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TEMPERATURE VARIATIONS OF THE LAST 700 YEARS RECONSTRUCTED FROM A TREE-RING CHRONOLOGY OF THE CENTRAL ALPS

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Parole Chiave – Anelli degli alberi, dendrocronologia, paleoclimatologia, Piccola Età Glaciale, Alpi centrali.

Riassunto – La variabilità delle temperature negli ultimi 700 anni ricostruita da una cronologia di anelli degli alberi delle Alpi Centrali. Nel presente articolo viene usata una cronologia di anelli annuali proveniente dalla Val Ventina (Alpi Centrali), formata da numerosi esemplari di larice (*Larix decidua* Mill.) eccezionalmente longevi, per testare un nuovo metodo per calcolare gli indici degli anelli e per ricostruire le temperature della regione. La standardizzazione è basata su una trasformazione esponenziale dei dati grezzi, effettuata prima del detrending allo scopo di stabilizzare la varianza producendo serie temporali omoscedastiche. In un secondo tempo vengono calcolati gli indici come scostamenti della funzione originale dal trend dell'età modellizato sulla serie proveniente dalla trasformazione. La cronologia così ottenuta contiene un forte segnale comune e mostra una correlazione significativa con le temperature massime estive (ottenute facendo la media dei mesi di Giugno e Luglio) della stazione meteorologica di Milano. Il modello usato per la regressione è basato solo sul periodo 1778-1950 dato che la relazione matematica tra il clima e la crescita degli alberi si indebolisce negli ultimi 30 anni. La serie delle temperature ricostruite riproduce sia la variabilità ad alta frequenza sia quella a bassa frequenza. Il periodo di temperature inferiori alla media corrispondente alla Piccola Età Glaciale è bene evidente nella ricostruzione e si estende approssimativamente dal 1575 all'inizio del 19^{imo} secolo. Le temperature estive del ventesimo secolo si collocano all'interno della naturale variabilità degli ultimi 700 anni.

Key words – Tree rings, dendrocronology, paleoclimatology, Little Ice Age, Central Alps.

Abstract – A tree-ring chronology from the Ventina Valley (Italian Alps) composed of several very old larches (*Larix decidua* Mill.) is used to test a new method to calculate tree-ring indices and to produce a regional temperature reconstruction. The standardization is based on a power transformation before detrending, which stabilizes the variance producing homoscedastic time series, and then using the residuals of the age-related trend fitted through the transformed measurements. The site chronology retains a strong common signal and shows a significant correlation with summer (mean of June-July) maximum monthly temperature measured at the meteorological station of Milan. The regression model is based only on the period 1778-1950, since the relationship between climate and tree growth becomes weaker in the last 30 years. The temperature reconstruction shows skill at reproducing high-frequency as well as low-frequency variability. A period of low temperature corresponding to the Little Ice Age is the major finding of the reconstruction and it extends from approximately A.D. 1575 to the early 19th century. Summer temperatures of the twentieth century appear to be within the natural variability of the last 700 years.

INTRODUCTION

The temperature and the length of the growing season are the limiting factors for tree growth at high altitude sites. Under such conditions it is possible to link the radial growth variability with monthly climatic parameters (e.g. FRITTS, 1976; SCHWEINGRUBER, 1988). In recent studies, tree rings have been used frequently to reconstruct past temperatures of various geographic regions (e.g. BRIFFA et al., 1990; D'ARRIGO and JACOBY, 1993; BRIFFA et al., 1995, 1998a).

The crucial step in a palaeoclimatic reconstruction based on tree rings is the removal from the time series of any nonclimatic signals (e.g. age trend). This procedure, which is commonly called "standardization", is applied to the tree-ring measurements of each individual tree before averaging the series to obtain a site chronology. Because it is not possible to develop a generally expected age trend, the standardization is the most subjective step in dendroclimatology, which led to the suggestion of a number of empirical models (e.g FRITTS, 1976; COOK and KAIRIUKSTIS, 1990). Generally, the hypothetical age trend is approximated by fitting a curve to the measured data and the ratio (or the residual) is calculated for each year as a dimensionless index. The growth-trend approximation might

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either be deterministic (i.e. linear trend, negative exponential curve), or stochastic (cubic splines). More recently, COOK et al. (1995) and BRIFFA et al. (1996) suggested a regional curve standardization (RCS), which uses a curve based on ring widths sorted by their cambial age. However, any type of standardization involves a certain loss of long-term climatic information. Therefore, palaeoclimatic reconstructions based on tree-ring indices should be interpreted as series with climatic information at intra-annual, inter-annual, decadal, and rarely centennial time scales.

The accuracy of long-term information depends essentially on the flexibility of the curve used for the detrending as well as on the time-series length. It can be stated that the better the trend curve fits the actual growth, the greater is the loss of long-term information (BRIFFA et al., 1998c). Furthermore, COOK et al. (1995) pointed out that the maximum wavelength of recoverable climatic information is related to the length of the individual tree series. For example, a 1000-year chronology composed of several 100-year long tree-ring series may be used to develop a climate reconstruction that will keep, at best, variability at time scales less than 100 years in length.

In a recent study, COOK and PETERS (1997) suggest to calculate the indices with a technique based on a power transformation prior to detrending. This method produces homoscedastic data, and taking the residuals after detrending provides unbiased tree-ring indices. In this study, this new method for the calculation of the indices was applied to a long larch (*Larix decidua* Mill.) chronology developed from the Italian Alps (STRUMIA and CHERUBINI, 1997). This chronology is composed of few but old trees and contains climatic information from an inter-annual to centennial time scale.

Global temperature shows a major increase in the last decades (JONES and BRIFFA, 1992) which is believed to be, at least partially, caused by the anthropogenic-related increase of atmospheric CO_2 and by the consequent greenhouse effect. Paleoclimatic reconstructions are a useful instrument to detect the recent climate change, since the magnitude and the pattern of past climate variability can be compared with the twentieth century changes (JONES et al., 1998). The purpose of this paper is to develop and discuss a temperature reconstruction and to compare recent and past temperatures of a sensitive region such as the European Alps. Furthermore, the reconstruction of the temperatures during the Little Ice Age (LIA) (BRADLEY and JONES, 1993) can be used to estimate the magnitude and the temporal extension of this event in the Italian Alps.

MATERIAL

The sampling site is located in the Ventina Valley (Fig. 1), a lateral valley of the Valmalenco, in the massif of Monte Disgrazia (46°20' N; 09°44' E). The stand, an open-canopy forest at the treeline, is at an altitude of about 2200 m a.s.l.

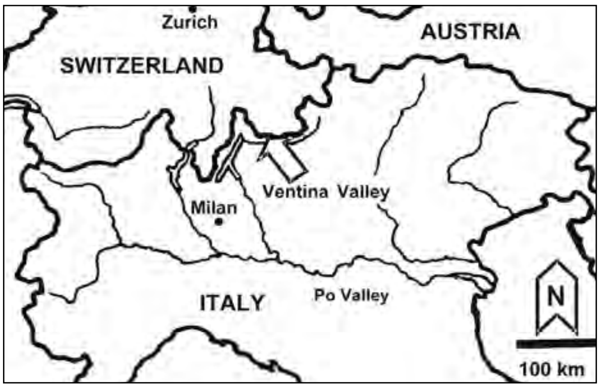

Fig. 1 – Geographical location of the study area.

The trees are scattered and the forest is today unmanaged, with dead trees still standing among living trees. From each leaving tree at least two cores were extracted in the summer of 1995. In addition, a few dead trees were sampled to extend the chronology further into the past. In total, data from 19 trees were included in the final chronology.

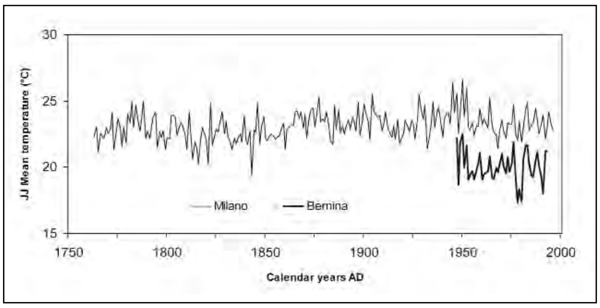

Fig. 2 – Mean of June-July temperature of Milan compared with the same record of the Bernina meteorological station. The two series have a correlation coefficient of 0.67, calculated for the period 1947-1993, significant at the 99% level.

The temperature record from the nearby meteorological station of Bernina is very short (1947-1993), therefore in this study the data from the meteorological station at Milan (45°47' N; 08°58' E), about 100 km south east of the sampled site, was used. The temperature record of minimum, maximum, and mean monthly temperature of Milan begins in A.D.1778 and it is homogeneous with several other stations of the

Alps and representative for a large geographical area. Summer temperatures from alpine stations were proved to be highly correlated (above 0.8) over large distances (about 500 km) as well as between high-altitude and lowland stations (BÖHM and SCHÖNER, personal communication). The mean of the June-July temperature of Milan shows high correlation (R=0.67; significant at the 99% level) with the data of the Bernina station, for the common period 1947-1993 (Fig. 2).

METHODS

Samples were measured using the LINTAB® tree-ring measuring table and the data were managed with TSAP® (RINN, 1996). Crossdating was carried out according to standard procedures (FRITTS, 1976) and verified with t-values, Gleichläufigkeit test (SCHWEINGRUBER, 1988) and correlation coefficients, provided by TSAP® and by the software COFECHA (HOLMES, 1994).

After crossdating, time series from all cores were averaged within trees to produce 19 individual raw data series. These data were then power transformed to obtain series with a stable variance. Unstandardized tree-ring series are heteroscedastic, i.e. they have a local standard deviation which depends on the local mean, where local stands for some subintervals within the time span of the whole tree-ring series (COOK et al., 1990). A logarithmic transformation produces homoscedastic tree-ring series. According to COOK and PETERS (1997) the log-transformation is often too severe, producing non-normally distributed data. They suggest using a power transformation:

(1) $R_t = R^p = R^{(1-b)}$

where R_t are the transformed data,
R are the original measured data,
$p=1-b$ is the coefficient of the power transformation,
b is the slope of the regression between local mean and local standard deviation in the logarithmic space.

COOK and PETERS (1997) describe the relationship between the local level (mean) and the local spread (standard deviation) as a power relationship. This can be interpreted as a linear regression in logarithmic space. They propose a calculation of the local mean and of the local spread for 2-year intervals, so that for each series *n-1* estimates (where *n* is the length of the series) can be used to calculate the regression slope.

This method was applied to each tree-ring series from the Ventina Valley. The transformed series were detrended by fitting a simple linear regression or a negative exponential curve (only in 1 case) and by calculating the residuals. Finally, the single tree series were averaged to produce a mean site chronology.

The statistical reliability of a chronology depends on two parameters: the common signal and the replication. The first is the mean correlation coefficient among the series, whereas the latter is the number of samples which are averaged in the chronology. Since the nonclimatic variability in growth is believed to be unique among individuals, the averaging reduces the noise proportionally to the number of samples that are averaged (BRIFFA and JONES, 1990). There are several statistics that combine in different ways the mean correlation coefficient between the trees and the sample depth to estimate the validity of a site chronology (BRIFFA and JONES, 1990). Subsample Signal Strength (SSS) was used to estimate the variance of the hypothetical infinitely replicated chronology, explained by the different sections with different sample size of the mean chronology (WIGLEY et al, 1984; BRIFFA and JONES, 1990).

Another problem affecting the early part of the chronologies is the artificial increase in the variance due to the decrease of the replication. OSBORN et al. (1997) proposed a method to adjust the increase in variance, based on the correlation function and on the number of samples. The variance of the Ventina Valley chronology was readjusted each time a sample dropped out from the maximal sample size.

The final chronology has been correlated with the temperature data of Milan to select monthly variables which influence tree growth. Since the climatic variables are often intercorrelated, it was necessary to validate the correlation function performing a multiple regression analysis after extracting the principal component (FRITTS, 1976; COOK and KAIRIUKSTIS, 1990). A temperature reconstruction was then carried out by calculating a regression between climatic data, used as the dependent variable or predictand, and the tree-ring chronology, used as the independent variable or predictor. The transfer function was estimated with the bootstrap method (TILL and GUIOT, 1990). In this procedure, the calibration-verification exercise is repeated for a certain number of times using different subsamples (usually at least 50) and the mean and the standard deviation of the correlation and regression coefficients give an assessment of the reliability of the model. If the coefficients of the calibration and of the verification periods are similar and the ratio between the mean and the standard deviation exceeds 2.0, the model is accurate and the relationship stable in time (GUIOT, 1991).

Spectral analysis of the predicted data was performed to analyze the patterns and the relationships of the series in the frequency domain (FRITTS, 1976). Spectral analysis estimates the variance (power) of each wavelength throughout the entire spectrum by means of a Fourier Transform of the autocorrelation coefficients. The spectrum of a time series is normally represented as a plot with the frequency (*w*) or the period on the X-axis and the power (F*(w)*) on the Y-axis both in logarithmic scale. A high value in the power, corresponding to a specific frequency, can be interpreted as a deterministic process (cycle) (e.g. CHATFIELD, 1975; FRITTS, 1976). Cross-power spectral analysis was also performed between the actual and reconstructed temperature. The cross-power spectral analysis studies the covariance between series in the frequency domain. The output is the coherency, which is analogous to the correlation coefficient, and measures the similarity of two series at each frequency (FRITTS, 1976).

RESULTS

Ventina Chronology

ID	First year (A.D.)	Last year (A.D.)	Length	Level vs. Spread Correlation	Power
Ven 01	1499	1994	496	0.56	0.03
Ven 02	1752	1994	243	0.35	0.31
Ven 03	1252	1957	706	0.30	0.38
Ven 04	1760	1994	235	0.20	0.70
Ven 05	1729	1994	266	0.32	0.35
Ven 06	1684	1994	311	0.35	0.44
Ven 07	1677	1994	318	0.41	0.24
Ven 08	1567	1994	428	0.42	0.27
Ven 12	1795	1994	200	0.22	0.57
Ven 13	1684	1994	311	0.37	0.19
Ven 14	1655	1994	340	0.30	0.32
Ven 15	1459	1994	536	0.35	0.40
Ven 17	1555	1994	440	0.37	0.39
Ven 19	1229	1868	640	0.39	0.49
Ven 20	1329	1977	649	0.41	0.39
Ven 22	1258	1958	701	0.20	0.59
Ven 23	1603	1972	370	0.39	0.39
Ven 24	1539	1994	456	0.35	0.36
Ven 25	1410	1780	371	0.48	0.38

Tab. 1 – Time span and statistics of the power transformation for the 19 larch trees used to develop the Ventina Valley chronology.

Table 1 shows the results of the power transformation. Because 13 out of 19 trees were transformed with a coefficient *p* between 0.25 and 0.5, the results are consistent with those of COOK and PETERS (1997). The maximum correlation between level and spread is 0.56 whereas the minimum one is 0.2, although the majority (14 to 19) ranges in the interval 0.25-0.45. The SSS statistic suggests that the most recent part of the chronology with the largest sample size explains 96% of the variance of the hypothetical chronology with an infinite number of samples, whereas the threshold of 75% is attained in A.D.1252 where the chronology is composed by only two trees. Few years later, in A.D.1329, with a sample size of 4 trees the chronology explains 85% of the variance of the hypothetical infinitely replicated chronology. The mean correlation between trees is high (0.61) and reveals a strong common signal among the Ventina Valley larches. After averaging, the variance has been adjusted according to the procedure described by OSBORN *et al.* (1997). The Ventina chronology is illustrated in Figure 3.

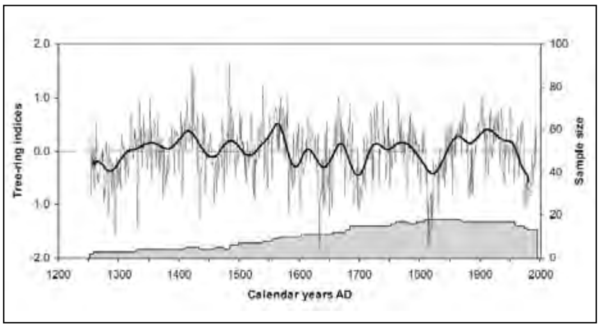

Fig. 3 – Tree-ring larch chronology of the Ventina Valley with sample depth. To show long-term variation, a 50-year filtered curve is overlaid.

CLIMATE-GROWTH RELATIONSHIPS

A correlation function was estimated between the tree-ring indices and minimum, maximum, and mean monthly temperatures, whereas for the multiple regression analysis only minimum and maximum temperature were used as predictors. Results are shown in Table 2. The highest correlation coefficients were found between growth and the maximum temperature of the summer months (May to August). In the multiple regression analysis, June and July minimum and maximum temperature are the predictors, which show significant relationships with the tree-ring indices: they explained about 60% of the variance in the tree-ring data (Rcalibration=0.67±0.04; Rverification=0.52±0.08). Spring temperature has a negative influence on the growth. These results are consistent with the model of a growth at high altitude sites controlled by summer temperature and are supported from the significant correlation coefficients between the Ventina Valley chronology and other larch chronologies of the Alps. The Ventina chronology has a correlation coefficient of 0.40, calculated for the period 1586-1994, with the Venegia Valley chro-

	Previous year								Current year									
	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O
Corr.																		
MAX	+	+	+	+	+	+							+	+	+	+		
MEAN			+											+	+	+		
MIN												-						-
Regr.																		
MAX	+	+	+	+							-			+	+			
MIN												-		+	+			

Tab. 2 – Relationship between tree-ring indices and temperature. Only significant correlation are reported (P=0.01) and for the regression only the significant predictors. June-July are the most important months for the growth of the Ventina Larch. Spring temperature has a negative relationship with the growth. Previous year's climate also seems to be important.

nology (Strumia and Cherubini, 1997), about 200 km west, and a correlation coefficient of 0.53 for the period 1252-1994 with a larch chronology of the Dachstein massif, in central Austria (Gindl et al., 1999), about 400 km north-west.

Temperature reconstruction

On the basis of the correlation function and the results of the regression analysis, the transfer function was estimated using the mean of the June-July maximum temperature as predictand, and the tree-ring indices of the current and of the following year as predictors. Since Briffa et al. (1998b) warned about a recent decrease in the sensitivity of tree growth to temperature in the Northern Hemisphere, the transfer function was calculated for the period 1778-1994 as well as for a subperiod 1778-1950. Results are stable for both the models, but the one calculated for the period 1778-1950 can reconstruct more variance in the temperature than the one for the period 1778-1994 (Tab. 3).

Period	1778-1994	1778-1950
Calibration	0.53±0.05	0.61±0.05
Verification	0.52±0.09	0.60±0.08

Tab. 3 – Calibration and verification multiple correlation coefficients and respective standard deviations for the two transfer functions estimated with the bootstrap method.

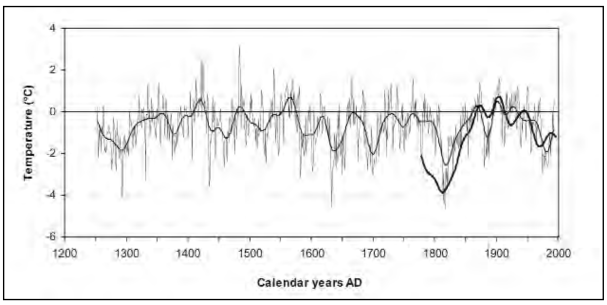

Fig. 4 – Reconstructed maximum temperature of June-July for Milan. In the vertical axes the temperature is plotted as departures from the 1901-1950 mean. The 20-year low-pass filter is plotted as a black line through the data. For the actual data only the low-pass filtered curve is represented.

The residuals of the regression are normally distributed and not significantly autocorrelated.

Finally, the equation estimated for the shorter period (1778-1950) was used for the reconstruction:

(2) $JJ_{MaxTemp} = 19.03\,(RW_t) + 4.48\,(Rw_{t+1}) - 12.95$

The temperature reconstruction is presented in Figure 4. A 20-year low-pass filter indicates cold and warm periods and clearly shows the strong long-term variability of the predicted temperatures. Spectral analysis shows that the variance (expressed as power) increases until a time-scale of 100 years (Figure 5a). Figure 5b illustrates the cross-spectral analysis between the reconstructed and the actual temperature in the overlapping period: the coherency is high (mostly about 0.4) all over the spectrum. Only for the periods around 8 years and between 20 and 40 years there is a decrease in the coherency between the two series.

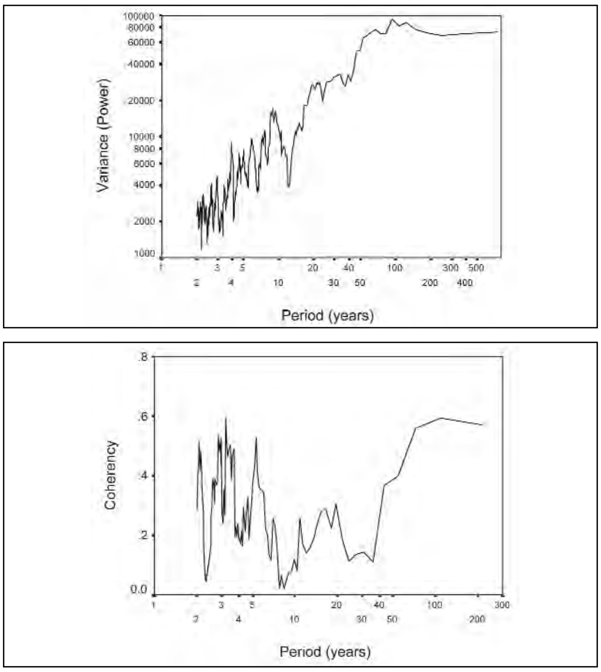

Fig. 5 – Spectral analysis of the predicted temperature (a) and cross-power spectral analysis between actual temperature and reconstructed temperature of Milan (b).

DISCUSSION AND CONCLUSIONS

The standardization method based on power transformation followed by a linear regression to eliminate the age-related trend worked very well to conserve possible long-term variations due to climate. This conservative method and the very old trees used in this study produce a tree-ring series with variation at centennial time scales. The power transformation based upon the relationship between level (mean) and spread (standard deviation) produces time series with stabilized variance. However, this correlation, although frequent in the ring-width raw data was sometimes low, suggesting that a criterion or method must be developed to help decide when a power transformation is necessary.

Correlation functions and multiple regression analysis between temperature and the tree-ring data showed that summer temperature is the most limiting factor affecting tree growth at this site. This relationship is well known for trees near their altitudinal limits and occurs because low temperatures limit respiration, photosynthesis and other biochemical processes involved in the growth mechanisms (FRITTS, 1976; TRANQUILLINI, 1979). Spring temperatures have a negative relationship with the growth of larch, because high temperatures in March or April can induce early resumption after dormancy, high respiration rate and consequently consumption of food reserves. Growth during previous years also has a strong influence on the current year's growth due to physiological preconditioning (FRITTS, 1976).

In the reconstruction of Milan summer temperature the coldest summers were found during the period 1800-1830. Those years are well known from historical sources for their low temperature (LE ROY LADURIE, 1971). Particularly A.D.1816, the famous "year without summer", is the coldest year in the record. The reconstruction shows a significant correlation (R=0.34) with a temperature reconstruction for Central Europe based on historical and documentary evidence (PFISTER, 1992) for the period 1525-1989. Significant cold periods occurred from 1275 to 1310; from 1425 to 1475; from 1575 to 1610; from 1620 to 1650; from 1690 to 1725 and the cited 1800-1830. Some of these correspond to cold phases found by BRIFFA et al.(1998a) in a reconstruction of Northern Hemisphere temperature anomalies: around 1450, from 1570 to 1610; at the end of 1600 and at the beginning of 1800. The Little Ice Age is a period of low temperature (BRADLEY and JONES, 1993) and of extensive glacier advances in the Alps (LE ROY LADURIE, 1971; GROVE, 1988). The magnitude and temporal extension of the LIA show geographical variability and evidence from other regions suggest that cool conditions might have been restricted to the Northern Hemisphere (COOK et al., 1991). In the reconstruction of Milan summer temperature, the LIA is apparent from approximately A.D.1575 to the early 19th century. The reference period 1901-1950 had relatively warm summers: only two periods in the past (around 1420 and from 1550 to 1570) show similar temperatures. Nevertheless, after A.D.1950 a cooling is apparent, so that twentieth century temperature seems to be within the normal variability of the last 700 years. A steady warming trend is absent in the last decades of both actual and reconstructed data.

Two peaks representing very low temperatures are located around 1630 and around 1700 and need further discussion. Such cooling phases were not found, at least with this intensity, in other reconstructions (PFISTER, 1992; BRIFFA et al., 1998a; GINDL et al., 1999). Albeit, in other reconstructions for the Alpine region (SERRE-BACHET et al., 1992) a cooling in the same period is visible. A possible source of non-climatic related variability in the Ventina chronology might be larch budmoth (*Zeiraphera diniana* Gn.) outbreaks. These lepidoptera larvae are common in the southern Alps and periodically devour the needles of the larches, causing reduction of growth and missing rings (PIGNATELLI and BLEULER, 1988; STRUMIA and SCHWEINGRUBER, 1997). The outbreaks can be synchronous in all the trees of a stand and their effects may not be eliminated by averaging. The possibility that such disturbances cause a bias in the temperature reconstruction can not be excluded.

The analysis in the frequency domain proves the skill of the reconstruction for predicting long-term variability: the predicted series contains variance with a frequency correspondent to a period of 100 years. The spectral analysis does not exhibit evidence of deterministic processes (cycles). Temperature seems to have a variability equally distributed at all wavelengths with a period lower than 100 years. The cross-power spectral analysis for the period overlapped by actual and reconstructed temperature shows a good agreement between the series for the high-frequency variation (period shorter than 5 years) and for multidecadal variability (period longer than 40 years). These results are due to the very old larch trees of the Ventina Valley chronology, and to the power-transformation, combined with a very conservative detrending method.

The uniformitarian principle is the basis of every dendroclimatological reconstruction (FRITTS, 1976). To predict past climate it is necessary to refer to modern conditions and to extrapolate the reconstruction according to the present climate-tree growth relationship. This relationship between the larch chronology and the temperature of Milan appears to be stable in time, over the long overlapping period, although in the last 30 years it weakens (Tab. 3). This decreasing sensitivity to temperature in tree growth of the last decades has been noticed at large spatial scale (BRIFFA et al., 1998b and c). The reason for this phenomenon is not clear: some changes in precipitation and temperature seasonality, such as the move to warmer springs and therefore to earlier snow melt, have been observed (GROISMAN et al., 1994) and proposed as possible forcing factors along with decrease in solar radiation, increase in atmospheric CO_2 concentration and changes in plant interactions and competition (BRIFFA et al.1998b).

In paleoclimatic reconstructions based on the calibration of tree growth to meteorological data, it is important to avoid using this period. Although in both the models presented here, there is a sufficient stability and similarity between calibration and verification, the model calibrated for the sub-period 1778-1950 was preferred, because any bias in tree-ring growth would produce a regression with biased coefficients and therefore to misleading model. BRIFFA et al., (1998b) suggest avoiding the recent part of the data set, because past temperature may be significantly overestimated, particularly where the loss of low frequency temperature sensitivity in the tree growth is great. Indeed, the problem of the uniformitarian principle remains. In the relatively short period in which measured climatic data overlaps tree-ring growth, this principle is broken. Recent changes are often blamed on anthropogenic causes and consequently are considered to have an effect only in the recent period. However, the occurrence of similar changes in the ecology and in the tree sensitivity also in the past could not be *a priori* excluded.

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