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Combining wood anatomy and stable isotope variations in a 600-year multi-parameter climate reconstruction from Corsican black pine

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ABSTRACT

We present a new multi-parameter dataset from Corsican black pine growing on the island of Corsica in the Western Mediterranean basin covering the period AD 1410–2008. Wood parameters measured include tree-ring width, latewood width, earlywood width, cell lumen area, cell width, cell wall thickness, modelled wood density, as well as stable carbon and oxygen isotopes. We evaluated the relationships between different parameters and determined the value of the dataset for climate reconstructions. Correlation analyses revealed that carbon isotope ratios are influenced by cell parameters determining cell size, whereas oxygen isotope ratios are influenced by cell parameters determining the amount of transportable water in the xylem. A summer (June to August) precipitation reconstruction dating back to AD 1185 was established based on tree-ring width. No long-term trends or pronounced periods with extreme high/low precipitation are recorded in our reconstruction, indicating relatively stable moisture conditions over the entire time period. By comparing the precipitation reconstruction with a summer temperature reconstruction derived from the carbon isotope chronologies, we identified summers with extreme climate conditions, i.e. warm-dry, warm-wet, cold-dry and cold-wet. Extreme climate conditions during summer months were found to influence cell parameter characteristics. Cold-wet summers promote the production of broad latewood composed of wide and thin-walled tracheids, while warm-wet summers promote the production of latewood with small thick-walled cells. The presented dataset emphasizes the potential of multi-parameter wood analysis from one tree species over long time scales.

1. Introduction

Beside high mountain areas, Mediterranean ecosystems belong to the most vulnerable ecosystems to current climate change (e.g. Navarra and Tubiana, 2013). The projected climate change for the Mediterranean area is challenging for ecosystems in two ways: (i) Drier and hotter summers will prolong and intensify drought periods, while (ii) lower precipitation sums during winter months will lead to soil water deficit already at the beginning of the vegetation period (Gao and Giorgi, 2008). For a precise evaluation of current climate change and the adaptation potential of different ecosystems, knowledge about past climate changes is crucial. Several terrestrial and marine archives, e.g. tree rings, lake sediments, ice cores, and corals, are used as proxies for past climate and environmental conditions (e.g. Mann, 2002; Luterbacher et al., 2012). Trees belong to the best archives for Holocene palaeoclimate research due to their worldwide distribution, high resolution (annual or even higher) and temporal coverage. Since trees are mostly susceptible to environmental conditions during their growing season, tree-ring based climate reconstructions mostly cover the summer season (Mann, 2002).

A great variety of parameters can be measured from tree-rings, including tree-ring width, maximum latewood density, several wood anatomical parameters as well as stable isotope ratios. Beside tree-ring width, latewood and earlywood width are often measured separately in order to gain climatic information for different seasons or individual months. Maximum latewood density can either be measured directly via X-ray densitometry (Polge, 1963) or can be determined indirectly via modelling (Decoux et al., 2004). Stable isotope ratios (mainly carbon and oxygen isotopes) and wood anatomical characteristics like cell size and cell number

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are measured to obtain environmental information (e.g. Edwards et al., 2008; Kress et al., 2010; Bale et al., 2011; DeSoto et al., 2011; Olano et al., 2012). Some of these parameters may be interrelated and show similar high- or low-frequency behaviour in their long-term variability (e.g. Gagen et al., 2006); others may be characterized by individual frequency distributions (e.g. García-González and Fonti, 2006). The combination of several tree-ring parameters can be useful in palaeoclimate research in order to strengthen the climate signal, to extend the reconstructed season or to reconstruct different climatic variables (McCarroll et al., 2003, 2011; Gagen et al., 2006; Kirdyanov et al., 2008).

Pilot studies of tree-ring based multi-parameter reconstruction approaches were conducted in the boreal forests of the high northern latitudes and in the southern French Alps, where summer temperature plays the most important factor constraining metabolic processes in trees (McCarroll et al., 2003, 2011; Gagen et al., 2006). In the Mediterranean region, a first multi-parameter study was conducted in the Pyrenean mountains (Esper et al., 2010), finding clear evidence of more than one forcing factor influencing long-term variability of $\delta^{13}C$, $\delta^{18}O$, MXD and TRW.

Long-term tree-ring based climate reconstructions for the last millennia are rather sparse for the Western Mediterranean (Esper et al., 2007; Büntgen et al., 2008; Szymczak et al., 2012b) while several long-term reconstructions exist for the Eastern Mediterranean basin (e.g. Griggs et al., 2007; Touchan et al., 2007; Popa and Kern, 2009; Heinrich et al., 2013) or larger regions like western and southern Europe (e.g. Serre-Bachet, 1994). Climate evolution in both parts of the basin is rather different (e.g. Roberts et al., 2012) underlining the necessity of reliable climate reconstructions for both parts of the basin in order to obtain a higher spatial resolution.

The mountainous island of Corsica in the Western Mediterranean basin offers a great potential for palaeoclimate studies (Szymczak et al., 2012a,b). With Corsican black pine (*Pinus nigra* subsp. *laricio*) Corsica hosts a long-living tree species with some individuals reaching ages up to 800 years which are among the oldest in the Mediterranean basin. However, high resolution proxy data records from Corsica for the last millennia are missing except for our summer temperature reconstruction derived from carbon isotope chronologies (Szymczak et al., 2012b). The closest record with the highest resolution for this period is a $\delta^{18}O$ record derived from a speleothem growing in Grotta Verde cave, Sardinia (Antonioli et al., 2003). Other palaeoclimate studies on or close to Corsica focused on longer time scales, e.g. pollen data from Lac de Creno (Reille et al., 1999), deep sea sediment cores from the Tyrrhenian Sea (Luterbacher et al., 2012) and glacial deposits like glacier moraines dating from the last glacial maximum (Kuhlemann et al., 2005).

The aim of the study is to test the potential of different tree-ring parameters derived from Corsican black pine for climate reconstructions. We developed at least 600-year long chronologies with annual resolution from a variety of tree-ring parameters (including tree-ring width, latewood width, earlywood width, cell lumen area, cell wall thickness, modelled wood density, as well as stable carbon and oxygen isotopes) from trees growing at high elevation sites in the mountains of Corsica in order to address the following research questions: (1) what are the relationships between different wood parameters; (2) what is the climatic forcing on these wood parameters; and (3) which wood parameters are suitable for being combined in a multi-parameter climate reconstruction?

2. Material and methods

2.1. Study site

The island of Corsica in the Western Mediterranean basin is characterized by a rugged topography with the main mountain range running from North to South (Fig. 1), with summits reaching up to 2706 m asl (Kuhlemann et al., 2005). The coastal Mediterranean climate is characterized by dry warm summers during May to September and temperate humid winters during October to April. With increasing altitude temperature decreases with a lapse rate of ca 0.57 °C/100 m and precipitation increases up to 1400 mm/a at 1000 m asl (Météo-France, 2010). Above 1500 m asl altitude, a continuous snow cover between December and April is common (Bruno et al., 2001). The dominating tree species in the mountains is Corsican black pine (*P. nigra* subsp. *laricio*) which forms a forest belt between 1000 and 1800 m asl and often builds the upper treeline (Gamisans, 1999). Corsican black pine is a long-living species with some individuals on Corsica being up to 1000 years old, making it a very suitable species for dendroclimatological studies (Szymczak et al., 2012b).

2.2. Development of chronologies from different tree-ring parameters

A large sample pool of *P. nigra* cores including 15 study sites in the Corsican high mountains was collected during several field campaigns with a standard increment borer (Fig. 1; Table 1). Tree-ring width, earlywood and latewood width were measured with a LINTB II measuring system (Rinntech, Heidelberg, Germany) to the nearest 0.01 mm. The cores were carefully dated and crossdated based on visual inspection (Stokes and Smiley, 1968) and statistical tests (sign test, *t*-test) performed with TSAP software (Rinn, 2003). To remove age-related growth trends, each raw measurement was detrended (by division) using a cubic smoothing spline which equals a frequency response of 50% at a wavelength of 32 years (Cook and Peters, 1981). Autoregressive modelling was applied prior to averaging of the detrended series. A biweight robust mean was used to calculate the chronology. A regional master tree-ring width chronology (TRW) for the main island was established including 524 samples from all 15 sites covering the time period AD 1077–2009 (Table 2). Earlywood (EWW) and latewood (LWW) width were separated by the colour difference between bright earlywood and dark latewood and measured separately for 255 samples. All three tree-ring chronologies (TRW, EWW, LWW) were constructed using a conservative detrending with a cubic spline with a length of 2/3 of individual sample length and a biweight robust mean after prewhitening the individual series.

Significant changes of cell size and cell wall thickness can be measured with the help of image analysis systems (e.g. De Micco et al., 2012). Cell size can be determined by measuring radial cell width and cell lumen area, cell wall thickness can be determined by radial cell wall thickness or maximum latewood density (e.g. Decoux et al., 2004; Rathgeber et al., 2006). Wood anatomical features on a cellular scale were measured in latewood from 18 trees (one core per tree) from four different sites. Earlywood cell dimensions were not measured due to limitations of the wood surface preparation method (Hetzer et al., 2014). For the wood anatomical analysis, trees of different age class were used in order to detect possible age-trends in cell parameters. After surface preparation, wood anatomical dimensions including cell lumen area (CLA), radial cell width (RCW) and radial cell wall thickness (CWT)were measured directly from the wood surface using imaging analysing tools from the software WinCell Pro 2010 (Regent Instruments Inc., Canada). Latewood density (MLD) was modelled applying a mechanistic model and a rectangular estimate of the cell size,an elliptical shape of the cell lumen, and a value of 1.530 kg/m^3 for the density of cell wall material (Stamm, 1929) as input parameters (Hetzer et al., 2014). Cell data were standardized with a modified tracheidogram method (Vaganov, 1990) into 10 equally spaced sections within latewood. Running median curves of the