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ORIGINAL ARTICLE

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Holocene tree-line variability in the Kauner Valley, Central Eastern Alps, indicated by dendrochronological analysis of living trees and subfossil logs

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Abstract The altitude of the Alpine tree-line has often been used as proxy for the climatic conditions in the Holocene epoch. The usual approach for establishing a record for this proxy is the analysis of pollen and macro remains. We analysed living trees and subfossil logs from the timberline ecotone in the innermost Kauner valley in the Central Eastern Alps in order to assemble a Holocene dendrochronological tree-line record. Data sets comprising age and height of living Stone Pines (*Pinus cembra* L.) were collected at one site. Sections of 170 subfossil Stone Pine logs from five other sites were dendrochronologically analysed and dated. Besides using dendrochronological analyses, radiocarbon dating served as a means of obtaining the age of some logs. For most of the samples we could provide dendrochronological dates (1-year dating precision, back to 5125 B.C.) or wiggle matched dates (between approx. 7100 and 5040 B.C., dating precision with 95% probability: ±7 years). In the first half of the 19th century the tree-line was located at about 2180 m a.s.l. in the innermost Kauner valley. After approximately A.D. 1860 the altitude of the upper limit of the occurrence of *Pinus cembra* individuals (tree-species-line) and, being closely linked, also that of the tree-line both rose. The current tree-line (trees >2 m) is located at 2245 m a.s.l. due to climatic conditions around 1980. Additionally we observed saplings up to a present (A.D. 2000) tree-species-line at approx. 2370 m a.s.l. The dendrochronologically analysed subfossil logs found at up to 2410 m a.s.l. date from within the last 9000 years (between approx. 7100 B.C. and A.D. 1700). In the space of the last 4000 years the dendrochronological tree-line record is not continuous, probably due to human impact. Tree-line positions similar to or slightly above the 1980 tree-line are established for the time periods approx. 1000 to 640 B.C. and A.D. 1 to 330 respectively. For the time period between approx. 7100 and 2100 B.C. the dendrochronologically analysed logs show nearly continuous evidence of a tree-line above the 1980s limit. Very high elevation of the tree-line, between 120 and 165 m above the 1980s level (2245 m a.s.l.) and even higher than the A.D. 2000 tree-species-line (2370 m a.s.l.), are recorded for the periods 7090–6570, 6040–5850, 5720–5620, 5500–4370 B.C., approx. 3510–3350 B.C. and 2790–2590 B.C. Additionally, a tree-line which was located at least 50 m above the 1980s limit can be shown for the periods 6700–5430, 4920–3350 and 3280–2110 B.C. The dendrochronological record from the Kauner valley, showing high and very high tree-line positions between approx. 7100 and 2100 B.C. with only two gaps (around 6490 B.C. and from 3350 to 3280 B.C.), suggests that summer temperatures as observed in the late 20th century were at the normal or the lower limit of the temperature range which can be assumed for long periods of the early and middle Holocene epoch.

Keywords Holocene · Alps · tree line · *Pinus cembra* · dendrochronology

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Introduction

The analysis of tree-line fluctuations is a classical approach to investigating the variability of the climate during the Holocene. For many years palynological research on material found in peat bogs or lakes within the timberline ecotone has been the methodological procedure for such studies (for the Western and Southern Alps: Welten 1952; Zoller et al. 1966; Carcaillet and Thinon 1996; Burga et al. 2001; Tinner and Theurillat 2003). For the middle part of the Eastern Alps Sigmar Bortenschlager and his group at the Institute of Botany, University of Innsbruck, have been carrying out palynological analysis since the late 1960s. His work and that of his colleagues (Bortenschlager 1970; Patzelt and Bortenschlager 1973; Bortenschlager et al. 1998; Bortenschlager 2000) has provided new results and insights on the variability of the Alpine tree-line. The pollen profiles established in the Alps have been used to reconstruct the vegetation history, e.g. in the context of glacier fluctuations (Zoller et al. 1966; Patzelt and Bortenschlager 1973) and of the climate (Bortenschlager et al. 1998; Burga and Perret 1998) during the Holocene. Besides analysing the pollen content of material from locations within the Holocene timberline ecotone, macro remains, e.g. needles, have also been used to investigate tree-line oscillations (Oeggl and Wahlmüller 1994; Wick and Tinner 1997) and to prove that at least single individuals were growing at a specific site and altitude.

Logs are a type of “mega” macro remains, including branches and roots as well as other remains of the tree itself. These wood remains provide additional potential for studying the Holocene tree-line variability. The number of tree-rings revealed in such finds allows the establishment of a precise minimum time period of tree growth at a specific site. The dating of pollen profiles and macro remains usually relies on radiocarbon dating. Remains of wood, e.g. logs, are also a perfect material for ^{14}C-analysis for age estimation. Moreover, the measurement of the tree-rings of such wood remains, especially tree trunks, offers the possibility of dendrochronological dating.

Tree-ring analysis of logs from sites in the Alpine timberline ecotone has the potential to establish a record of Holocene tree-line variability with high temporal resolution and accuracy. The limitations of this approach lie mainly in the site conditions, because the remains of the trees must be well preserved. Hence Alpine areas with favourable conditions, such as lakes and the widespread peat bogs, are needed for such investigations. The full potential of tree-ring analysis of logs from tree-line sites can only be exploited if there is a possibility of dendrochronological dating. Recently the establishment of new multi-millennial Alpine tree-ring chronologies (Nicolussi and Schießling 2001; Nicolussi et al. 2004) has enabled such dating. An absolutely dated and continuous tree-ring width chronology has been established back to 5125 B.C. based on wood samples from high elevation sites (> about 2000 m a.s.l.) in the Central Eastern Alps. Further chronologies are available for the early Holocene that are dated by wiggle matching of several ^{14}C-dates of synchronised samples. The synchronisation of tree-ring series with chronologies dated by wiggle matching allows improvement of chronological delimitation as compared with single ^{14}C-dates.

The analysis of subfossil logs and other wood remains from sites in the Holocene timberline ecotone in the Alps has been limited. Determination of the age of this kind of material (Furrer and Holzhauser 1984; Staffler and Feichter 1999) is usually based on single ^{14}C-dates, these studies rarely giving numbers of tree-rings of the samples investigated. However, a number of ^{14}C-dates of subfossil logs from locations within and above the current tree-line ecotone have been reported from Scandinavia (Dahl and Nesje 1996; Karlén 1999). These samples have also been used to reconstruct Holocene climate variability in this region (Dahl and Nesje 1996).

Here we present results on the variability of the Alpine tree-line during the Holocene from the Kauner valley in the Central Eastern Alps. In the innermost part of this valley, current tree-line changes have been investigated at one site and subfossil logs have been sampled at five additional sites in order to explore the past history of the tree-line in this area. Stone Pine (*Pinus cembra* L.), a coniferous species, is the dominant tree species in the tree-line ecotone in the Kauner valley (Schiechtl and Stern 1975).

Study sites

The inner section of the Kauner valley runs S-N, is located slightly to the north of the main Alpine ridge and is dominated by vast glaciers. This mountain area is part of the Ötztal Alps. The highest peaks in the innermost Kauner valley reach 3355 m (Glockturm) to 3510 m a.s.l. (Weißsee Spitze). Actual precipitation in this area is 1130 mm/a at about 2000 m a.s.l.

The contemporary potential altitude of the tree-line in the innermost Kauner valley (Fig. 1) has been fixed at between approximately 2200 and 2300 m a.s.l. (Schiechtl and Stern 1975). Schiechtl and Stern (1975) do not include the present changes in the tree-line position (TLP) due to current climatic change in the Alpine region. Hence current tree-line development was studied in two plots at site 1, each 35 m wide and 110 m and respectively 90 m long (Figs. 1 and 2). Plot 1 reached from 2170 to 2250 m and Plot 2 from 2285 to 2325 m a.s.l. Within the plots all Stone Pine individuals (*Pinus cembra* L.) taller than 8 cm were recorded. The lower boundary of plot 1 (site coded KM) was determined by the highest elevation of the presence in this area of mature individuals, as indicated by height (up to 21 m) and stem diameter (up to 0.7 m). Few saplings of the species *Pinus cembra* L. were growing higher than the upper limit of plot 2. A few single mature trees growing outside the plots were also studied. In addition to the living Stone Pine trees and saplings, dry dead trees found within the plots were also sampled and analysed. The date of germination and the life span of all living Stone Pines and stems analysed at site 1 were determined.

Sections of subfossil logs were collected at 5 different locations in the innermost Kauner valley. All samples found are of the species *Pinus cembra* L. Samples of logs found on the glacier forefield of the glacier Gepatschferner (site 2, site-code GP) have mainly been investigated to reconstruct the Holocene oscillations of this glacier (Nicolussi and Patzelt 2001). The subfossil stems were found at two different locations on the glacier forefield. For this paper only logs which were still embedded in till (n=25) at the position where they were found were

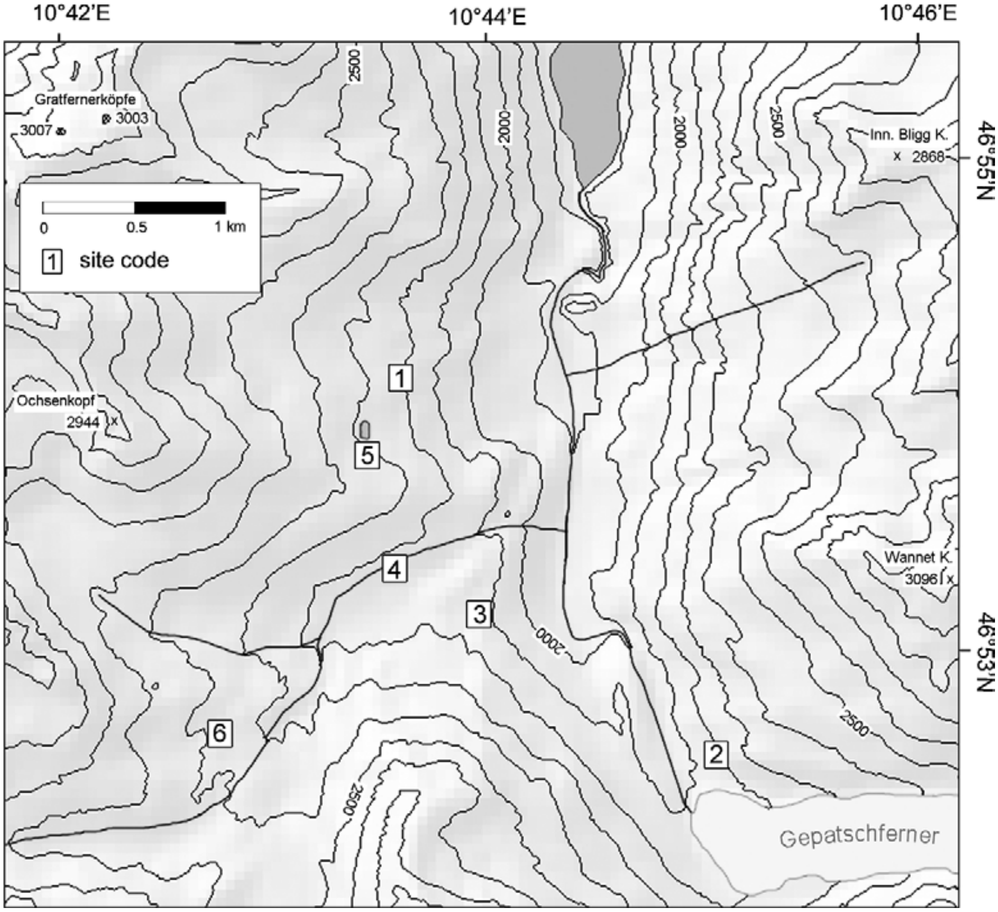

Fig. 1 The innermost Kauner valley and the location of the study sites. Site 1: Gepatsch Alm (living and dry dead trees, code KM), site 2: Gepatschferner (subfossil logs, code GP), site 3: "Ombrometer" (subfossil logs, GLI), site 4: Ochsenalm (subfossil logs, KOA), site 5: Daun moraine lake (subfossil logs, GDM), site 6: Krummgampen (subfossil logs, KG). Map source: Tirol Atlas, Institute of Geography, Univ. of Innsbruck

Fig. 2 The timberline ecotone in the innermost Kauner valley. The picture shows the area of site 1 with the upper end of the *Pinus cembra* L. forests and single trees at higher altitudes. The standing dead tree in the lower left part of the picture is tree KM-1 (see text). Photograph: K. Nicolussi

taken into consideration. Hence, the altitudinal position of growth could be determined for such stems. Other Stone Pine logs found on the slopes below the moraines and therefore lacking information about their position of growth (Nicolussi and Patzelt 2001) were not used for this study. Site 3 (site code GLI) is located above the lowest part of the forefield of the Gepatschferner. It is characterised by a relatively even relief where various peat bogs exist upon slopes and in small vales. 39 logs found at altitudes between 2135 and 2160 m a.s.l. have been dated. Site 4 (site code KOA) is located on both sides of the Riffl stream. Subfossil logs have been found in peat bogs located on the lower and flat parts of the slopes in this valley. The altitudinal range of these finds (n=41) ranges from 2160 to 2190 m a.s.l. Currently only a few small living Stone Pine individuals can be observed at sites 3 and 4. This is probably due to intensive grazing activities in this part of the valley. Most of the sections from logs (n=44) at site 5 (site code GDM, Figs. 3 and 4) originate from a small lake (2295 m a.s.l.) retained behind a late-glacial moraine. A few samples were taken from a small peat bog which developed at the lower end of this lake. Plot 2 of site 1 is on the edge of site 5, sites 1 and 5 being contiguous. Currently only small (<1.1 m in summer 2002) and young living individuals can be observed around the lake. The altitudinal range of the most elevated site where we found subfossil logs (n=21) in the Kauner valley is 2365–2410 m a.s.l. (site 6, code KG, Fig. 5). Peat bogs have developed in small vales and on flat slopes. Currently no living trees can be observed at this site.

Materials and methods

The position and altitude of the living Stone Pines analysed from site 1 were obtained by GPS measurements. We established the altitudinal position of the tree-line within the last few centuries using the heights of individual trees and saplings. Following Ellenberg (1996) we used a threshold of 2 m tree height. Tree heights were determined by measurement with a pocket ruler for the smaller trees and with an optical height meter for the lager trees (Suunto PM-5/1520). Firstly the age and the germination date of young and small individuals (height <2.8 m) were assessed by counting the annual cohorts. Additionally dendrochronological analysis of the real date of germination and estimations of possible differences between this and the former method of determination were carried out on a sub-group of very young Stone Pine individuals (n=15). The mean value of the differences found is 4.7±1.7 years. This was rounded to 5 and added to all age estimations made by cohort counting. Tall and mature trees were investigated through samples taken by using increment corers. Measurements of total tree-ring width were carried out on these cores to a precision of 0.001 mm using a LINTAB 4 measuring device and the software TSAP (Time Series Analysis and Presentation). The tree-ring series obtained were processed by standard tree-ring methods (e.g. Schweingruber 1988). The date of germination of these trees was fixed by adding an estimation of the tree-age at the sampling height to the number of tree-rings obtained from the cores. Sections were cut from dry dead trees found at site 1 with

Fig. 3 The Daun moraine lake (site 5, code GDM, 2295 m a.s.l.) dammed by a late-glacial moraine. Photograph: K. Nicolussi

Fig. 4 A subfossil log at site 5 from the early Holocene (site code GDM, 2295 m a.s.l.) Photograph: K. Nicolussi

a chainsaw. Life span and date of germination were determined in the same fashion as explained above for the mature living trees of site 1.

Sections were taken from the subfossil logs found at sites 2 to 6. The altitudes of the find locations were fixed by repeated measurements with a barometric altimeter to the nearest 5 m scale value. Complete (early wood plus late wood) ring widths were measured to a precision of 0.001 mm for at least two radii per sample. Tree-ring series for each sample analysed were established by synchronising and averaging the measurements of the radii. These sample series were used for comparisons with other single tree-ring series and reference chronologies. Since subfossil wood undergoes decay processes, particularly when

Table 1 Sites with sampled subfossil logs in the innermost Kauner valley

Site	Site code	Coordinates	Altitudinal range [m a.s.l.]	Logs [*n*]	Segment length [Ø ± 1 σ, max. length]
2	GP	10° 44′ E 46° 52′ N	2120–2275	25	138.3±59.4, 276
3	GLI	10° 43′ E 46° 53′ N	2135– 2160	39	216.6±73.9, 504
4	KOA	10° 43′ E 46° 53′ N	2160–2190	41	211.9±79.7, 414
5	GDM	10° 43′ E 46° 53′ N	2295	44	239.6±101.1, 509
6	KG	10° 42′ E 46° 52′ N	2365–2410	21	187.6±82.3, 374

embedded in peat bogs, the pith of such logs is sometimes not preserved and the sapwood is usually lost (Spurk et al. 2002). Hence the length of the tree-ring series of a sample indicates a minimum span for the lifetime of the tree in question. For sections with missing inner part of the stem the tree-ring number between the pith and the first tree-ring measured was estimated for use in further analysis.

For the most part dendrochronological dating was used to establish the temporal position of these subfossil samples within the Holocene. In addition radiocarbon dating was used, especially in the first phase of chronology building (Nicolussi and Schießling 2001) and for samples lacking a satisfactory dendrochronological match. This occurs when the tree-ring series is too short or where extreme growth positions lead to distorted tree-ring growth. All samples used for radiocarbon dating were taken after the dendrochronological measurements and at a fixed position within the tree-ring series of the particular section. This procedure allows the use of wiggle matching as an advanced radiocarbon dating technique after dendrochronological synchronisation of different ^{14}C-dated tree-ring series. Both the calibration of single ^{14}C-dates and wiggle matching were done using OxCal 3.9 (Bronk Ramsey 1995) and the IntCal98 calibration data set (Stuiver et al. 1998). In this paper we use only absolute dendrochronological dates and calibrated ^{14}C-dates for the presentation of the results and for discussion.

To compare our results with the present climatic background a new temperature data set, based on homogenised measurements was used (Böhm et al. 2001). These temperature values are available as monthly series calculated for a grid of the Alpine region with 1° resolution. We used the temperature data of the nearest grid point (47°N 11°E), which is about 25 km in a direct line from the innermost Kauner valley and covers the period from 1864 to the present. Because tree-ring growth in the Alpine timberline ecotone is mainly controlled by the variability of the summer temperature (Tranquillini 1979; Nicolussi 1995) we calculated a temperature series for the growing season (May to September) for our comparisons.

Results

The results for the present changes in the timberline ecotone in the innermost Kauner valley are based on the analysis of 412 living and 13 dry dead Stone Pines at site 1. Figure 6 shows the life span of the trees and saplings analysed by altitude of the growth stand. The gap in Figs. 6 and 7 between 2250 and 2285 m a.s.l. reflects the difference in altitude between the upper limit of plot 1 and the lower limit of plot 2. Trees more than 200 years old and more than 12 m tall (Figs. 6 and 7) can only be found in the lowest part of plot 1. Here we were also able to sample dry dead trees. These trees, having multi-centennial life spans (Fig. 6), do not show the same date of death, moreover the dates of the last tree-rings measured spread over the period A.D. 1717 to 1871. The tree-ring series of these mature trees show some tree-ring width minima of multi-year duration. The last of these growth depressions occurred around A.D. 1815 and is in accordance with the well-known climatic deterioration in the same decade (Fliri 1996). After A.D. 1820 the tree-ring series do not show any similar growth decline.

These improved climatic conditions after about A.D. 1860 allowed the establishment of new Stone Pines above the early 19th century tree-line at site 1 (Fig. 6). We found living trees (heights today of up to 10 m, Fig. 7) that started growing between A.D. 1870 and 1890 up to an altitude of 2210 m a.s.l. and thus about 30 m above the early 19th century tree-line (approx. 2180 m). Another Stone Pine (sample code KM-1, height: 4.2 m) germinated around A.D. 1880 at an altitude of 2245 m a.s.l. but died during the relatively cold 1970s (Fig. 6). Within the same decade a small and shrub-like Stone Pine (height <0.6 m, 2320 m a.s.l., Fig. 6) died after a lifetime of approx. 50 years indicating that the upper limit of the "Krummholz" belt rose above 2300 m a.s.l. in approx. A.D. 1920.

Living Stone Pines, which started to grow in around A.D. 1920, can be found at altitudes of up to 2245 m a.s.l. at site 1 (Fig. 6). These trees are now up to 4.8 m tall and have established a new tree-line (trees >2 m, Ellenberg 1996) at 2245 m a.s.l. Beside these living Stone Pines, the standing tree KM-1 (2245 m a.s.l.), which died in the late 1970s, also proves that the altitude of 2245 m a.s.l. was the limit of growth of mature trees in the late 20th century. Climatic conditions did not allow the establishment and survival of Stone Pine trees (>2 m) at higher altitudes at site 1. The decade of A.D. 1970/80 was the coldest period of the second half of the 20th century (Böhm et al. 2001) and the tree-line at 2245 m a.s.l. was in equilibrium with the climatic conditions of about A.D.1980. The increase in altitude of the A.D. 1980 tree-line above the early 19th century tree-line (2180 m a.s.l.) is about 65 m at site 1.

Since about A.D. 1980, intensive germination of *Pinus cembra* L. can be observed at site 1. Small individuals (<0.4 m) grow up to 45 m above the upper limit of plot 2 (2325 m a.s.l.). Through these Stone Pines, which often show shrub-like growth forms, a current (A.D. 2000) tree species limit (upper limit of the "Krummholz" belt, Körner 1998) can be defined as about 2370 m a.s.l. The germination phase in the late 20th century is synchronous with an observed temperature increase in the same time period (Böhm et al. 2001). From the growth forms and height of growth observed (further details will be discussed in a separate paper) and assuming that no significant decrease in temperature will occur in the near future, we expect the establishment of a new tree-line at about 2300 to 2320 m a.s.l. at site 1 which would be in equilibrium with the climatic conditions since about A.D. 1980.

From the innermost Kauner valley 170 tree-ring series from subfossil logs of the Holocene timberline ecotone are available. These series spread over a time period between approx. 7100 B.C. and A.D. 1700. The subfossil samples of the last approx. 7000 years are, with a few exceptions, dated dendrochronologically. ^{14}C-dates were also available for some of the logs from the middle and late Holocene

Fig. 5 A peat bog in the lower part of site 6 (Krummgampen, code KG, 2365 to 2410 m a.s.l.). Photograph: K. Nicolussi

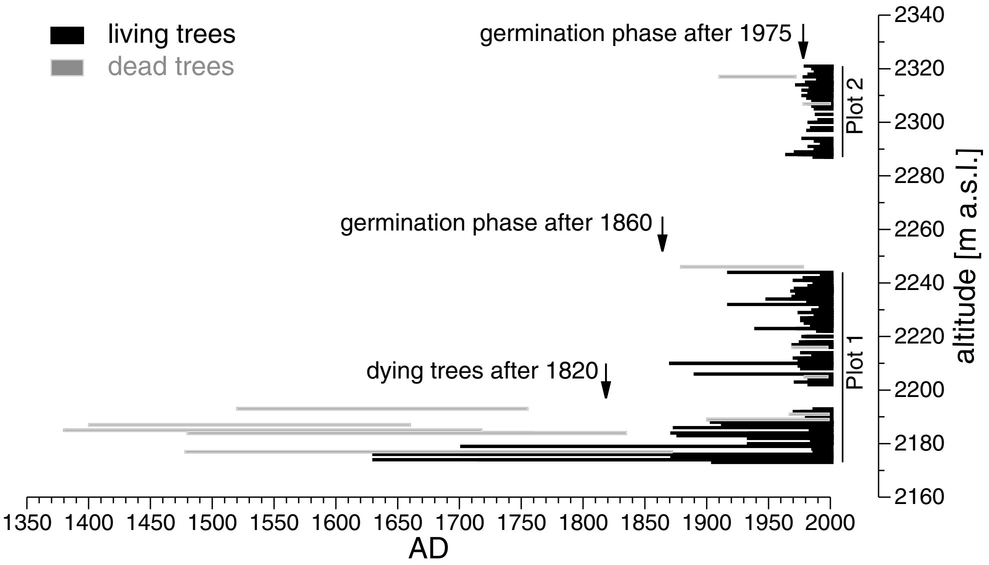

Fig. 6 The altitudinal distribution and life span of living and dry dead trees at site 1

(Table 2). Most of the tree-ring series from sections older than approx. 7000 years are synchronized with a floating chronology, dated by wiggle matching (Nicolussi et al. 2004) and hence highly accurate wiggle matching results are available for these samples also. The temporal distribution of dated tree-ring series, obtained from the subfossil logs is shown in Fig. 10 together with the altitude of the growth position. The different levels of dating (dendrochronological date, wiggle matching date, single ^{14}C-date) are indicated by different shading.

Samples from altitudes below c. 2200 m spread over the last c. 8000 years (Fig. 10). Most of them are from peat bogs (sites 3 and 4) at these elevations. A few sections from logs were collected on the forefield of the Gepatschferner (site 2). Figure 10 shows a concentration of tree-ring data between 3200 and 1700 B.C. Older samples are relatively rare. This can be explained by the collecting strategy: Only logs less than approx. 0.7 m below the surface were usually detected during our sampling. This is proven by the oldest section (KOA-10, approx. 6300 B.C., Table 2,

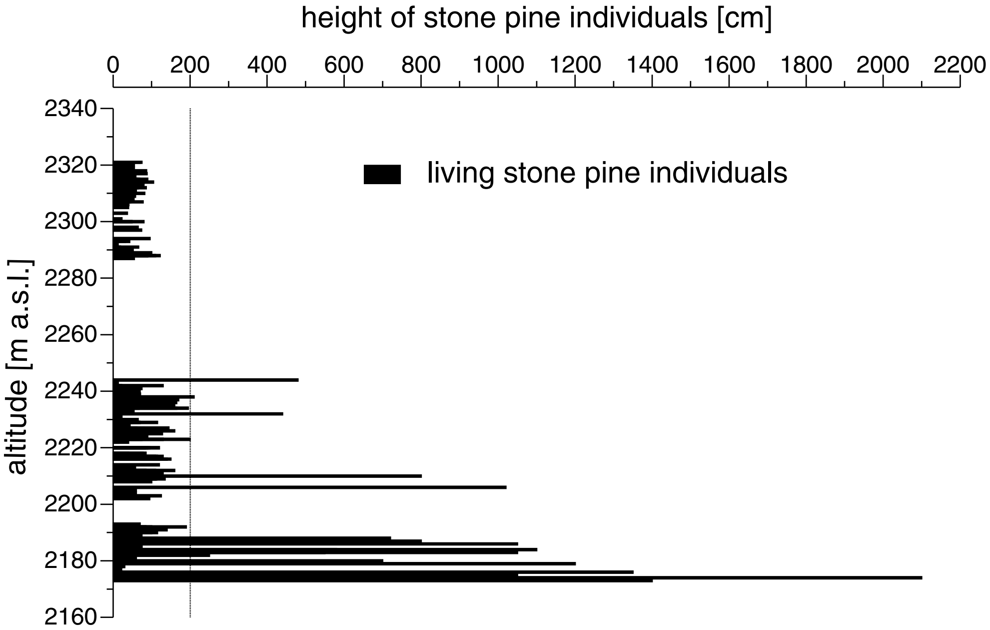

Fig. 7 The altitudinal distribution and the growth heights of living trees at site 1

Fig. 10) from an altitude below 2200 m a.s.l., which was found 1.3 m below the bog surface in a trench.

Samples younger than approx. 1700 B.C. are also quite rare. In contrast to the mid-Holocene period replication of subfossil logs shows repeated gaps for the last nearly four millennia. Neither collecting strategy nor possible climatic impact can explain this lack of samples completely. However, other studies suggest that this relatively low number of samples from the late Holocene is a result of the human impact which has been demonstrated at different sites in the Ötztal Alps. This influence on the vegetation has intensified since the Bronze Age (Patzelt 1996; Bortenschlager 2000). Grazing animals and burning of the forests caused deforestation within the timberline ecotone of the Central Alps. This is also supported by the observation of charcoal layers in peat bogs during sampling activities in the Kauner valley. Pollen analytical investigations and the analysis of charcoal remains also show that grazing activities started in the mid-Holocene epoch in the innermost Kauner valley (Krapf 2001). As a result, the gaps in the sample replication since the early Bronze Age must be mainly seen as an indication of human activities in this area, which were seemingly very intensive between approx. 1500 and 800 B.C.

However, evidence for climatically favourable conditions during the last 4000 years is given by logs found on the forefield of the glacier Gepatschferner. These samples indicate both possible high TLPs and glacier extents smaller than the observed extent of approx. A.D. 1930 (Nicolussi and Patzelt 2001). The logs from the Gepatschferner reveal favourable climatic conditions, which caused glacier retreat and allowed tree germination at high altitudes during different periods of the late Holocene, e.g. during the late Bronze Age (approx. 1000 to 640 B.C.) and the Roman Period (approx. A.D. 1 to 330). Also the ^{14}C-date of a small piece of wood (sample code: KG-1, VRI-1882, 2760±50 BP, 2 σ range: 1010–800 cal B.C.) with only 12 counted tree-rings found at site 6 at an altitude of about 2415 m a.s.l. indicates both a high position of the tree-species-line (the upper limit of the occurrence of *Pinus cembra* individuals) and a high possible position of the associated tree-line within the former period.

At site 5 (code GDM, 2295 m a.s.l.) 44 samples were collected and dated (Fig. 8). This site is directly connected to plot 2 of site 1. Site 5 is located above the 1980-tree-line and the former presence of mature Stone Pines at this location indicates climatic conditions during the lifetime of these trees better than those of the mid-20th century. Currently living Stone Pine individuals with heights up to 1.1 m (Fig. 7, as of summer 2002) and of an age of up to 40 years (Fig. 6) can be found just below the altitude of the lake. The subfossil samples from site 5 spread over a time period from approx. 6700 to 2100 B.C. (Fig. 8). So far no younger samples from this site have been found. The dated logs are distributed over three time periods which are divided by two major gaps at approx. 5430–4920 B.C. and around 3300 B.C. The first period with proven growth of mature trees at site 2 dates back to approx. 6700 to 5430 B.C. The tree-ring data set shows two small gaps in this period which emerge around 6490 B.C. (15 years) and 6015 B.C. (10 years). Most of the samples found at site 5 (GDM) are from two mid-Holocene periods (4920–3350 B.C. and 3280–2110 B.C.). Particularly high numbers of trees within these periods can be deduced from the accumulation of samples during the intervals approx. 4700 to 4200 B.C. and 3250 to 2700 B.C. The gap of about 70 years at approx. 3300 B.C. interrupts an almost 3000 year long phase of evidence for a high TLP from site 5.

Finds of subfossil logs at site 6 (Krummgampen, 2365–2410 m a.s.l.) are located at the same altitude as, or above the tree-species-line of A.D. 2000 observed at site 1. Evidence for the former presence of trees up to 2410 m a.s.l. is

Table 2 The ^{14}C-dates of subfossil samples from the innermost Kauner valley. Absolute dates were established using dendrochronological analysis for the majority of the sections from the past 7000 years. GrN-Groningen (conventional), Hd-Heidelberg, Hv-Hannover, VRI-Vienna

Sample	Length of the tree-ring series [yr]	^{14}C-sample [tree-ring series nr.]	Lab. No.	^{14}C-age [yr B.P.]	cal ^{14}C-age (1 σ) [yr]	cal ^{14}C-age (2 σ) [yr]	Absolute age tree-ring series [yr]
GDM-1	334	9–21	GrN 21551	7650±40	6505–6435 B.C.	6590–6420 B.C.	–
GDM-1B	334	133–163	GrN 27061	7490±30	6410–6340 B.C.	6430–6240 B.C.	–
GDM-2	207	192–207	GrN 21550	6510±25	5490–5460 B.C.	5530–5460 B.C.	–
GDM-3	339	22–41	Hd-17612–17700	5838±24	4730–4680 B.C.	4800–4600 B.C.	4703–4366 B.C.
GDM-4	309	9–30	GrN 21549	5990±25	4910–4870 B.C.	4940–4780 B.C.	4920–4612 B.C.
GDM-7	136	47–71	GrN 24824	7720±35	6590–6470 B.C.	6610–6460 B.C.	–
GDM-8/1	146	16–26	GrN 24825	4940±20	3715–3690 B.C.	3770–3650 B.C.	3938–3678 B.C.
GDM-11	445	14–29	GrN 24826	6945±30	5845–5770 B.C.	5890–5720 B.C.	–
GDM-12	290	82–128	GrN 24827	4335±20	2930–2890 B.C.	3020–2890 B.C.	3215–2926 B.C.
GDM-14	215	14–40	GrN 24828	7085±35	5955–5890 B.C.	6020–5870 B.C.	–
GDM-18	288	215–243	GrN 24829	4125±30	2700–2620 B.C.	2790–2570 B.C.	3035–2747 B.C.
GDM-21	150	6–33	GrN 24830	7215±35	6080–6020 B.C.	6120–5990 B.C.	–
GDM-25	178	36–49	GrN 24831	4990±30	3790–3710 B.C.	3810–3690 B.C.	3800–3622 B.C.
GDM-30	507	333–349	GrN 24832	3760±20	2200–2140 B.C.	2230–2130 B.C.	2625–2217 B.C.
GDM-31	273	45–74	GrN 24833	5200±20	4395–3975 B.C.	4005–3960 B.C.	4099–3827 B.C.
GDM-32	253	24–44	GrN 24834	4050±25	2620–2550 B.C.	2630–2470 B.C.	2665–2412 B.C.
GDM-34	169	22–28	GrN 24835	4955±20	3765–3700 B.C.	3780–3660 B.C.	3904–3736 B.C.
GDM-38	357	252–264	GrN 24836	4200±20	2810–2750 B.C.	2820–2740 B.C.	3155–2799 B.C.
GLI-17	209	3–33	GrN 25666	3780±30	2180–2140 B.C.	2300–2130 B.C.	–
GLI-44	165	10–21	GrN 25667	6180±30	5150–5050 B.C.	5260–5030 B.C.	5107–4942 B.C.
GLI-45	234	135–170	GrN 27732	2505±30	690–540 B.C.	800–510 B.C.	713–480 B.C.
GP-104	239	59–75	GrN 22766	3350±30	1690–1600 B.C.	1700–1520 B.C.	1796–1558 B.C.
GP-106	239	86–122	GrN 22767	6610±40	5560–5510 B.C.	5620–5470 B.C.	–
GP-107	142	38–50	GrN 23632	1371±17	648–669 A.D.	642–685 A.D.	616–757 A.D.
GP-112	140	91–98	GrN 23634	3460±20	1780–1730 B.C.	1780–1730 B.C.	1813–1674 B.C.
GP-125	62	25–34	GrN 24728	1725±25	250 – 350 A.D.	240–400 A.D.	269–330 A.D.
GP-128	117	66–75	GrN 24729	3400±30	1740–1680 B.C.	1780–1600 B.C.	–
GP-130	161	43–67	GrN 24541	3455±20	1780–1730 B.C.	1780–1680 B.C.	1819–1659 B.C.
GP-143	86	38–57	GrN 25194	1180±20	810–900 A.D.	770–900 A.D.	724–809 A.D.
GP-20	276	1–17	Hd-14356-14043	1930±20	55–85 A.D.	20–130 A.D.	53–328 A.D.
GP-21	86	47–65	GrN 22579	1815±35	130–250 A.D.	120–330 A.D.	244–330 A.D.
GP-2167	64	c. 45–64	VRI-1152	770±70	1190–1300 A.D.	1150–1330 A.D.	–
GP-2174	86	c. 67–86	VRI-1153	410±70	1430–1530 A.D.	1410–1650 A.D.	–
GP-22	236	45–66	GrN 22580	2810±40	1005–900 B.C.	1070–830 B.C.	952–717 B.C.
GP-60100	166	33–57	GrN 22581	1925±35	50–130 A.D.	1–140 A.D.	3 B.C. – 163 A.D.
GP-63	90	50–63	GrN 22582	2490±35	720–520 B.C.	790–480 B.C.	808–719 B.C.
GP-64	125	100–110	Hd-15472	2432±16	520–400 B.C.	550–400 B.C.	762–638 B.C.
GP-65	149	1–20	Hd-15749–15666	3445±23	1780–1730 B.C.	1780–1680 B.C.	1781–1633 B.C.
GP-80	109	66–89	Hv-11411	3420±70	1780–1620 B.C.	1890–1520 B.C.	1753–1645 B.C.
GP-96	204	65–100	GrN 27062	3710±20	2100–2035 B.C.	2150–2030 B.C.	2189–1986 B.C.
KG-11	374	235–257	GrN 24733	7910±30	6830–6680 B.C.	6840–6650 B.C.	–
KG-13	158	149–155	GrN 25213	6200±35	5190–5060 B.C.	5300–5040 B.C.	–
KG-17	346	36–43	GrN 25214	6400±30	5380–5320 B.C.	5480–5310 B.C.	–
KG-19	120	101–119	GrN 28700	6420±35	5470–5360 B.C.	5480–5320 B.C.	–
KG-2	131	17–36	GrN 24731	6380±30	5380–5310 B.C.	5430–5300 B.C.	–
KG-20	105	40–59	GrN 26450	6160±25	5210–5170 B.C.	5150–4990 B.C.	–
KG-31	131	69–85	GrN 28701	6140±35	5080–4990 B.C.	5150–4940 B.C.	–
KG-4	118	1–33	GrN 24928	6225±30	5260–5200 B.C.	5190–5060 B.C.	–
KG-6	197	7–26	GrN 24542	6205±25	5180–5070 B.C.	5280–5050 B.C.	5125–4929 B.C.
KG-7	298	208–219	GrN 24543	5680±30	4545–4490 B.C.	4600–4450 B.C.	4674–4377 B.C.

Table 2 Continued

Sample	Length of the tree-ring series [yr]	^{14}C-sample [tree-ring series nr.]	Lab. No.	^{14}C-age [yr B.P.]	cal ^{14}C-age (1 σ) [yr]	cal ^{14}C-age (2 σ) [yr]	Absolute age tree-ring series [yr]
KG-8	174	39–49	GrN 24544	7125±25	6015–5985 B.C.	6030–5970 B.C.	–
KG-9	161	31–58	GrN 24732	4640±25	3500–3450 B.C.	3520–3410 B.C.	–
KOA-1	192	123–164	GrN 24734	4690±30	3470–3370 B.C.	3530–3360 B.C.	3567–3375 B.C.
KOA-10	144	44–60	GrN 25668	7420±50	6380–6280 B.C.	6410–6200 B.C.	–
KOA-2	191	60–88	GrN 24735	4360±30	3020–2910 B.C.	3030–2900 B.C.	3046–2855 B.C.
KOA-5	307	30–46	GrN 24736	3580±25	1955–1880 B.C.	1980–1870 B.C.	2047–1741 B.C.
KOA-57	169	94–107	GrN 28702	4500±30	3340–3260 B.C.	3350–3090 B.C.	–
KOA-7	205	115–139	GrN 24837	3310±20	1590–1525 B.C.	1640–1520 B.C.	1851–1641 B.C.
KOA-8/2	78	17–26	GrN 24737	3740±25	2200–2130 B.C.	2210–2030 B.C.	2214–2137 B.C.

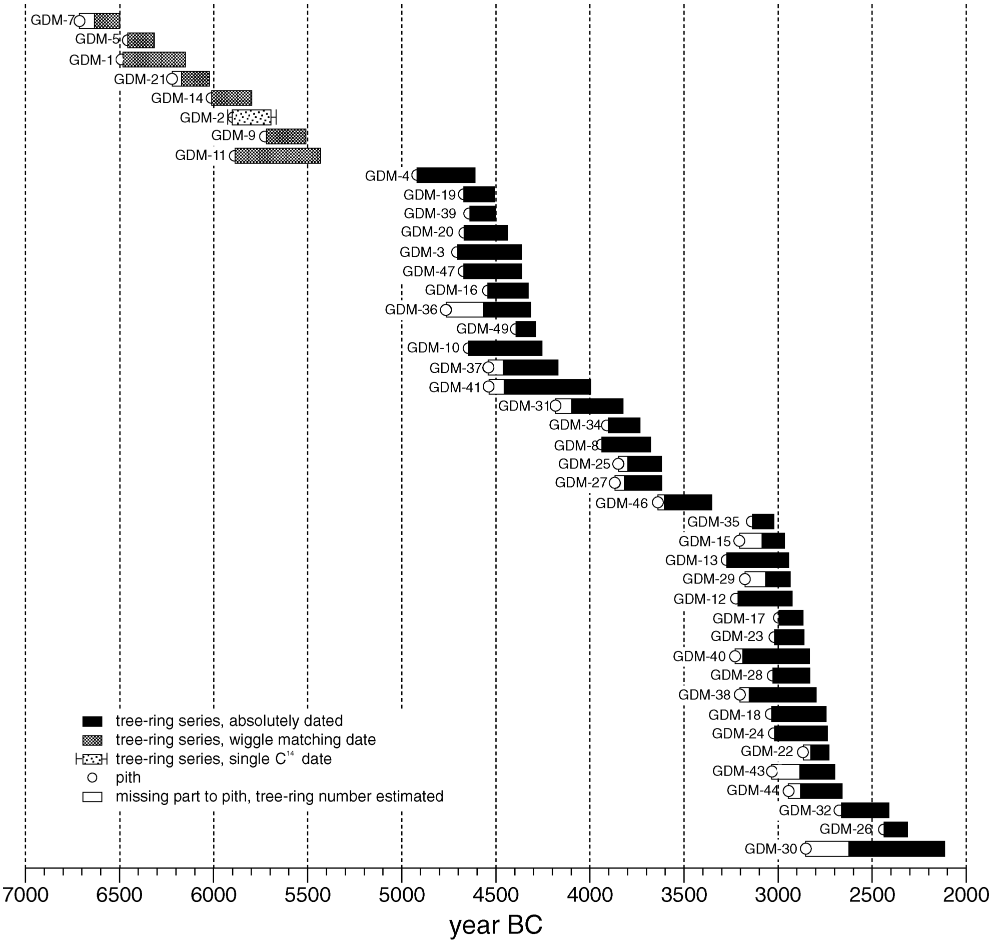

Fig. 8 The temporal distribution of dated subfossil logs plotted by their segment length at site 5 (GDM, 2295 m a.s.l.)

mainly for the first part of the mid-Holocene epoch, from c. 5500 to 4370 B.C. (Fig. 9). Only few samples are older (up to approx. 7100 B.C.) or younger (around 3450 B.C. and 2650 B.C.). The dendrochronological analysis of these samples shows that tree growth at such altitudes was possible, sometimes over a period of more than 350 years (e.g. tree KG-17, 2365 m a.s.l., approx. 5400 to 5050 cal B.C., Fig. 9), in the early and mid Holocene. Tree KG-7 grew at least 298 years (4674–4377 B.C., Fig. 9) at an altitude of 2400 m a.s.l. which indicates a multi-centennial duration of favourable growth conditions.

Discussion

Dendrochronological sequences for subfossil logs from the innermost Kauner valley spread over the last approx. 9000 years. During the late Holocene (after about 1700 B.C.) the

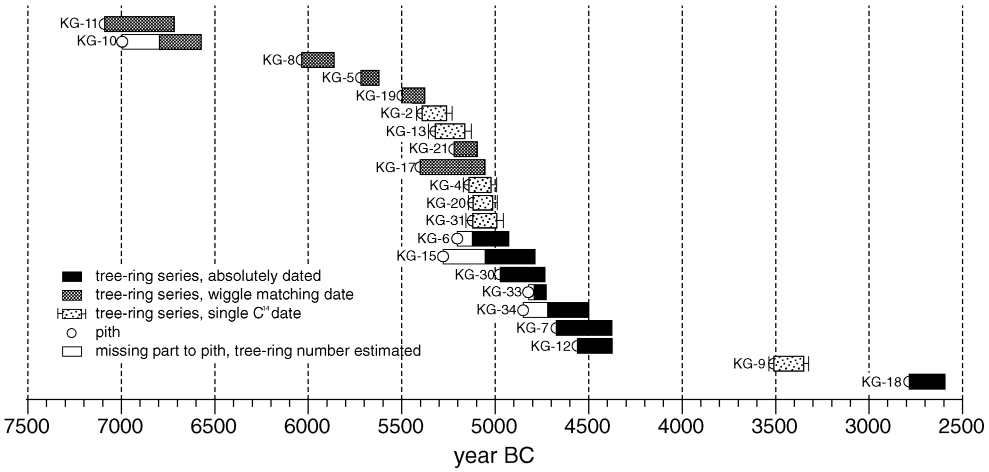

Fig. 9 The temporal distribution of dated subfossil logs plotted by their segment length at site 6 (KG, 2365 to 2410 m a.s.l.)

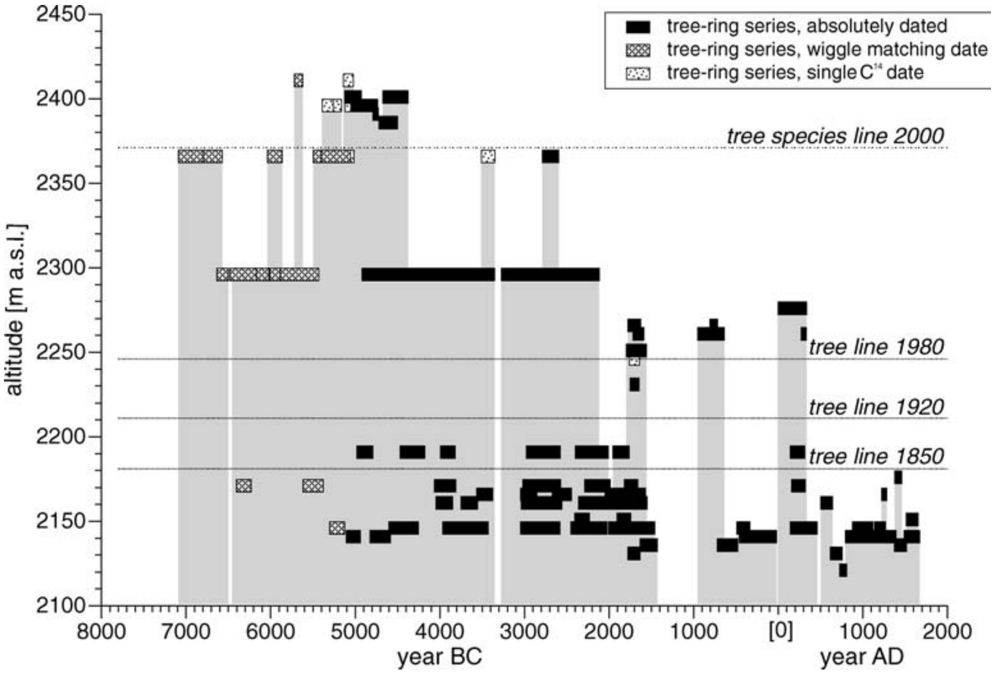

Fig. 10 The altitudinal and temporal position of tree-ring series from subfossil logs found in the innermost Kauner valley plotted by their measured and estimated life span (see text) in relation to the altitudes of the present tree-line and tree-species-line found at site 1. The grey tone indicates the presumed extension of Pinus cembra forest below the established tree-line

distribution of tree-ring series shows repeated gaps and evidence of tree-line positions above the 1980 tree-line is rare due to human impact on the timberline ecotone in this part of the Eastern Alps. However, favourable climatic conditions for tree growth at locations of relatively high elevation are demonstrated for the first centuries of the first millennium B.C. (approx. 1000 to 640) and A.D. (approx. 1 to 330), respectively. For the period from approx. 7100 B.C. to 2100 B.C. dendrochronologically analysed logs show evidence of tree growth above the 1980 tree-line with only two gaps. Very high altitudes of the tree-line, approx. as high or higher than the tree-species-line of A.D. 2000, are recorded for the periods 7090–6570, 6040–5850, 5720–5620, 5500–4370, approx. 3510–3350 and 2790–2590 B.C. TLPs which correspond to an expected level for the climatic conditions of the late 20th century (2300–2320 m a.s.l.) can be shown for the time periods 6700–6500, 6490–6020, 6010–5430, 4920–3350 and 3280–2110 B.C. In the middle Holocene epoch our dendrochronological tree-line record only shows one gap around 3300 B.C. During this gap no sample has been found at lower sites in the Kauner valley to date.

There are a few similar reports of finds of logs above the current tree-line in the Alps. Furrer and Holzhauser (1984) mention six ^{14}C-dates carried out on wood remains from locations above the "actual potential timberline" in the Swiss Alps. The results date between 4355±80 and 3515±80 B.P. (approx. 3000 to 1850 B.C.). Hence, these samples are partly contemporaneous with the accumulation of subfossil logs between 3280 and 2110 B.C. at site 5 (code GDM, 2295 m a.s.l., Fig. 8). Pott et al. (1995) ^{14}C-dated a few Stone Pine samples with up to nearly 200 tree-rings found at 2365 m a.s.l. in the Fimber valley, Eastern Alps, to within the period 6860±75 to 6140±75 B.P. (approx. 5700 to 5100 B.C.). The dates of these finds are comparable to those of the sections found at site 6 (code KG, Fig. 9) in the Kauner valley. Staffler and Feichter (1999) report the dates of small pieces of wood found at altitudes between 2380 and 2520 m a.s.l. in the valley of Langtaufers which is located just south of the Kauner valley. The calibrated dates again show mid-Holocene ages between approx. 5900 and 4100 B.C.

Our dendrochronological tree-line record shows that Stone Pines grew nearly continuously at high and very high altitudes between approx. 7100 B.C. and 2100 B.C. in the innermost Kauner valley. Also in the time window around 8.2 ky B.P. tree growth was possible at site 5 (GDM, 2295 m a.s.l.). Evidence is given by two trees. The Stone Pine GDM-1 (approx. 6480 to 6150 B.C., Fig. 8) shows reduced width growth from c. 6230 B.C. until the end of the tree-ring series. Within the lifetime of this tree the Stone Pine GDM-21 started to grow a couple of years before 6170 B.C. (Fig. 8). Also pollen analytical evidence from site 6 (KG, pollen profile Krummgampen, 2395 m; Krapf 2001) shows a reduced amount of tree pollen at approx. 6200 B.C. indicating a climatic deterioration.

The pollen profile established at site 6 by Krapf (2001) additionally shows minima of arboreal pollen around 5300, 4400, 3300 and 1500 B.C. These minima are contemporaneous with reductions in the tree-line altitude (e.g. 4400 B.C.) or missing evidence for a high TLP (e.g. 3300 B.C.) indicated by the dendrochronological tree-line record. On the other hand, analysis of pollen and macro remains in sediment cores from other highly elevated sites in the Alps (e.g. Wick and Tinner 1997; Tinner and Ammann 2001) suggest long time periods with high TLPs in the early and middle Holocene. Both of the longest optima, approx. 7000–6200 and 5000 to 4200 B.C. (Tinner and Ammann 2001), are concurrent with evidence for high TLPs from the dendrochronological tree-line record. The altitudinal difference between the present (1980/90) and the Holocene maximum TLPs in the Swiss Alps also shows high agreement with our study. Tinner and Theurillat (2003) report a TLP approx. 180 m higher which is of the same order as the value of 165 m found in the Kauner valley.

The dendrochronological tree-line record presented for the late Holocene partially shows similar limitations for the last millennia as pollen analytical records of tree-line variability. Human impact on forests of the Alpine timberline ecotone is recognised repeatedly by different authors (e.g. Wick and Tinner 1997; Bortenschlager 2000). An assessment of the cause of a reduction in altitude of the tree-line, caused by either human activities or natural climatic variability, is often impossible. These problems might be solved by analysis of material from specific sites, e.g. from glacier forefields, where human activities have always been limited or absent. The logs from the forefield of the glacier Gepatschferner (site 2) also indicate periods of high TLP in these last four millennia (approx. 1850–1550 B.C., 1000–640 B.C. and A.D. 1–330).

Holocene oscillations of Alpine glaciers and the variability of the Alpine tree-line are both mainly forced by summer temperature variations in a given region (Patzelt and Bortenschlager 1973). Regional differences in tree-line altitudes and glacier distribution, e.g. between the Central and the Outer parts of the Alps, can be better explained by the differing amounts of precipitation and the duration of sunshine in these areas, both influencing the length of the vegetation period and ablation period, respectively. The observed TLP rise in the Kauner valley of approx. 65 m between the 19th century and 1980 is somewhat lower than the increase of the mean equilibrium line altitude (ELA) for Austrian glaciers of about 90 m (Patzelt and Aellen 1990). An additional rise of the ELA since 1980 is causing a marked retreat of Alpine glaciers (Paul et al. 2004). Under the precondition of stable climatic forcing of glacier oscillations during the Holocene, the indicated high TLPs in the early and middle Holocene suggest concurrent ELAs which were at least 150 m above those prevailing in about A.D. 1980. According to Patzelt and Aellen (1990) such a rise of the mean ELA implies a retreat of the glacier area in Austria of about 70% compared to the extent in the 1980s. Evidence for a sizeable retreat of glaciers in the Alps is mainly reported for the Holocene epoch before approx. 1700 B.C. (Nicolussi and Patzelt 2000; Hormes et al. 2001; Schlüchter and Jörin 2004). Extended radiocarbon dating of samples found on Swiss glacier forefields indicating smaller ice extents than today, shows the greatest number of dates for a period of about 850 years from c. 5400 to 4550 B.C. (Schlüchter and Jörin 2004). This is predominantly consistent with the continuous extremely high TLPs in the innermost Kauner valley shown for the period after 5500 B.C. Our dendrochronological tree-line record additionally indicates ongoing high summer temperatures until approx. 4370 B.C. Evidence for TLPs at or above 2365 m a.s.l. at approx. 3400 B.C. and from 2790 to 2590 B.C. (Fig. 10) are also contemporaneous with large reductions in glacier extents in the Swiss Alps (Hormes et al. 2001; Schlüchter and Jörin 2004).

Usually a high degree of similarity in the changes of these two Alpine climate proxies, glaciers and tree-line, can be shown. Differences suggest changed forcing of the glaciers and probably higher amounts of winter precipitation (snow) in some periods of the Holocene epoch. Such changes in the forcing of glacier oscillations were shown for Scandinavian glaciers by Dahl and Nesje (1996). We may interpret the advances of Alpine glaciers reported for the mid 6th millennium B.C. (Suter 1981; Nicolussi and Patzelt 2001), which are partly contemporary with high TLPs (Nicolussi et al. in press), as evidence of increased winter precipitation. Patzelt (1987) also assumes increased precipitation in the 6th millennium B.C. based on accumulation rates of alluvial fans in the Inn valley.

Since growth of *Pinus cembra* at tree-line sites is mainly controlled by summer temperatures (Tranquillini 1979) we can roughly estimate minimum temperatures for the lifespan of the subfossil logs found up to approx. 165 m above the 1980 tree-line in the innermost Kauner valley. Using a temperature lapse rate of about –0.6 to –0.7°C/100 m we assess summer temperatures for those time periods as being at least 1.0°C higher than the values measured between about A.D. 1920 (the approx. germination of the living Stone Pine trees at the 1980 tree-line) and 1980. Summer temperatures for the late 20th century observed at high altitude stations were about 0.7°C (Böhm et al. 2001) above the 1920/1980 mean and at that value are still below the estimated minimum values for very high TLP periods within the Holocene.

Conclusions

1. The analysis of present (last approx. 200 years) tree-line variability shows a very low position following the mid-1810s climatic deterioration. After about 1860 the altitude of both the tree-species-line and the tree-line increased gradually by about 65 m until 1980.
2. Stone Pines (*Pinus cembra* L.) grew at sites above the late 20th century tree-line during long periods of the early and middle Holocene. Individual tree ages of up to 350 years indicate long time spans with favourable conditions for tree growth. Evidence for a position of the tree-line above the altitude of the 1980 tree-line is nearly continuous for the period between approx. 7100 and 2100 B.C.
3. The late Holocene (after about 2000 B.C.) contains only a few periods with tree growth above the 1980 tree-line position. However, both the effects of human impact documented by repeated gaps in the sample replication and the effect of climate variability can not be distinguished.
4. Generally the Holocene glacier record and the dendrochronological tree-line record show corresponding variability due to similar forcing. However, during some periods glacier advances are not concurrent with low tree-line positions, suggesting a modified climatic forcing of these glacier oscillations. Increased winter precipitation may be the cause of some differences in the proxy records.
5. Summer temperatures as observed after A.D. 1980 will lead to a higher position of the tree-line than at the moment. However, the current temperature values are still below the summer temperature level inferred from the subfossil logs for long time periods of the early and middle Holocene.

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