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A 560 yr summer temperature reconstruction for the Western Mediterranean basin based on stable carbon isotopes from *Pinus nigra* ssp. *laricio* (Corsica/France)

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Abstract

The Mediterranean is considered as an area which will be affected strongly by current climate change. However, temperature records for the past centuries which can contribute to a better understanding of future climate changes are still sparse for this region. We established a network of multi-century stable carbon isotope chronologies on Corsica to study long-term climate variation in the Western Mediterranean Basin. The chronologies show strong correlations with summer temperature and precipitation as well as summer cloud coverage. A summer temperature reconstruction (AD 1448–2008) reveals that the Little Ice Age was characterized by low, but not extremely low temperatures on Corsica. Relatively warm temperatures during the Maunder minimum may indicate a decoupling from climate cooling registered in northern latitudes. A comparison of the summer temperature reconstruction with a summer cloud coverage reconstruction indicates warm summers with reduced cloudiness during the periods AD 1480–1520 and 1950–2008 and cool and cloudy summers during AD 1580–1620 and 1820–1890. The distinct features of the reconstruction underline the uniqueness of the Corsican climate and highlight the necessity of a better temporal and spatial resolution of climate reconstructions for a more robust estimation of current climate change on a local scale.

1 Introduction

Mediterranean ecosystems are among the most sensitive ecosystems to current climate change (IPCC, 2007). Located in the transitional zone between the west wind drift and the subtropical high pressure belt, the Mediterranean basin already suffers from severe drought during summer months (Touchan et al., 2008). The expected strong temperature increase and precipitation decrease may intensify drought stress and lead to a northward extension of dry and arid land (IPCC, 2007; Gao and Giorgi, 2008).

An evaluation of current climate change and adaptation potential of different ecosystems is only possible with solid knowledge about past climate changes and related ecosystem responses. Available instrumental climate records are too short to detect long-term climate trends and to examine the full range of multicentennial climate variability (Hulme and Jones, 1994). Climate proxies such as tree rings, corals, and ice cores, are important archives to reconstruct climate changes back in time. Trees are one of the most important natural archives for recent and Holocene environmental conditions because they are widespread, sensitive to their environment, and provide a continous record with precise age control and annual resolution. Tree-ring width chronologies from the Mediterranean have been used to reconstruct temperature (Büntgen et al., 2008; Guiot et al., 1988; Popa and Kern, 2009; Serre-Bachet and Guiot, 1987; Serre-Bachet, 1994), precipitation (Akkemik and Aras, 2005; Akkemik et al., 2005; D'Arrigo and Cullen, 2001; Griggs et al., 2007; Till and Guiot, 1990; Touchan et al., 1999, 2003, 2005a, b, 2007), drought (Chbouki et al., 1995; Nicault et al., 2008) as well as variations of the NAO-Index (Glueck and Stockton, 2001) and the scPDSI-Index (Brewer et al., 2007; Esper et al., 2007).

Beside ring width, stable carbon isotopes in tree-ring cellulose also contain information about past climate variability and seem to be less influenced by non-climatic factors than tree-ring width (e.g. Danis et al., 2006; Gagen et al., 2007; Kress et al., 2010). The carbon isotope ratio of tree-ring cellulose is determined by fractionation processes during photosynthesis which in turn depend on the ratio of intercellular leaf to atmospheric CO_2 concentration (Farquhar et al., 1982) and the $\delta^{13}C$ value of atmospheric CO_2. Since the rate of photosynthesis strongly depends on climate conditions, $\delta^{13}C$ ratios of tree-ring cellulose often show high correlations with climate parameters and can be used to reconstruct temperature (Edwards et al., 2008; Etien et al., 2008; Gagen et al., 2007; Hilasvuori et al., 2009; Lipp et al., 1991; Masson-Delmotte et al., 2005; Treydte et al., 2009; Young et al., 2010), precipitation (Bale et al., 2011; Sho et al., 2009), water stress (Masson-Delmotte et al., 2005) or drought conditions (Kress et al., 2010). However, in comparison to tree-ring width studies, published long-term isotope records spanning more than 300 yr are relatively rare due to the generally high effort of constructing isotope chronologies.

We present four annually resolved long-term carbon isotope records (between 400 and 800 yr) derived from pine trees (*Pinus nigra* ssp. *laricio*) growing at high-elevation sites on the island of Corsica in the Western Mediterranean. Our objectives are to (i) extract regional signals and detect local differences between the established isotope records, (ii) evaluate the climate-isotope relationship and (iii) present a summer temperature reconstruction for the Western Mediterranean.

2 Study site

Corsica, an island located in the Western Mediterranean basin between 41–43° N and 8–10° E, is characterized by a steep relief with rugged mountain ranges and deep valleys. The climate of Corsica is influenced by its location in the subtropical Mediterranean and the mountain topography, resulting in dry warm summers (May to September) and temperate wet winters (October to April). Mean annual precipitation along the coast ranges from 105 mm a^{-1} to 814 mm a^{-1} and mean monthly temperature is around 15 °C (Météo-France, 2010). In general, temperature decreases (approximately 0.57 °C 100 m^{-1}) and precipitation increases (up to 1400 mm a^{-1} at 1000 m a.s.l.) with altitude. While temperature is strongly determined by altitude, precipitation shows a more complex spatial pattern with the northeastern part of the mountains being somewhat drier than the southern and western coastal mountain ranges. In higher elevations, snow is the main precipitation type in winter. Hence, a continuous snow layer is found from December to April in altitudes above 1500 m a.s.l.

Corscian pine (*Pinus nigra* ssp. *laricio*) is the dominating tree species in the mountains of Corsica and forms a forest belt between 1000 and 1800 m a.s.l. (Kuhlemann et al., 2009). Several individuals reach ages of more than 800 yr, which are among the oldest living trees found in the Mediterranean. We sampled *Pinus nigra* trees at 4 ecologically different upper tree line sites (Fig. 1, Table 1). The site Asco (1500 m a.s.l.)

is located on a blocky terminal moraine in the headwaters of an east-west striking valley north of Monte Cinto (2706 m a.s.l.). The site Ballone (1650 m a.s.l.) situated in a secondary valley of the dry Niolo high valley is characterized by a warm and dry local climate with more pronounced drought stress than at Asco. Trees sampled in Ballone grow on a steep slope with sparse vegetation cover. The upper tree line at site Capannelle (1700 m a.s.l.), located on the south-east exposed slopes of Monte Renoso (2352 m a.s.l.), is dominated by *Pinus nigra* and *Fagus sylvatica* (European beech). Since air masses from the east coast can reach the site nearly unhampered, fog occurs frequently and local climate is relatively cold and wet. The site Asinao (1350 m a.s.l.) is located in the northeast-southwest striking Asinao valley south of Monte Incudine (2136 m a.s.l.), the highest massif in southern Corsica. Sampled trees grow on a talus slope consisting of granite blocks with low water-holding capacity.

3 Materials and methods

We cored 5–6 trees per site since isotope values from *Pinus nigra* measured on individual trees show a comparably high variability, and thus a smaller sample number proved insufficient to represent the environmental conditions at a specific site (Szymczak et al., 2012). Mean ages of sampled trees range from 700 (Asco) to 390 yr (Capannelle; Table 1). After dating and crossdating the ring-width series of the collected tree cores with the program TSAP (Rinn, 2008), one core per tree was selected for isotope analysis based on the criteria no missing rings, distinct and straight tree-ring borders and high inter-annual conformity of tree-ring width curves to avoid tree-specific disturbances. Tree rings were separated with a scalpel and contemporaneous material from 5–6 trees per site was pooled prior to cellulose extraction. Pooling of several trees reduces the number of samples to be analysed remarkably and pooled samples from *Pinus nigra* correspond well to chronologies based on mean values calculated from analyses of individual trees (Szymczak et al., 2012). Cellulose extraction was shown to be an important prerequisite for the development of isotope series from *Pinus nigra*

(Szymczak et al., 2011). A detailed description of the extraction method for α-cellulose is given in Szymczak et al. (2012).

For carbon isotope analyses, subsamples from each year were weighed into tin capsules (0.4–0.7 mg). Carbon isotopes ratios were determined using a CE 1110 elemental analyser coupled online to a ThermoFisher Delta Plus mass spectrometer. Isotopic compositions are reported in permil using the conventional δ notation relative to VPDB-standard (Vienna Pee Dee Belemnite). Reproducibility (1 std. dev.) based on replicate analyses of standards IAEA-CH3 and USGS40 was $< \pm 0.1$ ‰.

Correlations between carbon isotope values and mean monthly precipitation, temperature and cloud coverage were calculated with the program DENDROCLIM 2002 (Biondi and Waikul, 2004). Since climate records from the island of Corsica cover only 50 yr for some coastal stations, we used a climate data set for Italy provided by the Tyndall Centre for Climate Change Research (Mitchell et al., 2002). This climate data set gives averages for temperature and precipitation (1901–2000) as well as cloud coverage (1943–2000) based on all Italian climate stations. The representativeness of this climate data set for Corsica is underlined by high correlations (e.g. correlation coefficients between August–September temperature and precipitation from Italy and Corsican climate stations are 0.8 and 0.6, respectively). Correlations of tree ring carbon isotope records with temperature and precipitation were calculated only for the time period 1951–2000 because the number of climate stations covering the early 50 yr is considerably lower. Correlations were calculated over an 18-months period from previous year May to October of the current year, thus including 2 vegetation periods (May–October) and one vegetation break. Correlations were calculated for each site as well as for a mean chronology of all four sites. We decided to use the mean chronology instead of a median chronology or a chronology consisting of the first principal component of a PCA-analysis because all chronologies are very similar indicated by strong correlations (0.96–0.99) and an identical climate response.

The application of carbon isotope chronologies as reliable climate proxy is hampered since the concentration and isotopic composition of atmospheric CO_2 was not constant over time due to fossil fuel burning. Changes in $\delta^{13}C_{atm}$ are recorded by a remarkable downward trend in $\delta^{13}C$ of tree-ring cellulose over the last approximately 150 yr. The raw $\delta^{13}C$ values of tree-ring cellulose are routinely corrected to a pre-industrial atmospheric $\delta^{13}C$ value by adding published annual values for $\delta^{13}C$ of atmospheric CO_2, as demonstrated by McCarroll and Loader (2004). A downward trend often remains after correcting for changes in the atmospheric CO_2-concentration (Treydte et al., 2001; Waterhouse et al., 2004; Gagen et al., 2007; Loader et al., 2007) which is attributed to plants' ability to adapt their metabolism to higher atmospheric CO_2 levels. Feng and Epstein (1995) and Kürschner (1996) provided correction factors for this plantphysiological response. The correction factors were estimated as 0.02 ‰ ppm^{-1} CO_2 (Feng and Epstein, 1995) and 0.0073 ‰ ppm^{-1} CO_2, respectively (Kürschner, 1996) and represent the upper and lower range of published potential discrimination values (Treydte et al., 2009). McCarroll et al. (2009) developed an alternative correction approach, the so-called "pin-correction", which calculates specific values for each individual tree by removing the low-frequency pattern from the $\delta^{13}C$ record using non-linear loess regression. The choice of the appropriate correction model is particularly critical for climate reconstructions because climate data are in most cases only available for the last 50 to 100 yr. Thus, the years most affected by the anthropogenic increase in atmospheric pCO_2 are used for calibration and verification of the climate-isotope relationship (McCarroll et al., 2009; Treydte et al., 2009). To test the influence of the correction model on the climate-isotope relationship, we calculated correlations for carbon isotope chronologies corrected for changes in atmospheric CO_2 concentration and the discrimination factors given by (i) Kürschner (1996) ($C_{Kü}$), and (ii) Feng and Epstein (1995) (C_{FE}). We did not apply the "pin-correction" of McCarroll et al. (2009) since this method is only suitable for isotope chronologies derived from individual trees and not for pooled chronologies.

The carbon isotope chronology from Asinao proved suitable for a summer temperature reconstruction, and the mean of all four sites for a summer cloud coverage reconstruction. The climate reconstruction was based on a linear regression model calculated with the software R (http://www.r-project.org). We used a split calibration-verification scheme and standard statistical parameters including the reduction of error (RE), coefficient of efficiency (CE), sign test (ST) and Pearson's correlation coefficient (r) to test the reliability of the reconstructions (Cook and Kairiukstis, 1990). The climate data set was split in two equal time periods used for calibration and verification and vice versa. Any positive value for RE- and CE-statistics indicates that the reconstruction is trustful (Cook and Kairiukstis, 1990; Fritts, 1976).

4 Results

4.1 Carbon isotope chronologies

Carbon isotope chronologies from the northern study sites show generally less negative values than chronologies form the southern sites (Fig. 1, Table 1). The raw values of all sites are characterized by a strong nonrecurring downward trend during the most recent years, making a correction procedure necessary. A downward trend even remains after correction for changes in atmospheric CO_2-concentration, indicating that also a correction for plantphysiological responses is required. The highest correlations can be observed between the two southern study sites for $C_{Kü}$-chronologies and between the two northern study sites for C_{FE}-chronologies (Table 2). Correlations are in general higher for C_{FE}- than for $C_{Kü}$-chronologies because of the strong common increase in $\delta^{13}C$ in the most recent years. Asco shows the weakest correlations with the other sites. Ballone is strongly correlated with Asco as well as with the southern sites. Most important, the high similarity of the carbon isotope chronologies from the different sites implies a common forcing on carbon isotope discrimination.

4.2 Climate isotope relationship

Carbon isotope chronologies show significant positive correlations with temperature during the vegetation period, namely in August and September (Fig. 2). Correlations are higher for the seasonal mean values including several months during the vegetation period, especially for July/August/September (JAS) and August/September (AS). In general, correlations with climate are remarkably higher for C_{FE}-chronologies. The sites Ballone and Asinao are more sensitive to summer temperature than Asco and Capannelle as indicated by higher correlations, e.g. for Asinao with August temperature ($r = 0.73$; $p < 0.05$).

In contrast to the temperature-isotope relationship, correlations with precipitation are less influenced by the correction factor for plantpyhysiological response (Fig. 2). All sites expect Asco show strong negative correlations with August and June/July/August (JJA) precipitation, with the highest correlations observed for Asinao and Ballone. A weaker but significant correlation (Asinao, Ballone and mean of all 4 sites) occurs with February precipitation. Correlations with precipitation and temperature are of similar magnitude.

The mean carbon isotope chronology of all four sites shows high correlations with both, August temperature and precipitation, but also with temperature and precipitation during several months of the vegetation period. Highest correlations with temperature occur in the later months (JAS and AS), while correlations with precipitation are highest in the months MJJA and JJA. The correlations with temperature are higher for the C_{FE}-chronology while the correlations with precipitation are similar using both correction models. The high correlations with climate variables of the mean chronology indicate that all sites are influenced by the same driving force which underlines the representativeness of the isotope chronologies for Corsica.

The correlations of summer temperature and precipitation indicate that both factors influence carbon isotope fractionation in tree rings of *Pinus nigra*. To account for a combination of both climate factors we calculated correlations with cloud coverage data from Italy (Fig. 2). Carbon isotope chronologies from all sites except Capannelle show significant negative correlations with cloud coverage in August and September as well as with a combination of several months during the vegetation period. Correlations are in general higher for C_{FE} – than for $C_{Kü}$ – chronologies and at Ballone and Asinao than at Asco. The highest correlation (−0.69) is observed for the mean of all 4 sites and MJJA cloud coverage and will thus be used for cloud coverage reconstruction.

4.3 Temperature reconstruction

The strongest correlation is observed between August–September temperature and the carbon isotope chronology from Asinao allowing a temperature reconstruction. We tested the influence of the correction factors on the resulting temperature reconstruction for correction factors ranging from 0.007 to 0.02 ‰ ppm^{-1} CO_2 (Table 3). A reliable reconstruction can only be derived from a carbon isotope chronology corrected with a factor of at least 0.012 ‰ ppm^{-1} CO_2. CE- and RE-values as well as correlation coefficients with climate are highest for chronologies corrected with a factor of 0.02 ‰ ppm^{-1} CO_2, i.e. the correction factor proposed by Feng and Epstein (1995). According to the Durbin-Watson statistics, a correction factor of 0.015 ‰ ppm^{-1} CO_2 is most suitable.

The statistical parameters indicate that carbon isotope chronologies corrected with a factor of 0.013 ‰ ppm^{-1} CO_2 or higher are suitable for a reliable temperature reconstruction. The mean difference for each year between the reconstructions calculated from differently corrected carbon isotope chronologies (factors 0.013–0.02 ‰ ppm^{-1} CO_2) is 0.5 °C, with a largest difference of 0.8 °C in AD 1497 (Fig. 3). The standard deviation, i.e. the calibration error, of each reconstruction is ±0.9 °C and hence larger than the error derived from the differently corrected carbon isotope series. Reconstructions based on differently corrected carbon isotope chronologies therefore fall within the uncertainty range of the other possible reconstructions. Thus, the different correction factors have only little influence on the values of the resulting reconstruction.

In the following, we present a temperature reconstruction derived from the C_{FE}-chronology from site Asinao. The reconstruction is based on linear regression and verified with a split verification-calibration scheme. High RE- and CE-values indicate high synchronicity between the 3 temperature reconstructions and underline the validity of the reconstruction (Fig. 4). The temperature reconstruction contains a strong low freuqency signal. In contrast, high frequency variability is reduced in single years, i.e. AD 1972 or 1996. This can be explained by the fact that temperature is not the only parameter influencing carbon istotope discrimination and that the reconstruction can only explain 48 % of the variability.

The temperature reconstruction covers the time period AD 1448–2008 (Fig. 5). Pooled chronologies consist of 5 or 6 trees, however, the age of individual trees is rather different so that not all parts of the chronologies have the same sample depth. Especially the oldest interval is often based on only 2 or 3 trees. At site Asinao, only the time period AD 1590–2008 is covered by 6 trees, and sample depth decreases to only 2 trees for AD 1448–1573. As a consequence, high temperatures and high variability reconstructed for the oldest years should be interpreted with caution.

Temperatures were relatively high with maximum temperatures comparable to today at around AD 1500 (highest reconstructed temperature in AD 1497). Temperatures decreased, with a short interruption around AD 1575, to lowest values at AD 1580–1620. The coolest temperature is recorded in the year AD 1617. Afterwards, temperatures increased again to a maximum at AD 1700–1720, followed by a longer period with low temperatures and almost no high frequency fluctuations during AD 1720–1900. The modern temperature increase commenced at approximately AD 1900, interrupted by two cooler phases (AD 1937 and 1970th). The strongest temperature increase is observed after AD 1980.

4.4 Cloud coverage reconstruction

The cloud coverage reconstruction mirrors well the high and low frequency variability in the instrumental data (Fig. 4). The validity of the reconstruction is supported by high

RE- and CE-values and little influence of the used calibration period on the resulting reconstruction. The reconstruction is limited to the time period 1448–2008, i.e. the time period covered by 3 of the 4 sites (Fig. 5). Phases with low cloud coverage occurred in AD 1480–1520, AD 1630–1680 and since AD 1950. The lowest cloud coverage is reconstructed for the most recent years with the lowest value in AD 2004. Periods with high cloud coverage occured around AD 1450–1485, AD 1580–1620, AD 1820–1890 with the highest coverage reconstructed for AD 1617.

A comparison between temperature and cloud coverage reconstruction reveals that the reconstructions show mostly antidromic behaviour, supported by a strong negative correlation ($r = -0.66$). This is not surprising since cloud coverage and temperature are not independent variables (correlation between cloud coverage and temperature $r = -0.61$). The most pronounced phases are visible in both reonstructions with opposed values. The periods AD 1480–1520 and AD 1980–2008 are characterized by high temperatures and little cloudiness. In contrast, the periods AD 1580–1620 and AD 1820–1890 were cool and cloudy (Fig. 5).

5 Discussion and conclusions

5.1 Carbon isotopes in tree-ring cellulose as climate proxy

Increasing atmospheric CO_2 concentration affects leaf internal discrimination against ^{13}C and must be considered when interpreting $\delta^{13}C$ values of tree-ring cellulose. As noted by several authors, a correction for the increase in atmospheric pCO_2 seems to be insufficient (Feng and Epstein, 1995; Gagen et al., 2007; Treydte et al., 2001, 2009; McCarroll et al., 2009) and should be combined with a correction for plant physiological responses to higher CO_2 levels. However, this correction is not well constrained. Published discrimination values were mainly derived from short-term experiments because the growth response of mature trees is difficult to assess due to their long life cycle. Thus, it is questionable whether these correction factors can easily be transferred to a long-term response of living trees. As a result from metabolic acclimation and age-related stand dynamics, CO_2-effects decline over time (Hättenschwiler et al., 1997). Elevated CO_2 may stimulate tree growth, however, the effect is species dependent (Dawes et al., 2011) and tree growth seems to be carbon-saturated already under present environmental conditions (Körner, 2006). Using wood from different species of old grown trees (among these several *Pinus*-species) in dry mountain environments, Feng and Epstein (1995) performed the only existing study that investigated long-term isotopic trends for the calculation of a discrimination factor. Since their trees were growing in rather similar environments than the Corsican pine trees investigated in this study, we used the FE correction factor which results in the highest correlations between corrected carbon isotope ratios and climate parameters. However, it should be kept in mind that there is a risk of selecting inappropriate carbon isotope correction factors by "tuning" them to the climate factor desired to be reconstructed, in this case summer temperature which shows an increasing trend during the past decades. Indeed, the reconstructed climate signal is influenced by the correction factors applied although in our study only the strength of the correlation is affected. The main signal remains constant, i.e. strongest correlations are always observed in the same months independent of the applied correction factor.

The FE correction factor is at the upper limit of published discrimination values and the strong physiological response to increased CO_2 contradicts the findings of Dawes et al. (2011) reporting that *Pinus uncinata* is less sensitive to increased CO_2 than *Larix decidua*. This different response can be attributed to differences in temperature sensitivity. At the upper tree line in the Alps and on Corsica, temperature is the most important parameter limiting tree growth, although in a different way. In the Alps, temperature determines the length of the vegetation period. Rising temperatures therefore prolong the vegetation period and stimulate tree growth. On Corsica, high temperatures limit tree growth as consequence of pronounced drought stress during the vegetation period. Due to low summer precipitation, trees are forced to reduce their photosynthetic activity in order to reduce water loss. Lower temperatures in combination with higher precipitation are therefore stimulating tree growth on Corsica. These findings underline the importance of site and species-specific correction factors for the physiological response to increased $p\mathrm{CO}_2$.

The highest similarities in the correlations between the corrected carbon isotope ratios and climate parameters are observed between Ballone in the northern part and Asinao in the southern part of Corsica. This suggests that there is no latitudinal dependency in the factors influencing carbon isotope discrimination. Instead, local site conditions are more important. Ballone and Asinao are the driest and most extreme study sites where trees grow either on a steep slope or on a blocky talus slope, both sites characterized by low water holding capacity. Trees at Capannelle and Asco grow at less steep slopes composed of more fine-grained material and a higher water holding capacity. In addition, site Capannelle is wetter than the other sites since it is not sheltered against clouds moving inland from the coast. Although the drier sites Ballone and Asinao react more sensitive to changes in temperature and precipitation, all sites show similar correlations with climate factors, with significant correlations occurring in the same months. This finding underlines the importance of a common driving force for isotope discrimination at all sites.

We observe higher correlations with temperature than with precipitation which is ascribed partly to the used climate dataset. Since temperature is more homogenous in space than precipitation, the temperature data from Italy are more representative for temperatures on Corsica than the precipitation data. The precipitation signal of the Corsican mountains is captured only partly in the Italian dataset, as indicated by the weaker correlations. However, the general consistency of the correlation patterns supports the validity of the Italian dataset for Corsican tree-ring data.

5.2 Summer temperature reconstruction

The presented 560 yr long temperature reconstruction for Corsica documents rapid temperature changes with temperatures remarkably lower but also at a comparable high level as modern temperatures (Fig. 5). The longevity of *Pinus nigra* ssp. *laricio* proves the adaptation potential of this tree species to different climates. *Pinus nigra* is a pioneer tree species with a wide ecological amplitude and perfectly adapted to Mediterranean mountain areas because it can withstand strong insolation, hot summers and drought stress during the vegetation period (Richardson, 1998). However, *Pinus nigra* needs sunny conditions and suffers from competition with *Fagus sylvatica* and *Abies alba* in the mountains (Kuhlemann et al., 2009) and with *Pinus pinaster* in lowland areas. Currently, *Pinus nigra* is the dominant tree species of Corsican forests but *Pinus pinaster* is better adapted to forest fires (Pimont et al., 2011). In a future drier climate with increasing fire frequency, *Pinus nigra* populations may therefore decrease in Corsican forests.

A comparison of the summer temperature reconstruction for Corsica with temperature reconstructions for the Alps (Büntgen et al., 2006) and the Pyrenees (Büntgen et al., 2008) reveals that all reconstructions report a strong temperature increase since approximately AD 1980 (Fig. 6). The Corsican temperature reconstruction shows higher similarities with the Alps than with the Pyrenees, with a remarkable cold phase (AD 1580–1620) evident in both records. However, the Corsica reconstruction does not mirror the alpine temperature minimum around AD 1820. At around AD 1500 and AD 1710, both reconstructions show diverging behaviour with high temperatures observed on Corsica and low temperatures in the Alps. Little similarities are found between the temperature reconstructions for Corsica and the Pyrenees, especially in the oldest part (AD 1448–1720). Both reconstructions run antidromic at around AD 1500. During AD 1720–2008, the simlarities between both reconstructed temperature records are higher, especially concerning the temperature increase after AD 1980. The warm period on Corsica during AD 1690–1740 is neither reflected by the Alps nor the Pyrenees, but is observed in a temperature reconstruction for the Carpathians (Popa and Kern, 2009). Popa and Kern (2009) suggested that the Carpathians were decoupled from the large scale cooling during the Maunder minimum, a period characterized by cool wet summers in Europe. On a hemispheric scale, the Maunder minimum was not a pronounced cold period (Landsberg, 1980) and possibly the climate of the

Mediterranean was decoupled from the European climate north of the Alps. This hypothesis is supported by Camuffo (1987) who reported that freezing of the Venetian Lagoon was very uncommon during the Maunder minimum.

Large volcanic eruptions are one of the major natural drivers for climate cooling by adding large amounts of aerosols and ash particles to the atmosphere (Briffa et al., 1998; D'Arrigo and Jacoby, 1999). Thus, volcanic eruptions are often followed by cool summers. Periods with enhanced volcanic activity occurred approximately AD 1560–1700, AD 1800–1820 and around AD 1900, as reflected by low values in the Corsican temperature reconstruction. A comparison with the freezing events of the Venetian lagoon (Camuffo, 1987) reveals that most of these years were characterized by low temperatures in Corsica, however, freezing occured also in some years with high temperatures. This might be explained by the fact that the reconstruction reflects summer temperatures while the freezing occured during winter.

In comparison to other temperature reconstructions it is notable that the last cold phase of the Little Ice Age (LIA) around AD 1850 is not prominent in the Corsican temperature reconstruction. The LIA on Corsica is characterized by relatively low, but not extremely low temperatures. This is attributed to the location of the studied sites. While temperature reconstructions for the Alps, the Pyrenees or the Carpathian Mountains were compiled from trees growing in large mountain ranges surrounded by extensive landmasses, the mountain range of Corsica is relatively small and surrounded by the Mediterranean Sea. Thus, the more maritime climate will be characterized by dampened temperature extremes. As a consequence, the climate of Corsica during the LIA was milder than in other mountain ranges characterized by a more continental climate. Another factor for less pronounced cooling on Corsica might be the small extension of glaciers on Corsica, although knowledge about the glaciation history of Corsica is still incomplete (Conchon, 1978, 1986; Kuhlemann et al., 2005; Reille et al., 1997). Large landmasses facilitate growth of extensive icefields with glaciers further accelerating cooling of mountain areas. Climate during the LIA was characterized by dry-cold winters in the Alps and cool-wet winters in the Mediterranean (Luterbacher et al., 2004; Pauling et al., 2006). Higher precipitation amounts allow a better refill of water reservoirs and hence less pronounced drought stress during the vegetation period with a positive influence on tree growth. The comparison of the temperature reconstruction with the summer cloud coverage reconstruction reveals that cool summers were accompanied by high cloud coverage and warm summers by little cloud coverage (Fig. 5). This is most obvious in the periods AD 1480–1520, 1950–2008 (both warm and little cloud coverage), 1580–1620 and 1820–1890 (both cool and high cloud coverage). Cool wet summers during the LIA were favourable for *Pinus nigra* on Corsica and can explain the lower sensitivity to colder temperatures compared to trees growing in the Alps or the Pyrenees. Discrepancies between the reconstructions from the Alps, Pyrenees and Corsica can further result from the studied proxies. Maximum latewood density used for the temperature reconstructions in the Alps and Pyrenees, is highly dependent on temperature while the carbon isotope series from *Pinus nigra* are influenced by both temperature and precipitation. Carbon isotope chronologies can therefore carry a mixed climate signal with e.g. humiditiy being more important than temperature in specific years.

The presented temperature reconstruction indicates that Corsican climate was different from the climate history in other European mountain regions, underlining the uniqueness of this mountainous Mediterranean island. However, large scale changes, as low temperatures during the LIA and recent warming are recorded, indicating the connection to large scale circulation dynamics. The climate regime of the Mediterranean is rather complex and is strongly influenced by the position of the polar front and the intertropical convergence zone (ITC). A southerly position of the polar front during the Last Glacial Maximum allowed Arctic airmasses to invade into the western Mediterranean more frequently and persistently than today (Kuhlemann et al., 2008), while a northward movement of the intertropical convergence zone entrains more subtropical airmasses to enter the Mediterranean basin. During the LIA, the position of the ITC has been further south in the Pacific region, whereas a northward shift can be observed during recent time (Sachs et al., 2009). These large scale circulation dynamics determine climate evolution on Corsica. A furhter northward shift of the ITC may have a serious impact on tree growth in Corsican mountains with a prolongation of drought periods during summer months. Palaeoclimate reconstructions based on tree-ring parameters can help to better understand the adaptation potential of different tree species to past and predicted future climate changes. The spatial and temporal resolution of existing future climate scenarios is still limited due to sparse coverage with longer instrumental climate data or climate proxies in the Mediterranean. Thus, this first multicentury temperature reconstruction from Corsica contributes to the understanding of past climate changes on a local scale.

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Table 1. Parameters of the study sites and carbon isotope chronologies. As: Asco, Ba: Ballone, Ca: Capannelle, Ai: Asinao, mean $\delta^{13}C_{Kü}$ (‰VPDB): mean value of carbon isotope chronology corrected with the correction factor from Kürschner (1996), mean $\delta^{13}C_{FE}$ (‰VPDB): mean value of carbon isotope chronology corrected with the correction factor from Feng and Epstein (1995).

	altitude (m a.s.l.)	latitude, longitude	no of trees	time period	mean tree age (in 2012)	mean $\delta^{13}C_{Kü}$ (‰VPDB)	mean $\delta^{13}C_{FE}$ (‰VPDB)
As	1500	42.24° N, 8.56° E	6	1185–2008	700	−20.66	−20.58
Ba	1650	42.21° N, 8.54° E	6	1404–2008	502	−21.17	−21.05
Ca	1700	42.05° N, 9.09° E	5	1582–2010	390	−21.51	−21.35
Ai	1350	41.50° N, 9.12° E	6	1448–2009	479	−21.66	−21.54

Table 2. Pearsons correlation coefficients between chronologies corrected with correction factors from Kürschner (1996; Kü-corrected) and Feng and Epstein (1995; FE-corrected).

Kü-corrected	Ballone	Capannelle	Asinao
Asco	0.33	0.25	0.29
Ballone		0.40	0.28
Capannelle			0.44
FE-corrected	**Ballone**	**Capannelle**	**Asinao**
Asco	0.49	0.34	0.44
Ballone		0.48	0.43
Capannelle			0.47

Table 3. Statistical parameters of temperature reconstructions derived from carbon isotope chronologies from site Asinao corrected with different correction factors. r: Pearsons correlation coefficient between carbon isotopes and Augsut/September temperature, DWS: Durbin-Watson statistics, CE: coefficient of efficiency, RE: reduction of error. The numbers 1 and 2 refers to different calibration periods, 1951–1975 (1) and 1976–2000 (2).

correction factor	r	DWS	CE1	CE2	RE1	RE2
0.007	0.56	1.4282	0.11	−0.49	0.32	0.43
0.008	0.57	1.4890	0.15	−0.35	0.33	0.44
0.009	0.59	1.5386	0.19	−0.24	0.33	0.45
0.010	0.51	1.5892	0.23	−0.12	0.33	0.46
0.011	0.62	1.6353	0.27	−0.03	0.33	0.46
0.012	0.63	1.5771	0.31	0.06	0.34	0.46
0.013	0.64	1.6891	0.34	0.12	0.34	0.47
0.014	0.65	1.7096	0.37	0.19	0.34	0.47
0.015	0.66	1.7194	0.39	0.23	0.34	0.47
0.016	0.67	1.7139	0.42	0.27	0.34	0.48
0.017	0.67	1.7050	0.43	0.30	0.34	0.48
0.018	0.68	1.6808	0.45	0.32	0.34	0.48
0.019	0.68	1.6553	0.46	0.33	0.34	0.48
0.020	0.68	1.6156	0.47	0.33	0.34	0.49

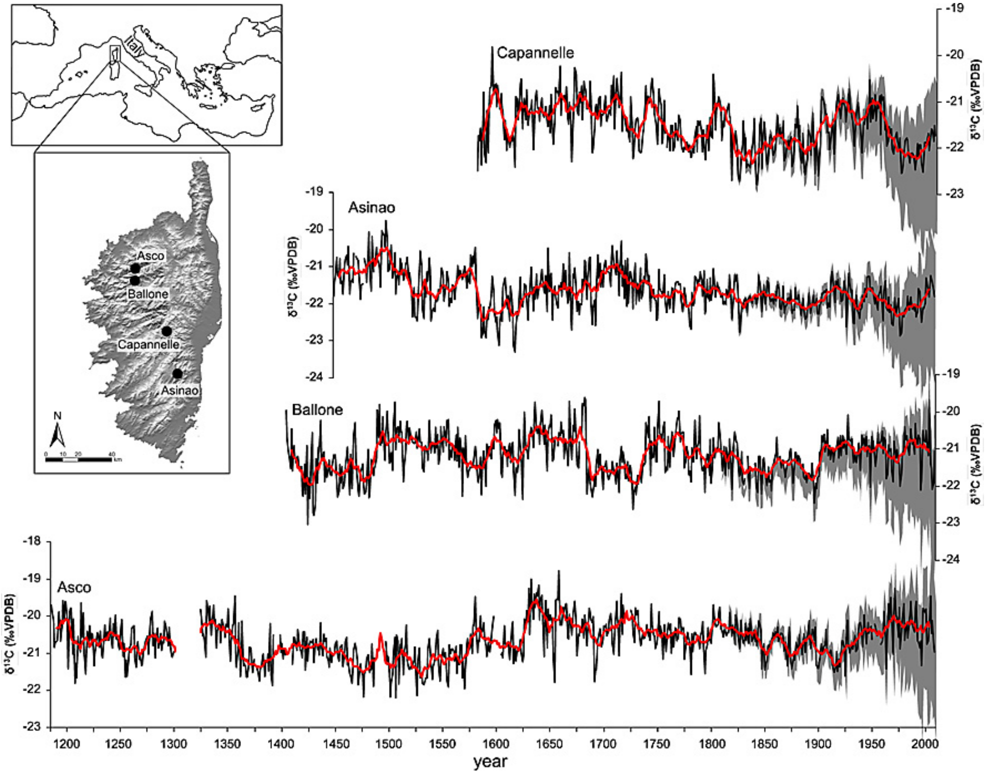

Fig. 1. Annually resolved carbon isotope chronologies for four mountain sites on Corsica. Isotope chronologies were corrected for changes in atmospheric CO_2 concentration using the correction factor provided by Kürschner (1996). Grey shaded area illustrate the range of isotope values corrected with different correction factors. Lower limit: raw uncorrected values, upper limit: corrected with the correction factor from Feng and Epstein (1995). Studied locations are marked on the map (left), small map shows the location of Corsica in the Mediterranean basin.

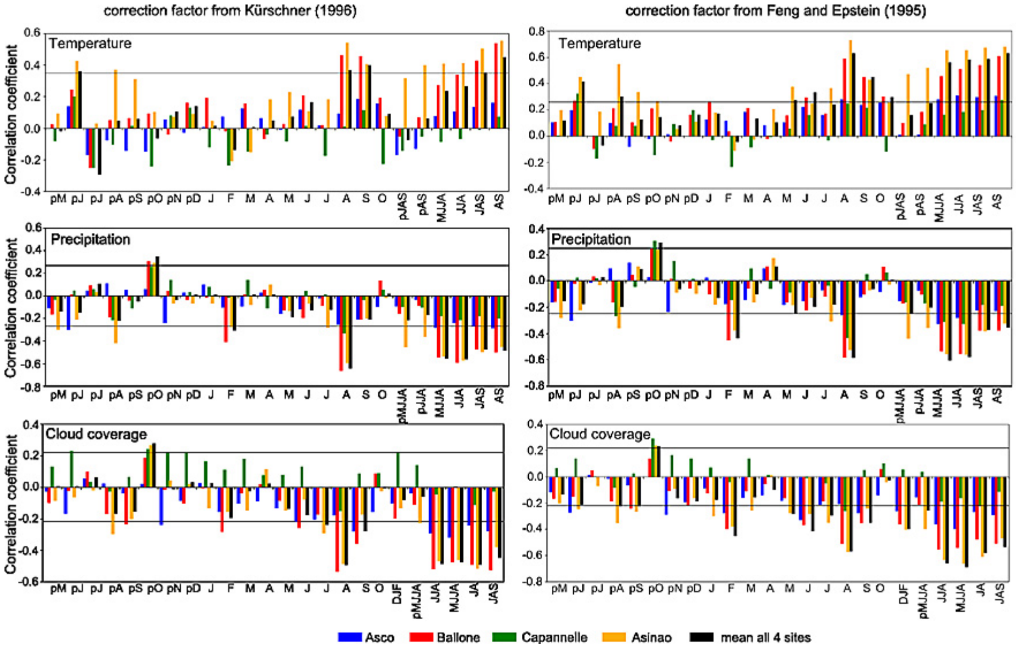

Fig. 2. Pearsons correlation coefficients for corrected carbon isotope chronologies and mean monthly temperature, mean precipitation and cloud coverage for the time period 1951–2000 (temperature and precipitation) and 1943–2000 (cloud coverage) plotted for an 18-months period from previous May (pM) to October of the current year. The vegetation period lasts from May to October. Black horizontal lines represent the significance level ($p < 0.05$).

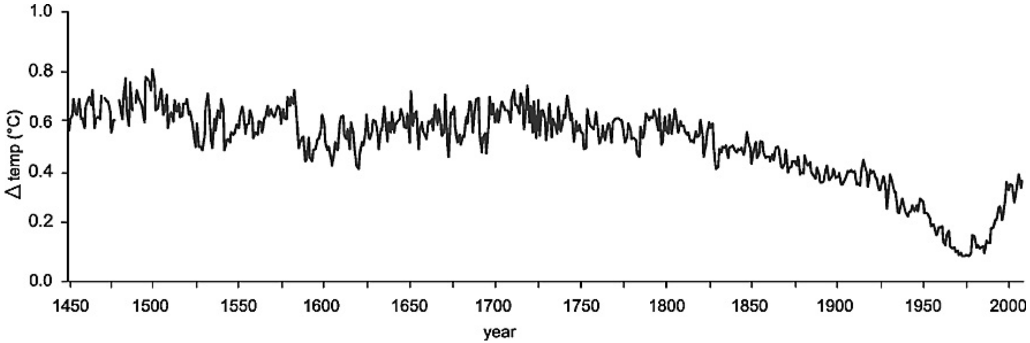

Fig. 3. Maximum difference between temperature reconstructions (Δ temp) derived from differently corrected carbon isotope chronologies from site Asinao. Carbon isotope chronologies were corrected with factors ranging from 0.007 to 0.02 ‰ ppm^{-1} CO_2.

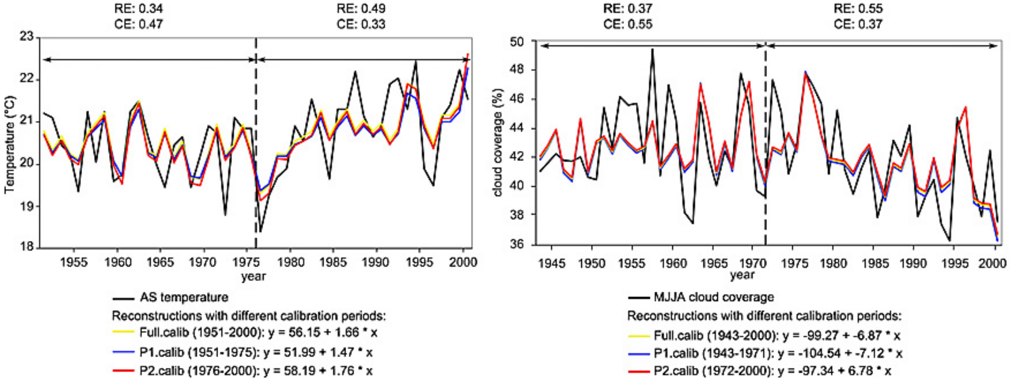

Fig. 4. Split calibration-verification scheme of temperature (left) and cloud coverage (right) reconstructions. The climate data set is divided in two equal time periods P1 and P2 for calibration and verification, respectively. RE: reduction of error; CE: coefficient of efficiency.

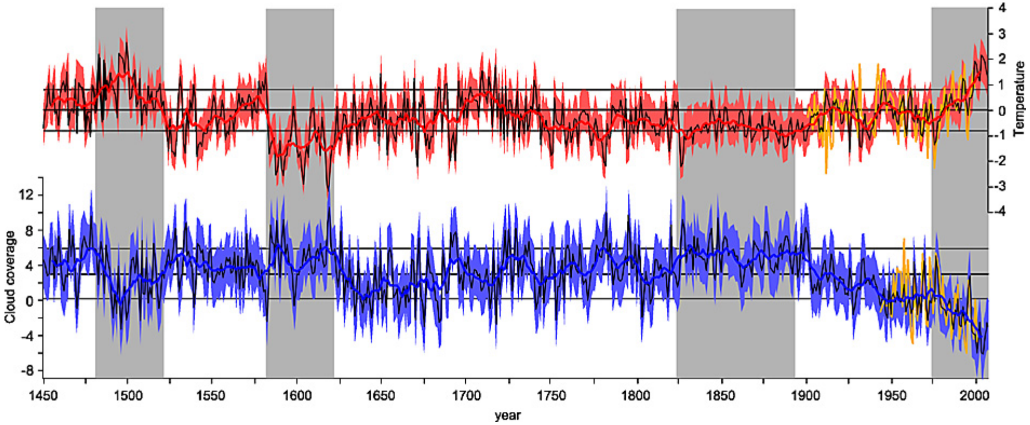

Fig. 5. Reconstructed August/September temperature (above) and MJJA cloud coverage (below) derived from the carbon isotope chrononlogy of site Asinao (temperature) and the mean of all 4 sites (cloud coverage) presented as deviation from the mean AD 1961–1990. The smoothed line represents an 11-yr running mean, the red and blue shaded areas around the chronologies illustrate the calibration errors (±1 standard deviation). Orange lines show the instrumental record, horizontal lines indicate the mean and ±1 standard deviations. Grey columns mark periods of antidromic behaviour between both reconstructions.

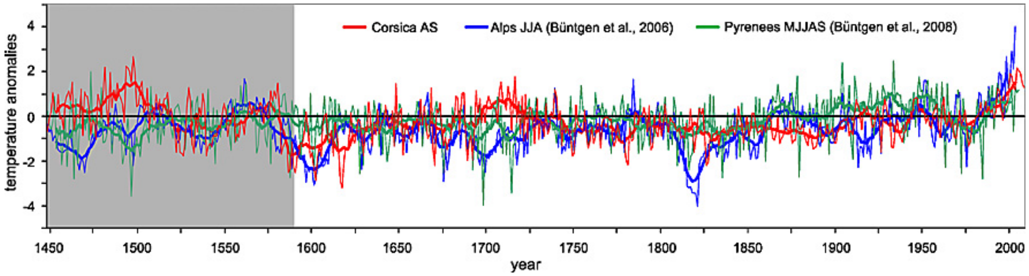

Fig. 6. Comparsion of the August/September temperature reconstruction from Corsica with summer temperature reconstructions from the Alps (Büntgen et al., 2006) and Pyrenees (Büntgen et al., 2008) (data available from NOAA Paleoclimatology Program: http://www.ncdc.noaa.gov/paleo/recons.html). Temperatures are expressed as anomalies. Reconstructions for the Alps and the Pyrenees are based on maximum latewood density series from *Larix decidua* and *Pinus uncinata*. Grey shaded area marks the part of the Corsican reconstruction where the pooled isotope chronology is based on less than 6 trees.