CLIMATIC SIGNAL IN TREE-RING CHRONOLOGIES OF *CEDRUS DEODARA* FROM CHITRAL HINDUKUSH RANGE OF PAKISTAN

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Abstract: Tree-rings are an important tool for the investigation of paleoclimatic records for regions or periods of time with no instrumental climatic data. However, the responses of different species and sites to various climatic parameters are unusual. In the present study, we developed tree-ring-width chronologies of *Cedrus deodara* from three different sites of Chitral Hindukush range of Pakistan. The study was conducted to understand tree-growth climate relationship and its applicability in proxy climate investigations. The chronologies covered the past 469 to 595 years, with a mean segment length (MSL) ranging from 148 to 223 years. Climatic data obtained from the three weather stations showed strong correlation and was found useful for tree-ring climate relationships.

Correlation Function (CF) and Response Function (RF) analysis showed that spring precipitation (March-May) is a critical limiting factor for tree-ring growth, and temperature prior to November may also play a major role in affecting tree ring-growth. The results exposed that the three sites have continuous relationship indicated that only single species from different locations are affected by the same environmental variables and hence can be used in climate reconstruction in combination. The *Cedrus deodara* chronologies developed at different locations had several corresponding narrow and wide marker rings indicating a large macroclimatic response to regional climatic conditions. The current study suggests that the tree-rings of *Cedrus deodara* from the Chitral Hindukush range could be used to develop chronologies for the reconstruction of seasonal climatic variables.

Keywords: *Cedrus deodara*, tree-growth, proxy climate, response function, Hindukush range.

1. INTRODUCTION

Dendrochronology is a "young science" and has been expanding rapidly in Pakistan and so far substantial progress has been made since the pioneer work of Champion *et al.* (1965), Khan (1968) and Sheikh (1985). These workers used *Pinus gerardiana*, *Pinus wallichiana* and *Juniperus excelsa* from Zhob District and Azad Jammu-Kashmir areas for age determination based on simple ring count without applying standard dendrochronological techniques. However, in other parts of the world investigators have used tree rings for a variety of applications, including: silvicultural treatments on managed forests (Guilley *et al.*, 1999; Bridge and Winchester, 2000); reconstruction of past climate (Briffa *et al.*, 2001; Watson and Luckman, 2001; Speer, 2010); reconstruction of insect outbreaks (Swetnam and Lynch, 1993; Speer *et al.*, 2001); reconstruction of past wildfires (Swetnam, 1993; Grissino-Mayer and Swetnam, 2000; Brown *et al.*, 2011); and reconstruction of earth processes (Yamaguchi *et al.*,

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1997; Gartner *et al*., 2001). In Pakistan these information are scanty and so far very little is known about the dendroclimatic potential of conifers. Among these, conifer *Cedrus deodara* is an important tree species and declared as the national symbol of Pakistan (Ahmed *et al*., 2011a; Khan *et al*., 2012).

Studies have shown that conifers could be used in climatic investigations including *Cedrus deodara* in the Himalayan region (Ahmed, 1987; Bhattacharya and Yadav, 1999; Yadav and Park, 2000; Singh and Yadav, 2007; Singh *et al*., 2009; Ahmed *et al*., 2009, Ahmed *et al*., 2011b). However, most of these studies were restricted to the western Himalayan region and few studies were conducted in eastern parts and all of them have been based on conifer species (Ahmed *et al*., 2011b). The eastern parts of the great Himalayan region have extensive forests with a number of species distributed in the moist and dry temperate parts of the country (Ahmed *et al*., 2006). These forested zones were elucidated for dendroclimatic potential of different conifer species by Ahmed *et al*., 1987. They explained the scope of dendrochronology in Pakistan and mentioned some suitable sites and tree species which could be used in tree-ring analysis. Ring-width series of *Juniperus excelsa* and *Juniperus turkestanica* from six different sites in the Hunza–Karakorum were used in reconstructing modes of regional climate over the past 500 years by Esper (2000). He derived all reconstructions from trees growing close to the upper timber line (4000 m a.s.l.). Similarly, Esper and Genrt (2001) presented a tree ring reconstruction of climate extreme years since 1427 AD from western central Asia. They classified the extreme growth reactions into event years – reflecting extreme years of individual trees, site point years – reflecting common extreme years within a site, and regional pointer year – reflecting common extreme years within the Karakorum and Tien Shan. Ahmed and Naqvi (2005) established tree-ring chronologies of *Picea smithiana* from moist and dry temperate forest of Himalayan range of Pakistan and demonstrated that dry temperate sites show low autocorrelation as compared to moist temperate sites. Whereas, Khan *et al*. (2008) developed a first 343 years (1663-2006 AD) dated tree-ring chronology from Afghanistan adjacent to Pakistan border. They suggested that this species have high dendroclimatic value and more information could be obtained if this chronology were correlated with other regional chronologies of the same species. Good crossdating with high correlation were achieved by Ahmed *et al*. (2009) for *Abies pindrow* and *Pinus wallichiana* from two different climatic zones and concluded that both the species are suitable for paleoclimatic reconstruction back to at least 500 years.

In addition, four conifer tree species from seven catchments in the upper Indus basin were explored for dendrohydrological potential by Ahmed *et al*. (2010). Based on their encouraging results they concluded that these tree species chronologies have high potential for dendrohydrological investigation. More substantial information regarding the tree-ring chronologies and their potential for dendroclimatic reconstruction is presented by Ahmed *et al*. (2011a) from northern Pakistan. They used six tree species and 28 chronologies, out of which several species had trees attaining ages of around 700 years. Correlations between site chronologies were consistently seen both between sites of the same species and between sites composed of different species. They also demonstrated that strong elevational gradient was present in this mountainous region which lends support to the practice of multi-species combination for better spatial and temporal coverage. This network of tree-ring chronologies led to the reconstruction of upper Indus basin river discharge level covering the period AD 1452-2008. However, there is still a considerable gap to explore some other promising sites which are expected to be sensitive to climate regime. Such sites are more desirable for the enhancement of tree-ring research (Fritts, 1976; White, 2007). Because, better understating of the spatial patterns in climate change variability requires expansion of sample collections over diverse areas (Huang and Zhang, 2007). Publications have shown that tree-ring chronologies provide valuable data bases for the enhancement of meteorological records (Pant and Borgaonkar, 1983; Ramesh *et al*., 1985; Hughes and Davies, 1987; Yadav and Bhattacharyya, 1994; Bhattacharyya and Yadav, 1992. But there is a paucity of weather stations in the vast region of northern Pakistan and the observed climatic records in these stations are usually of relatively small duration (around 40 years) with some missing information (Archer and Fowler, 2004; Ahmed *et al*., 2009). The lack of such information has hindered our ability to obtain a comprehensive long term climatic variability over large spatial scale (Huang and Zhang, 2007). Therefore, it is critical to develop long time-series of high resolution proxy data back in time for better understanding of the past climate variations (Cook *et al*., 2003; Zhang and Zhang, 2011). Such long-term climatic data series, derived from tree-rings, is desirable since that would be helpful in identifying pre-industrial climate variability, understanding of extra-regional climatic coupling, sequence, phasing and, perhaps more importantly, in distinguishing natural variations from anthropogenic causes (Yadav *et al*., 1997).

In this context previous studies demonstrated that the conifers including *Cedrus deodara* possess great potential and are recommended for climatic investigations due to the fact that the tree species exhibits positive tree-ring characteristics such as old age (longevity), good sensitivity and shows promising response to climate (Ahmed *et al*., 2011a, 2011b). In view of these considerations, the present study was conducted, and an attempt was made to report the dendroclimatological potential of *Cedrus deodara* from Chitral Hindukush range of Pakistan. The aims of the study were to develop multi-century long tree-ring chronologies for the species and to explore the relation-

ships between tree-ring growth and climatic variables. These findings are expected to provide baseline data for the regional climate variability in the past.

2. MATERIALS AND METHODS

The Study Area

Chitral Mountains are located in the Hindukush range of Pakistan that lies in the extreme north east of Malakand division Khyber Pakhtunkhwa (Khan *et al.*, 2010). The area is parallel to the pan shaped Wakhan corridor of Afghanistan (**Fig. 1**) spanning from 35°13' and 37°50' N latitude and 71°12' to 73°45' E longitude (Manfred and Zimmer, 2000; Ali and Qaiser, 2009). Geographically the area is bordered on the east by district Ghizer of Gilgit-Baltistan Province while Dir, Swat and Kunar (province of Afghanistan) lie in the south (Jan, 1997; Sethi, 2001). Nuristan province lies across the border to the west and on the Northwest by Wakhan corridor which separates Pakistan and Tajikistan (Jose, 1987; IUCN, 2004; Ali and Qaiser, 2005). Sample collection was conducted the 2 valleys, *i.e.* Chitral Gol and Bumburate located near Drosh and Chitral meteorological stations with elevation range between 1329 to 7708 m a.s.l. Sixty percent of the study area is situated at elevation above 3000 m, which is perennially snow-covered (Ajaz, 2004; Zarif, 2004). The runoff-source area below the snow line, at elevations of 1500 to 3600 m, is well vegetated and has ample precapitation (Alamgir, 2004). The district is mainly located in the dry temperate zone of Pakistan with an elevations range from 1070 to 7708 m creating many local climatic and vegetation zones.

Although the area is predominately arid, there is wide floristic variety of forest and non-forest vegetation due to the variety of ecological zones. Mixed conifer forests form an important zonal vegetation type in the area (Khan *et al.,* 2010) and are distributed between 1800-2900m a.s.l. on either side of River Kunar (Ajab, 1993; Ahmed, 1998). *Cedrus deodara* is the national tree symbol and the large evergreen tree with its natural distribution all along the Hindukush and Himalaya at altitudes ranging from 1800-5000m a.s.l. (Nasir and Ali, 1972; Ahmed *et al.*, 2011b). Tree-ring samples in form of cores of the species were collected at three valleys and three sites near the upper tree line in the Chitral Gol, Bumburate and Ziarat (**Fig. 1**; **Table 1**). The environments of the sites vary considerably in terms of topography and forest composition. The site at Kalash valley (2283m) has steep slope (62°) whereas, at Chitral Gol and Ziarat with comparatively low elevations and degree of slopes (**Table 1**). The main associates of *Cedrus* are *Pinus gerardiana*, *Pinus wallichiana*, *Picea smithiana*, *Abies pindrow*, *Juniperus excelsa*, *Quercus baloot* and *Quercus dilitata* in the study area (**Fig. 2**). The sites were deterministically chosen for sampling with the considera-

Table 1. *Site characteristics for five tree-ring sampling sites in the Chitral mountains.*

Site	Species	Long. (E)	Lat. (N)	Elev. (m)	Aspect	Slope
Kalash	CD	71°38	35°41	2283	NE	62°
Chitral Gol	CG	71°40	35°56	2331	W	28°
Ziarat	CD	71°48	35°21	2900	NW	27°

Note: CD = Cedrus deodara, Long = Longitude, Lat = Latitude
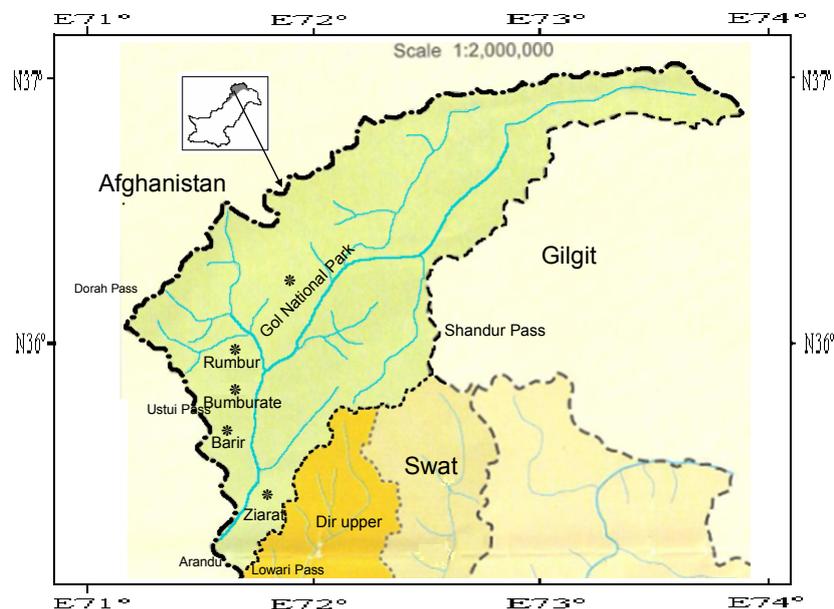
Fig. 1. *Location of tree-ring sampling sites are shown with stars.*

tion that they were subjected to least anthropogenic disturbance. Two increment cores per tree contingent upon the accessibility were obtained on 90° and as a result 19 to 27 samples for individual tree species were gathered (**Table 2**).

Dating and chronology preparation

The wood sample in the form of cores were air-dried, mounted, and sanded with progressively finer grade sandpaper in order to achieve a shiny surface of tree-ring boundaries (Stokes and Smiley, 1996). The prepared samples were subjected to standard dendrochronological techniques for visual cross-dating by employing skeleton plot procedure following the method outlined by Fritts (1976) and Cook and Kairiukstis (1990). This procedure

Fig. 2. Cedrus deodara *(National symbol of Pakistan) at Chitral Gol National Park site.*

enabled us to detect the problematic zones such as narrow or false rings and some of these were removed before continuing with the analysis (Grissino-Mayer, 2003; White, 2007. The visual cross-dated ring-width sequences were measured using VELMEX measuring system comprising of a microscope, movable stage joint with J2X measurement software. The individual ring measurements were obtained to the nearest 0.001 mm. In the next step the visual cross-dating ring width measurements were ensured using the quality control program COFECHA (Holmes, 1994; Grissino-Mayer, 2001). Poor correlation among many radii led to the rejection of few core samples for further analysis similar to the practice of Yadav *et al.* (1997). Finally, we selected 19 cores from 10 trees of Kalash valley, 27 of 16 trees of Chitral Gol and 23 samples from 16 trees of Ziarat valley for chronology preparation.

The measured series of individual dated sample was transformed to ring-width indices by employing ARSTAN software (Cook, 1985, Holmes, 1994). This procedure was practiced to remove age and other non-climatic trends and involved fitting a spline that was two thirds the length of the common period of the tree-ring series (Heinrich, 2004). The Expressed Population Signal (EPS; Wigley *et al.*, 1984) was used to assess the loss of common variance over time with decreasing sample size for all the chronologies. The chronologies were truncated when EPS dropped below the value 0.85. We used the three standardized tree- ring chronologies of *Cedrus deodara* in order to obtain various statistics that would be helpful in the exposition of the dendroclimatic potential in the climate change scenario. In addition, these chronologies will be useful to detect the potential of the species for the reconstruction of climate and river flow in the area in future.

Climatic Data

The climatic data derived from the meteorological stations located in close proximity of the sampling sites is suggested by workers for better interpretation of tree-growth climate relationships (Yadav *et al*., 1997; Heinrich, 2004). However, in northern Pakistan, meteorological stations with long, homogeneous records are few and usually located far from the forested areas or tree-ring study sites (Ahmed *et al*., 2009; Ahmed *et al*., 2011a). The climatic parameters from any such single station
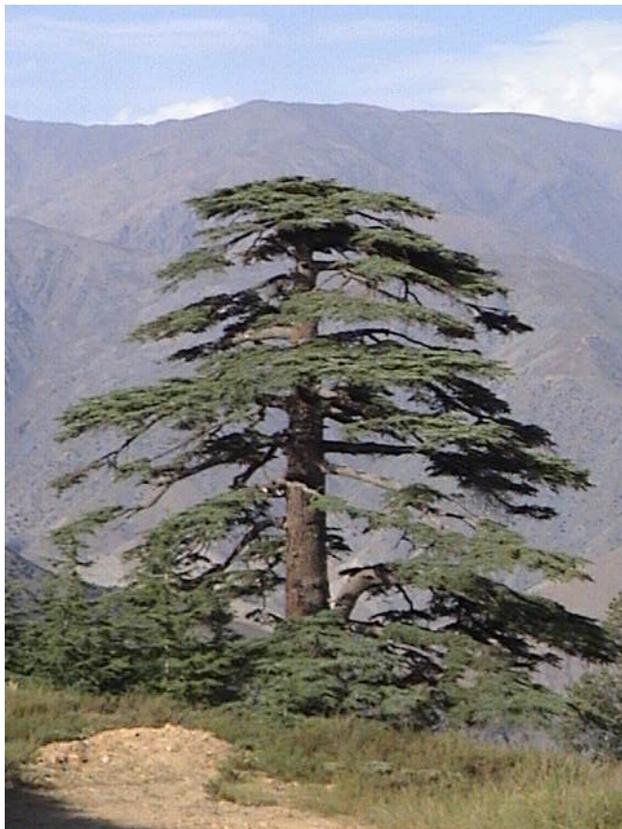
Table 2. S*ummary statistics of tree-ring width chronologies of* Cedrus *obtained from three different sites.*

Chronology Sites	No. of samples	Chronology Span	MAI (mm)	MSV	SD Mm	RBAR	SI	AR	EPS
CDK	(10) 19	1411-2006	0.88 (0.587/6.14)	0.227	0.587	0.442	0.667	0.877-0.006	1670
CDCG	(16) 27	1537-2006	1.44 (0.714/7.29)	0.210	0.714	0.287	0.637	0.853-0.002	1730
CDZ	(16) 23	1472-2005	1.49 (0.728/8.34)	0.213	0.728	0.471	0.539	0.824-0.001	1960

MAI: Mean (min/max.) annual increment; MSV: mean sensitivity value; SD: standard deviation; RBAR: mean correlation coefficient between all tree-ring series used in a chronology; SI: Series Intercorrelation; AR: variance related to autoregression; EPS: 1st year expressed population signal 0.85.

cannot be assumed to be representative of regional climate and may not provide ideal data for calibrating tree-ring data from distant sites (Mitchell *et al.*, 1996). In such cases averaging of two or more meteorological station records avoids many problems associated with record inhomogeneities and deferring station microclimates so that they can provide potentially more reliable data to calibrate tree-ring chronologies (Blasing *et al.*, 1981; D'Arrigo and Jacoby, 1993; Jacoby *et al.*, 2000). In addition, Fritts (1976) and Pant and Borgaonkar (1984) suggested the use of climatic data of stations located even at some distances from the tree-ring sites for the calibration of tree-growth climate relationships.

In the present study, we have employed climatic data of temperature and precipitation from Drosh (1400 m a.s.l.) and Chitral meteorological stations (1350 m a.s.l.) around 100 km of the sampling sites for tree-ring calibration in the Response function (RF) analysis. As some years in the monthly annual data were missing for both the stations for climatic variables. Therefore, we used average monthly temperature and total precipitation data for the period starting from 1965-2009. The location and type of data for both the parameters (temperature and precipitation) have not changed and the data for both the stations were tested and found homogenous for the entire period following Mitchell *et al.* (1996) and Heinrich (2004). The two climatic parameters for both the stations were found to be strongly correlated (r = 0.999, P<0.001) using Pearson product moment correlation for the entire period. However, the homogeneity plots for mean temperature and precipitation of Dir station exhibit inhomogeneities which were excluded from analysis.

Tree growth-climate relationship

Correlation and Response function analyses were used for the exploration of tree-growth climate relationship (Fritts, 1976). However, the response function (RF) techniques were used with the modification of Guiot *et al.* (1982) and Cook (1985). Among the three discrete versions of chronologies standard version was preferred due to the lag year effect (White, 2007; Yuan *et al.*, 2007). The selected chronology of each site and local climatic data (precipitation and temperature) were treated separately in the response function analysis. Average monthly temperature and total monthly precipitation starting from previous October to August of the current growth year were used. Mean monthly temperature and total precipitation is recommended by Fritts (1976) to perform adequate response function analysis. Forty three years climatic data (1965-2009) were taken for response function analysis. Gordon (1980) and Blasing *et al.* (1981) have suggested that a minimum 42 years predictors (ring-width data) and predictands (climatic record) is required to perform a reliable response function analysis. Correlations were also calculated between tree-ring chronologies and climatic data over multi-month seasons following Huang and Zhang (2007). Bootstrap method of

Guiot (1991) was followed for the test of significance of response coefficients derived from response function analysis.

3. RESULTS

Tree-ring chronology development

The tree ring-width chronologies of *Cedrus deodara* from three different sites of Chitral Hindukush range of Pakistan (**Table 2**; **Fig. 3**). The chronologies covered the past 469 to 595 years, with a mean segment length (MSL) ranging from 148 (TC) to 223 years (BD). *Cedrus deodara* at Bumburate Kalash valley exhibited an age range from 128 to 596 years while the chronologies from individual sites of Chitral Gol and Ziarat valley furnished a 469 and 533 years tree-ring chronology respectively. These chronologies were obtained between an altitudinal range of 2283m to 2900m a.s.l. and 27 to 62° moderate slopes (**Table 1**). Out of 42 trees (69 samples) 7 samples were found in the age range between 200 to 300 years, 6 were above 300 years while 2 samples attained ages above 550 years (**Fig. 3**). These sites are located on northeast, north and northwest aspects consisting of generally slow growing trees with a mean annual increment between 0.88 and 1.49 mm (1.27±0.10 mm). The standard deviation (stdv) of the raw values follows the rules that slow growing trees in these sites have low variance (0.587-0.728 mm). However, the value of mean sensitivity (MS) characterizing the year to year variability in tree-rings was almost similar and relatively high (0.21-0.227) compared to that of other species. The sites chronologies in terms of their quality regarding the usefulness for dendroclimatic studies were evaluated. The statistics of the chronologies showed that the EPS values attained were generally within recommended threshold value of 0.85 for the Chitral Gol site, Kalash and Ziarat valleys. The chronologies indicated that the early part of the chronologies has small sample size and limited to the year when the value for EPS dropped below 0.85 which resulted the cut-off in 1670 for Chitral Gol, 1730 for Kalash valley. Wheras, Ziarat chronology hold this value up to 1960 which is comparatively low from the prior two chronologies sites (**Table 2**). In addition, the running Rbar displayed high variability over time, this statistics was rather stable during the robust intervals (EPS > 0.85) of the chronologies.

The results disclosed that elevation also plays an important role in the growth pattern of *Cedrus deodara* in the study area. In comparison to the 2 chronologies at high elevations the tree-ring series at a low elevation have high mean ring width and standard deviation values (**Table 2**). The signal to noise ratio (SNR) in tree-rings ranged from 8.1 to 19.0, indicating that the ring width data had some autocorrelation (0.82-0.87) that was presumably caused the biological feedback. The relatively high values of intercorrelation being higher (0.53-0.66)
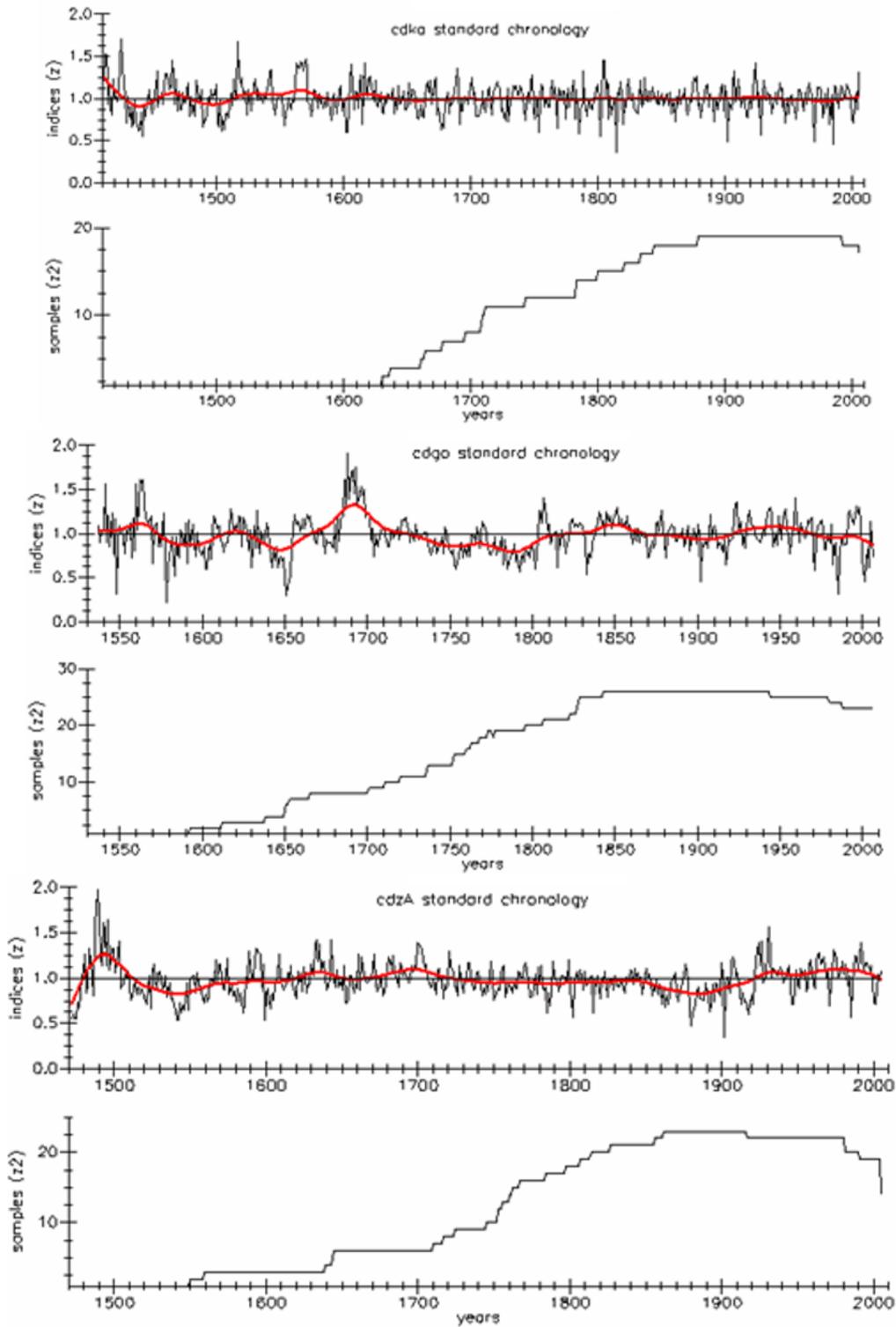
Fig. 3. *Standard tree-width chronologies of Cedrus deodara (top) with averages and a sample size (bottom) from Bumburate Kalash Valley, Chitral Gol National Park and Ziarat sampling Sites.*

for the low elevation. The relatively high level of VFE (Variance in First Eigenvector) (20.9 to 28.6%) indicating strong common signals among the trees constituting the mean chronology. Therefore, our tree-ring chronologies provided a robust estimate of the mean tree growth and are suitable for dendrochronological analysis.

The presence of a common climatic signal in the three chronologies was confirmed by the time span overlap analysis (TSOA). The cross correlations (CC) among the different site chronologies were tested for a common period of 100 years (1900-2000) time span. Correlation matrix (CM) of tree-ring width indices illustrate that *Cedrus deodara* from Chitral Gol site exhibited strong relationship (r = 0.67, P < 0.001) with Kalash valley and Kalash valley with Ziarat site (r = 0.54, P<0.01) and Ziarat with Chitral Gol (r = 0.65, P < 0.001) respectively. The high values of the first-order autocorrelation (AR; 0.82-0.87) are an indication of the low frequency variance embedded in the series, and could be explained by climate or by the lagged response of tree physiology. In addition, ARSTAN program computed overlapped time span in order to demonstrate the correlation between each sample. The statistical properties of different tree series resulting from ARSTAN for a common period are shown in **Table 3**. The results indicated that the mean correlation among all radii ranged between 0.32-0.37 and the eigenvector ranged between 21.8 and 45%. The mean correlation among all radii, mean correlation between trees, mean correlation within trees and variance associated with first eigenvector demonstrate that the species ring-width exhibited high correlation within trees. These results revealed that *Cedrus deodara* not only display strong correlation among samples of the same sites but also with different sites.

The extreme common narrow and wider rings in *Cedrus deodara* in the three different sites chronologies in the present study site were recorded. The years of narrow rings including the years 2001, 1999, 1998, 1995, 1988, 1984, 1952,1921, 1915, 1900, 1882, 1878, 1848, 1808, and 1752, while the wider rings appear in years 1932,1920, 1870, 1810, 1752, 1688, 1608, 1511, 1460 and 1420 respectively.

Growth/climate relationship

The results of the correlation function from the three different tree-ring sites using standard chronologies and climatic data from Chitral meteorological station (CMS)

(temperature and precipitation) is depicted in **Table 4**. The response function (RF) results from the same set of data as used in **Table 4** are presented in **Table 5**. The results in **Table 5** show temperature from January to May of the current year having a negative correlation with tree-ring width. The exception was April temperature which exhibited a positive correlation for *Cedrus deodara* at the Kalash tree-ring site. On the other hand, precipita-

Table 4. *Correlation coefficients between different tree-ring sites (standard chronologies) and climatic data from Chitral meteorological station (temperature and precipitation data). Only significant responses are shown (i.e. +/-).*

	CdK	CdCG	CdZ	+	-
pSepT					
pOctT					
pNovT					
pDecT					
JanT		-	-		2
FebT		-	-		2
MarT	-	-			2
AprT	+	-	-	1	2
MayT	-	-	-		3
JunT					
JulT					
AugT					
pSepP					
pOctP	+			1	
pNovP	-		-		2
pDecP					
JanP					
FebP	+	+		2	
MarP	+	+		2	
AprP	+	+	+	3	
MayP	+	+	+	3	
JunP	+	+		2	
JulP					
AugP					
Lag 1		+	+	2	
Lag 2					
Lag 3					
+	7	5	2	14	
-	3	5	5		13
Climate	63	61	52	58±3.3	
Lag	11	22	15	16±3.2	
Total	74	83	67	74	

Note. p=previous year, T= temperature, P= precipitation, CdK= Cedrus deodara from Kalash, CdCG=Cedrus deodara from Chitral Gol, CdZ= Cedrus deodara from Ziarat.

Table 3. *Time span overlap analysis of tree-rings chronologies in each site derived from ARSTAN program.*

Time span overlap		No, of trees overlap	No, of radii overlap	% variance in 1st eigen-vector	Mean correlation		
1st year	Last year				Among all radii	Between trees	Within trees
1879	1992	10	19	41	0.368	0.311	0.360
1843	1979	13	25	45	0.378	0.317	0.434
1827	1990	15	20	21.8	0.32	0.098	0.194

tion has a strong positive correlation with tree growth from February to June of the current year for all the sites. Response function (**Table 5**) shows a similar trend of positive and negative responses from March to May temperature of the current year for the species. However, previous December exhibited a negative correlation with tree growth in Bumburate Kalash and Gol National Park chronologies (**Table 5**). *Cedrus deodara* from Ziarat site shows a positive correlation from June to August of the current year. This trend was not observed in the correlation function (CF). The response of precipitation was quite similar for both the approaches with the exception of a negative and positive correlation in the month of current August.

In addition, some positive responses of precipitation in the month of October (labelled OctP) and December (DecP) of the previous year at Kalash was obtained. However, negative correlations in November (NovP) of the previous year were also recorded in both techniques (**Tables 4** and **5**). It is worthwhile to mention that the lag years contributed only 2 positive significant coefficients for *Cedrus deodara* in correlation function while response function yields 4 positive coefficients which are double than that obtained from the correlation function. The overall positive coefficients were 14 while the negative coefficients were 13 in the correlation function. This shows that both temperature and precipitation are significant. Beside the results of correlation function the response function resulted in 20 positive and 13 negative coefficients, which is almost similar to those obtained by the correlation function and the pattern appears consistent. From the results it is obvious that temperature tends to be negative for late winter and spring months. Whereas, precipitation is positive and generally concentrated between February and June of the current year. The correlation function shows an average of 58±3% variance that is explained by the climate and 16±3% by the lag years. The overall variance (i.e. climate + lag) obtained was 74±3% for all the sites. The response function analysis does not give the explained variance making this one of the drawbacks of this technique. In general, a relatively large amount of variance (67-83%) was obtained for all sites and the patterns were similar and consistent.

4. DISCUSSION AND CONCLUSIONS

Tree-ring chronologies

Tree ring data of *Cedrus deodara* were tested for their suitability for further study of dendroclimatology. Several other workers also reported that redial growth of this species is sensitive to climate in the eastern and western Himalaya (Bhattacharyya *et al*., 1992; Pant *et al*., 2000; Yadav, 2013; Ahmed *et al*., 2011a; Wahab, 2011). In the present study, the samples of *Cedrus deodara* correlate well with the site mean. The autocorrelation value at 3 locations of *Cedrus deodara* was low and the mean sensitivity was high. Consequently, on the basis of low auto-

Table 5. *Response coefficients between different tree-ring sites (standard chronologies) and climatic data from Chitral climatic station (temperature and precipitation data). Only significant responses are shown (i.e. +/-).*

	CdK	CdCG	CdZ	+	-
pSepT					
pOctT					
pNovT					
pDecT	-	-			2
JanT					
FebT	+			1	
MarT	-	-	-		3
AprT		-	-		2
MayT	-	-	-		3
JunT			+	1	
JulT			+	1	
AugT			+	1	
pSepP			+	1	
pOctP					
pNovP		-			1
pDecP					
JanP		+		1	
FebP	+	+	+	3	
MarP	+	+		2	
AprP	+	+		2	
MayP	+	+		2	
JunP	+	+		2	
JulP					
AugP		-			1
Lag 1	+	+	+	3	
Lag 2					
Lag 3			-		1
+	7	7	6	20	
-	3	5	5		13

Note. p=previous year, T= temperature, P= precipitation, CdK= Cedrus deodara from Kalash, CdCG=Cedrus deodara from Chitral Gol, CdZ= Cedrus deodara from Ziarat.

correlation at these locations of *Cedrus deodara*, it is suggested that the tree samples do contain some climatic information. The values of mean sensitivity reported in the present study were in the range values reported by other workers for the species (Bhattacharyya *et al*., 1992; Borgaonkar *et al*., 1996; Pant *et al*., 2000; Ahmed *et al*., 2009, Ahmed *et al*., 2010). This gives evidence that the species is suitable for further dendroclimatic investigations, including climatic reconstruction for temperature and precipitation.

As for as the individual chronology of the species are concerned, the Kalash chronology was the longest at 596 years (1411 to 2006), followed by Ziarat site chronology at 534 years (1472 to 2005) and Chitral Gol National Park at 470 years (1537 to 2006). From these results it is noteworthy that the *Cedrus* trees used in these chronologies are long lived and exhibited great age that extend significantly beyond the period of modern climate recorded history (1895-present). It is argued that modern

records are used to calibrate climate reconstruction (Fritts, 1976; White, 2007). Fritts (1976) has reported that older trees should be targeted for sampling at sensitive sites in order to extend the chronologies further back in the time frame beyond the calibration period. In the present study many increment core samples from each site in the chronologies were not included due to time constraints and small sample size. Additionally, in some tree samples could not be cross-dated well because of irregular growth (problematic zone) and complacent ring patterns. Consequently, these cores were not included in the present study.

The comparison of the correlations between different chronologies from the same site and from neighbouring locations exhibited strong correlation (P<0.01) within site and from different sites of the same species. This continuous relationship between sites indicated that only single species from different locations are affected by the same environmental variables and hence can be used in climate reconstruction in combination. These findings are in agreement with those of Battachachryya *et al.* (1988); Ahmed *et al.* (2010) and Ahmed *et al.* (2011a) who reported high mean sensitivity and good intra-species correlations.

The *Cedrus deodara* chronologies developed at different locations had several corresponding narrow marker rings indicating a large macroclimatic response to regional climatic conditions. These extremely narrow rings were also reported by other workers (Esper and Genrt, 2001, Esper *et al.*, 2001; 2002; Ahmed *et al.*, 2010; Zafar *et al.*, 2010) in the same species and even in other species. Some of the negative and positive extreme years listed by Wang *et al.* (2004) and Huttametta (2004) of other conifers from the neighbouring countries also correspond with exceptionally narrow and wider rings found in *Cedrus deodara* in the present study sites. However, Hughes *et al.* (2001) described a signature year if more than 18 out of 23 chronologies exhibit the same growth trend. Therefore, our results are not directly comparable. In the present study negative pointer years with a wide distribution within the study area are more common than positive years similar to that reported by Huang and Zhang (2007). A similar case of pointer years were also reported by Pourtahmasi *et al.* (2007) using *Juniperus polycarpos*. They concluded that the use of pointer years in climatic analysis and their relationship to certain modes of the atmospheric circulation can provide a base for the interpretation of a similar distribution pattern of pointer year's further back in time. Our initial study indicated that pointer years in *Cedrus* can be assigned to distinct local climate anomalies and thus can be utilized in inter-regional tree-ring network to evaluate the distribution and intensity of regional circulation pattern.

The *Cedrus deodara* had the greatest interseries correlation (r=0.67 to 0.88) and mean sensitivity. Greatest sensitivity and correlation of *C. deodara* at Chitral Gol was likely, because tree growth at this location was lim-

ited more singularly by precipitation, whereas, the temperature variable had greater influence on the growth at Kalash valley. A reliable sample depth may also be achieved by using expressed population signal (EPS) which was high for these sites (Heinrich, 2004; White, 2007). Therefore, it is suggested that *Cedrus deodara* on these sites requires extended sample size for reliable statistical estimates and cross-dating beyond 1750 and 1830 AD, respectively.

In the present study, an attempt was also made to check the homogeneity of the meteorological data for the three, *i.e.* Chitral, Drosh and Dir, meteorological stations so as to avoid the influence of systematic errors during the statistical comparison of tree-rings and climatic data. The comparatively low correlation patterns among different environmental variables of Dir meteorological station with the other two stations might be partly explained due to the larger distances and closeness of the station towards the moist temperate area like Upper Kohistan. It is also worthwhile to mention that Drosh is located near the Dir station, while Chitral is closely located to Drosh meteorological station. However, the overall outcome demonstrates strong correlation among climatic parameters of the three stations. Based on these results it was concluded that the climatic data of Chitral meteorological station could be used for further analysis due to the close proximity of the tree-ring sites.

Tree growth-climate relationship

Tree-ring width and climate were tested using both approaches, *i.e.* the *c*orrelation function and response function and it was concluded that was no marked difference in the results from both approaches. However, it is suggested that correlation function is better to use for further analysis because of two reasons: (1) the consistent results from both approaches means that there is no real advantage to using both methods all the time; only one method is sufficient, (2) the correlation function method provides some additional insights by having the amount of variance explained included as a part of the output. This view is supported by Blasing *et al.* (1984) who noted that the response function can be affected in unpredictable ways by often subjective decisions about the number of climate variables to include, confidence limits, number of eigenvectors to allow as candidate predictor in regression etc. Since correlation functions are more objective and easy to interpret. Copper, (1985) and Morzukh and Ruark (1991) have stated that in response functions, normal significance levels of coefficients are misleading because error estimates are underestimated, hence some coefficients can erroneously pass the test of significance. This usually causes greater number of significant coefficients in response functions than in correlation functions (Villalba, 1994; Biondi and Waikul, 2004).

The growth climate response showing the direction and magnitude of the effect of climatic variables on tree growth are shown for *Cedrus deodara* from all the sam-

pling sites exhibited high number of significant responses. The significant positive elements of precipitation were higher than that of temperature (**Tables 4** and **5**). Both types of approaches show negative response to temperature and positive response to precipitation in the month of April. This response was consistent in all chronologies. However, negative temperature response in previous October and from March to June and positive in April and May is evident from all chronologies. Correlation function analysis of *Cedrus deodara* chronologies has shown that temperature of current January and February exhibited a negative relationship with tree growth. It is evident that temperature of the current May has significantly negative effect while rainfall shows significant positive relationship in the month of April and May. It is noteworthy that all the sampling sites in the present study area are located on relatively high elevation in the zone of snowfall. Ahmed *et al.* (2009) has found that positive rainfall response at high altitudes is not clear, especially in the winter season. However, in the present study sites, the significant negative relationship of temperature and positive precipitation response can easily be explained for the months of May and June respectively. During May and June more than average temperature (significant negative) may result in a reduced growth in plants due to increased evapotranspiration and water deficit in the soil. Therefore, in such conditions more than average precipitation (significant positive) encourages growth. These results are supported by the findings of Yadav *et al.* (1997) who reported that the negative influence of temperature on tree growth is reasonable as the summer is very hot and dry at moderate elevation. Similar type of response is also reported by Ahmed *et al.* 2009a, 2009b) for *Picea smithiana* at Astore and Nalter for *Abies pindrow* from Murree and Ayubia. However, the present study sites are located on comparatively low elevation than Astore, Murree and Ayubia sites. This indicated a strong growth climate response on a wide area, despite the fact that these site and species are located away from each other and even in different climatic zone. Yadav *et al.* (1997) has described that site condition plays an important role in influencing the growth response of tree to monthly climatic variables. In the present study sites, some differences were evident that may be attributed to the site disparity. However, the general response of the species show similar trend despite the fact that there are differences with respect to topographical factors. As mentioned earlier, *Cedrus deodara* occurring sympatrically at Kalash site and Gol National Park site show strong intra-specific correlation with almost similar response to climatic variables. This indicates that this set of sites for the same species would be of great importance in the development of a wider network and possible combination. These results also accord with those reported by Singh *et al.* (2009) using the same species.

The correlation analysis has been carried out between the seasonal mean climatic variables and tree ring chronologies (**Table 6**). The season considered were previous autumn (SON), winter (DJF), spring (pre-monsoon, MAM), summer (monsoon, JJA) and current autumn (SON). The results revealed that winter temperature has a strong negative relationship with the tree growth of both the species which is difficult to explain. However, it was concluded that precipitation in the spring season has a significant positive relationship (r=0.64, p<0.001) while for temperature, it was negative. This means that summer precipitation has a direct relationship with tree growth which is more convenient and easy to explain. The climatic data of the study area show that high amount of precipitation occurs in the spring season, and only 32% of the total precipitation occurs in monsoon period (Alamgir, 2004). According to Hussain *et al.* (2007) Chitral is a rain shadow valley and out of reach of monsoon. In the spring season, the temperature increases gradually above the annual average value and May is the hottest month of the season, whereas the amount of precipitation during pre-monsoon period is comparatively high. As this season corresponds with the early part of the active growth period of the trees, due to increased temperature, loss of moisture occurs which affects tree growth, while greater precipitation in this period is conducive to better growth. This view is supported by Borgaonkar *et al.* (1996) who has reported that pre-monsoon (March-April-May) temperature and precipitation significantly affects the tree growth. As the temperature during this period determines the availability of moisture in the early period of growth

Table 6. *Correlation coefficients between different tree-ring sites (Standard chronologies) and climatic data from Chitral met station (temperature and precipitation data dividing into 5 seasons). Only significant responses are shown (i.e. +/-).*

	CdBK	CdCG	CdZ	+	-
Temperature					
1PAutumn/SON		-	-		2
2Winter/DJF	-	-	-		3
3Spring/MAM			-		1
4Summer/JJA					
5Autumn/SON					
Precipitation					
1PAutumn/SON					
2Winter/DJF	+	+		2	
3Spring/MAM	+	+	+	3	
4Summer/JJA		+	+	2	
5Autumn/SON					
Lag 1		+	+	2	
Lag 2					
Lag 3					
+	2	3	2	9	
-	1	2	3		6
Climate	60	59	39	52±3.4	
Lag	7	20	28	18±5.2	
Total	67	79	67	71±4.9	

Note. CdK= Cedrus deodara from Kalash, CdCG=Cedrus deodara from Chitral Gol, CdZ= Cedrus deodara from Ziarat.

though the higher temperature accelerates the process of photosynthesis, significant moisture deficiency occurs due to the high rate of evaporation and evapotranspiration. This may largely explain the negative relationship with temperature as we observed in the analysis for *Cedrus deodara*. Therefore, additional rainfall than average precipitation during pre-monsoon (M-A-M) is very functional in sustaining minimum requirement of moisture and is found to be favourable for tree growth. These results are also in agreement with Borgaonkar *et al.* (1994) who have reported a similar behaviour of the conifers from Kashmir valley using tree ring chronologies of *Picea smithiana* and *Abies pindrow* corresponding to Srinagar climate. However, in their study area May is hot and July is the hottest month with relatively less precipitation. Therefore, it was concluded that slightly excess of precipitation during these months is expected to be better for growth in their study area.

From the above discussion it is evident that high temperatures during the spring season (pre-monsoon) coupled with the availability of water from precipitation during the same period are of critical importance for tree growth. Using this relationship it is possible to reconstruct the pre-monsoon precipitation from this set of chronologies for Chitral area. Singh and Yadav (2005) have stated that the reconstruction of spring precipitation using a network of tree-ring chronologies is of great importance, because spring season climate over the Himalayan region is linked with south Asian monsoon system (Douville and Royer, 1996). However, it is suggested that due to some unexplainable responses, further response function analysis with data from some additional meteorological stations in the analysis of dendroclimatic modelling may be carried out. The interpretation of the present results is simply a guide to the climatic variables that influence tree growth and the direction and relative strength of the relationship until verified by further investigations.

Dendroclimatic analysis seems to indicate that total monthly precipitation is more important than monthly mean temperature. The growth climate response disclosed that generally high precipitation and negative temperature for March to May has a positive effect on tree growth of both the species which is more convincing. Therefore, conclusions were made to reconstruct precipitation for spring season (March-April-May) in future is expected to be beneficial. In the present study, by the application of different approaches were used in order to make decisions for further analysis. It is concluded that correlation analysis is better than response function because the consistent results from both approaches means that there is no real advantage to use both the methods all the time and presumably one method is sufficient. Additionally, the correlation function provides some extra insights by having the amount of variance explained as part of the output. As for as this study is concerned local data is well correlated with the tree ring-width and explained greater proportion of variance than grid data, therefore, local data is recommended for further analysis. From the results it is also evident that there is no substantial difference by using the three discrete versions of chronologies, however, standard chronology was preferred to use for further analysis due to the inclusion of lag years. The results of 15 month window and seasonalized window are consistent, though there is considerable difference in the amount of variance obtained, because with seasonal data the months have been combined together. However, seasonalized window is more convincing in terms of selecting suitable seasons for climatic reconstruction in future.

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