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The influence of low-frequency variability on tree-rings based climate reconstruction: a case study from central Italy (Roman coast)

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Tree rings are among the best sources of proxy data for reconstructing past climatic records. In this study we explore for the first time what type of climatic signals can be reconstructed from stone pine (*Pinus pinea* L.) based on tree-rings from central Italy (Roman coast). Samples from 112 stone pine trees from stands with different age classes were collected at two locations, Castel Fusano and Castelporziano. In determining the particular target variable for climate reconstruction we explored a wide range of climatic signals (from monthly to multiple year scale) for correlations with tree ring chronologies produced using a variety of detrending methods. We reconstructed short term (autumn-early winter) and long term (3 years precipitation) signals during the 150 years of available data using the "classical" detrending method but also methods preserving their low frequency variability (ABD and RCS) within the chronologies. By setting the best multiple year precipitation drivers at an annual scale and applying a simple percentile threshold approach, we identified the wettest and driest climatic events. The best accuracy in identifying the climatic thresholds was obtained with the ABD method, which also showed the best cross spectral correlation with a long precipitation record. Our reconstruction underpins that since ca. 1850 the Roman coast has experienced its driest conditions in terms of 2-3 year rainfall sums during the last 50 years of the 20th Century. This finding may be used in the context of identifying the long-term natural variability of the region in relation to climate change as it is expected to affect the Mediterranean.

Keywords - dendroclimatology; reconstruction; Mediterranean pinewoods; Pinus pinea, climate–growth relationships; detrending methods.

Introduction

The instrumental climate data, such as precipitation and temperature, are not long enough to determine the characteristic time scale and forcing of regional climate variability over several centuries but they can be extended back through long-scale proxy data. In the reconstruction of climatic or hydrological parameters it is important to extract signals out of proxy data that can be related to time scales useful in climatology or hydrology (Cook et al. 2007; Battipaglia et al. 2010; Touchan et al. 2010; Esper et al. 2012; Levanič et al. 2015; Schneider et al. 2015). These data may not only come from tree ring widths (TRWs) or other wood based parameters but can also include other environmental parameters such as lake sediments, bore-hole observations, coral records, and ice cores (Jones and Mann 2004; Jansen et al. 2007; Trachsel et al. 2012; Ahmed et al. 2013).

The target time scale of these signals follows the timing of meteorological variable events (e.g. daily) although parameters with longer time span and suitable for climatological or hydrological studies have been identified (i.e. of monthly or seasonal scales).

Tree ring width is directly influenced by climate and reliable climate reconstructions can be calculated if their relationships are well understood. Moreover, understanding climate-growth relationships is very important in order to predict the effects of environmental changes on tree growth. Tree-ring records can be examined at annual resolution, they are well-replicated and can be calibrated and validated against instrumental climate data. They are one of the best sources of proxy data to reconstruct past records of precipitation and drought on interannual to centennial time scales (Touchan et al. 2010).

Usually the first step necessary to reconstruct climate from proxy data involves filtering out any non-climate features such as the influence of tree age, so that only climatic features remain in the proxy. Anything other than these target signals, such as signals related to past or longer climatic impact retained in the proxy record, is considered as "noise" and is removed (Woodhouse et al. 2006) unless long-term climate trends are also of interest (Cook et al. 1995). For example, detrending tree-ring

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series, which are used to remove the non-climatic growth, can lead to the removal of additional climatic influences on growth from tree-ring chronology frequently related to low-frequency variability. As the low-frequency climate signal - and possibly some high-frequency signal - is removed during the typical standardization procedure, the analysis of changes in climate at the decadal or multi-decadal time scale may be inaccurate.

The Mediterranean area is very sensitive to climate change because it represents a transition zone between the humid western and central European domain and the arid North African desert belt. The climate of this region features a high variability of precipitation on the monthly, inter-annual and inter-decadal time scales (Dünkeloh and Jacobeit 2003), which strongly influence the interrelations among water resources, water availability, ecosystem functions, and land-use changes.

Climatic scenarios based on Global and Regional Circulation Models predict a decrease in the annual precipitation amount and a trend towards drier conditions (Gibelin and Déqué 2002; Dünkeloh and Jacobeit 2003; Brunetti et al. 2006; IPCC WG I 2013). Central Italy, which includes the coastal areas of the Tyrrhenian Sea, is the region with the most evident negative trends in total and seasonal precipitation, with a decrease of 10% per century on a yearly basis, and 20% and 13% decreases per century in spring and summer, respectively (Brunetti et al. 2006).

The analysis of tree-growth responses of *Pinus pinea* L. in relation to climate trends during the last century along the Tyrrhenian coast of central Italy has shown that precipitation is the main factor driving growth (Mazza and Manetti 2013). Moreover, the stronger correlations were shown by the precipitation accumulated over consecutive years because of the increase in soil water content stored following previous rainy years. Based on these results, a highly significant influence of previous climatic conditions in reconstructing climatic trends over time is expected.

The aim of this study is to identify the main climatic signals in tree rings of *Pinus pinea* as they can be used to evaluate the climate variability on the Roman coast during the last 150 years. Thus, we have tested a wide range of climate predictors from monthly to yearly time scale to reconstruct the climate. To preserve possible long-term trends in tree ring chronologies that may indicate changes in climate patterns, regional curve standardization (RCS) and age band decomposition (ABD) detrending methods were applied and compared with the "classical" standardized chronologies of the tree ring series

Material and Methods

Study sites and climate data

The study sites are located in a Mediterranean coastal area within two important and typical pine forests derived by old plantations in the Roman coast (central Italy). The pinewoods are Castel Fusano (41°43' N, 12°19' E) and Castelporziano (41°42'N, 12°24' E), which are in the Natural Reserve of the "Roman coast" (Mazza and Manetti 2013).

These areas were selected because of the presence of pine stands characterised by several age classes; the oldest approximately 160 years old. The study sites are located on a sand dune ecosystem within each pinewood to avoid either the influence of coastal erosion and the exposure of crowns to salty winds and surfactants in marine aerosols as they may affect the growth of pines (Raventós et al. 2001; Raddi et al. 2009). These pinewoods are characterised by a dominant crop layer of *Pinus pinea* with holm oak (*Quercus ilex* L.) and other typical broadleaf maquis shrubs that dominate the layers below the canopy. The soils are mainly developed from stabilised old dunes and have a rising water table.

The climate is Mediterranean, with medium-low yearly precipitation concentrated in the period from late autumn to early spring and a dry summer. We used datasets available from the two meteorological stations closest to the pinewoods to calculate mean temperature and total precipitation; data cover the period 1951-2009 (Ostia Idrovore, 41°44' N – 12°19' E and Roma Colleggio Romano, 41°53› N – 12°28› E). Total mean annual rainfall is 721 ± 167 mm; the lowest value during summer is 63 ± 41 mm, and the average annual temperature is 16.2 °C in the period 1980-2009.

Dendrochronological analysis

At each site, dominant and healthy trees with symmetric canopy, without visible injuries on the crown and the stem and no signs of past tree cutting in their neighbourhood, were selected. Two cores per tree were extracted with a 5-mm diameter increment borer at breast height on the cross-sides of the trunk. The increment cores were prepared according to the standard dendrochronological procedures (Fritts 1976; Schweingruber 1989). Tree-ring widths were measured from the bark to the pith with 0.01-mm precision by a computer-linked mechanical platform connected to a stereoscope. Each ring-width series was first visually checked and then statistically checked for cross-dating and measurements errors were performed by using the dendrochronology program library in R (dplR) (Bunn 2010). The series weakly correlated with the master site chronology were corrected if possible otherwise discarded. The age of cores containing the pith was determined by counting the calendar years assigned to the tree rings from the bark to the pith. Due to the same grid box of climate data and the high degree of synchrony, the tree ring chronologies of the two pinewoods were averaged. Descriptive statistics of the tree-ring chronologies are indicated in Table 1.

We applied both the 'classical' approach and two most recent options to remove the effect of age trend from tree ring width series: i) the 'traditional method (STD) based on indexes of tree-ring data obtained by fitting each series through the typical functions that retain the high-frequency climate information, according to standard dendroclimatic procedures (Fritts 1976; Cook and Peters1981; Cook and Kairiukstis 1990); ii-a) the regional curve standardization method (RCS, Briffa et al. 1992; Esper et al. 2003) applied to the raw tree rings width values and ii-b) the age band decomposition method (ABD, Briffa et al. 2001), which is based on decomposing the tree-ring width data into age classes (Sarris et al. 2011; Mazza and Manetti 2013).

RCS is inappropriate when samples are taken from trees of similar age as they form a common age class and have been exposed to the same climate conditions during time (Schofield et al. 2016). Theoretically, RCS requires large amounts of tree growth data distributed over a wide range of tree ages, from one species within a relatively small region (Briffa et al. 1996). In this study, the chronologies show a range of ages in each time period and therefore the RCS method suits the scale and type of analysis of this work.

The mean correlation between trees (rbar) was computed to assess the synchronization in the annual growth patterns among sampled trees and the common signal strength shown by the mean growth chronologies. The reliability of chronologies was tested using the Expressed Population Signal (EPS) (Wigley et al. 1984), which quantifies the degree of year-by-year growth variations shared by trees in a population of the same site. Only the series with high common signal (EPS ≥ 0.85) were included in the analysis.

Climate reconstruction skill

In determining the particular target variable for climate reconstruction we explored a wide range of climatic drivers explaining tree-growth variability, from monthly to yearly scale.

Climate-growth relationships were investigated for precipitation using the Pearson's correlations after testing the normal distribution with the Kolmogorov-Smirnov and Shapiro-Wilk tests over a stabilized growth period. The aim of this analysis was to reduce the influence of site characteristics on tree growth variability, especially during the establishment phase typical of the first years of growth, where the climatic signal is not well recorded (e.g., due to a strong competition with understory vegetation).

We used 16 independent monthly variables sequenced from September of the year prior to growth (t – 1, uppercase) to December of the year of growth (t, lowercase) under the assumption that cambial activity still continues during late autumn - early winter when favourable climate conditions occur, as observed in our sampling sites (Mazza and Manetti 2013). Seasonal climate-growth correlations were checked from September (t-1) to December (t) using 14 rotating seasonal periods of three months (e.g. September-October-November, SON; October-November-December, OND; November-December-January, NDj; etc.) and 11 rotating seasonal periods of six month from SONDjf to jasond. In addition, other integration periods from seven to twelve months were computed from September (t-1) to December (t) shifting at each step of one month for a total of 45 combinations [e.g. from September (t-1) to March(t), April(t), May(t), etc.; from October(t-1) to April(t), May(t); etc.].

Then, for identifying any possible effects of previous years' precipitation on tree growth, as a series of dry years in this climate could seriously affect tree growth and survival, we tested antecedent climatic variables up to 5 years prior and including the year of tree-ring formation.

The strength of the reconstruction model was tested by using regression and correlation statistics. A split-sample procedure into two subsets was used to verify model stability: an early calibration (1951-1987) and late validation period (1988-2009), a late calibration (1988-2009) and an early validation period (1951-1987). The skill of the reconstruction was assessed through the adjusted calibration R^2, the reduction of error (RE) and the coefficient of efficiency (CE) statistics (Cook et al. 1994; Wilson et al. 2006). In particular, RE is useful for verifying whether the reconstruction can accurately reproduce any changes between the calibration and validation period mean (Cook et al. 1994; Ammann and Wahl 2007); RE value greater than zero is considered positive skill (Fritts 1976).

Since there is always a loss of variance in the reconstruction when transfer functions are used to reconstruct climate parameters, which is proportional to the amount of unexplained variance during the calibration period (Esper et al. 2005; Moberg and Brattström 2011; McCarroll et al. 2013), specific tests coupled with the scaling method approach (z-scores transformation of the overlapped period) were applied to avoid variance loss (Büntgen et al.

2008; Popa and Kern 2009; Hafner et al. 2013; McCarroll et al. 2013; Poljanšek et al. 2013).

The strength of climate reconstruction was also tested through the comparison with a long climate dataset dating back to 1782 from the Climate Research Unit (CRU), University of East Anglia, UK, gridded on a 0.5×0.5 degree network that includes Ciampino and Fiumicino, two towns close to the studied pinewoods.

Time series analysis

Wavelet-based spectral analysis was applied both to the measured and the reconstructed precipitation time series to perform a multiscale wavelets correlation analysis. Wavelets are derived by a one-dimensional multiresolution analysis performing an additive decomposition of the original time series from 2 to 2^5 years (wavelet detail D_1, D_2, D_3, D_4 and D_5) based on the "Maximal Overlap Discrete Wavelet Transform - MODWT" method (Percival and Walden 2000).

Morlet wavelet analysis was also performed to assess significant spectral changes and coherence over time (Torrence and Compo 1998; D'Arrigo et al. 2005; Touchan et al. 2010). Wavelet coherence shows warmer and colder colours (red and blue, respectively) that represent regions with significant interrelation or lower dependence between the series. Arrows in the wavelet coherence plots show the lead/lag phase relations between the examined series. When two series are in phase, it indicates that they move in the same direction while anti-phase means that they move in the opposite direction (Grinsted et al. 2004).

Results

Site chronologies and climate signals captured in tree rings.

A total of 112 trees and 197 cores were used to compute the tree-ring chronologies that span from 53 to 158 years in length. Mean sensitivity (MS) varied from 0.228 to 0.352, which would suggest a high climate-sensitivity of these trees. First order autocorrelation prior standardisation (AC) was high but suitably it was removed in the series standardised with the "classical" approach (STD). Instead, it has been preserved in RCS and ABD to take into account the influence of past climatic signals in these chronologies. The *Gleichläufigkeit* (GLK - Schweingruber 1989) values ranged from 0.68 to 0.81. The average correlation between series (r.bt) varied from 0.55 to 0.80 and all the four site chronologies reached the minimum EPS value of 0.85, which is a widely-used threshold in dendroclimatic studies. This means that the chronologies can be considered representative of tree growth at the sites (Table 1).

In all cases, we observed a tendency towards longer than monthly integration periods of precipitation more strongly associated with growth variability during time. This phenomenon became much clearer when the chronologies produced by RCS and ABD were tested, whereas the STD chronology provided, in general, weaker correlations with yearly integration periods of precipitation (Fig. 1).

November and late autumn-early winter (OND) precipitation has shown the highest correlation coefficients at the monthly and/or seasonal scale. Increasing the time scale of climatic variables from monthly to multiple-seasons and then to multiple-years has also improved the correlation significance especially when the RCS and ABD chronologies were used. Integration periods of precipitation accumulated over 2 and 3 years resulted as the best climate proxy produced by the RCS and ABD chronologies.

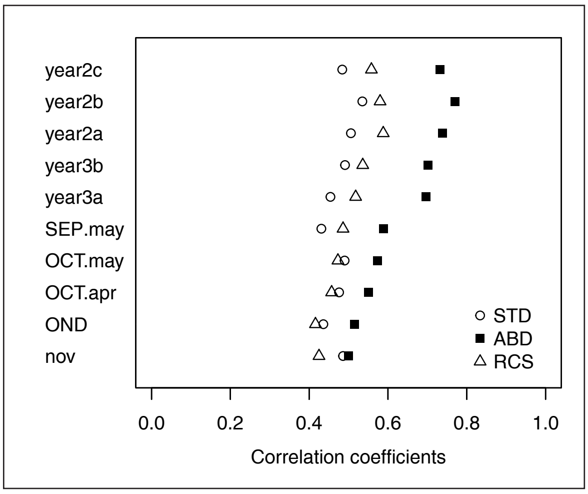

Figure 1 - Correlation coefficients between standardized chronologies and the main climatic drivers. Letters indicate various integration periods of precipitation accumulated over 3 years. Only significant coefficients are shown.

Frequency based climate reconstruction

Exploratory statistics showed that the mean site chronologies have good potential for climate reconstruction. The high correlations between the best explanatory variables and the site chronologies have allowed to elaborate a linear model where the short/long time scale climate variables are dependent variables and the standardized site chronologies are independent variables in the 1951-2009 period.

The regression model based on high-frequency signals (OND precipitation) retained in the STD chronology produced lower performances than the model based on low-frequency signals (3-year precipitation sums) retained in ABD (Fig. 2 - Table 2).

The explained variance both in the calibration and verification periods is significantly higher in the ABD chronology than the STD chronology (0.48

Table 1. - Main stands characteristics and dendrochronological statistics of the study sites (A and B indicate two different age classes). Mean diameter at breast height (DBH), mean width (MW), Gleichläufigkeit (Glk – Schweingruber 1988), mean sensitivity (MS) and first-order serial autocorrelation (AC1), computed for the raw tree ring series; AC1, mean inter-serial correlation (r.bt) and expressed population signal (EPS), computed for the indexed tree-ring series.

Stands characteristics

Pinewood	Time span (N° years)	Tree density (n ha^{-1})	Mean DBH (cm)	Basal area (m² ha^{-1})
Castel Fusano A	1843 – 2000 (158)	70	60.3	20
Castel Fusano B	1945 – 2009 (65)	226	41.7	30.8
Castelporziano A	1899 – 2009 (111)	99	69.8	37.9
Castelporziano B	1957 – 2009 (53)	92	53.5	20.7

Dendrochronological statistics

	N° cores/ N° trees	MW ± sd (mm)	Glk	AC1	MS	AC1	r.bt	EPS
Castel Fusano A	18/10	2.77 ± 2.62	0.68	0.89	0.242	0.13	0.55	0.90
Castel Fusano B	79/45	2.19 ± 1.86	0.72	0.78	0.239	0.17	0.62	0.99
Castelporziano A	45/27	2.15 ± 2.65	0.76	0.84	0.228	0.05	0.77	0.98
Castelporziano B	55/30	3.28 ± 2.19	0.81	0.63	0.352	0.17	0.80	0.99

- 0.74 and 0.19 - 0.24, respectively. Table 2). The RE and CE values were positive and high in ABD. The series reconstructed by ABD and the multiple year climatic drivers, based on precipitation accumulated over 3 years, adequately reproduced the variability of the instrumental records. Although the reconstructed series based on the scaling approach showed a better matching with the measured ones, weakly significant differences in the variances between measured and reconstructed climatic series were found (Fig. 3) as shown by the Barlett and Fligner-Killeen tests of homogeneity of variances (Table 2).

The analysis of decadal to multidecadal fluctuations in the reconstruction of multiple year drivers identified the main upward and downward trends. This showed that a long-term increase in precipitation occurred during the second half of the nineteenth century between 1866 and 1902 (τ = 0.38 and 0.59 with P<0.001 for CRU and reconstructed data,

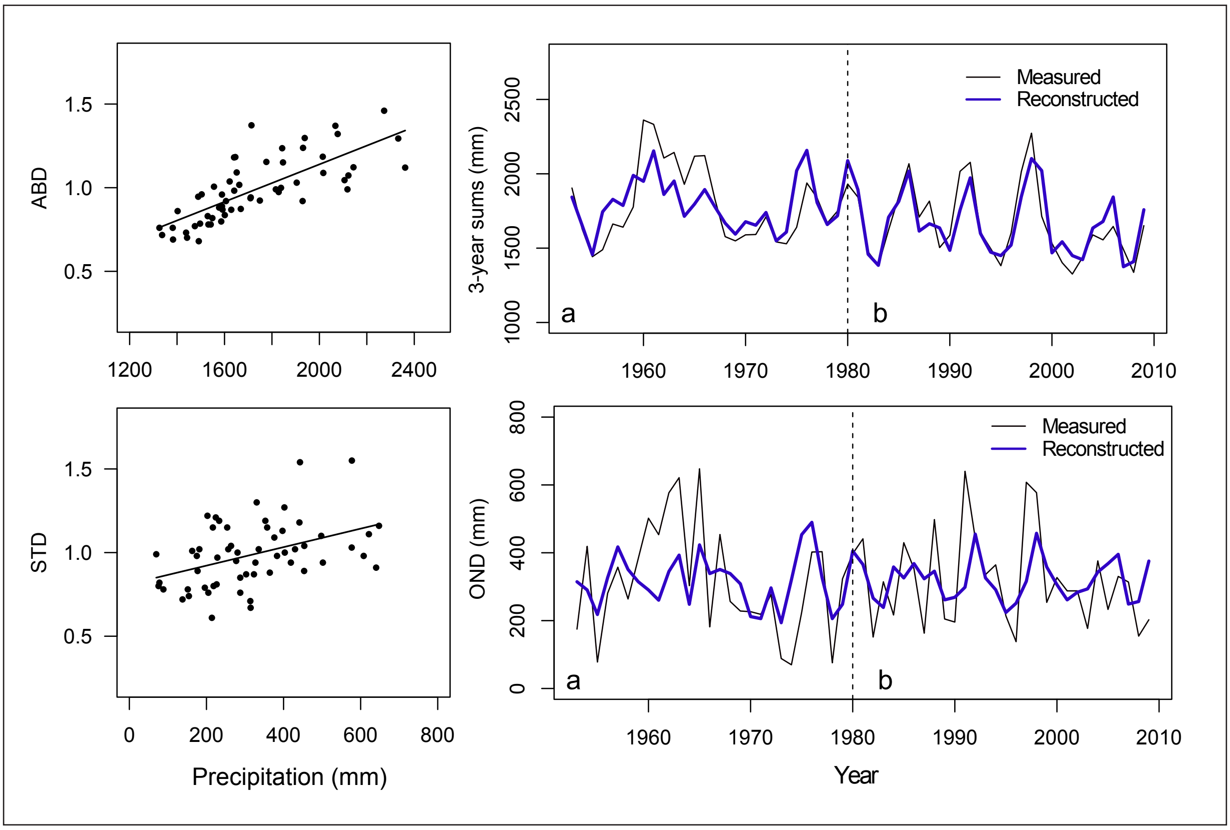

Figure 2 - Linear model between the best precipitation predictors and standard chronologies (ABD and STD) and measured versus reconstructed time series according to the best predictors for calibration and verification periods (long time-scale signal based on 3-year precipitation sums and short time-scale signal based on OND precipitation, respectively). The main reconstruction statistics are reported in Table 2.

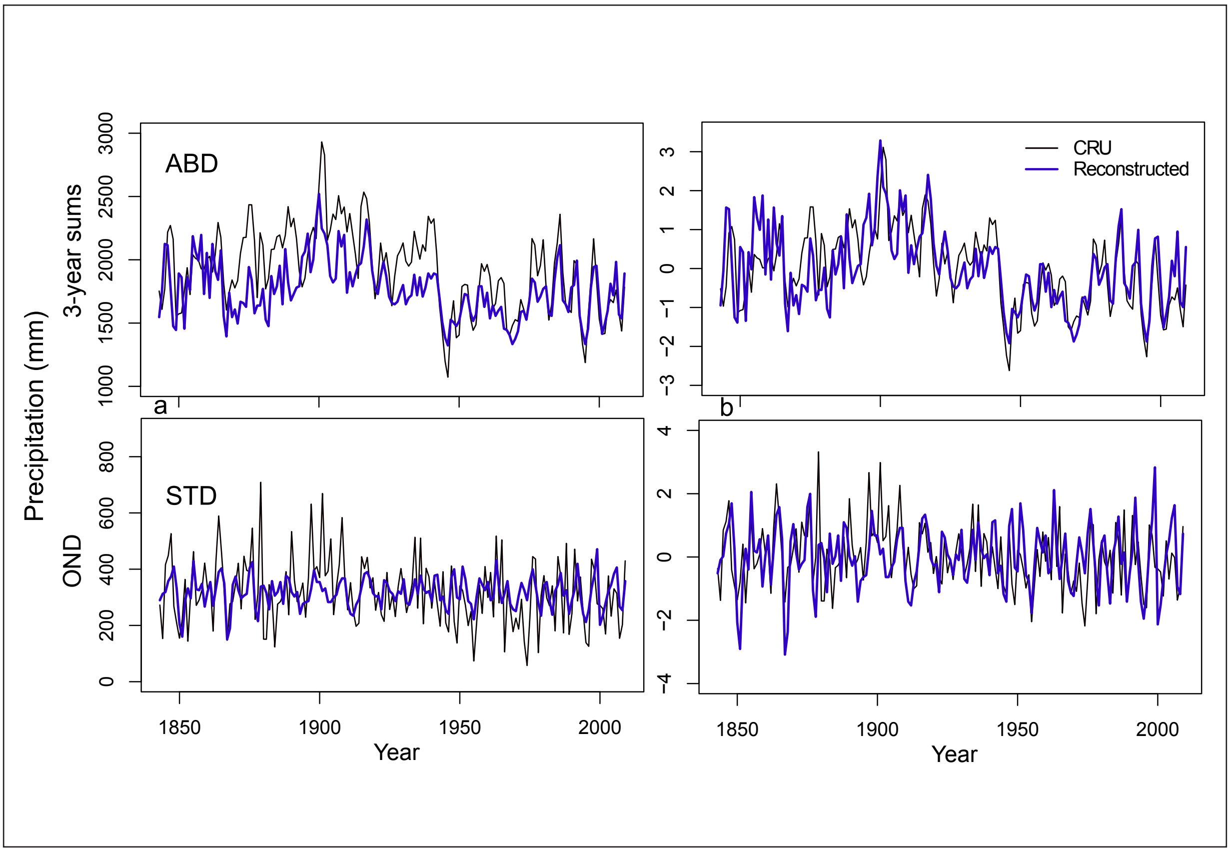

Figure 3 - Precipitation reconstruction according to the best predictors for both ABD and STD chronologies and CRU long dataset in mm (a) and z-scores produced with the scaling approach (b). Climatic predictors as in Fig. 2.

respectively). On the other hand, a significant precipitation decrease at multi-decadal scale during the first half of the twentieth century has been found between 1901 and 1946 (τ = -0.38 and -0.44 with P<0.001 for CRU and reconstructed data, respectively).

By setting the best multiple year precipitation drivers at the annual scale and applying a simple percentile threshold approach where the 95th and 5th percentile represent very rainy and very dry years (~1000 mm and 630 mm, respectively), we observed an increase in dry events and total absence of very wet periods during the twentieth century (Fig. 4a). Moreover, all reconstructed series have underestimated and overestimated both the wet and dry thresholds, and in particular the reconstructed precipitation based on the STD chronology (Fig. 4b). On the other hand, the best accuracy in reconstructing the wet and dry thresholds was obtained with the ABD method.

Table 2.- Reconstruction statistics computed over the inverted subperiods of calibration and verification and based on regression models between STD chronology and short time-scale signal (OND precipitation) and ABD chronology and long time-scale signal (3-year precipitation sums). RE stands for reduction of error; CE stands for coefficient of efficiency. Homogeneity of variances between measured and reconstructed climatic series was tested by applying Barlett (B) and Fligner-Killeen (F-K) tests.

		Cal: 1953-1980 – Ver: 1981-2009				**Cal: 1981-2009 – Ver: 1953-1980**			
		R^2cal	R^2ver	CE	RE	R^2cal	R^2ver	CE	RE
ABD	mm	0.48	0.74	0.60	0.70	0.74	0.48	0.60	0.70
	z-scores			0.54	0.66			0.54	0.66
STD	mm	0.19	0.24	0.05	0.05	0.24	0.19	0.17	0.17
	z-scores			-0.15	-0.15			-0.15	-0.15
		Full period (Weather Stations)				**Full period (CRU)**			
		Time span	R^2adj	B test	F-K test	Time span	R^2adj	B test	F-K test
ABD	mm	1953/	0.56***	4.4*	2.3	1843/	0.58***	2.1	4.6*
STD	mm	2009	0.16*	36.8***	26.1***	2009	0.18***	92.2***	62.3***

*significant at $p < 0.05$; ***significant at $p < 0.001$.

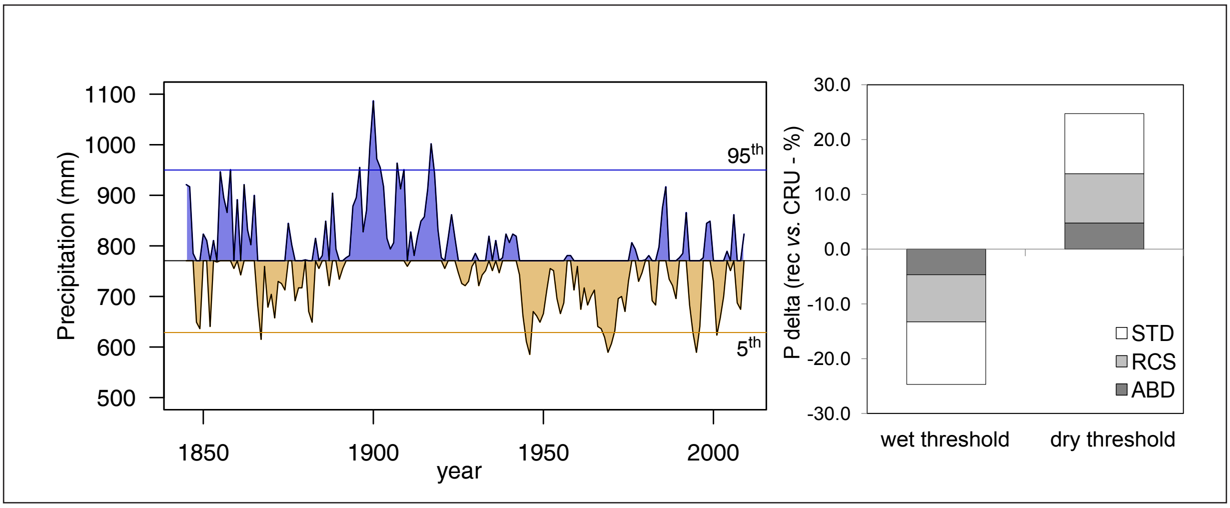

Figure 4 - Total annual precipitation reconstruction using ABD method obtained by setting the best multiple year precipitation drivers at annual scale. 95th and 5th percentile-based thresholds for the extremely wet and dry years (left). Percentage differences for wet and dry thresholds between reconstructed and CRU series (right).

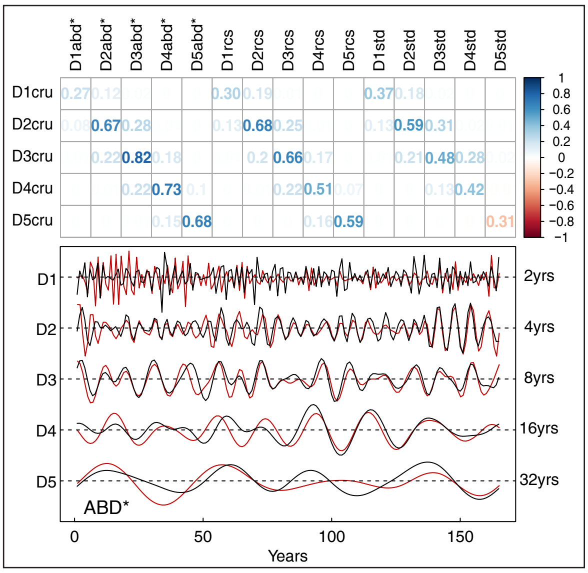

Figure 5 - Correlation coefficients between CRU and reconstructed time series of precipitation decomposed from 2 to 25 years via multi-resolution analysis (wavelet detail D1, D2, D3, D4 and D5). Only significant coefficients between ABD-RCS and long time-scale signal based on 3-year precipitation sums and STD and short time-scale signal based on OND precipitation are shown (top). Graphical matching between reconstructed (ABD) and CRU series at each wavelet detail (bottom).

Spectral analysis

Wavelets correlation coefficients between reconstructed and estimated (CRU) precipitation values are higher when the reconstruction is based on the ABD and RCS methods and the multiple year climatic drivers (Fig. 5). The highest correlation coefficients were obtained with ABD reconstructed series at wavelet details D_3 and D_4 (r = 0.82 and 0.73 with P < 0.001, respectively).

Wavelet coherence analysis allowed to identify phase and cross spectral relationships between reconstructed and estimated (CRU) precipitation time series. When methods preserving low-frequency variability were applied for long-term climate reconstruction, larger regions with significant interrelation were found (represented by warmer colours – red, Fig 6). Reconstruction based on ABD further emphasized an in-phase relationship throughout the twentieth century from 1920 to 1950 and during the last decades of the 20th century at 4-8 years decadal time pass (Fig. 6). After the year 1950, an in-phase relationship appeared also at multi-decadal frequency although it occurs towards the end of the time period covered by the chronologies. On the other hand, STD produced colder colours (blue) than ABD and anti-phase relationships, which indicate the presence of weaker connection between the series.

Discussion

In the Mediterranean basin, precipitation is one of the main factors that limit tree growth and is likely to be a target variable for the reconstruction of climate of the Mediterranean area (Luterbacher et al. 2006). The decrease in precipitation along the Mid-Tyrrhenian coast of Italy during the last century was found to be related with the decline in growth of *P. pinea* (Mazza and Manetti 2013). Moreover, time-scale based climate-growth relationships would suggest the importance of precipitation cumulated over several months (i.e., previous autumn-winter) and even over consecutive years for tree growth in Mediterranean sites at low elevation, as found in previous studies (Campelo et al. 2006; Sarris et al. 2007; Raddi et al. 2009; Mazza et al. 2014. The water needed for tree growth is not only stratified in the top soil layer and deeper moisture pools supplied by multiple years of rainfall are also used by deeper roots, which are typical of mature pine trees in the Mediterranean. The capacity to use water from

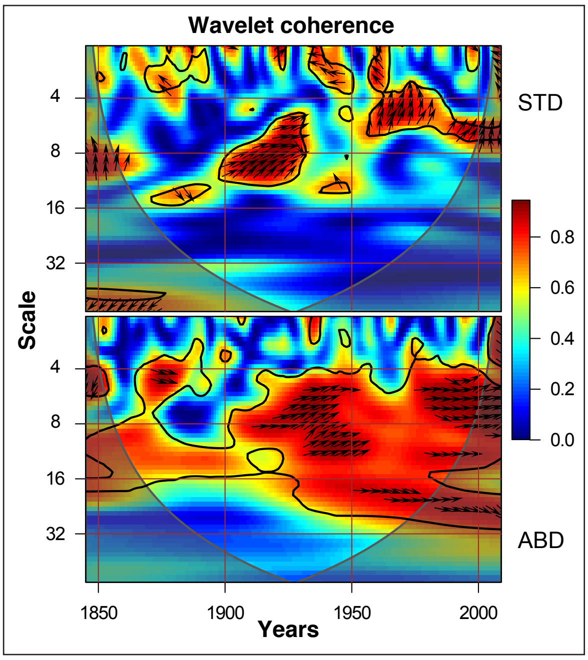

Figure 6 - Squared wavelets coherence between reconstructed (ABD, STD) and CRU series. Black lines show contours of areas 5 % significance level against red noise. The hatched line designates the cone of influence (COI); in areas outside of the COI, edge effects might distort the results and should not be interpreted. Arrows pointing to the right (left) show phase (anti-phase) behaviour between the two time series. Climatic predictors as in Fig. 5

deeper soil horizons helps the pines avoid the very strong competition exerted by the Mediterranean shrubs, which are characterised by a dense and shallow root system near the soil surface.

Most studies on tree-rings based on precipitation or drought reconstruction aim to extract signals from these proxy data that may be associated to time scales used in climatology (or hydrology). Normally, this reference time scale has a monthly resolution as this is the main time scale of instrumental meteorological records. Reconstructed climate variables from tree rings have been produced at monthly or seasonal time scales in most previous studies. This has been done by applying either the classical standardization method (Touchan et al. 2010; Zhang et al. 2011; Tejedor et al. 2016; Martin-Benito et al. 2016) or other detrending techniques to evaluate long-term climatic trends using ABD and RCS (Wilson et al. 2005; Esper et al. 2007; Nicault et al. 2008).

To our knowledge, this study is the first to provide a climate reconstruction based on long-term climatic drivers to reproduce precipitation accumulated during consecutive years as a result of the potential response of trees to climate variability at multi-year time scales (Sarris et al. 2011; Mazza and Manetti 2013; Dorman et al. 2015; Peltier et al. 2017). In tracking the low-frequency trends and climate variation, the comparison between reconstructed series and instrumental records showed a better performance of ABD and RCS compared to STD chronologies, and again of ABD in reproducing its high frequency variability (Fig.1). Analysis of decadal to long-term fluctuations in the precipitation reconstruction (i.e. ABD method) indicated similar patterns and trends compared to the instrumental estimated records (CRU, long dataset). Both CRU and the reconstructed climatic series showed a significant reduction in the mean annual precipitation at a multi-decadal scale (50 years) during the second half of the twentieth century when compared with its first half or with the second half of the previous century, 1850–1900 (~ 16 % and 20 % with $P<0.001$, respectively).

The detrending method that we applied also influenced the ability of the reconstruction in detecting wet and dry thresholds. The results showed the underestimation of the wet threshold by -4.7% for ABD, -8.6% for RCS and -11.4% for STD. The overestimation of the dry threshold produced by the reconstructed series was 4.8% for ABD, 9.0% for RCS and 11.0% for STD. Moreover, the matching between CRU precipitation and the reconstructed rainfall series in terms of extremes selected according the 95th and 5th percentile increased from 17% for STD to 38% for RCS and even to 63% for ABD. Similar results were produced by applying the 90th and 10th percentile.

We identified the wettest and driest climatic events through the 95th and 5th percentile threshold analysis. Individual years of extremely high precipitation in the reconstruction are the years 1875, 1889, 1900, 1901, 1902, 1915, 1916, and 1917. On the other hand, the driest years occurred during the second half of the twentieth century, in particular for 1945-46, for the periods 1967-1971 and 1994-95 and for 2001.

Although precipitation seems to be the primary driver for tree growth under Mediterranean climatic conditions (Macias et al. 2006; Andreu et al. 2007; De Luis et al. 2009; Sarris et al. 2011; Mazza and Manetti 2013), tree-ring based late summer temperature has also been reconstructed from central and southern Italy (Lionelli et al. 2017). In the Mediterranean area, high temperatures are often associated with low precipitation and drought especially during summer; this leads to an increase in tree transpiration rates and soil water evaporation (Vieira et al. 2009). Thus, the significant increase in temperature during the less rainy years may impose an overall growth limitation caused by water stress that can be recorded by tree rings, especially in areas where water availability is the most important limiting factor for tree growth (Sarris et al. 2011).

In our study, the most significant summer temperature signals were detected using the ABD chronology and seemed to be related to slow changes in climate compared to the typical high-frequency temperature signals detected using the classical standardization methods. Indeed, by applying the wavelets analysis the highest correlation coefficients between summer temperature (especially in June-July) and tree-ring widths were obtained at wavelets detail D_4 with ABD and RCS chronologies, although they were not highly significant (r = -0.51 with P < 0.001 and -0.27 with P < 0.01, respectively).

Conclusion

The Mediterranean area is highly sensitive to climate change as it represents a transition zone between the humid western and central European domain and the arid North African desert belt. Precipitation in this region exhibits high variability on monthly, inter-annual, and inter-decadal time scales. Our reconstruction underpins that since ca. 1850 the Tyrrhenian coast of central Italy has experienced the driest conditions in terms of 2-3 year rainfall sums during the last 50 years of the 20th century. This finding may be used to identify the long-term natural variability of the region in relation to climate change as it is expected to affect the Mediterranean region.

The possibility of obtaining a climatic reconstruction that goes beyond monthly or seasonal scales from tree ring data of species such as *Pinus pinea*, which shows the ability of utilizing moisture from deep moisture pools, leads us to consider tree rings as an ideal proxy. Thus, knowing the main climatic parameters that drive tree growth can play a key role in reconstructing past climatic records. Moreover, the methodology applied is particularly important to provide the most adequate detrending method in reconstructing long-term climate variability.

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