

Impact of climate and CO₂ on a millennium-long tree-ring carbon isotope record

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Abstract

We present one millennium-long (1171-year), and three 100 year long annually resolved $\delta^{13}\text{C}$ tree-ring chronologies from ecologically varying *Juniperus* stands in the Karakorum Mountains (northern Pakistan), and evaluate their response to climatic and atmospheric CO₂ changes. All $\delta^{13}\text{C}$ records show a gradual decrease since the beginning of the 19th century, which is commonly associated with a depletion of atmospheric $\delta^{13}\text{C}$ due to fossil fuel burning. Climate calibration of high-frequency $\delta^{13}\text{C}$ variations indicates a pronounced summer temperature signal for all sites. The low-frequency component of the same records, however, deviates from long-term temperature trends, even after correction for changes in anthropogenic CO₂. We hypothesize that these high-elevation trees show a response to both climate and elevated atmospheric CO₂ concentration and the latter might explain the offset with target temperature data. We applied several corrections to tree-ring $\delta^{13}\text{C}$ records, considering a range of potential CO₂ discrimination changes over the past 150 years and calculated the goodness of fit with the target via calibration/verification tests (R^2 , residual trend, and Durbin–Watson statistics). These tests revealed that at our sites, carbon isotope fixation on longer timescales is affected by increasing atmospheric CO₂ concentrations at a discrimination rate of about 0.012‰/ppmv. Although this statistically derived value may be site related, our findings have implications for the interpretation of any long-term trends in climate reconstructions using tree-ring $\delta^{13}\text{C}$, as we demonstrate with our millennium-long $\delta^{13}\text{C}$ Karakorum record. While we find indications for warmth during the Medieval Warm Period (higher than today's mean summer temperature), we also show that the low-frequency temperature pattern critically depends on the correction applied. Patterns of long-term climate variation, including the Medieval Warm Period, the Little Ice Age, and 20th century warmth are most similar to existing evidence when a strong influence of increased atmospheric CO₂ on plant physiology is assumed.

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1. INTRODUCTION

It is still uncertain whether the magnitude and rate of 20th century warming exceeds natural climate variability over the last millennium (Esper et al., 2002a; Esper et al., 2005a,b; Moberg et al., 2005; D'Arrigo et al., 2006; Frank

et al., 2007b; Juckes et al., 2007). Extracting centennial scale climate signals from tree-ring width and maximum latewood density data – the two most commonly used annually resolved proxy archives – remains a challenge due to age-related biases inherent in these tree-ring parameters (Fritts, 1976). While specific detrending approaches, such as Regional Curve Standardization (Esper et al., 2003), may overcome this age-related noise and conserve low-frequency climatic variations, stable isotopes of carbon

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($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) in tree-rings are becoming more frequently used as alternative climate estimators (Masson-Delmotte et al., 2005; Treydte et al., 2006, 2007). Recent work suggests that these parameters could retain climate information at all temporal frequencies including lowest frequency climate signals (Gagen et al., 2007). It is, however, also widely known that particularly $\delta^{13}\text{C}$ tree-ring records generally show a prominent downward trend of 1–2‰ starting around 1800–1850 AD. This trend is a direct result of $\delta^{13}\text{C}$ depletion in atmospheric CO_2 due to fossil fuel emissions, and as such needs to be corrected prior to any climatic reconstruction. Correction of this trend and utilization of $\delta^{13}\text{C}$ records rests on the assumption that the remaining high and low-frequency variations are climate related (Freyer and Belacy, 1983; Leavitt and Long, 1986; Kitagawa and Matsumoto, 1993; Leavitt and Lara, 1994; Feng and Epstein, 1995; Saurer et al., 1997; McCarroll and Loader, 2004). This approach, however, largely ignores the dependence of carbon isotope composition of tree-rings upon, amongst other things, the atmospheric concentration of CO_2 . Specifically, the isotopic composition may be expressed as:

$$\delta^{13}\text{C}_{\text{Tree}} = \delta^{13}\text{C}_{\text{atm}} - [a + (b - a)c_i/c_a] \quad (1)$$

with $\delta^{13}\text{C}_{\text{Tree}}$ being the tree-ring isotope value, $\delta^{13}\text{C}_{\text{atm}}$ the isotope value of atmospheric CO_2 , a and b representing fractionation due to diffusion ($a \approx 4.4\text{‰}$) and carboxylation ($b \approx 27\text{--}28\text{‰}$), and c_i and c_a being intercellular and ambient CO_2 concentrations (Farquhar et al., 1982). Consequently, the quasi-exponential decrease in atmospheric $\delta^{13}\text{C}$ by about 1.52‰ (AD 1850–1998) (Friedli et al., 1986; McCarroll and Loader, 2004) alone is likely not sufficient to account for the overall decrease of tree-ring $\delta^{13}\text{C}$. Namely, some increase in leaf internal discrimination against ^{13}C caused by higher atmospheric CO_2 concentration might also need consideration (Feng and Epstein, 1995; Treydte et al., 2001; Gagen et al., 2007; McCarroll et al., 2009). Many studies have assessed the effect of elevated CO_2 on plant growth and related plant physiological properties, such as rates of photosynthesis and stomatal conductance. From controlled fumigation experiments, mostly on small plants and for a relatively short period of time, one would expect a simultaneous reduction of stomatal conductance and stimulation of photosynthesis under elevated CO_2 , which after an initial adaptation phase may result in relatively little changes in c_i/c_a (Drake et al., 1997). From these studies, however, it is difficult to derive the possible c_i -response of natural trees that have been subject to only gradual changes in CO_2 concentration over the course of a century or longer. According to the formulations derived by Farquhar et al. (1989), the carbon isotope response depends on the relative increase of c_i compared to the increase of c_a : if c_i would increase at the same rate as c_i ($c_a - c_i = \text{constant}$), this would result in a strong increase in the discrimination and thus lower $\delta^{13}\text{C}$ would be obtained. If c_i would increase less – in a proportional way ($c_i/c_a = \text{const.}$) – there would be no change in the discrimination (Saurer et al., 2004). For oak trees exposed through their whole life to elevated CO_2 near a natural CO_2 -spring, an increased carbon isotope fractionation of 0.01‰/ppmv

was observed (Saurer et al., 2003). Some of the very few other published values of discrimination changes under elevated CO_2 were also positive, but slightly lower (0.0073‰/ppmv, Kürschner, 1996) or higher (0.02‰/ppmv, Feng and Epstein, 1995).

The effect of increased CO_2 on the isotope discrimination might be particularly strong for high-elevation tree sites, as these represent lowered CO_2 partial pressure environments (Körner et al., 1988, 1991). However, so far only one study systematically investigated non-climatic long-term trends contained in the residuals after correction for $\delta^{13}\text{C}_{\text{atm}}$ content changes (Feng and Epstein, 1995), and no study deals with this topic in a millennium-long context.

Here we present a millennium-long (AD 828–1998), annually resolved $\delta^{13}\text{C}$ tree-ring chronology from high-elevation juniper trees in northern Pakistan ('Mor') together with three centennial-long (AD 1900–1998) $\delta^{13}\text{C}$ chronologies from ecologically varying sites. Common variance and signal strength within and between sites are tested, and the 'Mor' chronology is checked for potential age-related biases by comparing young and old trees for similar periods. Climate signals are estimated for the high-frequency domain and various correction factors (cf) were applied including (i) a conservative correction for changes of the atmospheric $\delta^{13}\text{C}$ source value ($\delta^{13}\text{C}_{\text{atm}}$) only, (ii) correction for $\delta^{13}\text{C}_{\text{atm}}$ in conjunction with published values of 0.0073‰ (Kürschner, 1996) and 0.02‰/ppmv (Feng and Epstein, 1995), and (iii) corrections for $\delta^{13}\text{C}_{\text{atm}}$ together with a continuous range of potential discrimination changes from -0.05‰ to 0.1‰/ppmv. Various tests and statistical measures are considered to evaluate these different approaches with respect to their ability to capture the long-term climate signals recorded in regional station data. By systematically comparing the goodness of fit of the various corrections against local climate data, we define an "optimum" correction factor that is best suited to remove non-climatic trends from our high-elevation trees in the Karakorum. Based upon these corrections, we also provide new regional temperature reconstructions derived from tree-ring $\delta^{13}\text{C}$, and compare those records with existing regional evidence.

2. MATERIALS AND METHODS

2.1. Sites and wood samples

Our study sites include the western part of High Asia with the Karakorum and Himalayan Mountains in northern Pakistan (Fig. 1). This high mountain system predominantly interacts with westerly synoptic fronts and controls the formation of meridional troughs in the jet stream (Rossby-waves). Climate is of "Mediterranean character" with precipitation being highly variable during summer and at a maximum during winter and spring, resulting in extensive snow cover (Böhner, 2006). Sampling sites are located in three valleys south and north of the main Karakorum ranges in northern Pakistan, far away from settlements and roads or other potential sources of pollution. They cover the full ecological gradient of regional juniper forests and transect a SW-NE precipitation gradient with increasing rain shadow effects northward through the mountain

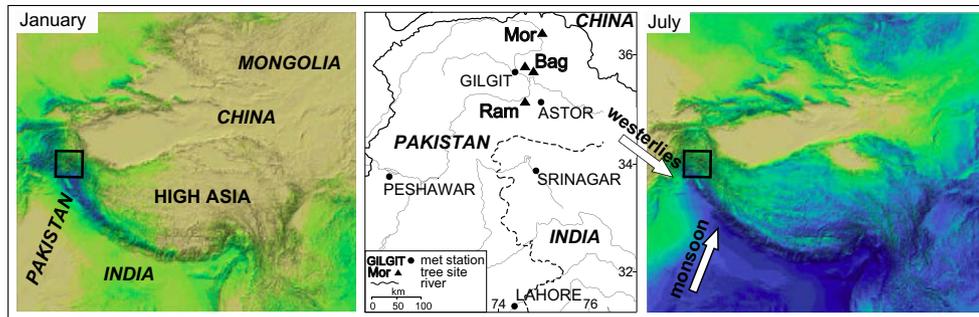


Fig. 1. Locations of tree sites (triangles) and meteorological stations (dots), and Central Asian precipitation patterns in January and July. The study area is dominated by westerly synoptic fronts throughout the whole year (dark colors: high precipitation amounts). “Bag” includes one high (3900 m a.s.l.) and one low (2900 m a.s.l.) elevation site. “Mor” contains >1000-year-old living trees. Maps reprinted from Boehner 2008 with permission of Taylor and Francis. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this paper.)

ranges. Three sites are situated near the upper (>3700 m a.s.l.) and one near the lower timberline (2900 m a.s.l.). According to local site ecology and vegetation cover classification, two sites were classified as cold/moist (Ram-high, Bag-high), one as warm/dry (Bag-low), and Mor (3900 m a.s.l.) – containing the >1000-year-old trees – as cold/dry. Except for Mor, $\delta^{13}\text{C}$ measurements are confined to 1900–1998 (Table 1). The sampling strategy was based on considering only sites with steep slopes (>35°) and trees growing on shallow and well-drained soils, to minimize potential effects of long-standing soil and ground water.

At all sites, 4 cores from 12 to 20 trees were sampled during a field trip in September/October 1999. Ring-widths were measured with a precision of 0.01 mm, crossdated, and 4–7 trees per site (2 cores per tree) with few missing rings and regular ring boundaries were chosen for isotope measurements. To facilitate analysis, we pooled most of the tree-ring material before cellulose extraction by mixing tree-rings of the same year from several individuals per site (Leavitt and Long, 1984; Treydte et al., 2001). We validated this approach at BAG-low by producing $\delta^{13}\text{C}$ chronologies from both analysis of pooled ring samples from five trees and averaging $\delta^{13}\text{C}$ time series from the same five trees analyzed separately. At the millennium-long site Mor-high, 14 cores from seven trees were pooled, but during selected periods single-tree measurements were undertaken. At all other sites samples were directly pooled.

Tree-rings were separated with a scalpel and samples ground using an Ultracentrifugal mill (Retsch ZM1). Cellulose was extracted and cellulose samples (250 μg) were burned to CO₂ at 1080 °C using a Carlo Erba 1500 elemental analyzer (CE Instruments, Milan, Italy), interfaced to an Optima IRMS (Micromass Ltd., Manchester, UK). $\delta^{13}\text{C}$ values are referenced to VPDB (Pee Dee Belemnite). Over-

all analytical precision, estimated from periodic standard deviation calculations using commercial cellulose standard (FLUKA), is $\pm 0.1\text{‰}$.

2.2. Meteorological data

For climate calibration, five stations were selected based upon their proximity to the tree sites, a low number of missing station values, and homogeneity and length attributes. Two of these – Gilgit (GIL, 1460 m a.s.l.) and Astor (AST, 2166 m a.s.l.) – are located in the study region with minimum distance of about 10 km (GIL-Bag; AST-Ram) and maximum distance of about 100 km (AST-Mor) to the tree sites (Fig. 1), but are relatively short (GIL = 48, AST = 36 years). Srinagar (SRI, 1587 m a.s.l.), is the closest station containing data over more than 100 years (AD 1898–1998), and significantly correlates with GIL and AST. Peshawar (PES, 360 m a.s.l., AD 1864–1990) and Lahore (LAH, 214 m a.s.l., 1864–1990), located at greater distances to the tree sites (200–300 km) but of >100-year length, correlate more weakly with the inner-mountainous stations GIL and AST but significantly to SRI (Treydte et al., 2006). To minimize influence of differing variances in estimating the regional signal, monthly precipitation data were normalized with respect to the individual station lengths. Additionally, we used nearby gridpoint data of a global $0.5^\circ \times 0.5^\circ$ monthly meteorological dataset over the 1901–1998 period (Mitchell and Jones, 2005).

2.3. Data treatment

Raw $\delta^{13}\text{C}$ measurements were corrected to a pre-industrial atmospheric $\delta^{13}\text{C}$ base value of -6.4‰ using the tables from McCarroll and Loader (2004). This correction lifts the

Table 1
Sampling site information.

Site name	Coord.	Altitude (m)	Expos.	Species	No. trees/samples	Period
Ram	35.74 N 74.59 E	3600	S	<i>Juniperus turkestanica</i>	4/8	1900–1998
Bag-high	35.90 N 74.56 E	3800	S	<i>Juniperus turkestanica</i>	4/8	1900–1998
Bag-low	35.90 N 74.56 E	2900	S	<i>Juniperus excelsa</i>	5/10	1900–1998
Mor	36.37 N 74.99 E	3900	SE	<i>Juniperus turkestanica</i>	7/14	826–1998

tree-ring $\delta^{13}\text{C}$ values by approximately 1.5‰ between 1850 and 1998. We then accounted for potential discrimination changes under elevated CO_2 concentrations by adding (i) $0.0073\text{‰}/\text{ppmv}$ CO_2 increase according to Kürschner (1996), and (ii) $0.02\text{‰}/\text{ppmv}$ CO_2 increase according to Feng and Epstein (1995) (Fig. 2). In a second step, we systematically changed these correction values to a range between -0.05‰ and $0.05\text{‰}/\text{ppmv}$, using 0.001‰ intervals. This procedure allowed an estimation of the effect of systematic discrimination rate changes reflecting various tree responses to increasing atmospheric $p\text{CO}_2$.

The best calibrating data set was identified using high-pass filtered isotope and climate data (residuals from 20-year cubic smoothing splines, Cook and Peters, 1981). Then the goodness of the fit between differently corrected $\delta^{13}\text{C}$ time series and the target in the low-frequency domain was assessed by correlation, comparing the linear trends of the regression residuals (D'Arrigo et al., 2006) and the Durbin–Watson statistic – a measure of the persistence in the residuals of a regression (between proxy and station data). Effects of the various corrections on long-term climate history are shown with the 1171-year long $\delta^{13}\text{C}$ record.

All significance levels are corrected for lag-1 autocorrelation (Trenberth, 1984), and variance on timescales <20 , $20\text{--}100$, and >100 years are classified as “high”, “mid”, and “low” frequency, respectively.

3. RESULTS

3.1. $\delta^{13}\text{C}$ tree and site records

Measurement series of the 5 trees at Bag-low (Fig. 3a and b) are fairly homogenous with a mean inter-series correlation of 0.66 for raw and 0.55 (both $p < 0.001$) for $\delta^{13}\text{C}_{\text{atm}}$ -corrected records. Signal strength analysis using the “Expressed Population Signal” (EPS) (Wigley et al.,

1984) indicates that for corrected data a minimum of 5 series would be sufficient to develop a site record that captures 85% of the variance of the theoretical population chronology. The maximum amplitude among four of the trees is only 0.47‰ , but the fifth has a significantly lower mean, differing by 1.04‰ from the average of the other trees. Nevertheless, the arithmetic mean of the 5 series correlates at 0.97 with the pooled record, validating the pooling method. Series are homoscedastic with no spread-versus-level relationship, as is generally the case with tree-ring width measurements (Fritts, 1976; Cook and Peters, 1997).

Mean $\delta^{13}\text{C}$ values among sites divide them into two groups: Bag-low and Mor-high being drier with isotope values (-17.82‰ and -17.87‰) about 1.3‰ higher than the more moist sites Bag-high and Ram-high (-19.05‰ and -19.25‰), suggesting reduced stomatal conductance under dry conditions, as indicated by investigations in other regions (Saurer et al., 1997; Treydte et al., 2001). $\delta^{13}\text{C}_{\text{atm}}$ -corrected mean site records correlate over the full common period (1900–1998) on average at 0.44 ($p < 0.001$) (Fig. 3c), with the highest correlation between Bag-high and Ram (0.61 ; $p < 0.001$) and the lowest correlation between Bag-high and Bag-low (0.29 ; $p < 0.01$).

3.2. 1000-year $\delta^{13}\text{C}$ record

Ring-width measurements from 1000-year-old living juniper trees at Mor-high contain non-climatic, age-related trends (Fig. 4a), commonly found in growth proxy data (ring-widths, wood density). In these junipers, age-trends and long-term temperature changes tend to mimic each other during the cooling from the Medieval Warm Period (MWP) into the Little Ice Age (LIA) (Esper et al., 2002b, 2003), making estimates of past climate variability challenging. When applying stable isotopes in tree rings for climate reconstruction, potential long-term biases in these parameters also need to be considered. Recently, evidence for

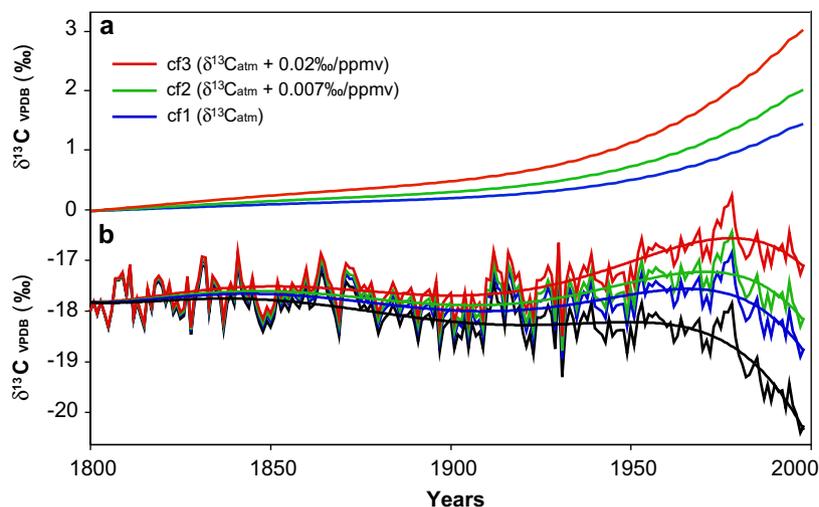


Fig. 2. (a) Correction factors since 1800 (cf) for changes in the atmospheric $\delta^{13}\text{C}$ (cf1), and accounting for plant physiological responses on atmospheric $p\text{CO}_2$ changes by increased discrimination after Kürschner (1996) (cf2) and Feng and Epstein (1995) (cf3). (b) Corrections applied to the tree-ring $\delta^{13}\text{C}$ record ‘Mor’.

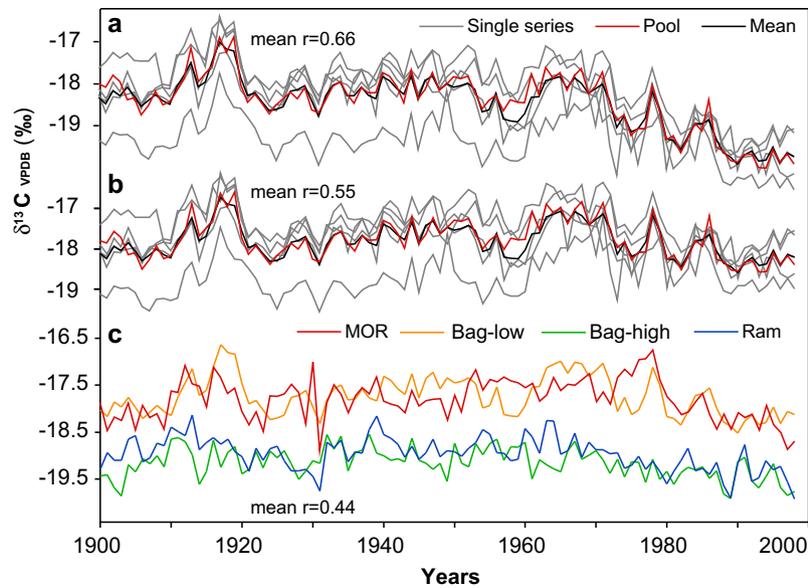


Fig. 3. Tree and site $\delta^{13}\text{C}$ records. (a) $\delta^{13}\text{C}$ records from five single trees at Bag-low and their arithmetic mean. Red curve is obtained from pooling tree rings of the same trees before cellulose extraction. (b) Same records, but corrected for anthropogenic changes of the $\delta^{13}\text{C}$ values in the atmosphere. (c) Pooled site chronologies including the most recent part of the millennial-long Mor-high record. In all cases, two cores per tree were combined for analysis.

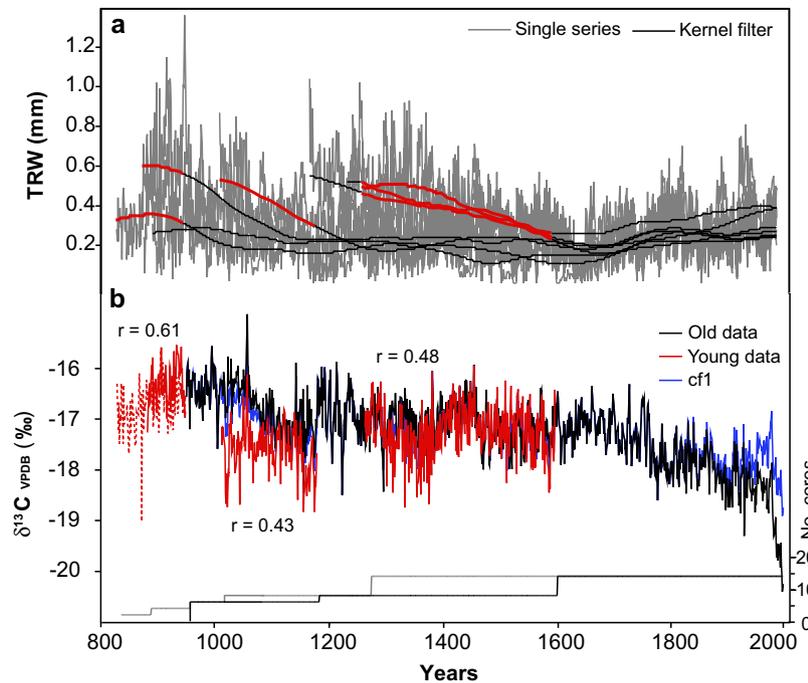


Fig. 4. Potential age-related biases in ring-width and $\delta^{13}\text{C}$ measurements over the last 1200 years. (a) Ring-width time series of the seven trees used for isotope analyses at Mor-high. 101-year smoothing Kernel filters indicate that the early segments (red) contain wider rings likely biased by age-related effects. (b) Continuous pooled carbon isotope record using cellulose from only “old” rings in comparison to the shorter segments (highlighted in red in a) using only “young” rings. r is the correlation between these timeseries for the periods 881–950, 1077–1178, and 1264–1599, the latter being another pooled series of 3 trees. Replication of core samples combined in the long record using only the old data (black) and all data (grey) are shown at the bottom. Blue is the combined site record corrected for changes in the atmospheric $\delta^{13}\text{C}$ source value.

potential tree age-related (non-climatic) centennial trends in oxygen isotopes of our investigated trees has been reported (Treydte et al., 2006). We therefore tested for potential age-

trends in carbon isotopes by generating a continuous time series over the past millennium using only “old” and narrow rings and comparing these data over three shorter

segments with the $\delta^{13}\text{C}$ values derived from “young” and wide rings (Fig. 4). The respective young segments (high-lighted red in Fig. 4) correlate between 0.43 and 0.61 ($p < 0.001$) with the overlapping old data. While these results demonstrate some common signal predominantly in the higher frequency domain, comparison of the lower frequency components reveals an unclear picture. Similar trends are to be seen in most parts of the 1264–1599 period, but deviating trends are found over the first half of the 14th century and over the early part of the 1012–1179 period with a single tree showing an offset of about 1.0‰ from the pooled mean of the 3 older trees. Including this tree with a 25% weight in the chronology does not change the overall pattern of the record, but nevertheless points to the fact of increased uncertainty with lower replication in this early part of the chronology. Overall, our data are not appropriate to sufficiently address whether there exists a $\delta^{13}\text{C}$ age-trend or not.

3.3. High-frequency climate signals

Climate correlations were calculated in the high-frequency domain to avoid biases from potentially non-climatic long-term trends. Particularly Mor-high and Bag-high respond significantly to summer temperatures (June/July), whereas precipitation relationships are weak. Only the warm/dry site Bag-low suggests a response to winter precipitation (particularly January) and the southernmost, more monsoonal site Ram shows no significant response to any of the tested instrumental data.

The signal associated with the grid point data (Fig. 5b) corresponds more strongly to that of the inner-mountainous station data (Fig. 5a) than to that of the extra-mountainous stations (Fig. 5c). This holds particularly during summer when PES and LAH are controlled by monsoonal conditions, and therefore do not fully represent the more

“Mediterranean” character of the study region (Treydte et al., 2006). This is in contrast to pre- and post-monsoonal seasons with more homogenous climate conditions due to dominating westerly synoptic fronts (Böhner, 2006). Therefore, further calculations are based on grid point data, providing continuous records back to AD 1901.

High-frequency correlations between grid point temperature and tree-ring isotope data increase when extending the calculation to the full 98-year time window (Fig. 6a, upper panel). Strongest signals appear during the summer (May to August) with all sites correlating positively. Focusing on seasonal conditions as expressed through the combination of months, Mor-high containing the millennium-long $\delta^{13}\text{C}$ record reacts most sensitively to temperature variations in June/July ($r = 0.48$), followed by the mean adjusted combined record Kara ($r = 0.42$), Bag-low and Ram.

Altogether, the results of high-frequency calibration tests, namely strong correlations with temperature suggest that the dominant control of internal CO_2 concentrations at our high-elevation sites is the efficiency of the photosynthetic active enzyme Rubisco rather than stomatal conductance. In this context temperature relationships have to be seen as an indirect link, e.g. to the amount of photosynthetic active radiation as a main driver (McCarroll et al., 2003).

3.4. Temperature and CO_2 : Disentangling long-term signals

We also considered the low-frequency component of the $\delta^{13}\text{C}$ series by correcting them in three different ways as described above (Fig. 2) and applied various calibration/verification approaches to test the performance of these corrections to capture regional temperature variability (Fig. 6a). Interestingly, correlations between the $\delta^{13}\text{C}_{\text{atm}}$ -corrected site records and summer temperatures are slightly weaker compared to the high-pass filtered data (e.g.

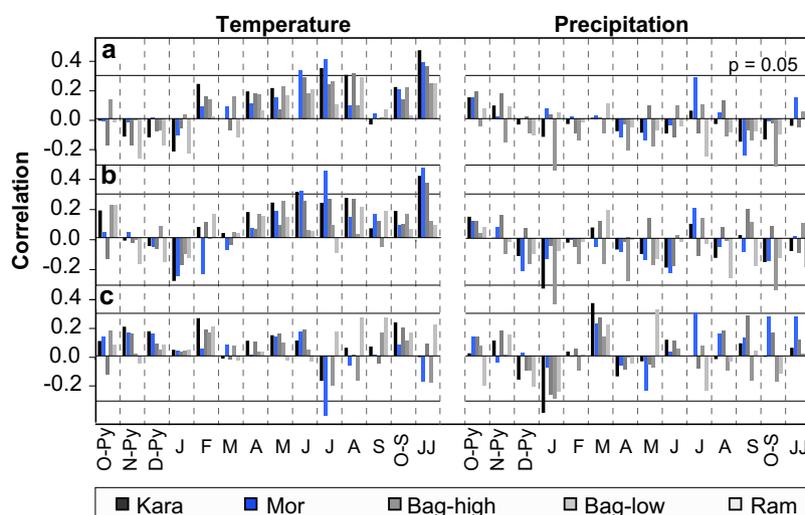


Fig. 5. Correlation coefficients between climate parameters and tree-ring $\delta^{13}\text{C}$ site records and their adjusted average Kara. Climate records are based on three meteorological data sets: (a) mean of the inner-mountainous stations Gilgit, Astor, Srinagar. (b) Closest grid point data (c) mean of the extra mountainous stations Lahore and Peshawar. Correlations are calculated over the common period 1951–1998 (precipitation) and 1955–1998 (temperature) using residuals from 20-year-splines (isotopes AND climate data).

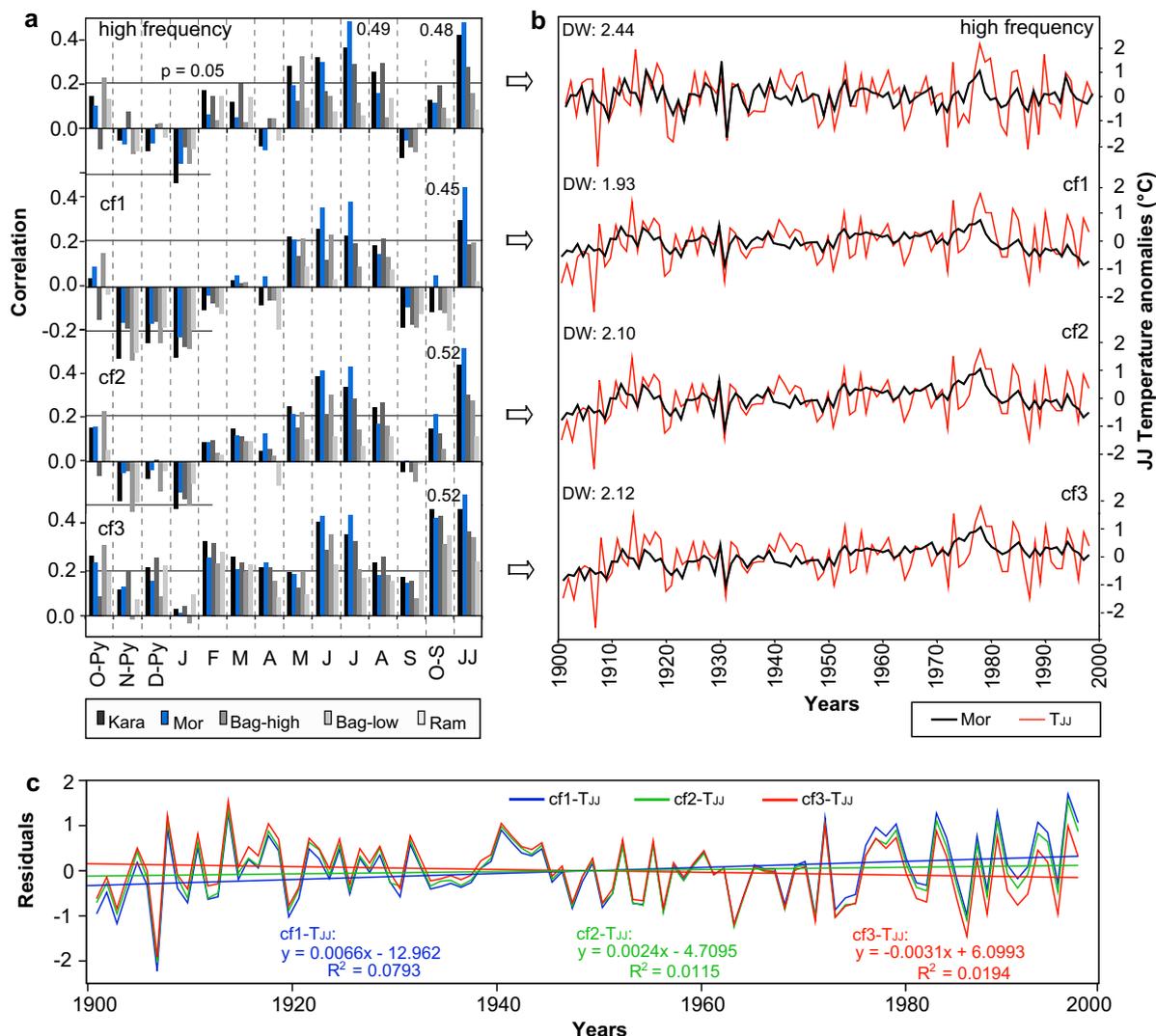


Fig. 6. Summarized climate calibration statistics of differently corrected δ¹³C records of Mor-high. (a) Correlation coefficients for monthly and seasonal temperatures of high-pass filtered data, and after application of different correction techniques (cf1–cf3, see Fig. 2). (b) Time series plots of June/July temperatures and tree-ring δ¹³C. DW is the Durbin–Watson statistic for residual autocorrelation. A DW value of 2.0 would be the optimum indicating that there is no autocorrelation in the regression model residuals. Substantially lower/higher values indicate positive/negative serial correlation. (c) Plots of residual trends (difference between target and proxy) through time.

Mor-high $r = 0.48$ and $r = 0.45$ for high pass and corrected time series, respectively) due to diverging trends of temperature and tree-ring δ¹³C particularly in the second half of the 20th century (Fig. 6b, cf1). Adding low-frequency by considering both the decrease in atmospheric δ¹³C and increase in discrimination by about 0.0073‰/ppmv (after Kürschner, cf2) results in similar or slightly higher correlations particularly during June/July (Mor-high $r = 0.52$, Kara $r = 0.43$) compared to the high-frequency correlations. Additional consideration of the discrimination effect of 0.02‰/ppmv after Feng and Epstein (cf3) increases the correlation results of the less sensitive sites and widens the seasonal window of positively correlating months. Relationships during summer are, however, not markedly enhanced. Altogether, correlation tests suggest that including a plant physiological response via ¹³C discrimination on elevated atmospheric

CO₂ concentration generally improves long-term temperature–δ¹³C relationships.

To test the robustness of the long-term signal, we calculated the Durbin–Watson statistic (DW) of the regression model residuals (Fig. 6b) and assessed linear trends of the residual time series (Fig. 6c) of Mor-high. The cf1 (DW = 1.93) and cf2 (DW = 2.10) corrected series reveal DW values close to the optimum of 2 suggesting that a stronger correction than the atmospheric correction only, but less than the “Kürschner correction”, would lead to lowest autocorrelation. The residuals of the differently corrected δ¹³C records and June/July temperatures (Fig. 6c) show no significant autocorrelation. The linear trend of the cf1 residuals is significant ($p < 0.01$), in contrast to the residual trends of the cf2 and cf3 models. Taking into account a moderate discrimination at the leaf level (cf2)

results in a minimum slope of the regression line. A trend-free fit, however, would appear somewhere in between the cf2 and cf3 corrected series.

Altogether our results clearly indicate that the widely used correction for the decrease in $\delta^{13}\text{C}_{\text{atm}}$ values alone does not result in an optimal fit to the long-term trend of the target instrumental data, namely summer temperatures at our high-elevation tree sites. Therefore, we systematically tested a range of potential discrimination changes under elevated CO_2 by increasing the correction factors stepwise from -0.05‰ to $0.10\text{‰}/\text{ppmv}$ (Fig. 7). In most cases optimum corrections and “transition zones” lie within the range between the cf1 and cf3 correction. At Mor-high with the strongest high-frequency temperature signal, the tests reveal highest R^2 (0.3) and nearly zero slope when correcting for an assumed discrimination change of $0.012\text{‰}/\text{ppmv}$ – a value between cf2 and cf3. DW values of 2.0 are reached when correcting for discrimination changes of only $0.005\text{‰}/\text{ppmv}$ (Fig. 7c). At Bag-high optimum values are reached when applying a stronger correction with a discrimination change of about $0.015\text{‰}/\text{ppmv}$, a number supported by three statistical measures. Tests at Bag-low and Ram with weakest temperature correlations suggest that even higher discrimination changes would be necessary to achieve better test

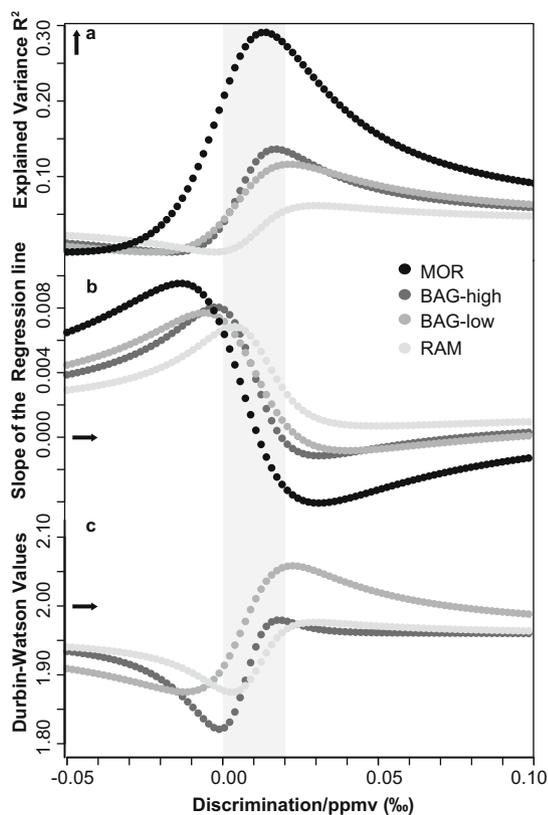


Fig. 7. Effects of a stepwise discrimination increase on statistical test values describing the strength of relationships between target and proxy (a) for the explained variance R^2 , (b) for the trends in the residuals, (c) for Durbin–Watson values; Arrows indicate in which direction optimum values would be reached; Grey shadow displays the range between the cf1 and cf3 correction.

statistic values. Overall, these tests clearly indicate that it would not be appropriate to derive a universal correction factor applicable independently from ecology and climate sensitivity of individual sites. In fact, such tests need to be repeated for every new data set.

In the following we apply the “optimum” correction values ($\text{cf}_{\text{opt}} = 0.012$) derived from site dependent R^2 , residual regression tests and DW statistics on the Mor-high $\delta^{13}\text{C}$ record used for temperature reconstruction.

3.5. Millennium-long temperature reconstruction

Summer temperatures over the past millennium were assessed by linear regression over the 1901–1998 period using cf1, cf3 and cf_{opt} corrected Mor-high records (Fig. 8a and b). Correcting the data for atmospheric $\delta^{13}\text{C}$ changes only (cf1) suggests by far warmest conditions between AD 950–1100, and 20th century temperatures below the overall mean of the past millennium, with coolest conditions in the 1990s. This pattern does not mirror at all the current state of knowledge concerning regional long-term climatic episodes such as the Medieval Warm Period (MWP), Little Ice Age (LIA) and recent warming (Bao et al., 2002; Esper et al., 2002b; Bräuning and Mantwill, 2005; Esper et al., 2007). In comparison, the cf_{opt} corrected record generally represents well-known key variations such as warm conditions during the MWP before AD 1100, a cooling trend into the Little Ice Age with minimum temperature around 1800, and a warming trend into the 20th century. For cf_{opt} the 1990s are substantially below MWP temperatures. This long-term temperature pattern is quite similar to a 1000-year ring-width record developed for the same region (Esper et al., 2002b). The overall temperature amplitude is 1.4 °C reaching from $+0.95\text{ °C}$ in the 950s to -0.45 °C around AD 1800 (max. and min. of 60-year spline). Finally, the cf3 corrected record, although not supported by statistical tests, suggests late 20th century temperatures on par with MWP conditions.

Interestingly, so-called “Little-Ice-Age-type events” (Wanner et al., 2000) likely forced by interactions between volcanic eruptions and solar minima (e.g. Maunder or Dalton minimum) are not recorded in any of the reconstructions. This could be related to the earlier stated fact, that warmer conditions seem to produce stronger and more uniform reactions of the carbon isotope ratios due to reduced stomatal conductance than cool conditions (Treydte et al., 2001).

4. DISCUSSION

We were able to systematically demonstrate that low-frequency patterns in our millennium-long $\delta^{13}\text{C}$ tree-ring chronology are not only related to climate variation, i.e. temperature but most likely depend on assumptions of the plant physiological response to anthropogenic changes in the atmospheric CO_2 concentration. In the following we discuss (a) potential age-trends and high-frequency signals, (b) low-frequency signals and CO_2 -correction, and finally (c) our Millennium-long temperature reconstruction.

(a) So-called juvenile effects with depleted $\delta^{13}\text{C}$ values in the first 30–50 years of growth are reported from several

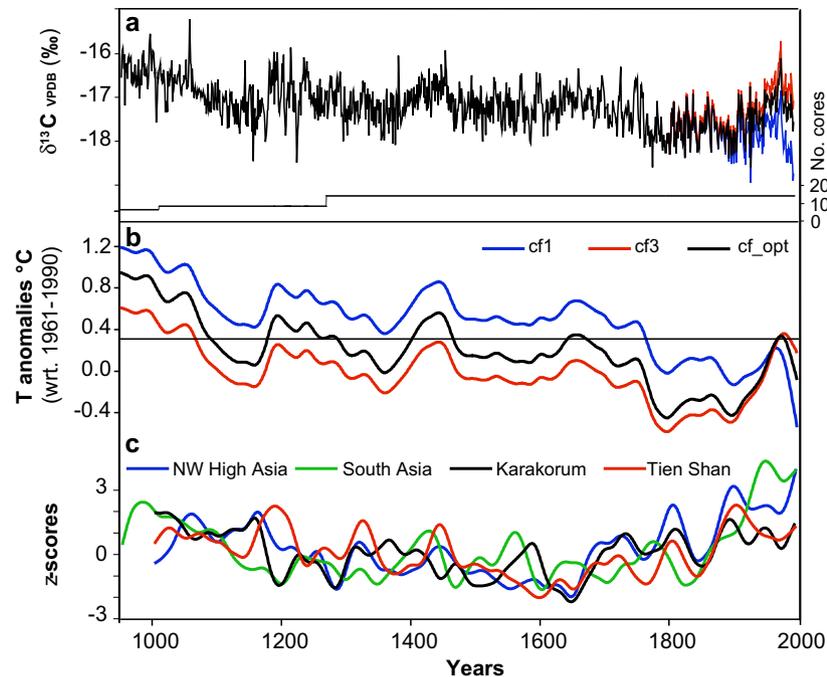


Fig. 8. Temperature reconstruction for the Karakorum and comparison with regional records (a) Mor-high record after application of the cf1, cf3 and the “optimum” correction. The record starts in AD 950 with a replication of three trees (6 cores). (b) Reconstructions in °C based on the cf1, cf3 and cf_opt corrections. (c) Regional temperature reconstructions for the past millennium (Karakorum = Esper et al., 2002b, Tien Shan = Esper et al., 2003, NW High Asia = Esper et al., 2007, South Asia = D’Arrigo et al., 2006). Records in (b) and (c) are smoothed with 60-year cubic smoothing splines with a 50% variance cut-off at 60 years.

investigations, mostly explained by recycling of depleted ^{13}C respired by young trees growing close to the forest floor or below the canopy of surrounding trees (Schleser and Jayasekera, 1985; Bert et al., 1997; McCarroll and Loader, 2004; Gagen et al., 2007). Such effects are probably reduced in the Karakorum tree-line situation with meager soils, open and windy slopes and sparse tree cover. We cannot fully exclude potential age-related changes in the hydraulic activity or in the photosynthetic rate of our trees, which also could be mirrored in the $\delta^{13}\text{C}$ values (Yoder et al., 1994; McCarroll and Loader, 2004, and references herein). Our data are, however, not sufficient to appropriately address whether there exists an age-trend or not, which is in contrast to the findings from oxygen isotope data of the same trees and sites clearly pointing to such an effect (Treydte et al., 2006).

Strong high-frequency correlations to summer temperatures (June/July) and weak precipitation relationships at high-elevation sites (particularly Mor-high and Bag-high) suggest that leaf internal CO₂ concentrations in these altitudes are mainly controlled by the carboxylation efficiency of the photosynthetic active enzyme Rubisco during the vegetation period rather than by variations in stomatal conductance. Since, however, several inter-related climatic factors influence photosynthesis, at least part of the temperature signal may be indirect as well due to correlation between temperature and other controlling factors, such as irradiance, sunshine duration or vapor pressure deficit (McCarroll et al., 2003; McCarroll and Loader, 2004; Frank et al., 2007a). Calibration tests at our sites are lim-

ited in this sense due to the absence of sufficiently long instrumental series of such more “biologically relevant” data. In comparison Bag-low as a warm/dry site in the high-frequency correlates most strongly and negatively with winter precipitation (particularly January). This relationship suggests that here stomatal conductance mainly controls carbon isotope fixation via its dependency on soil moisture, i.e. spring water supply provided by snowmelt.

(b) Including the low-frequency domain in the correlation analyses clearly indicates that the widely used correction for the decrease in $\delta^{13}\text{C}_{\text{atm}}$ values alone does not result in an optimal fit to the long-term trend of the target instrumental data. Obviously some of the low-frequency signal is still suppressed by non-climatic trends in the records, which is hypothesized to be related to the increase of atmospheric CO₂ concentration and plant physiological reactions via leaf internal ^{13}C discrimination changes (Feng and Epstein, 1995; Treydte et al., 2001, 2007; Saurer et al., 2003; Gagen et al., 2007; Kirilyanov et al., 2008; McCarroll et al., 2009).

Although simply applying published values for such discrimination changes (Feng and Epstein, 1995; Kürschner, 1996) significantly improve the climate signal in our Karakorum records, these values are mostly derived from eco-physiologically different conditions and therefore are not directly transferable to our sites: Kürschner (1996) used *Quercus petraea* in greenhouse experiments under elevated CO₂ (350–700 ppmv). Feng and Epstein (1995) used $\delta^{13}\text{C}$ tree-ring records from several species and different sites with a striking downward trend starting at the beginning

of the 19th century and $p\text{CO}_2$ increase from 277 ppmv in AD 1744 to 351 ppmv in AD 1988. To see if the CO_2 concentration is related to the unexplained depletion in the trend of $\delta^{13}\text{C}_{\text{plant}}$, they plotted the difference between $\delta^{13}\text{C}$ of tree rings and $\delta^{13}\text{C}_{\text{atm}}$ as a function of CO_2 concentration and found a highly significant linear relationship with a slope of the regression line of $0.02\text{‰}/\text{ppmv}$. From our knowledge these numbers (0.0073 and $0.02\text{‰}/\text{ppmv}$) represent the lower and upper range of potential discrimination values published, even partly among non-tree species (Beerling and Woodward, 1995; Miglietta et al., 1998; Saurer et al., 2003), and therefore are an appropriate basis for our tests.

There are, however, some general problems related to directly transferring discrimination values from (a) short-term (e.g. seasonal observations) to long-term response (decadal to centennial scales), (b) juvenile trees to mature trees and (c) greenhouse conditions to the forest level. Moreover CO_2 changes in the natural environment might be accompanied by changes in other environmental parameters such as temperature and/or relative humidity and nutrient availability, and the trees' response to all of these changes may be different than the response to CO_2 concentration changes alone. There exist additional uncertainties about the linearity of the response to low and high atmospheric CO_2 concentrations: The response to an increase of pre-industrial 280 to present 380 ppmv might be stronger than the response in a more "saturated" CO_2 environment between e.g. ambient 350 and 550 (or higher) ppmv. This hypothesis is partly confirmed by the strong difference of 0.013‰ between the discrimination numbers of Kürschner, derived from greenhouse experiments at higher than present $[\text{CO}_2]$ and those of Feng and Epstein derived from $\delta^{13}\text{C}$ tree-ring records.

With our approach of statistical testing across a broad range of discrimination factors to identify those most consistent with the target climate data, we overcame some of the limitations described above. These tests also explicitly show that it may not be possible to propose a standard optimum correction universally applicable independently from individual site ecology and climate sensitivity. Therefore, all statistical tests applied that finally lead to an optimum correction factor valid for a specific $\delta^{13}\text{C}$ record, need to be individually repeated for and adapted to any new data set. Moreover the test results also highlight the need for significant relationships between proxy and target to define optimum correction factors for discrimination changes in every single record.

We have also shown that the correction required optimizing the fit between $\delta^{13}\text{C}$ and instrumental relationships, depends on the chosen goodness of fit metric. This holds particularly prior to 1950 when the CO_2 increase was relatively small, thereby making any assessments especially with the pre-1950 data insecure. Considering the fit over the full period of overlap mitigates some of these uncertainties. However, a limitation of this approach is that it assumes both the $\delta^{13}\text{C}$ -climate and $\delta^{13}\text{C}$ - CO_2 relationships are linear and stationary.

Besides, there exists some additional uncertainty concerning the long-term trends in the instrumental data

(Frank et al., 2007a), particularly when using grid point data from regions with patchy spatio-temporal coverage of site meteorological records (Mitchell and Jones, 2005). So, the difficulty to clearly define an optimum correction factor for our sites might also be partly related to this uncertainty of the target data, as well as to dependencies upon the particular time periods and seasons chosen for analysis (Frank et al., 2007a).

An alternative correction approach recently published by McCarroll et al. (2009), the so-called "pin-correction" claims to act independently of any instrumental target since it is based on physiological constraints only: (a) a passive plant physiological response to higher atmospheric CO_2 concentration, where $c_a - c_i$ is kept constant and (b) an active response, where c_i/c_a is kept constant. The approach aims to remove only that portion of decline in $\delta^{13}\text{C}$ (increase in c_i) that could be attributed to the increasing atmospheric CO_2 concentration c_a , thus hopefully leaving trends that are due to climate. However, the long-term fitting applied in step one (non-linear loess regression) directly impacts the slope and direction of the trend of the pin-corrected record. The stiffness of this function can be widely varied "to fit the low-frequency behavior of the data" (McCarroll et al., 2009), but it remains unclear, which fit is the most appropriate to describe this low-frequency pattern. Therefore, either subjective user decisions or objective metrics are required, such as spectral or wavelet methods, generalized cross validation or comparisons with the instrumental target. At least with the latter case similar limitations inherent to our approach would emerge.

(c) Applying different corrections to the millennium-long $\delta^{13}\text{C}$ tree-ring record dramatically highlights the importance of potential physiological reactions on the reconstructed long-term temperature signal and particularly questions the commonly used correction for atmospheric $\delta^{13}\text{C}$ changes only. The cf_{opt} corrected reconstruction, however, provides more insight in the overall long-term temperature pattern of Western High Asia. Recently, Esper et al. (2007) reported that comparison of high-elevation composite ring-width records from the Karakorum and Tien Shan with earlier temperature reconstructions (Esper et al., 2002b, 2003) has generated additional doubt that the low-frequency temperature history in this region is fully understood. Our reconstruction confirms much of the picture already known such as the existence of a MWP, cooler conditions during the LIA and warming towards the 20th century. This match broadly acts as a long-term validation for the correction factor derived from statistical comparisons to instrumental data. Even though, due to lower sample depth, some care is needed in the interpretation of our data during the MWP, in turn, the reconstruction provides additional suggestions that High Asian temperatures during the MWP might have exceeded recent conditions. This finding is also hypothesized, but difficult to confirm with ring-width data from living trees (Esper et al., 2007).

Since our tree-ring $\delta^{13}\text{C}$ based reconstruction of summer temperatures in the Karakorum is produced on the basis of empirical correlation results, rather than causative mechanistic links, the corrections applied and the reconstruction itself nevertheless need to be interpreted with care, and with

reference to other possible climatic controls. Although not seen in the correlations, we cannot exclude that during dry years the signal tends to be dominated by stomatal conductance, such as variation in air humidity and those variables controlling the soil moisture status (Gagen et al., 2007). So, assumptions of temporal stability in the relationships between climate and tree-ring isotopes might be generally questionable. Reynolds-Henne et al. (2007) recently stated, that long-term trends in isotope records of Swiss tree sites are not well represented by 20th century relationships, as the sensitivity to climate conditions seems to increase strongly during this period of increased anthropogenic influences. Physiologically dominated growth (controlled e.g. by competition for nutrients) may change to climate limited growth in a very short period of time, even in mature temperate trees located at what are considered non-limiting sites.

Being aware of these above described limitations, we are not aiming to provide an ultimate and general correction for tree-ring δ¹³C changes that is independent of site-specific conditions. We can, however, provide evidence for a long-term response of trees to increased atmospheric pCO₂ via leaf internal δ¹³C discrimination changes, a fact not yet systematically accounted for in many studies that use tree-ring δ¹³C as a proxy for climate reconstruction.

5. CONCLUSIONS

We evaluated the response of a millennium-long (1171-year) and three 100-year δ¹³C tree-ring chronologies from ecologically varying *Juniperus* stands in the Karakorum Mountains/Pakistan to climatic and atmospheric CO₂ changes.

Our results systematically prove, that the widely used correction of δ¹³C tree-ring records for anthropogenic changes in atmospheric δ¹³C alone may not appropriately capture the long-term climatic changes as recorded in 20th century station data. Obviously an additional plant physiological response to increasing atmospheric CO₂ concentration needs to be taken into account, a fact widely ignored when correcting δ¹³C tree-ring records to meet pre-industrial “natural” conditions. This response is basically related to higher ¹³C discrimination at the leaf level, resulting in lower tree-ring δ¹³C values. Whether such responses have an influence on the photosynthetic rate and/or above or below ground biomass production is still unclear.

The statistical approach for correcting those discrimination changes as it is presented here appears to improve the quality of our long-term temperature signal. The method is straightforward and can easily be tested on the many published tree-ring sets available in the literature, since it requires isotope and meteorological data only. It is limited, however, in sense that the shape of the reconstruction is no longer independent from the (often insecure) trends in the instrumental data. Therefore, the consequences of possible over-fitting have to be explored and understood before a site-specific correction factor can be recommended. Similar limitations, however, may appear with recently published, alternative correction approaches (McCarroll et al., 2009).

Therefore, from our perspective, δ¹³C tree-ring records are still strongly limited in contributing to the ongoing discussion on long-term frequencies and amplitudes of climate change over the past millennium, although they carry strong climate information in the high-frequency domain.

Future studies need to be carried out, which, in the optimum case, combine different approaches: (i) application of large data sets, representing different site conditions and species under varying climatic conditions and regions with dense and high quality target (climate) records, and (ii) application of advanced physiological models.

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