern France) during the Lateglacial–Holocene transition: a multi-proxy record of Lake Lautrey. *Quaternary Science Reviews 25*, 414–445.

Maisch, M. 1995: Gletscherschwundphasen im Zeitraum des ausgehenden Spätglazials (Egesen-Stadium) und seit dem Hochstand von 1850 sowie Prognosen zum künftigen Eisrückgang in den Alpen. *In* SANW/ASSN (eds.): *Gletscher im ständigen Klimawandel. Jubiläums-Symposium der Schweiz. Gletscherkommission 1993 Verbier (VS) "100 Jahre Gletscherkommission – 100,000 Jahre Gletschergeschichte"*, 81–100. V/d/f Hochschulverlag AG & ETH, Zürich.

Mayewski, P. A., Meeker, L. D., Whitlow, S., Twickler, M. S., Morrison, M. C., Alley, R. B., Bloomfield, P. & Taylor, K. 1993: The atmosphere during the Younger Dryas. *Science 261*, 195–197.

Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlen, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van Krevel, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R. R. & Steig, E. J. 2004: Holocene climate variability. *Quaternary Research 62*, 243–255.

Melvin, T. M. 2004: *Historical Growth Rates and Changing Climatic Sensitivity of Boreal Conifers*. Ph.D. dissertation, University of East Anglia, 271 pp.

Miramont, C., Sivan, O., Rosique, T., Edouard, J. L. & Jorda, M. 2000: Subfossil tree deposits in the Middle Durance (Southern Alps, France): Environmental changes from Allerod to Atlantic. *Radiocarbon 42*, 423–435.

Müller, B. V. 2000: *Datierung fossiler Hölzer am Übergang Jüngere Dryas / Präboreal*. Diploma thesis, University of Zurich, 101 pp.

NRC (National Research Council) 2006: *Surface Temperature Reconstructions for the Last 2,000 Years*. 132 pp. National Academic Press, Washington D.C.

Osborn, T. J., Briffa, K. R. & Jones, P. D. 1997: Adjusting variance for sample-size in tree-ring chronologies and other regional-mean time-series. *Dendrochronologia 15*, 89–99.

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Benders, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, B., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pépin, L., Ritz, C., Saltzman, E. & Stievenard, M. 1999: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature 399*, 429–436.

Ramsey, C. B., Van Der Plicht, J. & Weninger, B. 2001: Wiggle matching' radiocarbon dates. *Radiocarbon 43*, 381–389.

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S. J., Larsen, L. B., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E. & Ruth, U. 2006: A new Greenland ice core chronology for the last glacial termination. *Journal of Geophysical Research 111, D06102*, doi: 10.1029/2005JD006079.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, F. G., Manning, S., Bronk Ramsey, C., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Taylor, F. W., van der Plicht, J. & Weyhenmeyer, C. E. 2004: IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. *Radiocarbon 46*, 1029–1058.

Rinn, F. 1996: *TSAP – Time Series Analyses Presentation. Reference Manual (version 3.0)*. 263 pp. RinnTech, Heidelberg.

Roig, F. A., Le-Quesne, C., Boninsegna, J. A., Briffa, K. R., Lara, A., Grudd, H., Jones, P. D. & Villagran, C. 2001: Climate variability 50,000 years ago in mid-latitude Chile as reconstructed from tree rings. *Nature 410*, 567–570.

Schaub, M. 2003: *Fossile Föhren der Uto-Autobahnbaustelle als Zeugen spätglazialer Klimaschwankungen*. Diploma thesis, University of Zurich, 80 pp.

Schaub, M., Büntgen, U., Kaiser, K. F., Kromer, B., Talamo, S., Andersen, K. K. & Rasmussen, S. O. 2007: Lateglacial environmental variability from Swiss tree rings. *Quaternary Science Reviews*, in press.

Schaub, M., Kaiser, K. F., Kromer, B. & Talamo, S. 2005: Extension of the Swiss Lateglacial tree-ring chronologies. *Dendrochronologia 23*, 11–18.

Schweingruber, F. H. 1996: *Tree Rings and Environment. Dendroecology*. 609 pp. Haupt, Bern.

Schweingruber, F. H., Bräker, O. U. & Schär, E. 1979: Dendro-climatic studies on conifers from Central-Europe and Great-Britain. *Boreas 8*, 427–452.

Spurk, M., Friedrich, M., Hofmann, J., Remmele, S., Frenzel, B., Leuschner, H. H. & Kromer, B. 1998: Paleo-environment and radiocarbon calibration as derived from Lateglacial/Early Holocene tree-ring chronologies. *Quaternary International 61*, 27–39.

Spurk, M., Kromer, B. & Peschke, P. 1999: Dendrochronologische, palynologische und Radiokarbon-Untersuchungen eines Waldes aus der Jüngeren Tundrenzeit. Naturwissenschaftliche Untersuchungen zum Weichselspätglazial in der Niederlausitz bei Cottbus (Land Brandenburg). *Quartär 49/50*, 34–38.

Stainforth, D. A., Aina, T., Christensen, C., Collins, M., Faull, N., Frame, D. J., Kettleborough, J. A., Knight, S., Martin, A., Murphy, J. M., Piani, C., Sexton, D., Smith, L. A., Spicer, R. A., Thorpe, A. J. & Allen, M. R. 2005: Uncertainty in predictions of the climate response to rising levels of greenhouse gases. *Nature 433*, 403–406.

Treydte, K., Schleser, G. H., Helle, G., Frank, D. C., Winiger, M., Haug, G. H. & Esper, J. 2006: The twentieth century was the wettest period in northern Pakistan over the past millennium. *Nature 440*, 1179–1182.

Veit, H. 2002: *Die Alpen – Geoökologie und Landschaftsentwicklung*. 352 pp. UTB, Eugen Ulmer, Stuttgart.

Wagenbach, D. 1989: Environmental records in alpine glaciers. *In* Oeschger, H. & Langway, C. C. (eds.): *The Environmental Record in Glaciers and Ice Sheets*, 69–83. John Wiley, Chichester.

Wick, L. 2000: Vegetational response to climatic changes recorded in Swiss Late Glacial lake sediments. *Palaeogeography, Palaeoclimatology, Palaeoecology 159*, 231–250.

Wigley, T. M. L., Briffa, K. R. & Jones, P. D. 1984: On the average of value of correlated time series, with applications in dendroclimatology and hydrometeorology. *Journal of Applied Meteorology 23*, 201–213.

Wurth, G., Niggemann, S., Richter, D. K. & Mangini, A. 2004: The Younger Dryas and Holocene climate record of a stalagmite from Holloch cave (Bavarian Alps, Germany). *Journal of Quaternary Science 19*, 291–298.