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## TECHNICAL NOTE

# Spectral analysis on mountain pine tree-ring chronologies

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## Abstract

The present study applies classic spectral analysis techniques to investigate cyclic patterns in four tree-ring chronologies of *Pinus montana* Miller from the Central Italian Alps (Valle del Gallo). Three of the chronologies were derived from mountain pine populations located in relatively undisturbed areas of the valley bottom and valley slopes, and one from a population located in an area of the valley bottom occasionally affected by sheetfloods. Each chronology consists of raw, standard, and residual data. We estimated power spectra by applying the Blackman–Tukey Method, the Maximum Entropy Method, the Multitaper Method, and the Lomb–Scargle Fourier transform, and tested the results against appropriate red noise models. The power spectra of the standard chronologies from undisturbed areas yielded statistically significant and reproducible interdecadal-scale cyclicities with main peaks closely spaced around a mean value of  $\sim 0.05$  cycle/year, in association with statistically non-significant albeit reproducible peaks at higher frequencies. The chronology of trees affected by sheetfloods yielded no statistically significant cyclicities, probably because sheetfloods altered tree growth. Raw chronologies, instead, yielded power spectra dominated by the growth trend, while residual chronologies yielded flat power spectra. Our analysis suggests that tree growth, if not disturbed by external geomorphological factors, was controlled by environmental and/or climatic conditions that oscillated in the last  $\sim 150$  years on interdecadal ( $\sim 20$  years) to decadal scales.

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## Introduction

Tree-ring width time series are natural archives of past regional climatic conditions, which commonly oscillate with interdecadal to decadal periodicities. Although, the existence of a relationship between climate and tree rings is well established, the origin of

the observed periodicities remains controversial (Fritts, 1976). Several hypotheses have been put forward in the literature that relate these periodicities to, for example, solar activity (Douglass, 1928; Vercelli, 1949; Bitvinskis, 1990; Cecchini et al., 1996), ocean–atmosphere dynamics (Linderholm, 2001; D'Arrigo et al., 2003; Gray et al., 2004), or an interplay of both mechanisms (Rigozo et al., 2005).

In many areas of the physical and natural sciences, spectral analysis is commonly used to detect periodic or quasi-periodic components of time series, as well as to

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compare different time series and investigate how they differ or relate (Percival and Walden, 1993).

Both periodic and quasi-periodic natural processes can be characterized by estimating the power spectrum of a time series – a measure of the relative amplitudes and periods of the different frequencies that form the signal. For example, a random process like white noise (a random noise signal that has an equal amount of energy at all frequencies) has a power spectrum homogeneously distributed across all frequencies, whereas a periodic process like radioactive decay allocates all power to single spectral line(s). Power peaks that rise from a continuum of background red noise (a noise signal with energy monotonically decreasing as the frequency increases) realistically characterize deterministic natural processes.

In the field of climate studies, spectral analysis is one of the methods used to reconstruct past climate variability (Schulz et al., 2000; Ghil, 2002; Ghil et al., 2002; Wunsch, 2003).

In this paper, we investigate to which extent classic spectral analysis methods are efficient in revealing the cyclic signature of tree-ring data with the aim, on a longer-term scientific commitment, to contribute to the development of climatic models capable to explain any such potentially present variability. Our study is focused on tree-ring chronologies of mountain pine from the Central Italian Alps and on climatic time series.

## The study area

The study area is located in Valle del Gallo (Lombardy, northern Italy) at altitudes between 1900 and 2200 m a.s.l (Fig. 1). A mountain pine forest (*Pinus montana* Miller) dominates the vegetation of the valley. In this high mountain environment, instability processes are very common, and consist especially of debris flows that constructed several fans now dominating the landscape of the valley bottom (Santilli et al., 2002). One of these debris flow fans is also affected by sheetfloods that, descending from a small tributary valley, deposited silt material at the stems base, without however inducing any evident mechanical damage (Pelfini et al., 2005a; Santilli et al., 2002). In any case, these processes frequently altered tree growth, and only in some undisturbed areas of the valley slopes and valley bottom trees growth is undisturbed.

In the last years, some reference chronologies of mountain pine were built in Valle del Gallo for dendrogeomorphological dating of debris flows (Pelfini and Santilli, 2003; Santilli and Pelfini, 2002, 2005), as well as to study stream erosion processes (Pelfini et al., 2005b) and to perform dendroclimatic analysis (Pelfini et al., accepted).

## Materials and methods

### Dendrochronological data

The four tree-ring chronologies of mountain pine considered in this study come from four different locations (Fig. 1): trees located on undisturbed areas of the valley bottom (chronology c200), on undisturbed areas of the two opposite valley slopes (chronology c300 on the western slope, and chronology c400 on the eastern slope), and trees located in an area of the valley bottom occasionally affected by sheetfloods (chronology c500).

For each population, we sampled 30 dominant trees showing regular growth and crown, taking two or three cores from each stem. Samples were prepared for measurement according to standard methods (Schweingruber, 1988). The growth curves of all samples were constructed by measuring the ring width with accuracy of 0.01 mm using the software TSAP (Rinn, 1996) and by means of image analysis using the software WIND-ENDRO. We checked date accuracy and measurement quality of each series both statistically and visually by using the software COFECHA (Holmes, 1983; Grissino-Mayer, 2001) and TSAP-Win (Sander, 2004), respectively. For each population, we selected the growth series showing a good correlation ( $r > 0.5$ ) with their mean chronology (Hofgaard et al., 1999). In order to remove long-term growth trends, like the age trend and non-climatic trends related to stand dynamics (Fritts, 1976; Schweingruber, 1988), all selected series were standardized by using a cubic smoothing spline function with a 50% cut-off at 60-year wavelength using the software ARSTAN (Cook and Holmes, 1986; Holmes, 1994). By applying a biweight robust mean to the time series, the program output supplied both standard and residual chronologies, the latter derived by using an autoregressive (AR) model (Cook and Briffa, 1990) that removes the autocorrelation, resulting in a series of independent observations. In this study, we used raw-data, standard, and residual chronologies. The standard tree ring chronologies are shown in Fig. 2.

### Climatic data

Some meteorological stations exist close to the study area. Temperature and precipitation data from Cancano, Bormio, and Livigno stations were used in a previous study on the influence of climate on mountain pine growth (Pelfini et al., accepted). However, the shortness of these data time series, in particular temperature, hampered the applicability of spectral analysis methods. For this reason, we utilized annual and monthly average temperature and precipitation values collected in the city of Milan (about 150 km to the

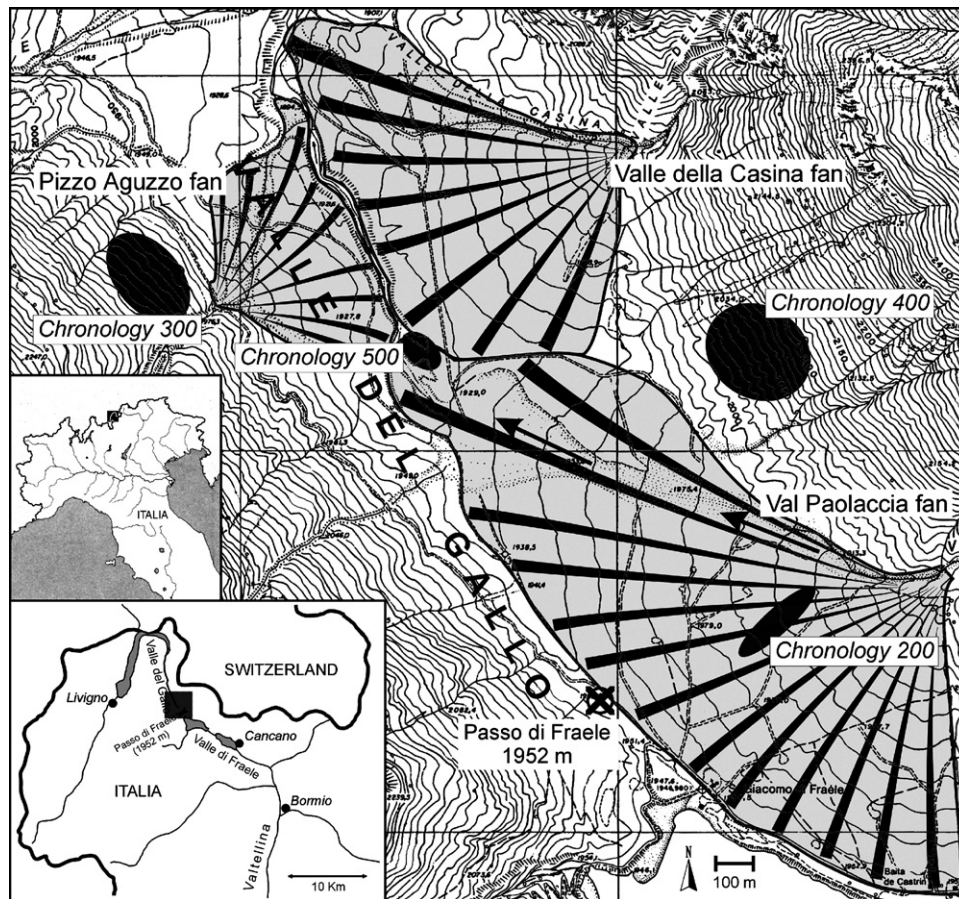


Fig. 1. Map of the upper Valle del Gallo with position of the sampled mountain pine populations.

southwest of the studied area) since 1763 (temperature) and 1764 (precipitation) (Maugeri et al., 2002a,b). In spite of the distance between the studied area and Milan, and in spite of the different environmental conditions, correlations could be found because the climatic variability influencing tree growth acts at a regional scale (Fritts, 1976).

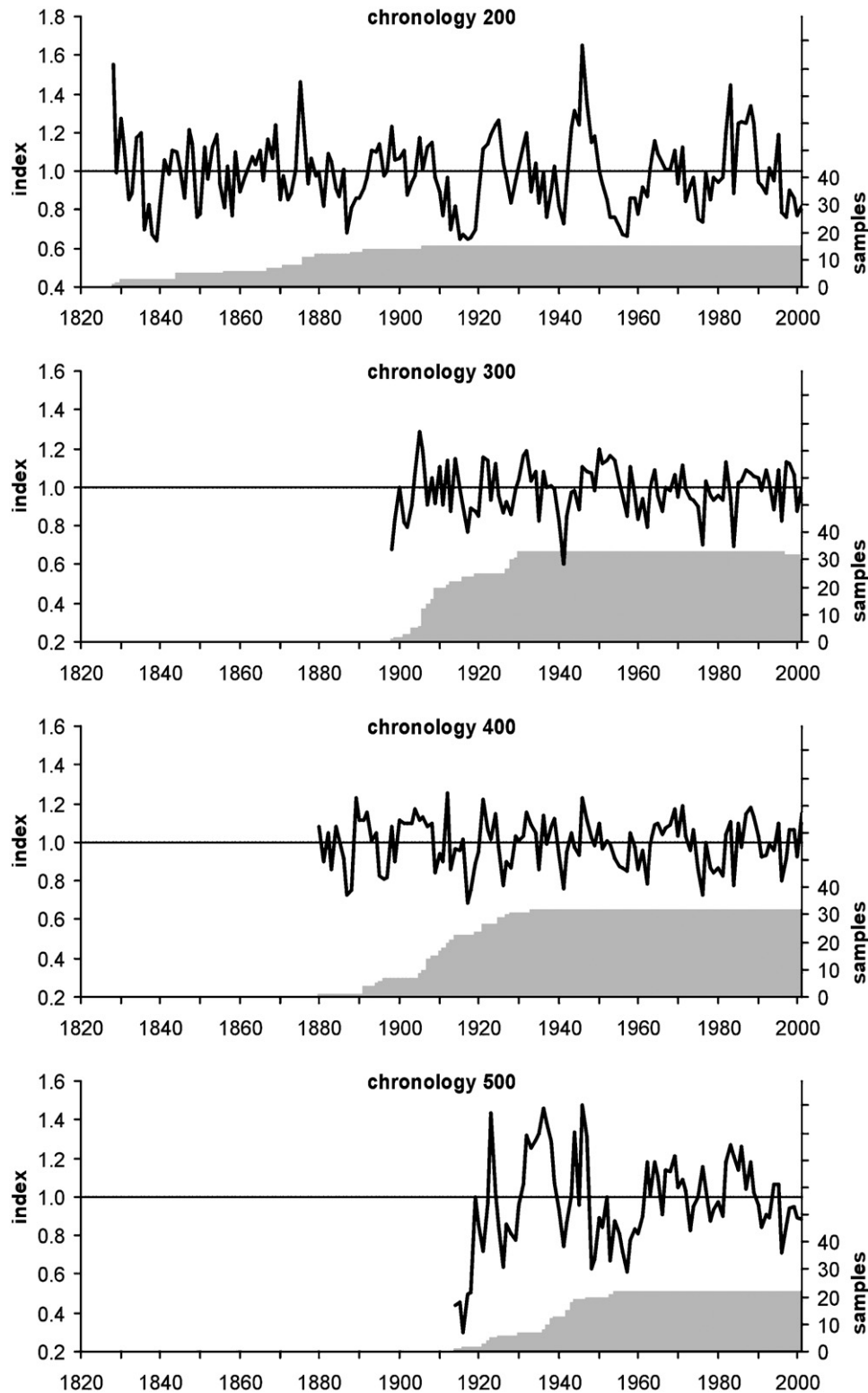
### Spectral analysis methods

In order to estimate power spectra of time series, a number of methods exist with different characteristics that generate spectra with different resolution. Therefore, in order to obtain reliable results, more than one method must be used, and the results compared (Weedon, 2003). Two software tools available in the public domain were used: the SSA-MTM Toolkit (Ghil et al., 2002), and the Redfit Tool (Schulz and Mudelsee, 2002). With the SSA-MTM Toolkit, we performed spectral analysis by using the Blackman–Tukey Method (BTM), the Maximum Entropy Method (MEM), and the Multitaper Method (MTM), which we briefly describe hereafter (for additional information and references, see Weedon, 2003).

The BTM computes the autocovariance of the data by comparing the time series with itself once it has been offset by an amount – called the ‘lag’ – that runs from zero (no offset) to the number of time series points minus one; then, a lag window is applied to truncate the autocovariance sequence to a certain lag value  $M$  in order to eliminate the highest and most noisy autocovariance terms, and, finally, the windowed autocovariance sequence is Fourier-transformed. In our analysis, we applied a Bartlett (triangular) window type with size values around  $N/10$  (where  $N$  is the number of data points in the time series).

The MEM is equivalent to fitting the data as though they correspond to a high-order AR process. The order of MEM method is the number of AR components to be included in the analysis and determines the spectral resolution; it determines also the level of smoothing because usually the number of spurious peaks grows with the MEM order. For the MEM order parameter, we utilized values  $< N/10$  and  $> N/3$  (where  $N$  is the number of data points in the time series).

In the MTM method, a series of prolate spheroidal tapers are applied to the time series; the different tapers suppress different parts of the time series. The total power spectrum is then estimated by averaging the



**Fig. 2.** Mountain pine tree-ring standard chronologies from the valley bottom (c200), the western slope (c300), the eastern slope (c400), and from an area affected by sheetfloods (c500).

individual spectra given by each tapered version of the data set. The smoothing of the spectrum increases with the number of tapers used.

The Redfit Tool determines the spectrum of a time series by means of the Lomb–Scargle Fourier transform; it was used in this study to confirm the results obtained

with the methods implemented in the SSA-MTM Toolkit, and to test if the reproducible power peaks were significant against a red noise background generated from an AR1 process. To assess the statistical significance of a spectral peak, the upper confidence interval of the AR1 noise was calculated for different significance levels (90%, 95%, and 99%) based on a  $\chi^2$  (chi-squared) distribution (the degrees of freedom of which depend on the actual spectral analysis setting).

In spectral analysis, the frequency resolution increases with increasing data length. The four chronologies used in this study should be long enough (i.e., 90–170 years) to resolve regular components in the order of tens of years, albeit the finite resolution of the resulting spectra may not allow identifying their exact periodicities.

## Results

The power spectra of the raw-data tree ring chronologies, computed with different methods as outlined above, show a systematic distortion in the low frequency part of the spectrum, interpreted as due to the fact that in a raw chronology the growth trend allocates (unwanted) power at frequencies equal to the data length.

The power spectra of the standard chronologies yielded interdecadal and decadal-scale cyclicities as illustrated hereafter. The spectral estimates of the standardized chronology c200 generated with the BTM and MEM showed the presence of a peak centered at  $\sim 0.05$  cycle/year. In the spectrum generated with the Redfit Tool, a same peak centered at  $\sim 0.05$  cycle/year reached the 99% confidence level (Fig. 3). Other peaks, statistically below the 90% confidence level, were identified at  $\sim 0.08$  and  $0.12$ – $0.13$  cycle/year. Two closely

spaced peaks at  $\sim 0.05$  cycle/year were observed in the spectrum generated with MTM.

The spectral estimate of the standardized tree ring chronology c300 generated with BTM yielded a quite broad peak at  $\sim 0.05$  cycle/year, whereas in the spectral estimate generated with MEM, a sharper peak centered at  $\sim 0.05$  cycle/year was observed, together with a smaller peak at  $\sim 0.12$  cycle/year. Two closely spaced peaks at  $\sim 0.05$  cycle/year, and two closely spaced peaks at  $0.11$ – $0.12$  cycle/year were observed in the spectrum generated with MTM. In the spectrum generated with the Redfit Tool, the peak centered at  $\sim 0.05$  cycle/year reached the 95% confidence level, whereas a broad peak centered at  $\sim 0.12$  cycle/year did not reach the 90% confidence level (Fig. 4).

The spectral estimate of the standardized chronology c400 generated with BTM yielded a broad peak at  $0.05$ – $0.06$  cycle/year, whereas in the one generated with MEM, a sharper peak centered at  $0.05$ – $0.06$  cycle/year was observed, together with smaller peaks at  $\sim 0.09$ – $0.10$  and  $\sim 0.13$  cycle/year. Two closely spaced peaks at  $0.05$ – $0.06$  cycle/year and smaller peaks at  $\sim 0.10$  and  $0.13$ – $0.14$  cycle/year were observed in the spectrum generated with MTM. In the spectrum generated with the Redfit tool, the peak centered at  $\sim 0.05$  cycle/year reached the 95% confidence level, whereas smaller peaks at  $\sim 0.10$ ,  $\sim 0.13$ , and  $\sim 0.23$  cycle/year did not reach the 90% confidence level (Fig. 5).

Finally, in the spectral estimate of the standardized chronology c500 generated with BTM, no evident peaks were observed; in that generated with MEM, two peaks were observed at  $0.02$ – $0.03$  and  $0.07$ – $0.08$  cycle/year, respectively, whereas two closely spaced peaks at  $0.02$ – $0.04$  cycle/year, as well as a smaller peak at  $\sim 0.08$  cycle/year, were observed in the spectrum generated with MTM. In one of the spectra generated with

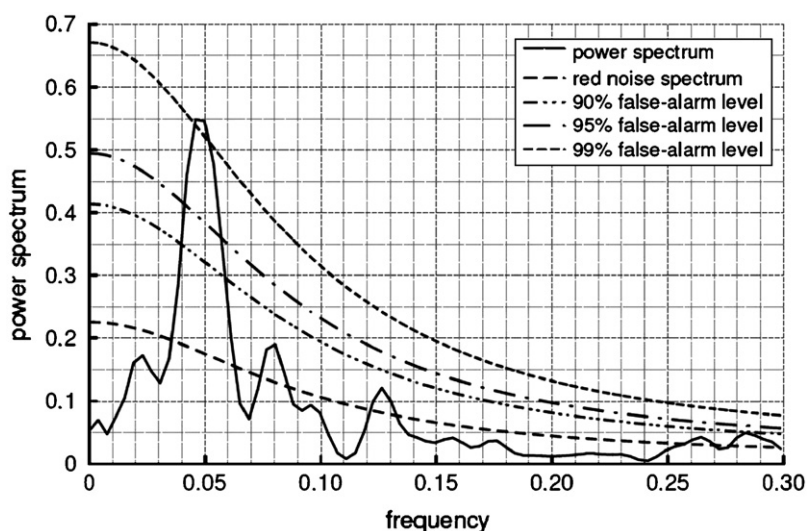


Fig. 3. Spectral analysis of chronology c200 obtained with the Redfit Tool (number of WOSA segments = 3, Welch window).

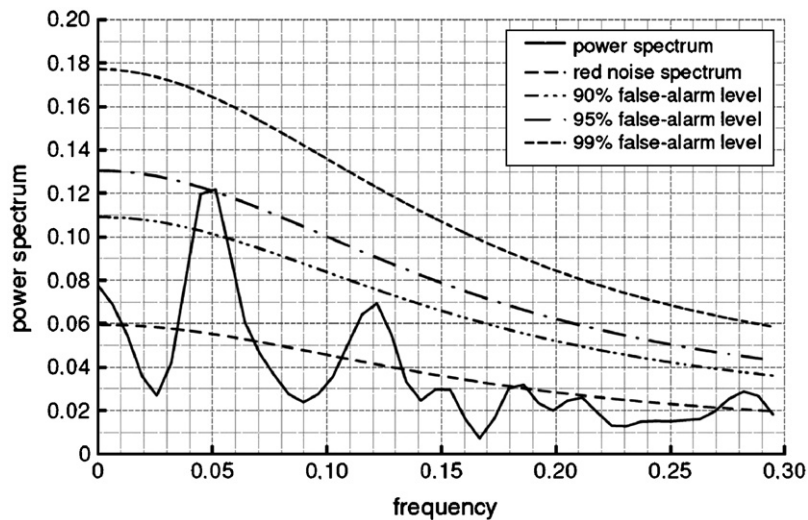


Fig. 4. Spectral analysis of chronology c300 obtained with the Redfit Tool (number of WOSA segments = 3, Welch window).

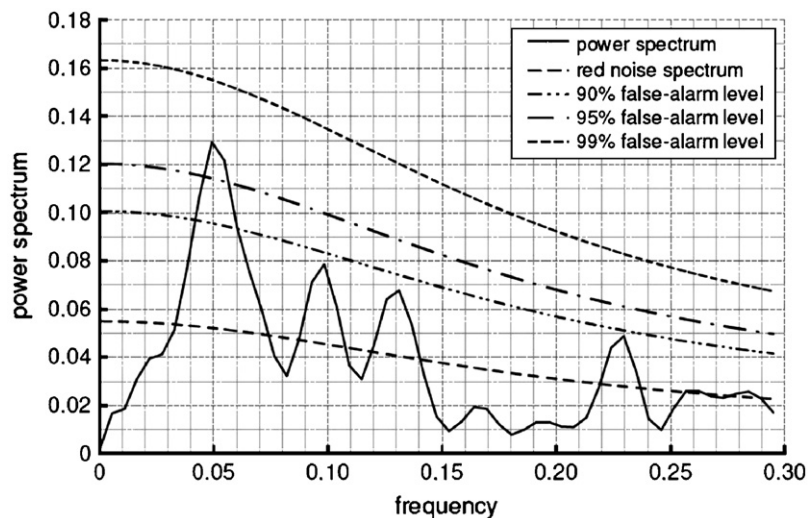


Fig. 5. Spectral analysis of chronology c400 obtained with the Redfit tool (number of WOSA segments = 3, Welch window).

the Redfit Tool, a peak at 0.01–0.02 cycle/year reached the 95% confidence level (Fig. 6a), but by changing the WOSA parameters, no significant peaks were observed (Fig. 6b).

As an additional experiment, we applied spectral analysis to the residual chronologies. The power spectra generated with different methods resembled those typical of white noise, with no statistically significant peaks.

In order to investigate the presence of relations between the periodicity in the tree-ring width time series and climatic variables, we analyzed temperature and precipitation data series using the same spectral analysis methods applied to the tree-ring chronologies.

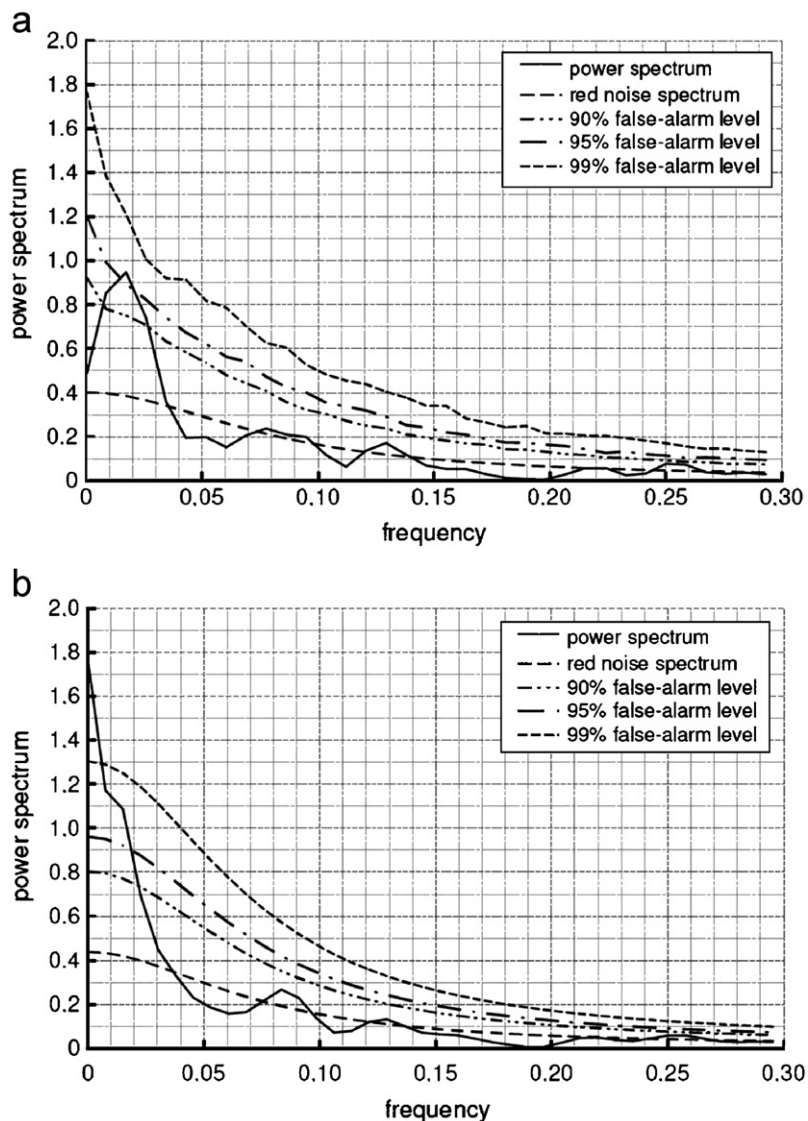
The spectral estimates for the annual mean temperature showed the presence of a peak centered at  $\sim 0.05$  cycle/year. In the spectrum generated with the

Redfit Tool, the peak centered at  $\sim 0.05$  cycle/year reached the 90% confidence level (Fig. 7a).

Furthermore, we analyzed the temperature variability of late spring and summer months (i.e., the tree growing year-period), and found in the spectra for May (Fig. 7b), June, and September a peak centered at  $\sim 0.05$  cycle/year. In the spectra generated with the Redfit Tool, this peak reached the 95% confidence level for the monthly temperature of May, and the 90% confidence level for the monthly temperature of June and September.

Finally, the spectral estimates for the mean temperature for the period May–September showed the presence of a peak centered at  $\sim 0.05$  cycle/year. In the spectrum generated with the Redfit Tool, this peak reached the 95% confidence level.

Less clearly interpretable results were obtained for the precipitation data time series. The spectra of the annual



**Fig. 6.** Spectral analyses of chronology c500 obtained with the Redfit Tool (number of WOSA segments = 3 in panel (a), and number of WOSA segment = 2 in panel (b); Welch window).

mean precipitation and of the monthly precipitation for all months, did not show any statistically significant peak around 0.05 cycle/year, but peaks scattered at frequencies both lower and higher than 0.05 cycle/year.

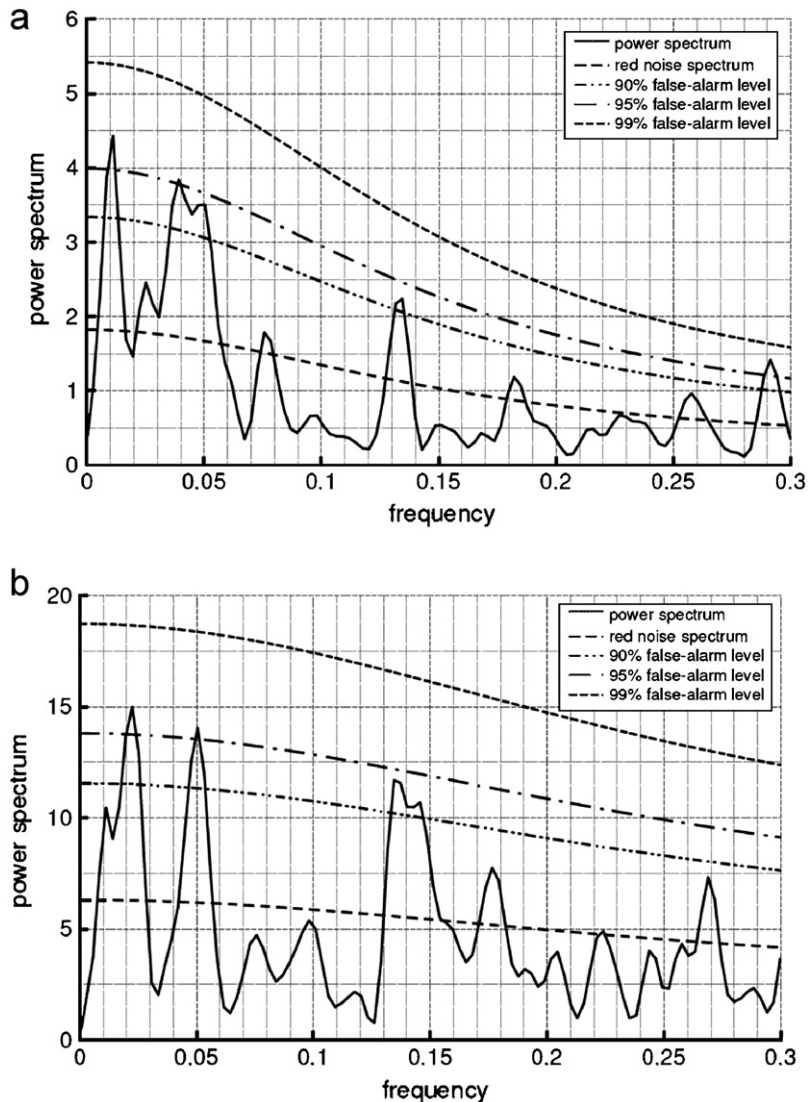
## Discussion and conclusions

We showed that spectral analysis is efficient in resolving cyclicities in standardized tree-ring chronologies; raw-data chronologies yielded power spectra dominated by the growth trend, and residual chronologies yielded flat power spectra.

The power spectra of standardized tree-ring chronologies from undisturbed areas of the valley bottom (c200) and valley slopes (c300 and c400) showed a

statistically significant peak centered at  $\sim 0.05$  cycle/year ( $\sim 20$  year cycle), which was reproduced by all methods used. Additional power peaks were further commonly observed in the 0.08–0.13 cycle/year range ( $\sim 12$ – $8$  year cycles), but these were never proven statistically significant with respect to appropriate red noise models. Instead, power spectra of chronology c500 obtained from trees located in an area affected by sheetfloods yielded neither statistically significant peaks nor reproducible results because slope instability induced (and presently induces) growth anomalies (Pelfini et al., 2005a).

Our analysis suggests that tree growth rates – if not disturbed by external geomorphological factors – were controlled by environmental and/or climatic conditions that oscillated in the last  $\sim 150$  years on interdecadal ( $\sim 20$  years) to decadal scales. Since the spectra of the



**Fig. 7.** Spectral analysis of the mean annual temperature (a) and of the May monthly temperature (b) obtained with the Redfit tool (number of WOSA segment = 3, Welch window).

analyzed temperature series broadly show the same periodicity found in tree ring chronologies, we tentatively hypothesize that a common driving factor influenced both temperature variability (at least in the spring-summer period) and tree growth. In particular, we speculate that the statistically significant  $\sim 20$  years periodicity found in standardized tree ring chronologies should be mostly controlled by the similar periodicity observed in average temperature values, and this is because tree growth at high altitude is largely influenced by atmosphere thermal conditions.

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