A 520 year record of summer sunshine for the eastern European Alps based on stable carbon isotopes in larch tree rings.

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Key points

- The first summer sunshine reconstruction for the European Alps

Abstract

A 520-year stable carbon isotope chronology from tree ring cellulose in high altitude larch trees (*Larix decidua* Mill.), from the eastern European Alps, correlates more strongly with summer temperature than with summer sunshine hours. However, when instrumental records of temperature and sunshine diverge after AD 1980, the tree ring time series does not follow warming summer temperatures but more closely tracks summer sunshine trends. When the tree ring stable carbon isotope record is used to reconstruct summer temperature the reconstruction is not robust. Reconstructed temperatures prior to the 20th century are higher than regional instrumental records, and the evolution of temperature conflicts with other regional temperature reconstructions. It is concluded that sunshine is the dominant control on carbon isotope fractionation in these trees, via the influence of photosynthetic rate on the internal partial pressure of CO_2, and that high summer (July-August) sunshine hours is a suitable target for climate reconstruction. We thus present the first reconstruction of summer sunshine for the eastern Alps and compare it with the regional temperature evolution.

Key words

Carbon isotopes; dendrochronology; climate change; cloud cover

1. Introduction

The ring widths of larch (*Larix decidua* Mill) trees growing high in the eastern European Alps tend to be sensitive to the temperature of June, and to a lesser extent July (Hafner et al. 2011). Stable carbon isotope ratios measured on cellulose from the same tree rings correlate with the temperature of July and August. In a pilot study Hafner et al. (2011) suggested that combining these two proxies might provide a strong record of past changes in temperature for the entire summer season, June to August. However, recent work in northern Fennoscandia has raised concerns about using stable carbon isotopes in tree rings to reconstruct temperature, even when correlation and verification with local temperature data is very strong (Young et al. 2010; Gagen et al. 2011).

The ratio of ^{13}C to ^{12}C in wood cellulose, expressed relative to a standard using the delta notation ($\delta^{13}C$), is strongly linked to the concentration of carbon dioxide inside the (leaves or) needles averaged over the growing season (McCarroll and Loader 2004). Air (containing carbon dioxide) enters the needles via the stomata and the carbon dioxide is enzymatically fixed during photosynthesis to produce carbohydrates, which are used to supply all of the needs of the growing tree, including the formation of wood cells. The main controls on the carbon isotope ratio of the resulting photosynthates are the relative rates at which CO_2 enters (stomatal conductance) and is removed (photosynthetic rate) from the internal leaf spaces. In dry environments stomatal conductance dominates the $\delta^{13}C$ signal, recording changes in air humidity and soil moisture availability, linked to antecedent precipitation. In cool, high altitude or high latitude settings, where moisture stress is less common, the dominant signal in $\delta^{13}C$ is likely to be the rate of photosynthesis. Photosynthetic rate is linked to temperature, via the rate of production of the photosynthetic enzyme, but more commonly the limiting factor is the supply of energy in the form of photon flux, or sunlight (Beerling 1994) which drives the photosynthetic reation. The $\delta^{13}C$ of tree rings measured at sites that do not

75   experience frequent moisture stress is theoretically controlled more strongly by sunlight than

76   by temperature.

77   Although sunlight is, in theory, the strongest control on carbon isotope fractionation under

78   cool moist conditions, in practice $\delta^{13}C$, in the recent calibration period, often correlates most

79   strongly with summer temperature. A likely explanation is that temperature and sunshine are

80   very strongly correlated at the inter-annual scale and temperature is measured precisely and

81   accurately, whereas long records of photosynthetically active radiation flux are rarely

82   available, forcing reliance on less direct measures such as hours of sunshine or percentage

83   cloud cover.

84   If summer sunshine and summer temperature remained strongly and uniformly covarying

85   over long timescales it would not matter which one was used for calibration and

86   reconstruction, and this was the assumption in some earlier work (McCarroll and Pawellek

87   2001; McCarroll et al. 2003). In northern Finland, for example, $\delta^{13}C$ of pine trees correlated

88   more strongly with summer temperature than either tree ring widths or densities and also

89   gave better verification statistics using local meteorological data (McCarroll et al. 2011).

90   However, when this proxy was used to reconstruct summer temperature back to AD1640

91   (Gagen et al. 2007) it was clear that temperature estimates prior to the calibration period were

92   too high. The offset was demonstrated by comparison with the long early instrumental

93   temperature records from Tornedalen (Gagen et al. 2011). Similar results were obtained in

94   north-west Norway, but in this case there was a period in the instrumental measurements

95   where there was a clear divergence between summer temperature and percentage cloud cover,

96   indicating that temperature and sunshine may not remain tightly coupled at non-interannual

97   timescales (Young et al. 2010). In this case when temperature and cloud cover diverged, the

98    $\delta^{13}C$ values followed the cloud cover (sunshine) rather than temperature (Young et al. 2010).

99   The long $\delta^{13}C$ records from pine trees in northern Fennoscandia have now been robustly

100   reinterpreted as records of past summer sunshine or cloud cover, depending on the

101   availability of local meteorological data for calibration and verification (Gagen et al. 2011;

102   Young et al. 2012; Loader et al. 2013). In this area there are very clear offsets between the

103   tree ring $\delta^{13}C$ records and high quality reconstructions of summer temperature (Melvin et al.

104   2012; McCarroll et al. 2013), pointing to long periods of divergence between temperature and

105   sunshine, perhaps indicating large scale changes in circulation in the past (Loader et al.

106   2013). Similar divergence between summer temperature and sunshine, at decadal or multi-

107   decadal timescales, has also been found within a General Circulation Model (Gagen et al.

108   2011).

109   In the European Alps, as elsewhere, tree ring $\delta^{13}C$ has generally been interpreted either as an

110   indicator of moisture stress, in drier areas, or of summer temperature in higher, cooler ones.

111   For example, Kress et al. (2010) measured carbon isotope ratios in larch trees from the

112   Lötschental in the Valais; one of driest regions in Switzerland, and found very strong

113   correlations with a drought index based on temperature and precipitation amount. In the same

114   valley Treydte et al. (2001) reported strong correlations between $\delta^{13}C$ in spruce tree rings and

115   temperature, precipitation and relative humidity, concluding that relative humidity is a

116   suitable target for reconstruction. In the French Alps, Daux et al. (2011) also report strong

117   correlations between larch $\delta^{13}C$ and summer relative humidity. Strong correlations with

118   parameters linked to moisture stress have also been reported for beech trees (Saurer et al.

119   1997) and for pines growing at dry Alpine sites (Gagen et al. 2004, 2006). On the more moist

120   southern side of the Swiss Alps, Reynolds-Henne et al. (2007) report a low but consistent

121   correlation between $\delta^{13}C$ in Scots pine trees and summer temperature. Alpine tree ring $\delta^{13}C$

122   chronologies have not, thus far, been interpreted in terms of past variations in sunshine.

123   The aim of this paper is to use a 520 year $\delta^{13}C$ chronology from the eastern Alps to test the

124   hypothesis that, based on first principles, the dominant control on isotopic fractionation is

125 summer sunshine rather than temperature in this region. Given the paucity of sunshine

126 records over this region, this is tested by critically assessing the veracity of temperature

127 reconstructions by comparing them with both long instrumental series and temperature

128 reconstructions, based on other lines of evidence.

129 **2. Sites and data description**

130 Tree ring samples for isotopic analysis were obtained by sub-sampling 12 trees from a *Larix*

131 *decidua* tree ring chronology built using living trees from two alpine (1700 m a.s.l.) sites;

132 Dleskovška plateau (46°21'N, 14°42'E, close to the border with Austria) and Vršič (46°26'N,

133 13°43'E, close to the border with Italy) in the Slovenian Alps (see Hafner et al. 2011 for more

134 details of site selection). The chronology also includes some roof timbers from St. George's

135 church in the coastal region of Slovenia (Piran, 45°31'N, 13°34'E) and two of these were

136 included to extend and strengthen the early part of the isotope chronology. The building

137 timbers originate from 'alpine sites near the border between Slovenia and Italy' (Levanič et

138 al. 1997).

139

140 From each tree or beam, 12-mm cores were extracted, air-dried, absolutely dated and then

141 divided into annual tree rings using a scalpel under magnification. The youngest 50 tree rings

142 of each tree were excluded from further analysis to avoid potential "juvenile trends" in the

143 $\delta^{13}C$ chronology (Gagen et al. 2007), although recent work on larch suggests that this might

144 not be necessary (Daux et al. 2011). Tree rings were not separated into early and late-wood

145 components because the rings were often too narrow to provide enough α-cellulose and

146 because it has been shown that for conifers the isotopic ratios of early and late wood are

147 strongly correlated and good results are obtained when using the whole ring (Kress et al.

148 2009). For each tree ring the α-cellulose was isolated using standard techniques (Loader et al.

149 1997; Rinne et al. 2005). The purified samples were homogenized using a Hielscher

150   ultrasonic probe (Laumer et al. 2009) and freeze-dried for at least 48 hours prior to

151   measurement of $\delta^{13}C$ ratios.

152

153   Carbon isotope analysis, using samples of 0.30–0.35 mg of α-cellulose, was performed using

154   a mixture of combustion and pyrolysis techniques. Pyrolysis allows both carbon and oxygen

155   isotope ratios to be measured on the same sample (Young et al. 2011a; Woodley et al. 2012),

156   which is advantageous when dealing with thin rings, as in this study. For combustion the

157   samples were weighed into tin capsules and combusted over chromium(III) oxide and

158   copper(II) oxide at 1,000°C. For pyrolysis, samples were weighed into silver capsules and

159   pyrolysed over glassy carbon at 1,090°C. In both cases work was conducted in the Swansea

160   University stable isotope laboratory using a PDZ Europa ANCA GSL elemental analyzer

161   interfaced to a PDZ Europa 20–20 stable isotope ratio mass spectrometer using the methods

162   described by Young et al. (2011a). For comparison, samples from one tree were pyrolysed at

163   higher temperature (1,330°C) in a Finnigan TC/EA high temperature elemental analyzer

164   interfaced (by ConFloIII) to a ThermoFinnigan DeltaPlus Advantage isotope ratio mass

165   spectrometer at the University of Helsinki. Analytical precision was typically ±0.1 per mille

166   ($\delta^{13}C$). The $\delta^{13}C$ values obtained by pyrolysis and combustion on the same samples were very

167   similar (mean values -22.98‰ for combustion and -23.11‰ for pyrolysis, correlation r =

168   0.94, n = 512). The small differences in mean and variance were removed by scaling the

169   pyrolysis values to match those of combustion following the procedure described by Young

170   et al. (2011a).

171

172   After scaling, the $\delta^{13}C$ values were corrected first to remove the atmospheric decline in the

173     $\delta^{13}C$ values of atmospheric carbon dioxide, by simple addition using an extrapolation of the

174   values provided by McCarroll and Loader (2004), and then for changes in the response to the

175   rising carbon dioxide content of the atmosphere using the pre-industrial (PIN) correction

176   proposed by McCarroll et al. (2009). The effect of the two corrections is shown in Hafner et

177   al. (2011). The PIN correction is based on the physiological constraints on a plastic response

178   to rising carbon dioxide levels and makes no attempt to fit the isotope data to any climatic

179   signal, thus preserving the independence of the meteorological data sets to be used for

180   calibration. The effect of the PIN correction on the reconstruction was checked by including

181   and excluding the period that is affected (discussed later).

182

183   Examination of the individual tree δ^{13}C series suggests that the temporal evolution of the

184   mean isotope curve is not an artifact of changes in sample depth or the mixture of different

185   tree cohorts, and the longer tree series follow the trend of the mean. With only 14 trees,

186   including cohorts of similar age, it is difficult to test conclusively for the presence of age

187   trends. Much larger data sets for Scots pine in Fennoscandia show no evidence for an age

188   trend after a short (<50yrs) juvenile period (Gagen et al. 2008; Young et al. 2011b) and a

189   similar study would be required for Alpine larch, but there are insufficient published data at

190   present. However, the trend of a linear correlation between δ^{13}C and ring number provides

191   some indication of the extent of age related trends in these trees, and seven of the trees show

192   a rise over their series length, of which four are statistically significant (p<0.05), whilst the

193   other seven show a decline, of which three are significant. There is certainly no evidence to

194   suggest a consistent age trend in larch δ^{13}C that might confound any climatic interpretation of

195   the mean series.

196

197   Of the five calendar centuries covered by the mean δ^{13}C record (Fig. 1), the highest century-

198   mean occurs in the 18th (-22.64‰) followed by the 17th (-22.78‰) and the lowest in the 19th

199   (-22.92‰). Mean values of the 16th and 20th centuries are almost the same (-22.88‰ and -

8

200 22.89‰). Taking half centuries, the mean value for the period 1951 to 2000 (-22.79‰) is the

201 fourth highest, with higher values covering the period AD 1651 to 1750. The lowest is the

202 first half of the 20th century, followed by the first half of the 17th century.

203

204 **3. Calibration and verification of the climate signal**

205

206 A pilot study (Hafner et al. 2011) calibrated carbon isotopes from this chronology, together

207 with other potential paleoclimate proxies for the last 100 years, using meteorological data

208 from Villacher Alps meteorological station in the Austrian Alps, which is part of the

209 HISTALP network (Auer 2007). Strong positive correlations were reported with the mean

210 temperatures of July and August, weaker but significant correlations with September

211 temperatures but not with June. Sunshine hours in July and August also gave strong

212 correlations, with insignificant values for June and September. Significant negative

213 correlations were reported for the precipitation totals of July and August. The data presented

214 here give very similar results, but we are able to extend the correlations back to AD1884,

215 which is the length of the sunshine data (Table 1). In all cases combining the meteorological

216 data from July and August improves the correlation with $\delta^{13}C$.

217

218 Over the period for which both temperature and sunshine data are available (AD1884 to

219 2006), $\delta^{13}C$ correlates more strongly with July to August (JA) temperature than with JA

220 sunshine, and these two climatic variables are strongly correlated with each other (r = 0.73,

221 *p<0.001*). Since JA temperature gives the highest correlation, in the absence of other

222 information that would be the logical choice as a target for reconstruction. However, some

223 care is required when comparing sunshine and temperature correlations, because temperature

224 is measured with greater accuracy and precision than sunshine hours and also because

225   temperature changes smoothly across space, whereas sunshine (cloudiness), and precipitation

226   variations are more spatially variable. This means that the inter-annual temperature variations

227   experienced in the sampled forest and measured at a distant meteorological station are likely

228   to be more similar than the same values for sunshine, so if the real influence of temperature

229   and sunshine on a proxy are equally strong, temperature will likely give higher correlation

230   values due to the superior instrumental robustness and spatial homogeneity of the temperature

231   variable.

232

233   Split-period verification tests conducted over the common period for which local temperature

234   and sunshine data are available show that temperature may not be the best target for

235   reconstruction (Fig. 2). The squared correlation (R^2) values over the two halves of the

236   instrumental data are very similar for sunshine, but for temperature the correlation over the

237   recent period (AD1946 to 2006) is much lower than that over the earlier half (AD1884 to

238   1945). Also, although the Reduction of Error (RE) values for temperature are higher than

239   those for sunshine, this is not true for the more challenging Coefficient of Efficiency (CE)

240   statistic. Low CE results indicate an offset in the absolute values of the measured and

241   predicted temperatures. In this case the offset occurs because the temperature and sunshine

242   records diverge after 1983and the isotope values follow the evolution of the sunshine record,

243   rather than rising with summer temperatures.

244

245   There are two reasonable explanations for the offset between summer temperature and stable

246   carbon isotope ratios over the last few decades. One possibility is that the offset reflects the

247   direct influence of increasing carbon dioxide concentrations on fractionation of carbon by

248   these trees. A correction has already been made for this effect, but the PIN correction used

249   (McCarroll et al. 2009) only removes any decline in the isotope values that could be

250 accounted for by rising CO_2. Treydte et al. (2009) have proposed an alternative correction

251 that effectively tunes the stable isotope values to the target climate variable. Applying this

252 procedure would certainly remove the offset but the calibration and verification would be

253 compromised because the isotope and temperature data would no longer be independent. The

254 alternative explanation is that the dominant control on photosynthetic rate, and therefore on

255 stable carbon isotope fractionation, is photon flux rather than temperature and the divergence

256 between $\delta^{13}C$ and summer temperature represents the divergence between temperature and

257 sunshine. If the strong correlation between temperature and $\delta^{13}C$ is indirect, via photon flux,

258 and recent warming is due to increased greenhouse gas concentrations, then a divergence

259 between temperature and sunshine, and between temperature and $\delta^{13}C$, is precisely what

260 would be expected.

261

262 Given the available sunshine data, it is not possible to conclude definitively, using correlation

263 analysis, whether the dominant signal in the $\delta^{13}C$ of these larch trees is summer temperature

264 or summer sunshine. Apart from the last few decades, where steeply rising atmospheric CO_2

265 is a confounding factor, there are no prolonged periods of divergence between temperature

266 and sunshine at Villacher Alps.

267

268 The veracity of a JA temperature reconstruction based on the correlation with $\delta^{13}C$ can be

269 investigated to some extent using longer gridded temperature data (Böhm et al. 2010) that is

270 available for the Eastern Alps (43° - 49° N and 12° - 19°E). Over the common period

271 AD1851 to 2006 the Villacher Alps and eastern Alpine temperatures are very strongly

272 correlated (r = 0.93 p<0.001) and over that period they each give the same correlation with

273 the $\delta^{13}C$ results (r = 0.56 p<0.001). However, the eastern Alpine series extends back to

274 AD1763, allowing much longer periods for calibration and verification.

275

276   Using longer calibration and verification periods (122 years each) should reduce the impact

277   of the recent short period of clear offset, but even so, when $\delta^{13}C$ values calibrated over the

278   recent period, AD1885 to 2006, are used to predict the temperatures for the earlier period,

279   AD1763 to 1884, there is a clear overestimate of summer temperatures, resulting in a CE

280   value close to zero (Fig. 3). If the period of offset after AD1983 is removed, and the $\delta^{13}C$

281   values are calibrated over AD1885 to 1983, the offset remains and in this case the verification

282   statistics are even worse, because there is then no difference between the average

283   temperatures over the calibration and verification periods, so that RE and CE become

284   equivalent.

285

286   Although comparison with the long eastern Alps summer temperature record produces

287   verification statistics that are above zero, it indicates a clear problem with interpreting $\delta^{13}C$ as

288   a record of temperature. Even if the last few decades, when rapidly rising CO_2 causes some

289   uncertainty in the $\delta^{13}C$ values, are ignored, it is clear that $\delta^{13}C$ will tend to overestimate the

290   temperature of the past. The reason is simply that although the mean JA temperature for the

291   period AD1760 to 1884 is the same as that for AD1885 to 1983, the mean $\delta^{13}C$ values for the

292   earlier period are higher than those for the recent period. Unfortunately, meteorological

293   records are not sufficiently long to determine whether there is a similar long-term offset

294   between temperature and sunshine or cloud cover.

295

296   Comparisons of the $\delta^{13}C$ chronology with other reconstructions of summer temperature for

297   the Alpine region also suggest that temperature is not the appropriate interpretation (Fig. 4).

298   Documentary evidence provides perhaps the most powerful proxy measure of past

299   temperature (Brázdil et al. 2005, 2010) and reconstructions with monthly resolution, based

300   mainly on data from Switzerland, Germany and the Czech lands, have been provided by

301   Dobrovolný et al. (2010). When the δ^{13}C chronology is scaled to the mean documentary-

302   based JA temperature values there are many clear anomalies and long periods where the two

303   records disagree, despite being forced to the same mean value over the common period

304   AD1500 to AD1854. The isotopes underestimate temperatures between AD1630 and 1660,

305   but generally overestimate between AD1660 and 1840. Very high over-estimates occur in

306   AD1600 and 1601 (3.75 and 3.95˚C) and between AD1692 and 1697 (3.24˚C in 1694). A

307   similar comparison with the longer reconstruction of JJA temperature by Trachsel et al.

308   (2012), although scaled over a different period (AD1486 to 1996) shows a similar pattern of

309   prolonged offsets. In particular, whereas the Trachsel et al. (2012) record shows a long-term

310   increase between about AD 1700 and 1950, the isotope record shows a long-term decline.

311   The period between AD1825 and 1996 is almost continuously negative.

312

313   An alternative and arguably more reasonable interpretation of the long-term evolution of the

314   δ^{13}C chronology is that it represents mainly changes in sunshine. If this is true then

315   comparing the δ^{13}C curve with temperature reconstructions may reveal periods when

316   sunshine and temperature were less coupled than they appear to be over the period for which

317   sunshine records are available. Using both the documentary (Dobrovolný et al. 2010) and

318   multi-proxy based reconstructions (Trachsel et al. 2012) there are several clear periods where

319   temperature and δ^{13}C (interpreted for sunshine) behave in-phase, but several where they

320   diverge (Fig. 4, Fig 5). The period between about AD1570 and 1590 stands out as particularly

321   cold and cloudy, whereas the years around AD1600 were sunny. Between AD1625 and 1650

322   it was not cold but very cloudy and as temperatures declined in the second half of the 17th

323   century it become increasingly sunny, culminating in the sunniest period in the record in the

324   first decade of the 18th century, when it was also warm. Most of the remainder of the 18th

325   century is unremarkable, with both temperature and sunshine oscillating close to the values

326   experienced in the latter half of the 20th century, apart from the AD1790s, which were sunny.

327   From AD1800 to 1825 it is both cold and cloudy. Between AD1825 and 1875 there is a rise

328   in temperature but a drop in sunshine, so that compared to the last half millennium, the period

329   between AD1825 and 1940 is relatively warm but cloudy. It is notable that when the δ^{13}C

330   record is scaled over a very long period, to match the Trachsel et al. (2012) reconstruction,

331   and expressed in anomalies relative to the 20th century, the offset between temperature and

332   sunshine of the last few decades does not look unusual at all.

333

334   **4. Sunshine reconstruction based on δ^{13}C**

335   Given the long term evolution of the δ^{13}C chronology, and the reasonably good correlation

336   with measured values, we propose that July/August sunshine is the most appropriate target

337   for climate reconstruction using stable carbon isotope ratios in larch trees growing at high

338   elevation in the southeastern Alps. Climate reconstructions based on regression (inverse

339   calibration; using the proxy to predict climate) always underestimate the variability of climate

340   in the past, the magnitude of the effect being proportional to the amount of unexplained

341   variance (McCarroll et al. 2013). Given a correlation of r=0.55 with the total hours of

342   sunshine for July and August combined, a regression-based reconstruction grossly

343   underestimates the variability of sunshine over the period of measurement, so the

344   reconstruction has been scaled to match the mean and variance of the meteorological data

345   (Fig. 6).

346   It must be stressed that this sunshine reconstruction needs to be interpreted with caution. It is

347   based upon a small sample of trees from only two sites and the uncertainty around the annual

348   values is very large. Ignoring uncertainty in the estimate of the mean isotope values, two

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349   standard errors of the prediction gives ± 102 hours of sunshine. However, it is the first such

350   reconstruction for the Alpine region and when considered alongside reconstructions of

351   temperature and precipitation may provide a more synoptic view of changes in climate over

352   time.

353   Three years stand out as having very high isotope and predicted sunshine values: AD2006,

354   AD1911 and AD1705. The autumn of AD2006 was exceptionally warm and dry (Luterbacher

355   et al. 2007). The summer of AD1911 was both hot and sunny and it also had the lowest

356   July/August rainfall in all the available records. The scaled reconstruction over-estimates

357   sunshine and this probably represents increased stomatal control on fractionation due to very

358   dry conditions. Similar conditions would explain the very high value for AD1705, and in the

359   summer (July-August) temperature reconstruction of Dobrovolný (2010) AD1705 is strongly

360   positive, and is warmer than AD1706. AD1706 in the Casty et al. (2005) reconstructions is

361   listed as one of the warmest and driest summers, but those records also include June. Other

362   very sunny summers include: AD1696, 1719, 1600 and 1601.

363   Two summers have anomalously low isotope values: AD1840 and 1913. The summer of

364   1913 was very wet and cold and although sunshine measured at Villacher Alps was not

365   anomalously low, it may have been considerably cloudier at the field site. The summer of

366   AD1840 was cold but is not listed by Casty et al. (2005) as particularly wet regionally. Other

367   summers inferred to be very cloudy include: AD1804, 1580, 1868, 1582, 1630 and 1850.

368   **5. Discussion and conclusions**

369   Although $\delta^{13}C$ from high altitude larch trees in the Slovenian Alps correlate most strongly

370   with mid to late summer temperature, we conclude that the dominant control, and most

371   suitable target for reconstruction is actually mid- to late-summer sunshine. This argument is

372   based on four lines of evidence:

373   1. Mechanistic models of carbon isotopic fractionation by trees suggest that the

374   dominant control can be either stomatal conductance or photosynthetic rate.

375   Photosynthetic rate is controlled more strongly by sunshine (photon flux) than it is by

376   temperature.

377   2. Since the 1980s there has been an increase in summer temperature but not in hours of

378   summer sunshine. The $\delta^{13}C$ results follow the stable sunshine data rather than the

379   rising temperature record.

380   3. Even if the recent period of divergence between summer temperature and sunshine is

381   ignored, when $\delta^{13}C$ is calibrated over the last century it tends to overestimate the

382   measured summer temperatures of the past. This is not the case when sunshine is the

383   reconstruction target.

384   4. If $\delta^{13}C$ is calibrated to temperature it produces a time-series that conflicts with other

385   temperature reconstructions for the Alpine region that are based on strong evidence.

386 The summer sunshine reconstruction that we provide is the first for the Alpine region, but it

387 needs to be treated with caution. It is calibrated using the best available data, which is total

388 hours of sunshine of July and August, which is not the same as the mechanistic control on

389 fractionation, which we suggest would be photosynthetically active radiation (PAR). Given a

390 correlation between carbon isotope ratios and hours of summer sunshine of 0.55, only about

391 30% of the variance in the isotope chronology is explained by the available sunshine record.

392 We would normally avoid using isotopes for climate reconstruction unless about half of the

393 variance is explained (McCarroll et al. 2003), but since this is a novel interpretation of this

394 proxy in an Alpine setting it is presented to encourage discussion and critique. A more

395 reliable reconstruction would require greater replication and sampling of trees from several

396   different sites, but even then the quality of the calibration might be compromised because of

397   the paucity of suitable meteorological data.

398   If the δ^{13}C chronology is interpreted in terms of changes in sunshine rather than temperature,

399   it likely provides a more synoptic view of changing climate over the last 500 years. Perhaps

400   the harshest period of the Little Ice Age in the Alps, between AD1560 and 1600 is the largest

401   negative anomaly in terms of sunshine, and this is followed by another cloudy period in the

402   first half of the 17th century. The second half of the 17th century sees sunshine increase and

403   the 18th century is generally sunnier than the 20th. Between AD1800 and 1950 there is a

404   general decline in sunshine followed by a recovery in the last 60 years.

405   There is no reason to expect sunshine records in northern Fennoscandia to correlate with

406   those in the Alps, but there are some similarities that are worthy of note. In both areas the 18th

407   and 19th centuries were generally sunnier than the 20th century and in both areas there are

408   cold intervals that were relatively sunny and warmer intervals that were cloudy, indicating

409   divergence of temperature and sunshine at multi-decadal timescales. However, just as the

410   periods of most extreme warm and cold summers do not coincide between the two regions, so

411   the sunniest and cloudiest periods are also out of phase.

412   If temperature and sunshine have not remained strongly coupled at multi-decadal timescales

413   in the Alpine region it has implications for understanding and modelling climate change. The

414   influence of changing temperatures on clouds, and therefore on sunshine, is the greatest

415   source of uncertainty in the modeling of climate change (Trenberth and Fasullo 2009; Gagen

416   et al. 2011). Reliable records of the changing relationship between temperature and sunshine

417   over a long period would provide a powerful test of the ability of general circulation models

418   to deal effectively with temperature/cloud feedbacks. The European Alps is an area with

419   unrivalled evidence of changes in past temperature (Dobrovolný et al. 2010; Trachsel et al.

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420   2012) but given that the sunshine reconstruction is based on a single δ^{13}C chronology, it

421   would be imprudent to use the relationship between temperature and sunshine presented here

422   for model evaluation. Greater replication and addition of different field sites would

423   strengthen the record, but will not deal with the problem of calibration. Perhaps the most

424   powerful test of the hypothesis that tree ring δ^{13}C chronologies can represent changes in

425   sunshine would be an independent reconstruction of a sunshine parameter based on the

426   wealth of documentary sources that have been collected for this region (Brázdil et al. 2010).

427   A reconstruction of past changes in circulation, using stable oxygen isotopes in tree rings,

428   might also help to explain periods of divergence between sunshine and temperature and also

429   account for the temporal offsets in climate extremes in different regions.

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575 **Tables**

576 **Table 1.** Pearson's correlation coefficients and statistical significance (p) of the correlation
577 between climate variables and $\delta^{13}C$ over the common period AD1884-2006.

578

Month(s)	Temperature ˚C	p	Sunshine hours	p
June	-0.05	0.57	0.05	0.60
July	0.51	0.00	0.48	0.00
August	0.48	0.00	0.37	0.00
September	0.26	0.00	0.20	0.03
June/July	0.29	0.00	0.36	0.00
July/August	0.62	0.00	0.55	0.00
June to August	0.45	0.00	0.46	0.00

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583 **Figures**
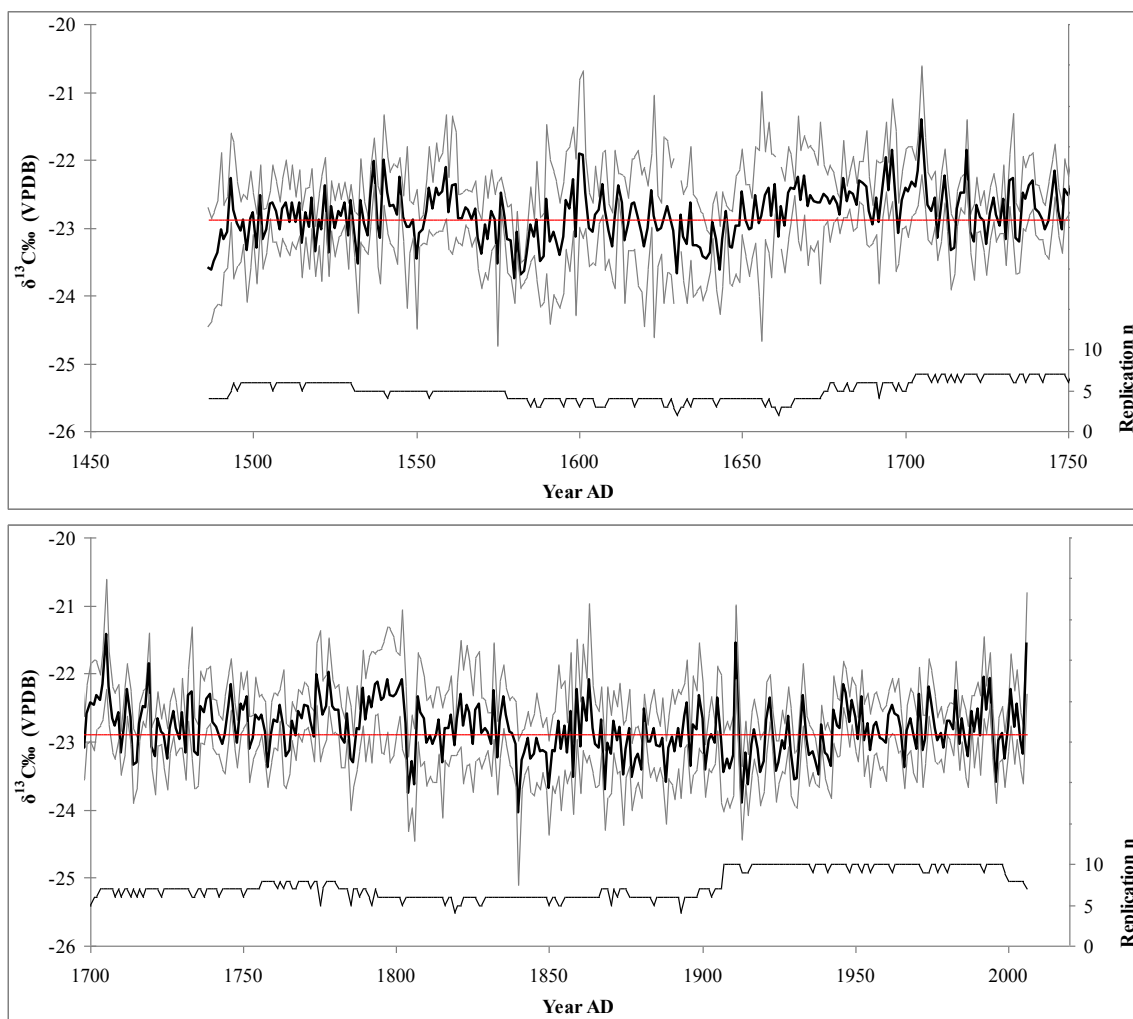
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587 **Figure 1.** The mean isotope chronology (black) with 95% confidence limits (grey) and

588 replication. The horizontal (red) line is the mean of the 20th century.

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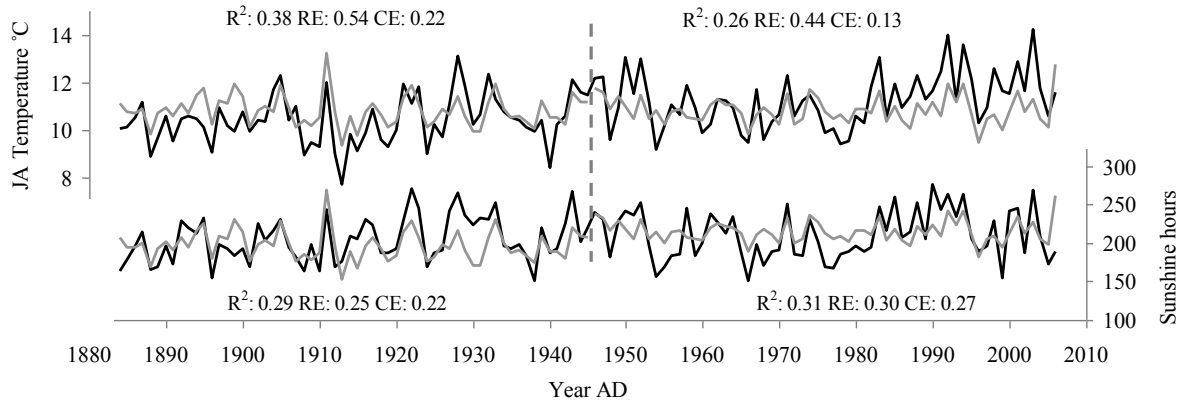
**Figure 2**. Measured (black) and predicted (grey) values for July/August temperature and sunshine hours using split-period calibration and verification. R^2 is the squared correlation between predicted and measured values, RE and CE are Reduction of Error and Coefficient of Efficiency statistics.

600
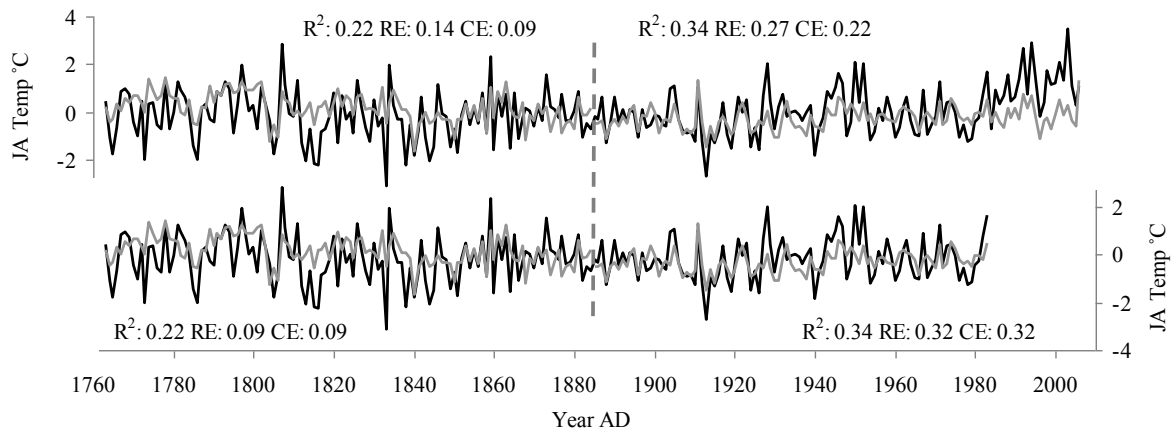
Figure 3. Measured (black) and predicted (grey) values for July/August temperature anomalies (relative to AD1901 to 2000) using split-period calibration and verification. R^2 is the squared correlation between predicted and measured values, RE and CE are Reduction of Error and Coefficient of Efficiency statistics. In the lower graph the modern part of the records has been truncated at AD1983 to check the effect of removing the period of clear offset.

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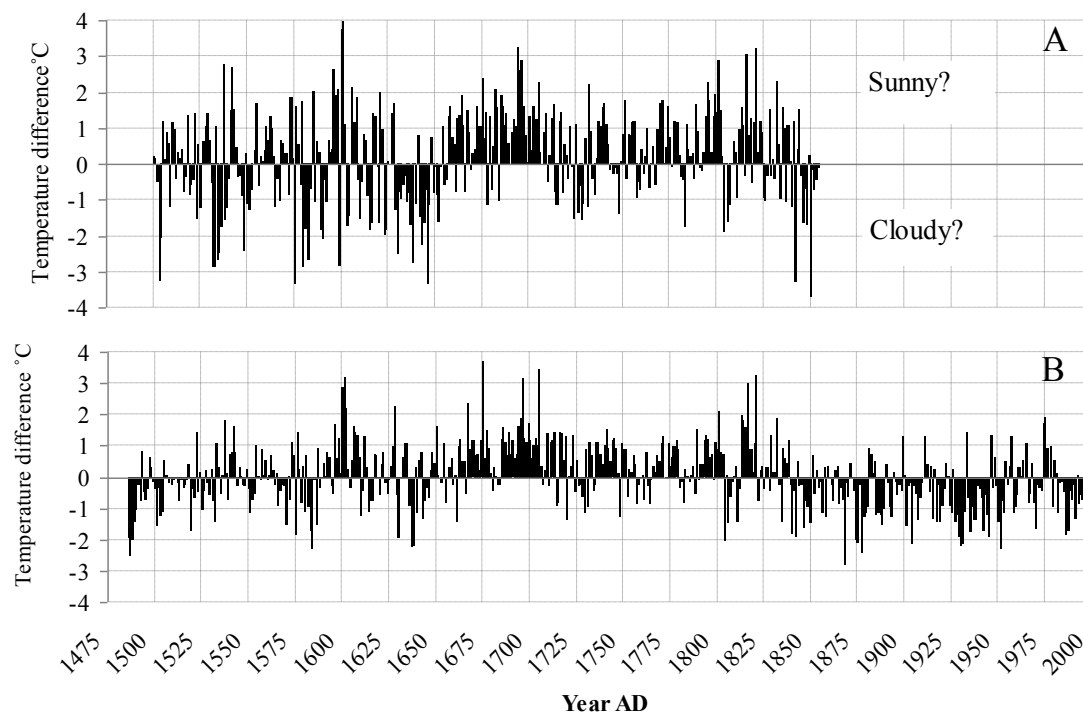
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615 **Figure 4.** Difference in temperature reconstructed by scaling the $\delta^{13}C$ chronology to fit the

616 mean and variance of two summer temperature reconstructions for (A) Central Europe

617 (Dobrovolný et al. 2010) and (B) the Greater Alpine Region (Trachsel et al. 2012). The

618 shorter Central European record is based on documentary evidence and represents the mean

619 JA temperature relative to AD1961 to 1990. The longer Greater Alpine Region record is a

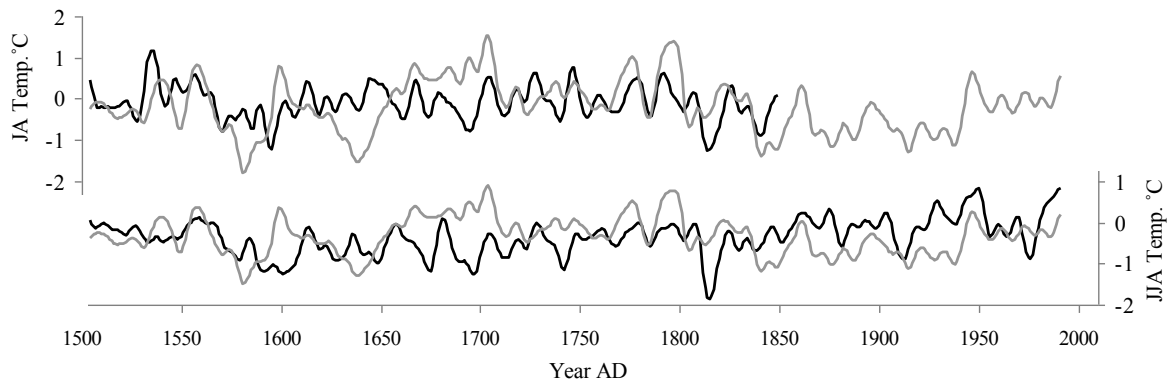620 multi-proxy reconstruction of JJA temperature relative to the period AD1901 to 2000.

621 Positive values indicate that $\delta^{13}C$ would over-estimate temperature. An alternative

622 explanation is that the positive and negative values indicate periods of high and low sunshine.

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628 **Figure 5**. Temperature reconstructions (upper) for Central Europe (July/August: Dobrovolný
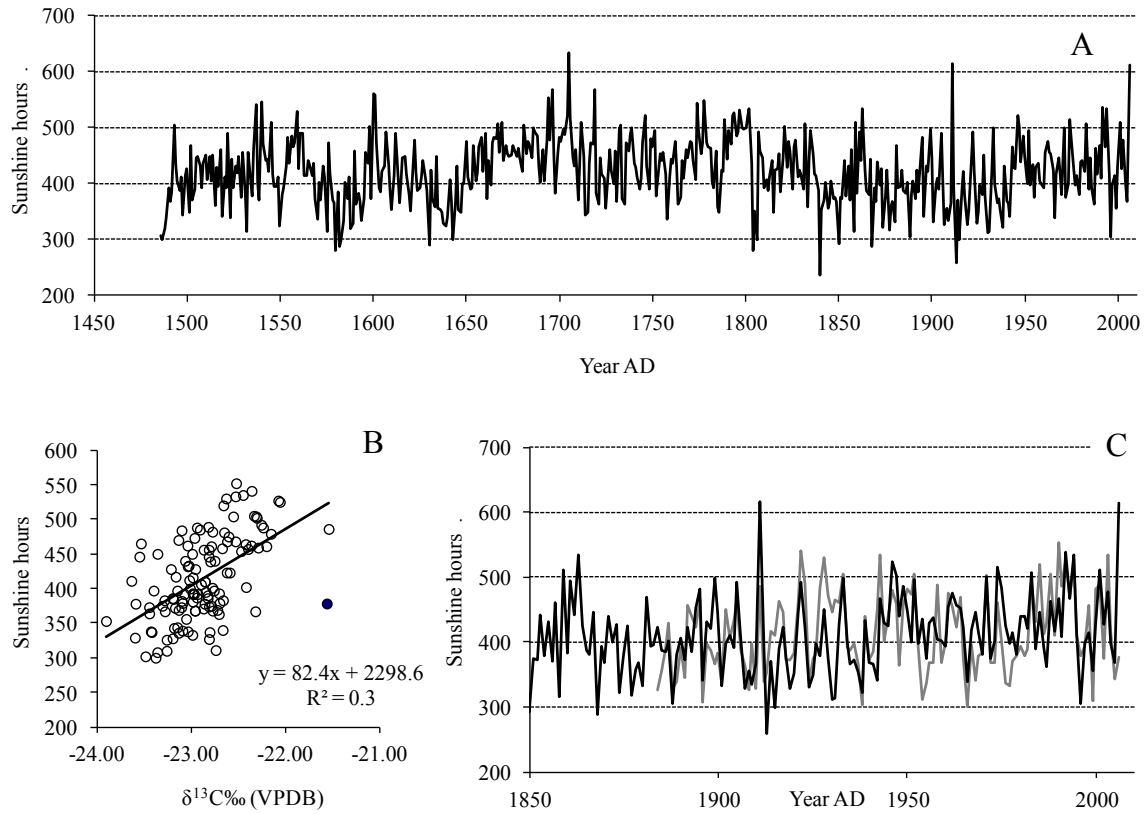
629 et al, 2010) and (lower) for the Greater Alpine Region (June to August: Trachsel et al. 2012)

630 compared with the $\delta^{13}C$ chronology (in grey) scaled to match their mean and variance. Values

631 are temperature anomalies relative to AD1961 to 1990 (upper) and to AD1901 to 2000

632 (lower) smoothed with a 10yr Gaussian filter.

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Figure 6. July and August total sunshine hours reconstruction based on $\delta^{13}C$ from high altitude larch trees (A) and a scatter plot (B) and line-graph (C) showing the fit with sunshine hours measured at Villacher Alps in the Austrian Alps (measured series is the shorter grey line). Note that AD2006 is a clear outlier (filled dot on B) possibly reflecting the extreme dry conditions experienced during this year.

640