Exploring the potential of tree-ring chronologies from the Trafoi Valley (Central Italian Alps) to reconstruct glacier mass balance

GIOVANNI LEONELLI, MANUELA PELFINI AND PAOLO CHERUBINI

BOREAS

Leonelli, G., Pelfini, M. & Cherubini, P.: Exploring the potential of tree-ring chronologies from the Trafoi Valley (Central Italian Alps) to reconstruct glacier mass balance. *Boreas*, 10.1111/j.1502-3885.2007.00010.x. ISSN 0300-9483.

Two tree-ring chronologies of stone pine (*Pinus cembra* L.) and two of Norway spruce (*Picea abies* Karst.) were constructed on the basis of data from three high-altitude sites in the Trafoi Valley (Central Alps, Italy) to test tree species sensitivity to climate at different sites and to explore the potential of the two species for reconstructing the mass balance of two glaciers in the same region (the Careser and Hintereis glaciers). Influence of climate on tree-ring growth and on glacier mass variations was tested by means of Pearson's correlation and response functions. At highest altitude sites, both species appeared to be sensitive to July temperatures, while stone pine also showed higher sensitivity than Norway spruce to previous winter precipitation. Comparing the dendrochronological and glaciological series, stone pine showed higher negative correlations with glacier mass balance series than Norway spruce. These different relationships reflect different species responses to climate, and stone pine is potentially useful in reconstructing past glacier mass balance in the Central Alps. Extreme climatic events induce different and even contrasting responses of tree-ring growth and glacier mass variations and may therefore bias tree-ring-based glacier mass balance reconstructions.

Giovanni Leonelli (e-mail: giovanni.leonelli@unimi.it) and Manuela Pelfini, Department of Earth Sciences, University of Milan, via Mangiagalli 34, Milan, I-20133 Italy; Paolo Cherubini, WSL Swiss Federal Research Institute, Dendro Sciences, Zuercherstrasse 111, Birmensdorf, CH-8903 Switzerland; received 26th January 2007, accepted 29th June 2007.

Climate is one of the most important factors driving both biological and geomorphological processes, particularly at high altitude. In order to evaluate whether current climate changes are within the range of natural variability, it is important to obtain information about past climatic conditions. Climate-sensitive phenomena at high-altitude sites may therefore provide useful climatic information. Tree-ring growth and glacier mass balance are two of the most sensitive natural indicators of climatic change through time. Both tree rings (e.g. Briffa *et al.* 1990; Watson & Luckman 2001; Hughes 2002; Esper *et al.* 2002) and glaciers (e.g. Pelfini & Smiraglia 1992, 1997; Haeberli *et al.* 1999; Oerlemans 2005) provide information on past climatic variability, although at different time scales. Climate-sensitive tree-ring chronologies can provide estimates of baseline climate over centuries to millennia, whereas direct observations of glacier variations in the Alps only started at the beginning of the last century (World Glacier Monitoring Service, W.G.M.S., 1959–2000; Comitato Glaciologico Italiano and Consiglio Nazionale delle Ricerche, C.G.I. and C.N.R., 1959–1962; Desio 1967). Tree rings may therefore be used to obtain information on glacier variations over a longer span of time.

At high altitudes, tree growth is usually limited by summer temperatures, but tree responses to climate can be difficult to interpret since these can vary through time (e.g. Briffa *et al.* 1998) and they are a function of tree age (e.g. Carrer & Urbinati 2004). Moreover, they depend on tree species, on edaphic and environmental conditions and on vegetation dynamics (Graybill & Idso 1993; Nicolussi *et al.* 1995; Rolland *et al.* 1998; Theurillat & Guisan 2001). Glacier responses to climate are complex and depend mainly on the processes inducing the variations in their mass. Glacier terminus variations occur after a certain reaction time that follows a change in the mass balance and they last until the glacier has finally reached a new equilibrium (Haeberli 1995; Pelfini *et al.* 1998). These variations depend on factors such as geometry, bedrock substrate, valley structure and ice thickness, and provide an indirect, filtered and delayed indication of climate change (Oerlemans 2001). Mass balances are strongly influenced by snowfall and melting processes and thus represent a direct and undelayed signal of climate (Dyurgerov 2002; Haeberli 2003).

Tree-ring growth and glacier mass balances are determined by different processes and can respond differently to climatic conditions through time. Many studies have nevertheless found that these two proxy records correlate negatively and are inversely driven by climate in their variations (La Marche & Fritts 1971; Bednarz 1984; Tessier 1986; Pelfini 1999). These findings imply that it is possible to estimate past mass balance variations from tree-ring data. Some models consider tree-ring chronologies and related indices in reconstructing the net mass balance of one glacier (Nicolussi & Patzelt 1996) and the mass balance variations of four glaciers in a region comprising about 300 km (Lewis & Smith 2004), or in reconstructing the winter and summer balance (Larocque & Smith 2005). Other models include dendrochronologically reconstructed temperature and precipitation values, deriving climate information also from tree-ring chronologies from very distant sites about 1800 km from the studied glacier (Watson & Luckman 2004).

DOI 10.1111/j.1502-3885.2007.00010.x © 2007 The Authors, Journal compilation © 2007 The Boreas Collegium

Before developing a tree-ring-based reconstruction of mass balance, it is important to test the sensitivity of tree species to climate and the correlation of tree-ring chronologies with the glacier mass balance series. In this article, we analyse Norway spruce (*Picea abies* Karst.) and stone pine (*Pinus cembra* L.) tree rings and their responses to climate in the Trafoi Valley (Central Italian Alps). Furthermore, we compare the tree-ring chronologies with the mass balance series of two glaciers of the same region with the aim of establishing which species should preferably be used in future tree-ring-based reconstruction of mass balance and to evaluate the relationships between dendrochronological and glaciological series.

Study area

The Trafoi Valley is oriented west–east in the upper part and south–north in the lower part. The valley is located in the Central Alps in Italy at the northern border of the Ortles-Cevedale Group, which has the largest glaciated area in the Italian Alps. Toward the south there is the Ortles Peak (3905 m a.s.l.) and there are numerous high-elevation mountains with peaks over 3000 m a.s.l. (Fig. 1). The landscape consists of several different landforms resulting from intense glacial activity. Nowadays, along the southern end of the valley, there are four glaciers (Vedretta del Madaccio, Ghiacciaio Trafoi, Vedretta Bassa dell'Ortles, Vedretta Superiore dell'Ortles), but no mass balance record is available.

The local climate is typically continental, with both maximum temperatures and maximum precipitation during summer. Average monthly temperatures at the Monte Maria weather station (1335 m a.s.l., period 1967–2004; Fig. 1) range from -1.4°C in January to 15.4°C in July, while total monthly precipitation (period 1924–2004) ranges from 31 mm in January to 86 mm in August, with an annual mean of 677 mm (data from the Hydrological Office, Bolzano, Italy).

Vegetation is characterized mainly by mixed forests of European larch (*Larix decidua* Mill.), stone pine (*P. cembra* L.) and Norway spruce (*P. abies* Karst.). Larch and stone pine cover the upper part of the slopes forming the tree line, while the forest on the lower part of the slopes consists mainly of spruce and larch. Mountain pine (*Pinus mugo* Turra), in the shrub form, is also present in patches covering very steep and rocky slopes and the areas characterized by coarse substrate (e.g. proglacial zones, fluvial areas and debris fans).

Material and methods

Climate data

Climate data were collected from two stations (Monte Maria and Silandro) located in Val Venosta, approximately 17 and 21 km from the study area, respectively (data from the Hydrological Office, Bolzano, Italy) (Fig. 1). For our purposes, we collected monthly mean temperatures and total precipitation. Since the climate series at the two stations were different in length and data were missing (Table 1), we constructed a single complete series with monthly temperature data and one series with monthly precipitation data estimating the mean values from the original series using the program MET (Grissino-Mayer *et al.* 1996).

Dendrochronological data

Four tree-ring chronologies were built sampling stone pine and spruce trees at three different sites on the west-facing slopes of the Trafoi Valley (Fig. 1). European larch was not sampled because in the interior valleys of the Alps this species is cyclically affected by insect outbreaks (*Zeiraphera diniana*) that could induce a strong reduction in tree-ring growth (e.g. Weber 1995), thus

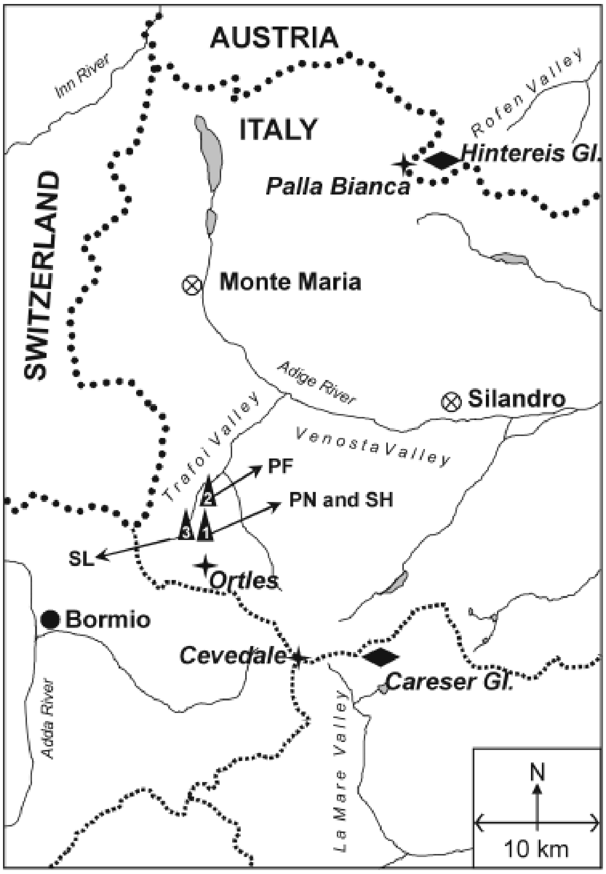

Fig. 1. Simplified map of the study area. The positions of the three sites (triangles 1, 2 and 3) are shown together with the corresponding four tree-ring chronologies (PN, pine near the glaciated area of the Ortles–Cevedale Group and SH, spruce at high altitude; PF, pine far from the glaciated area; SL, spruce at low altitude). The locations of the two selected glaciers (rhombuses), the two weather stations of Monte Maria and Silandro (crossed circles), the main peaks (stars) and the main rivers (simple lines) are also indicated. Dashed lines correspond to the main watersheds.

Table 1. Characteristics of the two monthly climate series considered, with intercorrelations between the series.

Series characteristics			Series intercorrelations
Meteorological station	Monte Maria	Silandro	
Altitude (m a.s.l.)	1335	718	
	Temperature		
First year	1967	1926	$r = 0.98$
Last year	2004	2004	$n = 348$
Length of the series (years)	38	79	
Missing data (%)	0.0	12.7	
Mean annual temperature (°C)	6.5	9.8	
	Precipitation		
First year	1924	1921	$r = 0.84$
Last year	2004	2004	$n = 972$
Length of the series (years)	81	84	
Missing data (%)	0.0	0.0	
Mean annual precipitation (mm)	677	490	

Fig. 2. The first site, close to the Borletti hut (2188 m a.s.l.): stone pine and Norway spruce in a mixed forest dominated by European larch. View toward east.

adding noise to the climatic signal. Two sites lie near the tree limit, one at 2100 m a.s.l., the other at 2150 m a.s.l. The first is close to the Borletti hut (Fig. 2) and the second site, 3 km to the north of the first, is close to the end of the valley. The third site is at the valley bottom, at 1620 m a.s.l., on the same mountain flank of the Borletti hut.

The first site is characterized by a mixed forest of scattered larch and stone pine trees (Fig. 2), with pines growing in the upper and NNW-facing part of the slope. In the lower part of the site, at approximately 2050 m a.s.l., there are some old spruce trees in a forest which is otherwise mostly dominated by larches. At this site, both stone pine (PN: pine near the glaciated area of the Ortles–Cevedale Group) and Norway spruce (SH: spruce at high altitude, also near the glaciated area) were sampled by extracting 2 cores from the stems of 15 dominant trees of each species. Cores were taken at 90° from the slope direction at a height of 1.3 m above the ground. Branch insertions and parts of the stem with geometrical abnormalities were avoided.

At the second site, old larches and stone pines grow sparsely on the slope up to the tree limit. Here, 15 pines (PF: pine far from the glaciers) were sampled following the same methods applied at the first site.

The third site is characterized by a closed spruce forest mixed with some sporadic larch. The trees here grow close together. At this site, more than at the others, factors besides climate could have influenced tree-growth variability, such as competition for light, the availability of nutrients and logging activity. These may have made it more difficult to recognize the common climatic signal identified at the other sites. Since the influence of climate on tree growth is predicted to be less strong at lower than at higher altitudes, we therefore sampled a higher number of trees, namely 20 spruce (SL: spruce at low altitude), to create a reference chronology containing a stronger common signal (Fritts & Swetnam 1989). At this site, too, we used the same sampling methods applied at the first site.

In the laboratory, each core was fitted on wood supports and polished using increasingly finer grained sandpaper up to P400. Tree rings were counted and samples were cross-dated using a simplified skeleton-plot method (Yamaguchi 1990) before measuring the ring widths. Measurements were then taken with an accuracy of 0.001 mm, analysing high-definition images of the cores using the program WinDENDRO (Regent Instruments, Quebec, Canada). For each population, the ring-width series were cross-dated and checked both visually and statistically with the programs TSAPWin Professional version 0.55 (Rinntech, Heidelberg, Germany) and COFECHA (Grissino-Mayer 2001).

After the cross-dating procedure, we selected for further analysis only the cores that correlated well ($r > 0.5$) with the mean site chronology (Hofgaard *et al.* 1999). Site chronologies were constructed using the program ARSTAN (version 41; www.ldeo.columbia.edu/trl). To preserve low-frequency variability in the tree-ring chronologies, raw ring-width measurements were detrended by dividing each value by the one predicted by the regional curve (RC) (e.g. Briffa *et al.* 1992). The RC was calculated as the mean function of the ring-width series, previously aligned according to their cambial age, and a cubic smoothing spline with a 50% frequency response cut-off at 67% of the series length was fitted through the data (Cook *et al.* 1995). The autocorrelation was removed from each series using an autoregressive model (Cook & Briffa 1990). A biweight robust mean was applied to each series, resulting in the residual chronologies. In constructing the standard chronologies, we followed the same steps, but without removing the autocorrelation.

Glaciological data

We considered two glaciers from the same region of the study area: the Careser (Italy) and the Hintereis (Austria) (Fig. 1). These glaciers are approximately 40 km apart, on opposite sides of the Alpine range. They differ considerably in size and geometry. The Careser glacier is a small (3.4 km^2), 2.2 km long, south-facing mountain glacier in the Ortles–Cevedale Group. The Hintereis is a valley glacier 8.5 km^2 in area, 7.1 km long, ENE-facing, within the Ötztaler Group (Austria). We selected the Careser and Hintereis glaciers because of their proximity to the study area and they have the longest net mass balance series in Italy (38 years) and in the Central Alps (52 years), respectively. For the Careser, we referred to the net mass balance series collected by the C.G.I. and published by the World Glacier Monitoring Service (W.G.M.S. 1959–2000 and on-line values: http://www.geo.unizh.ch/wgms/). For the Hintereis, we referred to Dyurgerov (2002) up to the year 1999, because this published series is the most complete, and to the W.G.M.S. values from 2000 until 2004 (the two series were previously compared for homogeneity) (Fig. 3).

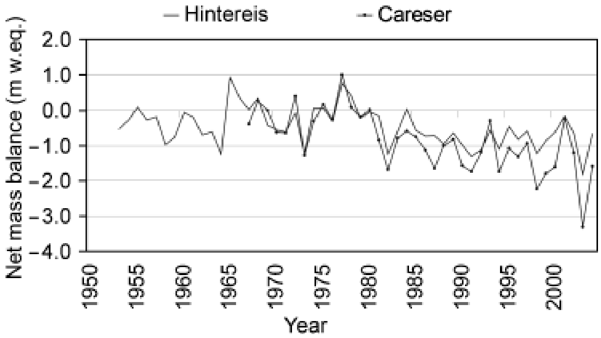

Fig. 3. The two net mass balance series considered in this study (see text for reference). The two records show a strong positive relationship.

Tree-ring chronologies and glacier mass balance series: relationships with climate

We assessed the relationships between tree-ring growth and climate by means of Pearson's correlation and response function linear models (Fritts 1976; Fritts & Guiot 1990). The four residual ring-width chronologies were compared with monthly temperature and precipitation data over the longest period available: 1927–2004 (78 years). To take account of winter precipitations, we performed the dendroclimatic analysis from October of the year prior to growth to September of the year of growth (hydrological year). Simple correlations and 1000 bootstrapped response functions were computed using the program PRECON (Fritts *et al.* 1991).

We applied the same linear models to test glacier mass balance sensitivity to climate using the same climate data over the longest common period available: 1968–2004 (37 years). The two glaciological series were previously standardized and detrended by dividing each raw value by the one predicted by a linear regression of negative slope, resulting in two mass balance index (MBI) series. Following the same procedure of climatic analysis applied to the four chronologies, the MBI series were compared with the monthly temperatures and precipitations from October of the previous year to September of the current year.

The relationships between tree-ring chronologies and the two MBI series were assessed by testing the agreement between pairs of series (*Gleichläufigkeit* index, Glk; Schweingruber 1988) and using Pearson's correlation.

Results

Tree-ring chronologies: relationships with climate

The four ring-width chronologies constructed at the three sites are between 300 and more than 400 years long (Fig. 4). The two chronologies of Norway spruce are longer than those of stone pine (Table 2). The SL chronology has the highest values of mean ring width, standard deviation and first-order autocorrelation. Like the PN chronology, it has a period with a stable signal shorter than the one shown by the SH and PF chronologies (subsample signal strength, SSS – Wigley *et al.* 1984; Cook & Briffa 1990 – at 85% from 1776). For each chronology, the SSS was calculated considering the longest common period of its tree-ring series.

At the high-altitude sites, dendroclimatic analysis revealed that Norway spruce and stone pine respond similarly to climate, whereas some bigger differences in tree-ring response are evident for spruce at lower altitudes (Fig. 5A, B). At high altitudes, tree-ring growth is sensitive to July temperatures: all three chronologies correlated positively and statistically significantly with July temperatures; the response functions were positive. Pine growth at both sites is also positively influenced by August temperatures (PN: nearly significant

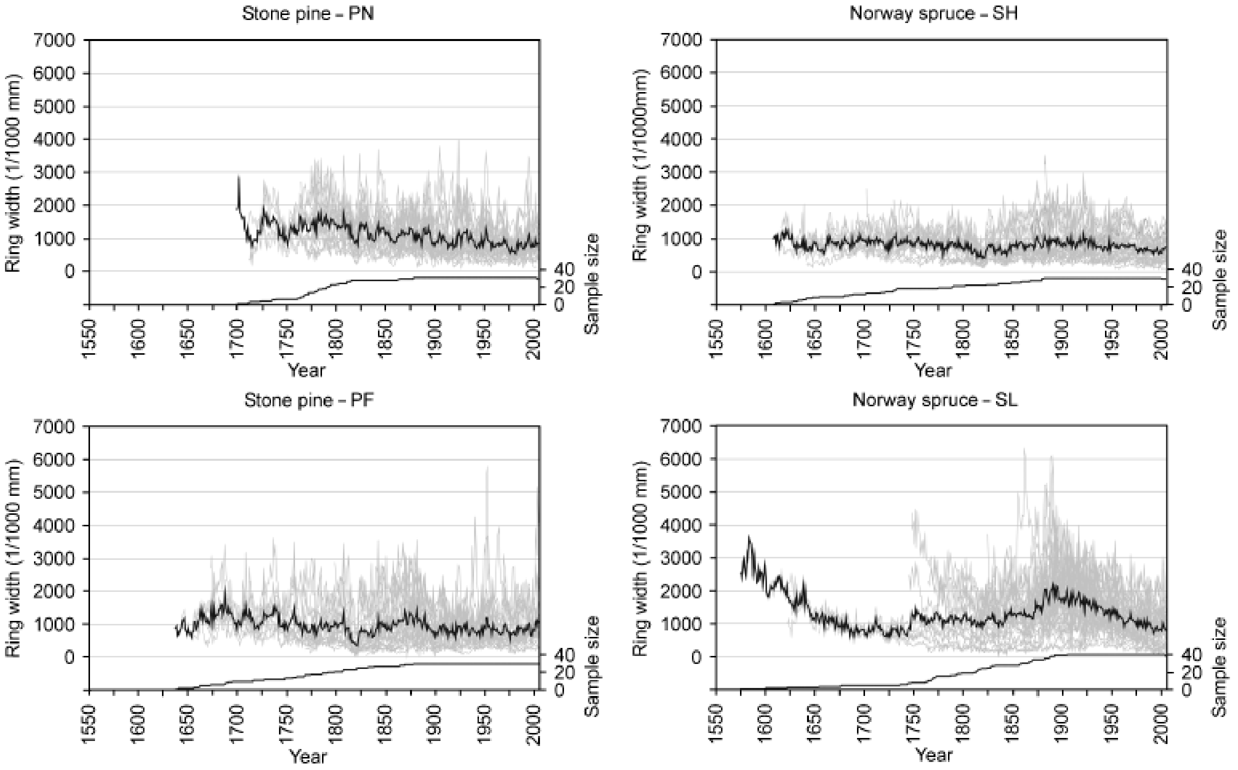

Fig. 4. The four chronologies constructed for this study (stone pine on the left, Norway spruce on the right). The measurement series (grey), mean chronology of the unstandardized ring-width series (black) and sample size (bottom line) are shown for each group.

Table 2. Site altitude and principal statistics of the four residual chronologies of Norway spruce and stone pine calculated with the RCS method.

Plot	SH	SL	PN	PF
Site number	1	3	1	2
Altitude (m a.s.l.)	2050	1620	2100	2150
First year of chronology	1607	1574	1699	1636
First year with SSS at 85%	1639	1776	1778	1695
Last year of chronology	2004	2004	2004	2004
Chronology length (years)	398	431	306	369
Number of trees	15	17	15	14
Number of radii	29	30	28	27
Initial number of radii	30	40	30	30
Mean ring width (mm)	0.84	1.39	1.07	0.95
Standard deviation	0.29	0.51	0.44	0.45
Mean sensitivity	0.17	0.15	0.17	0.18
Autocorrelation order 1[a]	0.71	0.91	0.74	0.75
ARMA model (AR)	3	3	1	4
	Common interval analysis			
First year of common interval analysis	1735	1910	1816	1825
Signal-to-noise ratio	12.36	15.13	10.9	12.81
Expressed population signal	0.93	0.94	0.92	0.93
Variance in the first principal component (%)	44.6	38.8	38.7	40.2
Among-series average correlation	0.41	0.36	0.35	0.37
Within-trees average correlation	0.40	0.57	0.50	0.57
Between-trees correlation	0.43	0.35	0.35	0.36

[a] Values relate to the standard chronology.

correlation). March and April temperatures are negatively correlated with pine ring width. The response functions in March were also significant for the PN chronology. Precipitation in January (when it falls mostly as snow) has a positive and significant effect on tree-ring growth at all sites (SH chronology excluded).

There was a slight positive correlation with July temperatures for spruce at the low-altitude site (SL),

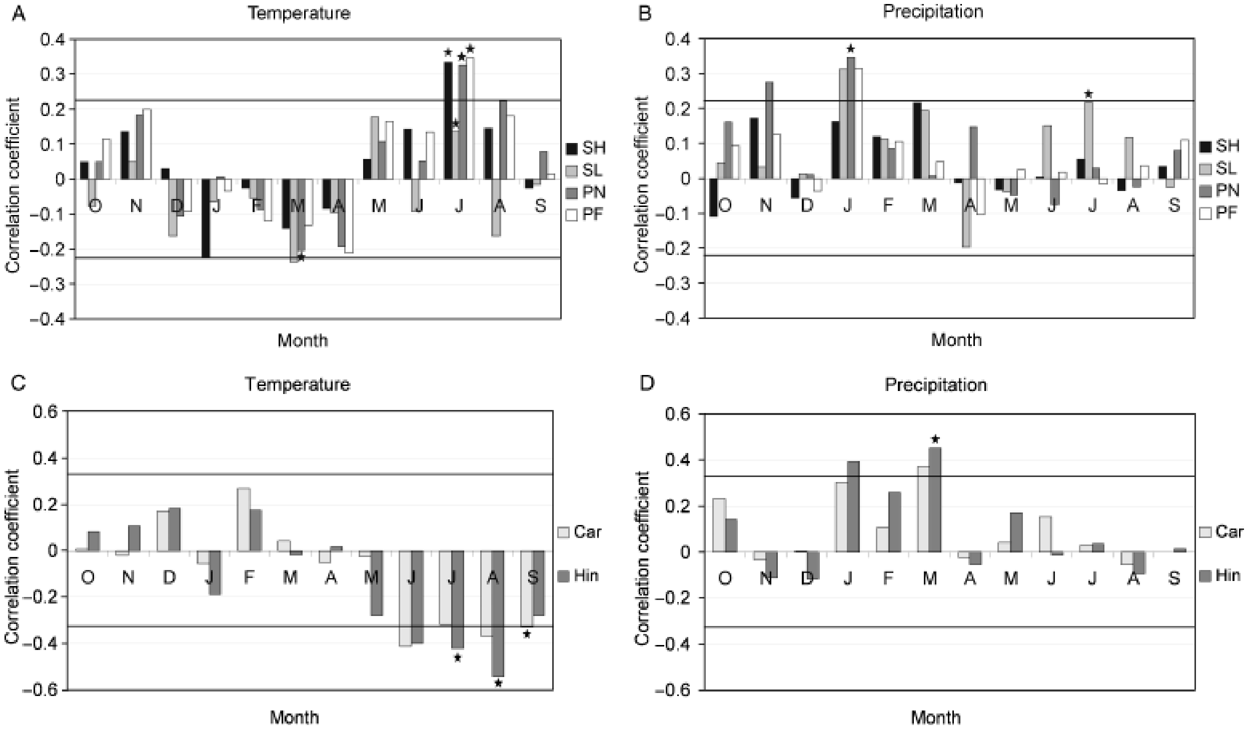

Fig. 5. Correlation coefficients calculated between the four residual chronologies (SH, SL, PN and PF) and the climate series of monthly mean temperatures (A) and monthly total precipitation (B) from October of the previous year to the current September. The period of analysis of the regional climate from the two weather stations is from 1927 to 2004. The lower part of the figure shows the correlation coefficients calculated between the MBI series (Car = Careser; Hin = Hintereis) and the climate series of monthly mean temperatures (C) and monthly total precipitation (D) for the same months. The period of analysis of the regional climate from the two weather stations is from 1968 to 2004. In all graphs, the two horizontal bold lines indicate the significance level ($p < 0.05$) for the correlation function; the asterisks indicate significant response function elements.

but this was not significant. However, the response function analysis was significant. Larger differences were found when analysing the influence of precipitation. Precipitation during the early summer months had the strongest influence on tree-ring growth at SL, with a direct, positive effect of precipitation in June (correlation coefficients) and July (response functions).

Mass balance series: relationships with climate

Summer temperatures were strongly negatively correlated with the two net MBI series considered. The response functions model revealed significant negative elements for July and August (Hintereis) and September (Careser). Winter precipitation correlates positively with the net mass balance series of both glaciers (Fig. 5D): we found a positive, significant, correlation between the MBI series and January (Hintereis) and March precipitation (snow accumulation). Response functions in March were also significant (Hintereis). Most of the correlation values were generally slightly higher in absolute values for the Hintereis mass balance series than for the Careser series.

Comparing between the mass balance series and the temperature data revealed almost opposite patterns in the correlation coefficients with respect to those found for the tree-ring chronologies (Fig. 5A, C). The correlation coefficient patterns from the comparison with precipitation data revealed a positive influence of winter precipitation (snow) on both glacier net mass balance and tree-ring growth. The amount of variance explained by climate with the bootstrapped response functions model was lower for the four tree-ring chronologies than for the glacier mass balance series. Variance accounted for by climate was lower for spruce (0.391 and 0.466, for SH and SL, respectively) than for pine (0.587 and 0.532 for PN and PF, respectively), whereas for the mass balance series variance was 0.656 for Careser and 0.794 for Hintereis.

Tree-ring chronologies and glacier mass balance series comparisons

Both the residual and the standard tree-ring chronologies were compared with the two MBI records calculating the inverse Glk index and the correlation coefficient. The residual chronologies always showed lower values of both Glk and correlation coefficient than the standard chronologies. We therefore decided to consider just the standard chronologies when comparing with the glacier MBI series.

Calculating similarity indices (Glk, correlation coefficient and *t*-value) among all four standard ring-width chronologies, we obtained higher values when two chronologies of the same species were compared (Table 3). The SL ring-width chronology showed the lowest values of correlation coefficient when comparing the two species. The two pine chronologies are more synchronized and better correlated to each other than the two spruce chronologies. Over the longer common period (SSS > 85%: 1778-–2004), the Glk and correlation coefficient values are generally lower.

The two mass balance series share a common decreasing trend and show an inverse interval trend only in the years 1987 and 1988 (Fig. 3). During their overlapping period, the two MBI series show high values of both Glk (94%, $p < 0.001$) and the correlation coefficient ($r = 0.79$) (Table 3). Even though they are so different in size and exposition, and on opposite sides of the Alps, the two glaciers show similar mass balance patterns linked to the similar climatic conditions that act on the regional scale (Diolaiuti *et al.* 2002). Particularly important is the role of air temperature, which is the main variable responsible for the large-scale correlation of glacier mass balances. The values of the similarity indices obtained by comparing the two glacier mass balance series are similar to those obtained by comparing the pine ring-width chronologies (Table 3).

The standard tree-ring chronologies were compared with MBI series over a common period using the inverse Glk index and the correlation coefficient calculated between pairs of series (Table 4). In all comparisons, different time periods were considered: the time span covering the whole period of each series and the common period for both series (1967–2004).

For both glaciers, the correlation coefficient calculated between the dendrochronological and the glaciological series showed negative values for stone pine and positive or close to zero values for Norway spruce. In the common period, correlation coefficient values ranged from +0.07 (SL vs. Hintereis) to − 0.07 (SH vs. Careser) for spruce, and from − 0.09 (PN vs. Careser) to − 0.42 (PF vs. Hintereis) for pine.

The inverse Glk values were higher for stone pine than for Norway spruce, indicating a higher asynchronicity with the MBI series of both glaciers for the stone pine chronologies. In the common period, inverse Glk highest values (pine chronologies) ranged from 58% (PN vs. Hintereis) to 67% ($p < 0.05$; PF vs. Hintereis).

Pine chronologies showed stronger negative relationships with the MBI series than did spruce chronologies. Both pine chronologies and glacier MBI series showed years with extreme index variation (Fig. 6). We therefore decided to perform again a correlation analysis on the series without the outlier values. We excluded years presenting outlier values in the pine standard chronologies and the two MBI series. Following a similar approach, one proposed by Vogel & Schweingruber (2001) to detect negative and positive pointer values, we considered as threshold value 1.5 standard deviations of each time series in the period 1953–2004 (1967–2004 for Careser series) (Fig. 6). Calculating the correlation coefficient between pairs of series without outliers, we obtained higher absolute values for PF chronology with respect to the complete series comparisons (Fig. 7A): in the common period 1967–2004, we found values of correlation of − 0.59 (vs. Careser) and − 0.68 (vs. Hintereis). For PN we obtained higher values when comparing the chronology with the Careser MBI, but lower values when comparing with the Hintereis MBI (Fig. 7B): in the common period, we found values of correlation of − 0.20 (vs. Careser) and of − 0.19 (vs. Hintereis).

Table 4. Correlation coefficients and inverse Glk's calculated between the four standard chronologies and the two MBI series considered.

		Careser (1967–2004)	Hintereis (1967–2004)	Hintereis (1953–2004)
Corr. Coeff.	SH	− 0.07	− 0.03	− 0.07
	SL	0.00	0.07	0.01
	PN	− 0.09	− 0.29	− 0.24
	PF	− 0.17	− 0.42	− 0.34
Inv-Glk	SH	44	42	44
	SL	50	53	56
	PN	61	58	59
	PF	64*	67*	66*

Asterisks indicate the statistical significance level: *95%.

Table 3. Some similarity indices calculated among the four standard chronologies for the period 1967–2004 (left) and for the common period 1778–2004 (right), where all the chronologies present a SSS > 85%. Values of the comparisons within the same species are given in italics.

		1967–2004			1778–2004		
		SH		Careser	SH		
Glk	SL	*75***	Hintereis	94***	*71****		
CC		*0.72*		0.79	*0.74*		
TV		*6.2*	SL	7.8	*16.6*	SL	
Glk	PN	75**	81***		67***	70***	
CC		0.51	0.21		0.19	− 0.03	
TV		3.6	1.3	PN	2.8	0.5	PN
Glk	PF	67*	78***	*94****	65***	64***	*76****
CC		0.35	0.06	*0.85*	0.50	0.37	*0.51*
TV		2.3	0.4	*9.8*	8.6	6.1	*8.8*

The same indices were also calculated for the two MBI series considered. Glk = *Gleichläufigkeit*; CC = correlation coefficient; TV = *t*-value. Asterisks indicate the statistical significance level: *95%; **99%; ***99.9%.

Discussion

Our four tree-ring chronologies at different sites appeared to correlate differently with climate; main

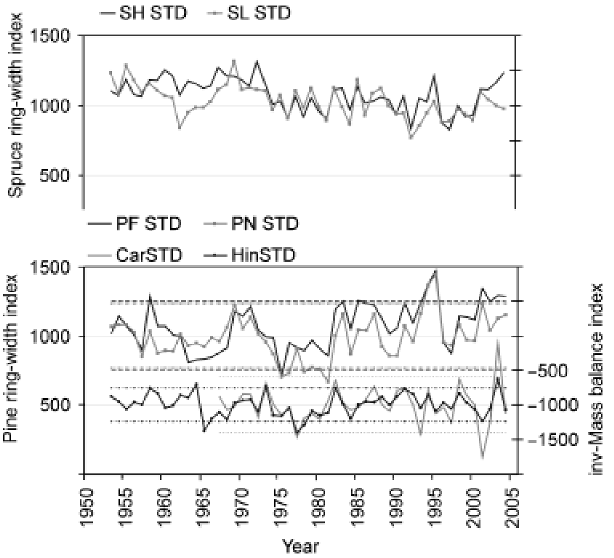

Fig. 6. The four standard chronologies in the period 1953–2004 and the inversely plotted MBI series of the selected glaciers. For pine chronologies and the two MBI, horizontal dashed lines correspond to ± 1.5 standard deviations of each time series.

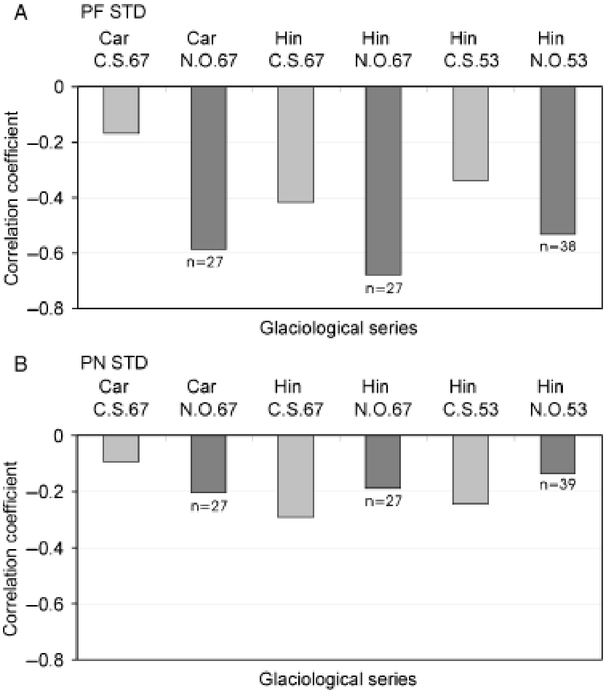

Fig. 7. Correlation coefficient calculated between the two pine standard chronologies and the MBI series. Car = Careser MBI; Hin = Hintereis MBI; C.S. = complete series; N.O. = no outliers; 67 = series since 1967; 53 = series since 1953.

differences were noticed especially between high and low-altitude sites. Overall, we observed a strong influence of summer temperatures on tree-ring growth and a lesser influence of winter precipitation. At high altitudes, tree-ring growth is mainly limited by July temperatures, with pine showing a sensitivity also to August temperatures. Spruce at low altitudes (SL) is less sensitive to summer temperatures.

For both spruce and pine, we also found a negative correlation with spring temperatures (March and April), which is consistent with other observations of stone pine in the Alps (Urbinati *et al.* 1997; Oberhuber 2004) and probably linked to tree respiration enhanced by above-average temperatures in springtime (Urbinati *et al.* 1997).

We observed a positive correlation with winter (especially January) precipitation, which is mostly snow. This is probably related not only to the storage of water in the soil, but also to the fact that the snow cover protects the soil from freezing, thus allowing the trees to capture water earlier in the vegetation season (Tranquillini 1976). The SL chronology appeared to be more sensitive to precipitation than the three chronologies at higher altitudes, especially in the summer months, when it correlated positively with precipitation. Lack of water during the growing season tends to have more impact at low-altitude sites, inducing growth stress, as has also been reported by Vogel & Schweingruber (2001).

Comparing the four chronologies and the two net mass balance series considered, we found that stone pine chronologies showed higher negative correlations than spruce chronologies. The different correlations with MBI series of the two glaciers are a result of the different responses to climate found for the two species. A similar comparison performed between the Hintereis mass balance series and the tree-ring chronologies in Austria (Nicolussi 1994) also shows higher negative correlation values for the pine chronologies than for the spruce chronologies.

Spruce chronologies did not correlate with the glacier mass balance series, whereas the tree-ring growth variations in stone pine were negatively correlated with the glacier mass variations. This is reflected in the higher negative correlations and higher asynchronicity shown by the pine chronologies with both the glacier mass balance series. The correlations obtained considering the complete series are not very strong. However, we found that the Hintereis MBI series shows the highest negative correlations with both pine chronologies. Similar climatic conditions influence the response of both trees and glaciers, but probably glacier size plays a key role in modulating glacier responses to climate. In general, high summer temperatures negatively affect glacier mass balance and positively influence tree-ring growth. We also found that abundant winter precipitation positively affects both tree-ring growth and glacier mass balance, which leads to a weaker negative correlation.

Extreme climatic events can induce strong variations in climatically limited high-altitude physical and biological systems. However, these events do not seem to induce proportional opposite variations in the two systems. We found that after excluding those years presenting outlier values in the PF ring-width chronology and in the two mass balance series, the negative correlations were considerably higher (up to – 0.68). Variations within established threshold values show high opposite patterns in the two systems.

An example of extreme climatic conditions strongly influencing both tree-ring growth and glacier mass balance is the summer of 2003. In this period, Europe experienced the hottest summer in the past 500 years (Luterbacher *et al.* 2004) and vegetation responses were different, depending mainly on site elevation. The strong heat flow induced faster tree growth, especially at high altitude, whereas at low altitude tree growth decreased especially because of drought stress, as reported for the Swiss Alps by Jolly *et al.* (2005). The two selected glaciers lost 3.316 (Careser) and 1.814 m w.eq. (Hintereis). We found that in our study area, and for the selected chronologies and glaciers, in the case of extreme climatic events (like that of the year 2003) the relationships between tree-ring growth at high altitude and glacier mass balance do not seem to be linear. Cold summers with abundant precipitation inhibit tree growth at high altitude and positively affect the net mass balance of glaciers, but the two responses, driven by different processes, show different intensity. Similarly, but contrary, during hot summers tree-ring growth at high altitude is usually enhanced but glaciers show stronger melting rates.

Conclusions

Although this study refers to a small sample of chronologies and glaciers from the Central Alps, our results may lead to more general conclusions. Tree-ring growth at high-altitude sites is sensitive especially to July (and August, for pine) temperatures and to winter precipitation. Spruce at low-altitude sites, however, showed lower sensitivity to summer temperatures and higher sensitivity to summer precipitation. Glacier mass balance is influenced by summer month temperatures and by winter precipitation. We could identify stone pine at high altitudes as the most suitable species for correlations with the mass balance of the two selected glaciers of the Central Alps.

Correlating tree-ring chronologies and glacier mass balance series can be problematic because: (i) their variations are affected by different (biological and physical) processes, (ii) different climatic factors may influence them differently and during different periods of the year, and (iii) the recent rapid atmospheric warming, and especially the presence of extreme climatic events, seems to induce different and even contrasting responses of high mountain geo- and ecosystems, increasing deviations from conditions of dynamic equilibria, which may have developed during relatively stable climatic conditions through the Holocene.

We found that, under extreme climatic conditions, forcing factors induce non-proportional opposite variations in tree growth and in glacier mass, a fact that should be considered as a limit for tree-ring-based mass balance reconstructions. However, tree-ring chronologies are a unique source of information about past climatic conditions, especially in the absence of instrumental meteorological or glaciological data and can therefore be used to reconstruct past glacier variations.

Acknowledgements. – This research was funded by the MIUR-COFIN 2005 project 'Increasing rate of climate change impacts on high mountain areas: cryosphere shrinkage and enviromental effects' (National and Local Coordinator, Professor C. Smiraglia). We thank Professor C. Smiraglia and Professor W. Haeberli for their critical revision and for making useful suggestions about the manuscript. We also thank Silvia Dingwall for revising the English, Josée Frenette (UQAT) for fieldwork assistance and the Parco Nazionale dello Stelvio for authorizing research in its territory.

References

Bednarz, Z. 1984: The comparison of dendroclimatological reconstructions of summer temperatures from the Alps and Tatra Mountains from 1741–1965. *Dendrochronologia 2*, 63–72.

Briffa, K. R., Bartholin, T. S., Eckstein, D., Jones, P. D., Karlén, W., Schweingruber, F. H. & Zetterberg, P. 1990: A 1,400-year tree-ring record of summer temperatures in Fennoscandia. *Nature 346*, 434–439.

Briffa, K. R., Jones, P. D., Bartholin, T. S., Eckstein, D., Schweingruber, F. H., Karlen, 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., Schweingruber, F. H., Jones, P. D., Osborn, T. J., Shiyatov, S. G. & Vaganov, E. A. 1998: Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. *Nature 391*, 678–682.

Carrer, M. & Urbinati, C. 2004: Age-dependent tree-ring growth responses to climate in *Larix decidua* and *Pinus cembra*. *Ecology 85*, 730–740.

Comitato Glaciologico Italiano and Consiglio Nazionale delle Ricerche 1959–1962: *Catasto dei Ghiacciai Italiani*, 4 vols. Turin, Italy.

Cook, E. R. & Briffa, K. R. 1990: Data analysis. *In* Cook, E. R. & Kairiukstis, L. A. (eds.): *Methods of Dendrochronology*, 97–162. Kluwer Academic Publishers, Boston.

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

Desio, A. 1967: *I ghiacciai del Gruppo Ortles–Cevedale (Alpi Centrali)*. 874 pp. Comitato Glaciologico Italiano, Turin.

Diolaiuti, G., Smiraglia, C., Reynaud, L., D'Agata, C. & Pavan, M. 2002: Relation entre les bilans de masse de la Sforzellina et ceux des autres glaciers en Europe. Influence des facteurs localisation géographique et taille du glacier. *La Houille Blanche 6/7*, 59–63.

Dyurgerov, M. 2002: Glacier mass balance and regime. Data of measurements and analysis. *Institute of Arctic and Alpine Research, University of Colorado, Occasional Paper 55*, 268 pp.

Esper, J., Cook, E. R. & Schweingruber, F. H. 2002: Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science 295*, 2250–2253.

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

Fritts, H. C. & Guiot, J. 1990: Methods of calibration, verification, and reconstruction. *In* Cook, E. R. & Kairiukstis, L. A. (eds.):

Methods of Dendrochronology, 163–217. Kluwer Academic Publishers, Boston.

Fritts, H. C. & Swetnam, T. W. 1989: Dendroecology. A tool for evaluating variations in past and present forest environments. *Advanced Ecological Research 19*, 111–188.

Fritts, H. C., Vaganov, E. A., Sviderskaya, I. V. & Shashkin, A. V. 1991: Climatic variation and tree-ring structure in conifers: empirical and mechanistic models of tree-ring width, number of cells, cell size, cell-wall thickness and wood density. *Climate Research 1*, 97–116.

Graybill, D. A. & Idso, S. B. 1993: Detecting the aerial fertilization effect of atmospheric CO_2 enrichment in tree ring chronologies. *Global Geochemical Cycles 7*, 81–95.

Grissino-Mayer, H. D. 2001: Evaluating crossdating accuracy. A manual and tutorial for the computer program COFECHA. *Tree-Ring Research 57*, 205–221.

Grissino-Mayer, H. D., Holmes, R. L. & Fritts, H. C. 1996: *The International Tree-Ring Data Bank Program Library Version 2.0, Users' Manual.* 106 pp. Laboratory of Tree-Ring Research, University of Arizona, Tucson, Arizona.

Haeberli, W. 1995: Glacier fluctuations and climate change detection. *Geografia Fisica e Dinamica Quaternaria 18*, 191–199.

Haeberli, W. 2003: Glacier and permafrost changes in high-mountain areas. *In: The State of Ecological and Earth Sciences in Mountain Areas*, 6–10 September, Banff, Canada.

Haeberli, W., Frauenfelder, R., Hoelzle, M. & Maisch, M. 1999: On rates and acceleration trends of global glacier mass changes. *Geografiska Annaler 81 A*, 585–591.

Hofgaard, A., Tardif, J. & Bergeron, Y. 1999: Dendroclimatic response of *Picea mariana* and *Pinus banksiana* along a latitudinal gradient in the eastern Canadian boreal forest. *Canadian Journal of Forest Research 29*, 1333–1346.

Hughes, M. K. 2002: Dendrochronology in climatology – the state of the art. *Dendrochronologia 20*, 95–116.

Jolly, W. M., Dobbertin, M. & Zimmermann, N. E. 2005: Divergent vegetation growth responses to the 2003 heat wave in the Swiss Alps. *Geophysical Research Letters 32*, L18409, doi: 10.1029/2005GL023252.

La Marche, V. C. & Fritts, H. C. 1971: Tree rings, glacial advance and climate in the Alps. *Zeitschrift für Gletscherkunde und Glazialgeologie 7*, 125–132.

Larocque, S. J. & Smith, D. J. 2005: Little Ice Age proxy glacier mass balance records reconstructed from tree rings in the Mt. Waddington area, British Columbia Coast Mountains, Canada. *The Holocene 15*, 748–757.

Lewis, D. & Smith, D. 2004: Dendrochronological mass balance reconstruction, Stachona Provincial Park, Vancouver Island, British Columbia, Canada. *Arctic, Antarctic, and Alpine Research 36*, 598–606.

Luterbacher, J., Dietrich, D., Xoplaki, E., Grosjean, M. & Wanner, H. 2004: European seasonal and annual temperature variability, trends, and extremes since 1500. *Science 303*, 1499–1503.

Nicolussi, K. 1994: Jahrringe und Massenbilanz. *Zeitschrift für Gletscherkunde und Glazialgeologie 30*, 11–52.

Nicolussi, K., Bortenschlager, S. & Körner, C. 1995: Increase in tree-ring width in subalpine *Pinus cembra* from Central Alps that may be CO_2-related. *Trees 9*, 181–189.

Nicolussi, K. & Patzelt, G. 1996: Reconstructing glacier history in Tyrol by means of tree-ring investigations. *Band 32*, 207–215.

Oberhuber, W. 2004: Influence of climate on radial growth of *Pinus cembra* within the alpine timberline ecotone. *Tree Physiology 24*, 291–301.

Oerlemans, J. 2001: *Glaciers and Climate Change*, 148 pp. A. A. Balkema, Lisse.

Oerlemans, J. 2005: Extracting a climate signal from 169 glacier records. *Science 308*, 675–677.

Pelfini, M. 1999: Dendrogeomorphological study of glacier fluctuations in the Italian Alps during the Little Ice Age. *Annals of Glaciology 28*, 123–128.

Pelfini, M., Belloni, S., Rossi, G. & Strumia, G. 1998: Response time of the Lys Glacier (Valle d'Aosta). An example of a dendrogeomorphological and environmental study. *Geografia Fisica e Dinamica Quaternaria 20*, 329–338.

Pelfini, M. & Smiraglia, C. 1992: Recent fluctuations of glaciers in Valtellina (Italian Alps) and climatic variations. *Journal of Glaciology 38*, 309–313.

Pelfini, M. & Smiraglia, C. 1997: Signals of 20th-century warming from the glaciers in the Central Italian Alps. *Annals of Glaciology 24*, 350–354.

Rolland, C., Petitcolas, V. & Michalet, R. 1998: Changes in radial tree growth for *Picea abies*, *Larix decidua*, *Pinus cembra* and *Pinus uncinata* near the alpine timberline since 1750. *Trees 13*, 40–53.

Schweingruber, F. H. 1988: *Tree Rings. Basic and Applications of Dendrochronology*. 276 pp. Reidel Publishing, Dordrecht.

Tessier, L 1986: Chronologie des Mélèzes des Alpes et petit âge glaciaire. *Dendrochronologia 4*, 97–113.

Theurillat, J.-P. & Guisan, A. 2001: Potential impact of climate change on vegetation in the European Alps: a review. *Climatic Change 50*, 77–109.

Tranquillini, W. 1976: Water relations and alpine timberline. *In* Lange, O. L., Kappen, L. & Schulze, E. D. (eds.): *Water and Plant Life. Problems and Modern Approaches. Ecological Studies 1*, 473–491. Springer Verlag, Berlin.

Urbinati, C., Carrer, M. & Sudiro, S. 1997: Dendroclimatic response variability of *Pinus cembra* L. in upper timberline forests of Italian Eastern Alps. *Dendrochronologia 15*, 101–117.

Vogel, R. B. & Scheweingruber, F. H. 2001: Centennial variability of tree-ring width of spruce, fir, oak in relation to climate in Switzerland for the last 450 years. *Dendrochronologia 19*, 197–209.

Watson, E. & Luckman, B. H. 2001: Dendroclimatic reconstruction of precipitation for sites in the southern Canadian Rockies. *The Holocene 11*, 203–213.

Watson, E. & Luckman, B. H. 2004: Tree-ring-based mass-balance estimates for the past 300 years at Peyto Glacier, Alberta, Canada. *Quaternary Research 62*, 9–18.

Weber, U. M. 1995: Ecological pattern of larch budmoth (*Zeiraphera diniana*) outbreaks in the Central Swiss Alps. *Dendrochronologia 13*, 11–31.

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

World Glacier Monitoring Service (W.G.M.S.) 1959–2000: *Fluctuations of Glaciers*, World Glacier Monitoring Service, Department of Geography, University of Zurich, Zurich.

Yamaguchi, D. K. 1990: A simple method for cross-dating increment cores from living trees. *Canadian Journal of Forest Research 21*, 414–416.