Original article

The dendroclimatic potential of conifers from northern Pakistan

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ABSTRACT

A collection of 28 tree-ring chronologies from six different species located in northern Pakistan were evaluated in terms of their potential for dendroclimatic reconstructions. 15 of the sites are new while the remaining 13 (all *Juniperus excelsa* M. Bieb.) have been reported earlier. Several species had trees attaining ages of around 700 years (*Cedrus deodara* (D. Don) G. Don, *Pinus gerardiana* Wall. ex D. Don., *Pinus wallichiana* A.B. Jacks and *Picea smithiana* (Wall.) Boiss.) but the juniper was clearly the oldest with some trees greater than 1000 years. Correlations between the site chronologies declined with increasing separation distance. This was consistently seen both between sites of the same species and between sites composed of different species. This led to a situation where a much stronger correlation occurred between two different species growing at the same site than between sites of the same species but separated by as little as 0.5 km. Such results highlight the obvious strong elevational gradients present in this mountainous region (where some elevations are over 7000 m). They also lend support to the practice of multi-species combinations for better spatial and temporal coverage. The best prospects for this appear to be *C. deodara* and *P. gerardiana* and are consistent with studies from neighbouring India. The comparison to 0.5° gridded climate data was strongest from the same two species though *P. smithiana* at one site was also highly significant. A general climate correlation pattern from all species was evident that starts with a strong negative relationship to temperature in the previous October, then turns towards positive during winter, before again becoming significantly negative by the current May. The previous October signal is thought to be a lag effect where hot temperatures (and low soil-moisture) stress the trees, thereby reducing reserves available for the following spring. Similarly, hot temperatures in late spring (May) lead to greater soil moisture losses and tree transpiration costs. Conversely, there is an extended strong positive precipitation correlation from late winter to spring (January–May). This ends abruptly and there is no evidence of a summer (June–September) monsoon signal seen in the rainfall correlation functions.

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Introduction

The northern area of Pakistan covers about 72,000 km^2 and lies between latitude 34–37°N and longitude 72–78°E (Fig. 1). The collision of Indo-Pakistan and Asiatic plates has resulted in some of the highest mountain peaks in the world that help form the Karakoram, Hindukush and western Himalaya ranges. Other mountain systems occur elsewhere within Pakistan but not with such dramatic peaks or extensive glaciers.

The forest associations growing in the northern areas were originally described by Champion et al. (1965) based on the general topography and associated moisture regime. Four broad associations were described (i.e., subtropical, moist temperate, dry temperate and sub-alpine zone) but Champion et al. (1965) recognized that species presence alone could not always be used to indicate a climatic zone. Several species having wide ecological tolerances to different climate regimes were consequently described in more than one of the forest associations (e.g., *Cedrus deodara*). An additional complicating factor is the climate history of the area. During past glacial episodes, forest species would have been excluded from extensive areas and possibly isolated. The subsequent spread from glacial refugia could be continuing (i.e., recovering) even today and this may help explain some observed disjunct species distributions (e.g., *Pinus roxburghii* Sarg.). Conversely, the long history of human activity in the region is also likely to have been an influence on forest distribution. Recent research by

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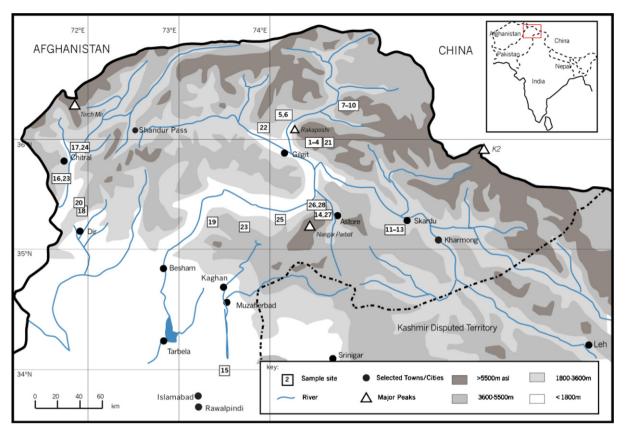 *E-mail address:* gondwanadendro@gmail.com (J. Palmer).

Fig. 1. Map of northern Pakistan showing the location of the tree-ring sites (sample details provided in Table 1) (redrawn from Archer and Fowler, 2004).

Miehe et al. (2009) has shown that during the last five millennia, the extensive dwarf shrublands in the region have replaced woodlands and forest. The authors argue that the driving force has been the human presence and grazing pressures resulting in desertification and not triggered by a change in climate (desiccation).

Climatically, the northern region is pinched between tropical and continental climatic influences and consequently appears to have quite different climatic controls to those from the eastern or Greater Himalaya (Archer and Fowler, 2004). During the summer months, the tropical monsoon from the Bay of Bengal produces heavy precipitation that predominantly falls in the southeast region of the Himalayas. The monsoon weakens as it travels from east to west, with heavy rainfall seen in Kashmir but the monsoon is rarely able to have a significant effect as far west as the Karakoram mountains resulting in little summer precipitation being recorded (Fowler and Archer, 2006). Although westerly winds bring precipitation to the west during winter (originating from Mediterranean and Caspian Sea regions), the pattern of total annual precipitation still generally increases from west to east (Winiger et al., 2005). Arid conditions exist at lower elevations in the west so melt-water from mountain glaciers and seasonal snow remains as the major components of runoff, whereas monsoonal precipitation in the more humid east contributes much of the riverflow (Fowler and Archer, 2006). Linked to this, the glaciers experience winter accumulation and summer ablation in the west, but there is predominantly synchronous summer accumulation and summer melt in the east.

An analysis of instrumental temperature records from seven locations in the Karakoram and Hindu Kush Mountains has shown that winters have become warmer and summers are cooler (Fowler and Archer, 2006). Another finding has been that the diurnal temperature range (DTR) has consistently increased since the middle of the 20th century. The authors think this is a result of changes in large-scale circulation patterns and feedback processes associated with the Indian Monsoon. The downward trend in summer temperatures is noted as being consistent with the observed expansion of some Karakoram glaciers, which is in direct contrast to reported rapid glacial retreats in the Eastern Himalaya (Phillips et al., 2000; Rees and Collins, 2006). Fowler and Archer (2006) argue that the Western Himalaya is displaying a different response to global warming to that "normally" reported elsewhere.

Only a limited amount of tree-ring research has been conducted in Pakistan and all of it has been based on conifer species. The starting point was an introductory paper by Ahmed (1988) that also mentions the problems encountered with tree age estimation. Subsequent papers present initial *Abies pindrow* (Royle ex D. Don) Royle tree-ring chronologies from a moist temperate region (Ahmed, 1989) and then switch to a focus on population dynamics of *Juniperus excelsa* and *Pinus gerardiana* in dry temperate areas (Ahmed et al., 1990a,b, 1991). Ahmed and Sarangzai (1991a,b) and Ahmed et al. (2009a) estimated age and growth rates of various conifer species. The first international publication focused on the climate potential from *J. excelsa* tree-rings was published by Esper et al. (1995). The same species was subsequently used to determine common variance between high elevation sites (Esper, 2000), climate signals in extreme years (Esper et al., 2001), long-term tree-ring variations (Esper et al., 2002, 2003, 2007) and ultimately led to the millennial precipitation reconstruction based on tree-ring oxygen-isotope concentrations (Treydte et al., 2006). Ahmed and Naqvi (2005) have presented four tree-ring chronologies of *Picea smithiana* from various climatic zones and Ahmed et al. (2006) investigated the phytosociology and structure of forests from different climatic zones. Recently, Khan et al. (2008) looked at the potential of *P. smithiana* from a site in neighbouring Afghanistan and Ahmed et al. (2009b) presented

Table 1
Summary details of the 15 northern Pakistan chronology sites.

Species code[a]	Site name and code[b]	Latitude (N)	Longitude (E)	Elev. (m)	Cores/ trees	MRW[c]	Corr[d]	%M[e]	MS[f]	Max period (years)	SSS ≥ 0.85[g] (trees)	AC1[h]	Rbar[i]	SNR[j]	EPS[k]
ABPI	Astore-Rama AST [14]	35°20.6′	074°47.8′	3450	28/17	0.92 ± 0.34	0.59	0	0.184	1505–2005 (501)	1556–2005 (6)	0.302	0.409	18.7	0.949
ABPI	Murree-Ayubia MUA [15]	34°01.8′	073°23.7′	2550	13/7	1.66 ± 0.97	0.55	0	0.262	1678–2005 (328)	1787–2005 (6)	0.362	0.338	6.7	0.869
CDDE	Bumburet (Kalash) BUK [16]	35°41.0′	071°38.1′	2590	19/10	0.97 ± 0.61	0.67	0.1	0.227	1411–2006 (596)	1661–2006 (5)	0.524	0.431	13.6	0.932
CDDE	Chitral-Gol NP CGP [17]	35°54.4′	071°44.3′	3030	27/16	1.57 ± 0.76	0.67	0.1	0.210	1537–2006 (470)	1651–2006 (6)	0.376	0.442	19.0	0.950
CDDE	Islam Baiky (Dir) ISB [18]	35°20.7′	071°55.7′	2660	62/31	1.13 ± 0.59	0.68	0.1	0.249	1511–2006 (496)	1531–2006 (8)	0.255	0.386	33.3	0.971
CDDE	Mushfar (Gilgit) MSF [19]	35°30′	074°05′	2860	30/15	0.66 ± 0.40	0.90	2.1	0.534	1296–2007 (712)	1404–2007 (2)	0.291	0.737	75.8	0.987
CDDE	Zairat (Chitral) ZAC [20]	35°21.1′	071°48.0′	2900	23/17	1.58 ± 0.79	0.54	0	0.213	1472–2005 (534)	1717–2005 (8)	0.467	0.287	8.1	0.890
PCSM	Chera (Gilgit) CHE [21]	36°01.9′	074°35.3′	3110	18/10	1.10 ± 0.57	0.73	0.2	0.278	1394–2005 (612)	1467–2005 (4)	0.476	0.562	23.1	0.959
PCSM	Naltar (Gilgit) NLT [22]	36°08.9′	074°10.8′	3400	35/22	0.83 ± 0.40	0.65	0.1	0.215	1387–2005 (619)	1465–2005 (5)	0.232	0.497	32.6	0.970
PIGE	Bumburet (Kalash) BUK [23]	35°41.0′	071°38.1′	2590	20/11	0.67 ± 0.29	0.67	0.1	0.220	1403–2006 (604)	1468–2006 (4)	0.287	0.471	11.6	0.920
PIGE	Chitral-Gol NP CGP [24]	35°54.4′	071°44.3′	3030	21/11	0.52 ± 0.24	0.59	0.1	0.214	1260–2006 (747)	1419–2006 (6)	0.307	0.405	10.9	0.916
PIGE	Joti (Chilas) JOT [25]	35°24′	074°07′	2670	28/15	1.06 ± 0.50	0.83	1.3	0.413	1559–2007 (449)	1671–2007 (3)	0.305	0.626	45.2	0.978
PIGE	Mushkin (Shalguatum) MUS [26]	35°30′	074°45′	2640	18/9	0.92 ± 0.54	0.85	0.9	0.383	1362–2007 (646)	1544–2007 (3)	0.319	0.712	22.3	0.957
PIWA	Astore-Rama AST [27]	35°20.6′	074°47.8′	3450	44/25	0.93 ± 0.61	0.632	0.0	0.172	1317–2005 (689)	1560–2005 (8)	0.288	0.386	27.6	0.965
PIWA	Mushkin (Shalguatum) MUS [28]	35°30′	074°45′	2750	12/6	1.34 ± 0.76	0.84	0.2	0.263	1730–2007 (278)	1758–2007 (2)	0.604	0.695	27.4	0.965
JUEX	BAG [1–4]CHP [5,6]MOR [7–10]SAT [11–13]					Details described in Esper et al. (2002, 2007).									

[a] Species codes are Abies pindrow (ABPI), Cedrus deodara (CDDE), Juniperus excelsa (JUEX), Picea smithiana (PCSM), Pinus gerardiana (PIGE) and Pinus wallichiana (PIWA).

[b] Only the site code number is shown in Fig. 1.

[c] Mean ring-width ± standard deviation.

[d] Inter-series correlation.

[e] Percentage of missing rings.

[f] Mean sensitivity.

[g] Sub-sample signal strength (Wigley et al., 1984).

[h] First-order autocorrelation.

[i] Mean inter-series correlation.

[j] Signal-to-noise ratio.

[k] Expressed population signal.

Table 2
Comparison of the correlations between different species from the same site and examples from some neighbouring locations.

Site 1	Species	Site 2	Species	Distance (km)	Corr.	Comments
BAG1	JUEX	CHE	PISM	0.1	0.805	There is an obvious decline in the strength of the correlation thought to be
BAG2	JUEX	CHE	PISM	0.1	0.683	caused by the steep increase in elevation. This trend is also seen within the same
BAG4	JUEX	CHE	PISM	0.3	0.661	species (JUEX).
BAG5	JUEX	CHE	PISM	0.5	0.392	
BAG1	JUEX	BAG2	JUEX	0.1	0.675	
BAG1	JUEX	BAG5	JUEX	0.5	0.531	
MUS	PIGE	MUS	PIWA	0.2	0.594	A dramatic reduction over a relatively short distance that is also seen
MUS	PIGE	AST	PIWA	30.4	−0.056	within the same species.
MUS	PIWA	AST	PIWA	30.2	0.129	
AST	ABPI	AST	PIWA	0.2	0.671	Strong same-site/different species correlation but poor
AST	ABPI	MUA	ABPI	192	0.022	different-sites/same species values.
AST	PIWA	MUS	PIWA	30.2	0.129	
BUK	CDDE	BUK	PIGE	0.1	0.755	Strong within-site correlations between the different species that
CGP	CDDE	CGP	PIGE	0.3	0.571	continues between the sites (and within the same species).
BUK	CDDE	CGP	CDDE	43.3	0.718	
BUK	PIGE	CGP	PIGE	43.3	0.598	
CGP	CDDE	BUK	PIGE	43.0	0.606	
BUK	CDDE	CGP	PIGE	43.3	0.463	

preliminary climatic response functions from the same species in Pakistan .

In this paper we present the results from an initial investigation into the potential of the most common conifer species found in Pakistan. Apart from the *J. excelsa* investigations mentioned earlier, the potential of the other species had yet to be evaluated.

Methods

Study sites

The sampling sites were from a range of locations chosen to cover a broad geographic area (Fig. 1). The survey should only be considered as preliminary and aimed at demonstrating the potential for dendroclimatic studies. However, local population pressure has resulted in an increased demand for fuelwood so trees are becoming increasingly remote and sites heavily depleted. Sadly, no rapid change to this pattern of forest decline is expected to occur and as such, the opportunity for extensive collections should be considered sooner rather than later. For example, at the Astore site, the forest now occurs over a kilometer beyond where samples were originally taken some 20 years earlier by Ahmed (1989). Assuming there is no change to current pressures and practices, then this forest resource is likely to be exhausted within another 10–20 years.

In this study a total of 6 species from 5 genera have been collated – *A. pindrow* (West Himalayan fir, ABPI), *C. deodara* (Himalayan cedar, CDDE), *J. excelsa* (Greek juniper, JUEX), *P. smithiana* (West Himalayan spruce, PISM), *Pinus wallichiana* (Himalayan blue pine, PIWA) and *P. gerardiana* (Chilgoza pine, PIGE) (Table 1).

Table 3
Summary of correlation functions between tree-ring chronologies and monthly temperature and precipitation data from the relevant 0.5° grid climate database (Mitchell and Jones, 2005).

	Species	Temperature												Precipitation												Lag			Variance		
		pO	pN	pD	J	F	M	A	M	J	J	A	S	pO	pN	pD	J	F	M	A	M	J	J	A	S	1	2	3	Climate	Lag	Total
AST	ABPI		+							+				+						+	+						+		27.9	2.9	30.9
MUA	ABPI							−	−																			+		23.0	12.4	35.4
BUK	CDDE	−					−	−									+	+		+						+	+		35.8	22.1	57.9
CGP	CDDE	−							−								+	+	+		+					+			36.5	18.7	55.2
ISB	CDDE	−					−	−	−								+		+	+						+			27.9	18.6	46.5
MSF	CDDE	−	+	+			−										+	+	+	+						+			48.9	6.3	55.2
ZAC	CDDE	−						−	−										+	+		+				+			29.0	11.4	40.4
Bag1	JUEX	−	+					−	−	−	−						+			+						+	+		28.6	24.6	52.2
Bag2	JUEX		+	+		+														+			+			+	+	+	26.8	22.0	48.8
Bag4	JUEX	−	+					−	−	−										+						+	+	+	29.7	24.8	54.5
Bag5	JUEX																									+	+	+	19.6	19.2	38.8
CHE	PCSM	−						−	−										+							+			28.4	9.8	38.2
NLT	PCSM							+	+						+	+					−							46.2	0.5	46.7
BUK	PIGE	−					−	−	−								+	+		+									30.6	8.3	38.9
CGP	PIGE							−	−							+		+		+									32.8	4.4	37.2
JOT	PIGE	−				−			−									+		+						+			34.5	12.9	47.4
MUS	PIGE	−						−		−					+	+	+	+	+										35.8	3.5	39.3
AST	PIWA	+					+	+																		+			35.5	8.1	43.6
MUS	PIWA	−							−						+	+				+						+	+		28.6	19.5	48.1
Total	+	1	5	2	0	0	1	0	0	2	3	0	0	1	0	0	6	8	9	5	12	0	2	0	1	14	6	3			
	−	12	0	0	0	0	1	5	13	8	3	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0			

a) *Abies pindrow* (ABPI) tree-ring chronologies
   i)   Astore (AST)
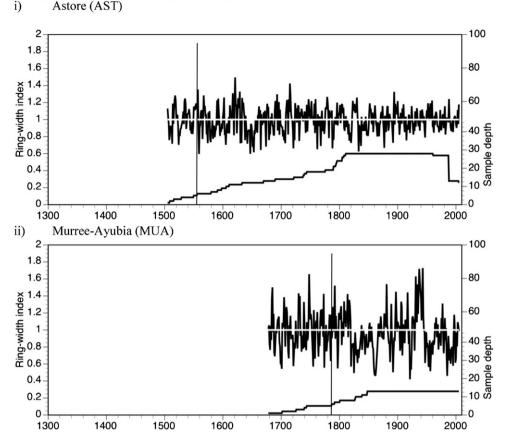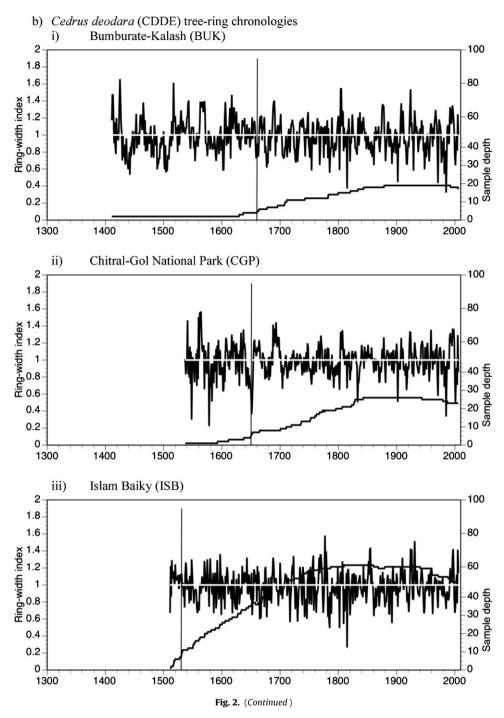

ii)   Murree-Ayubia (MUA)

Fig. 2. Plots of tree-ring indices and associated sample depth from different species and sites. The vertical line indicates the position where the sub-sample signal strength (SSS) is greater than 0.85 (see Table 1). (a) *Abies pindrow* (ABPI) tree-ring chronologies: (i) Astore (AST) and (ii) Murree-Ayubia (MUA). (b) *Cedrus deodara* (CDDE) tree-ring chronologies: (i) Bumburate-Kalash (BUK), (ii) Chitral-Gol National Park (CGP), (iii) Islam Baiky (ISB), (iv) Mushfar (MSF), and (v) Zairat (ZAC). (c) *Picea smithiana* (PISM) tree-ring chronologies: (i) Chera (CHE) and (ii) Naltar (NLT). (d) *Pinus gerardiana* (PIGE) tree-ring chronologies: (i) Bumburate-Kalash (BUK), (ii) Chitral-Gol National Park (CGP), (iii) Joti (JOT), and (iv) Mushkin (MUS). (e) *Pinus wallichiana* (PIWA) tree-ring chronologies: (i) Astore (AST) and (ii) Mushkin (MUS).

Species codes follow the general convention listed on the International Tree-Ring Data Bank – ITRDB (Grissino-Mayer, 1993). The authors collected all the core samples but those from *J. excelsa* have been described in the earlier publications of Esper et al. (2002, 2007).

One of the aspects of increasing interest is the potential for multiple species combinations for dendroclimatic reconstructions. A key factor in determining the validity for species pooling is their similarity in responding to climate variables. This is where studies of different species found occurring at the same site can provide valuable insights. In this study, five different locations had two different species present, enabling interspecies correlations (Table 2) and comparisons of the their responses to climate data (i.e., their correlation functions, Table 3). The five sites were:

- At both the Chitral Gol National Park (CGP) and the Bumburate Valley (BUK) both *C. deodara* and *P. gerardiana* were cored. Our observations concur with the descriptions made by Singh et al. (2009) that these species are often found growing on steep rocky slopes with little soil cover. Trees were often in open, widely spaced stands reducing the likelihood of inter- and intra-specific competition affecting growth. Himalayan cedar appears to grow in a wider range of conditions to Chilgoza pine, which is restricted to the dry temperate areas (Champion et al., 1965). The latter species only forms pure stands in remote mountainous areas

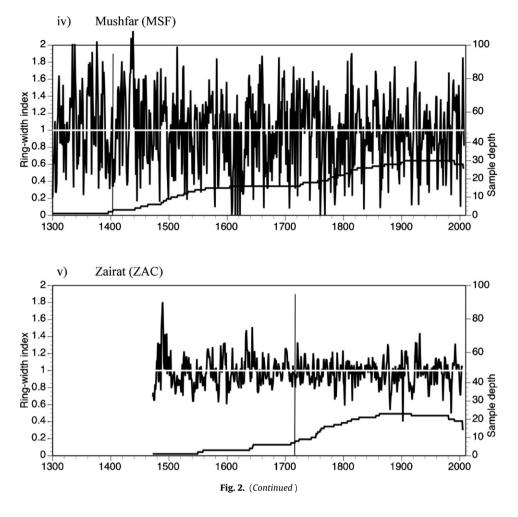adjoining Afghanistan and in Balochistan province (Ahmed and Sarangzai, 1991a).
- At Astore (AST) the *P. wallichiana* and *A. pindrow* trees form a mixed closed-canopy stand on a steep slope that becomes *Betula utilis* D.Don dominated at timberline. Extensive fuelwood cutting is evident on the lower approaches and trails now extend virtually to timberline and as mentioned earlier the entire stand appears threatened. *P. wallichiana* is known to have a wide range of tolerances and is found in association with other species such as *P. gerardiana* (see below).
- The site Mushkin (MUS) had the unusual situation where there was a stand of *P. gerardiana* on an exposed steep ridgeline below an access road and *P. wallichiana* occurred above the road where the slope eased. The only reason why the *P. gerardiana* had remained was because fuelwood harvesting required carting the wood uphill to the road as the lower ridge dropped steeply and directly into a river. So although a favoured species for burning, the Chilgoza pine trees presented a very labour-intensive task for harvesting.
- A direct comparison can be made between *J. excelsa* and *P. smithiana* taken from virtually the same location (but given two different names – Chera and Bagrot). The *P. smithiana* was at 3130–3075 m a.s.l. and the *J. excelsa* was very similar at 3050–3100 m a.s.l. (for sites Bag1 and Bag3; Esper et al., 2007). The sampling trip in 2007 to collect the *P. smithiana* trees (site CHE) passed through the stumps of the former

Fig. 2. (*Continued*)

Bagrot sites (Bag1 and Bag3) discovered by Esper in 1993 (Esper et al., 2007).

Tree-ring data

The cores from the trees were prepared for measurement by first being glued onto mounts and then progressively sanded with finer paper until a highly polished surface was produced. Then, using a low powered microscope, the ring-width growth patterns were matched within and between trees (i.e., crossdated) and the exact calendar years assigned. This process followed the techniques described by Stokes and Smiley (1968). The ring-widths were measured using a Velmex measuring stage (accurate to 0.001 mm)

and measure J2X software linked to a personal computer system. The measurement series from each core was then cross-checked for possible dating errors using the software COFECHA (Holmes, 1983; Grissino-Mayer, 2001). The cross-dated series were then compiled into site chronologies using the program ARSTAN (Cook, 1985). The age-related growth effects were removed by single-detrending using the Friedman variable-span smoother in the program options. Since the purpose was simply to explore higher frequency climate relationships, other more conservative filtering approaches could be left to later studies. For similar reasons, the "standard" chronologies from the ARSTAN output were selected for subsequent climate response modeling. Part of the aim is to explore the levels of influence exerted by former years of growth (i.e., lags

Fig. 2. (Continued)

or autocorrelation) found in the different species hence the preference of the standard chronology version. Autocorrelation in the tree-ring series is an important consideration when attempting climate reconstructions. A summary of the sites and the tree-ring chronologies is given in Table 1 and the standard chronologies plotted in Fig. 2. More detailed explanations of the terms can be found in general texts such as Fritts (1976) and Cook and Kairiukstis (1990).

To provide some insight into the relationship between tree-growth and climate the response and correlation function analyses were calculated using the software package called the Dendrochronology Program Library (DPL) (Holmes, 1992). The period of tree-growth in the region is generally thought to commence around March and cease by the end of September, so the 12-month interval of October in the previous year to the end of the current growing season (September) was selected. Included in the analyses was the investigation of the contribution from 3-years of prior growth.
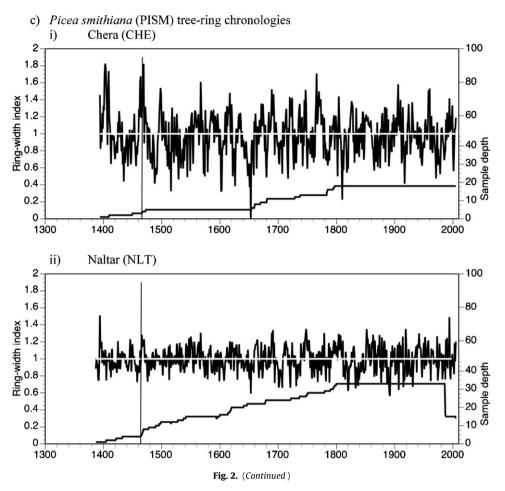
Climate data

An often-cited constraint to dendroclimatic studies in the Himalayas is the paucity of long meteorological records for statistically calibrating to the tree-rings (Cook et al., 2003; Bhattacharyya et al., 1992). One approach has been to interpolate seasonal data into a 0.5° latitude–longitude grid data set that can then be applied to the tree-ring location (e.g., Cook et al., 2003). Such an approach has been adopted here to cover the tree-ring sites in northern Pakistan using the CRU TS 2.1 (http://www.cru.uea.ac.uk/) data. Each tree-ring chronology was analysed with their respective

climate data using 0.5° gridded data for the period 1901–2002 (Mitchell and Jones, 2005). Data from a few local stations is available (e.g., Gilgit) but more importantly, for many of the tree-ring sample sites no local records occur, or they are at much lower elevations. Consequently, preference was given to using a "standard" set of climate grid-data available for all the sites to simply help identify the strongest prospects for further investigation/reconstruction. Subsequent studies could concentrate on the differences seen between local stations and the associated grid data, or checking for changes in the response function patterns through time.

Results and discussion

A wide range of growth rates was seen between different sites of the same species (Table 1) with some growing at over twice the rate seen at others (e.g., C. deodara at Mushfar compared with Ziarat). One interesting trend shown by ABPI, CDDE and PCSM sites was an increase in inter-series correlations (Rbar) and signal-to-noise ratios (SNR) with decreasing growth-rates (MRW) (Table 1). So, in general it follows that the slower growing sites are better prospects for climatic studies. However, both PIGE and PIWA appear to show the reverse trends. Here, the best prospects are those with faster growth rates. Clearly there are differences in ecological tolerances by species and only with a study covering a species full range can any relationship be confirmed.

One important consideration for dendroclimatic studies is the potential age of the trees. Table 1 shows several species had trees

c) *Picea smithiana* (PISM) tree-ring chronologies
    i)   Chera (CHE)

    ii)   Naltar (NLT)
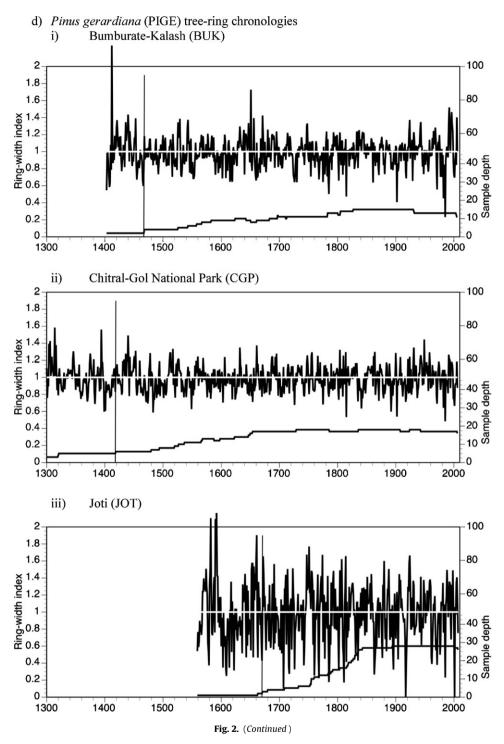

Fig. 2. (*Continued*)

attaining ages of around 700 years (*C. deodara*, *P. gerardiana*, *P. wallichiana* and *P. smithiana*) and older ages possible as indicated by studies of the same species from India (e.g., Singh et al., 2004; Singh and Yadav, 2007). The earlier collections of juniper (Esper et al., 1995) were the oldest so far from Pakistan, with some trees significantly greater than a 1000 years and no other species seems likely to match this.

Overall, there is a reduction in correlation strength between sites with increasing separation distance (Fig. 3). The same general trend is seen both between sites of the same species and between sites of different species. This is perhaps to be expected given the mountainous terrain. However, one surprise was the strength of the correlations between different species found growing at the same locations (Table 2). At the Bagrot site (BAG; originally sampled by Esper et al., 1995; and recently also called Chera, CHE) we have a high correlation between *J. excelsa* and *P. smithiana* growing in adjacent stands (i.e., BAG1 and CHE; Table 2). However, as you climb in elevation to other juniper stands (BAG2, 3 and 5) the correlations drop, a trend that is seen even between the pairs of juniper sites themselves, pointing to the steep elevational gradients typical for this high mountain region. We end up with the situation of a higher correlation occurring between different species than between the same species and separated by only about 0.5 km. With only a pair of sites for *P. wallichiana*, *P. smithiana* and *A. pindrow* only very limited comment can be made on the coherence within these species. However, all three species had higher correlations with other species growing closer to them than with the same species but further away. This then, supports the earlier results but more sites are needed to strengthen the case.
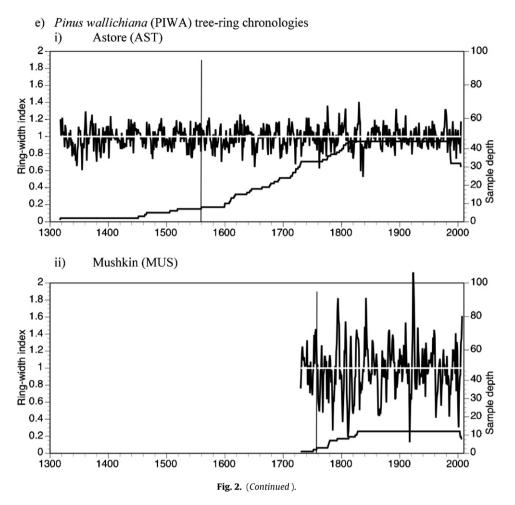
Finally, in Table 2 we also show the situation between *C. deodara* and *P. gerardiana* at two locations – Chitral Gol National Park (CGP) and the Bumburate Valley (BUK). Both species are present at both sites. On this occasion we see both strong inter-species correlations and intra-species correlations sustained (albeit declining) over a distance. This would suggest this pair of species then has the best prospects for wider network development and possible amalgamation similar to the results obtained by Singh et al. (2009).

The tree-growth climate relationship for all the sites was summarised in Table 3. Rather than presenting multiple individual figures, we opted for only a summary table of the significant monthly climate correlations, lags and the percentage of variance explained. A similar broad pattern across all the species can be seen for temperature and rainfall. There is a strong negative response to previous autumn temperatures that then hints at a positive association during winter before becoming strongly negative again by late spring/early summer. The rainfall response was virtually only positive with the greatest correlations seen during late-winter and spring (i.e., January–May) where in May it not only peaks but also abruptly ends. Almost nothing is significant during the summer and autumn months (June–September) that is generally regarded as the summer monsoon period. We have interpreted this lack of significant correlations as meaning there is no inherent summer monsoon signal contained within the trees from the range of sites investigated.

One interesting aspect shown in the comprehensive millennial rainfall reconstruction based on oxygen isotope concentrations in tree-rings (Treydte et al., 2006) was that the highest correlated single month for precipitation was July. So, although winter-snow

d) *Pinus gerardiana* (PIGE) tree-ring chronologies
   i)   Bumburate-Kalash (BUK)

   ii)   Chitral-Gol National Park (CGP)

   iii)   Joti (JOT)

Fig. 2. (*Continued*)

melt was important, there was also a contribution made by summer rain (July) as perhaps reflected by the overall annual precipitation being significantly correlated to isotope measurements from ring widths. The Treydte et al. (2006) study was based on *J. excelsa* and included the Bagrot sites. How then, can we explain this apparent difference in rainfall response reported in the earlier study to the results presented here, when even using some of the same sites? The answer we feel, lies once again with elevation. Treydte et al. (2006) identified a difference in response within the Bagrot sites and selected the highest (3900 m a.s.l., "Bag-high", cold/moist) and lowest (2900 m a.s.l., "Bag-low", warm/dry). In Table 3 we see a

poor correlation to our grid climate data by the high elevation Bag5 compared to the low elevation site Bag1. Also, only the >1000 year old trees from the more northern and high elevation (3900 m a.s.l.) "Mor" site were used in the final Treydte et al. (2006) rainfall recon- struction that was classified as having a third type of response – cold/dry. We believe we are describing the pattern seen from lower elevation sites (i.e., warm/dry) or from more westerly locations than those used by Treydte et al. (2006) for the rainfall recon- struction. One possible explanation is that residual or weakened bands of cloud from the summer monsoon only reach the highest zones of forest and are driven by the strong orographic effects of

e) *Pinus wallichiana* (PIWA) tree-ring chronologies
i)   Astore (AST)

ii)   Mushkin (MUS)

Fig. 2. (*Continued*).

the immense mountain ranges. Our sample sites are located either below or beyond the area influenced by the summer monsoon – hence the difference seen in the summer rainfall correlations.

The negative prior autumn (October) temperature response shown by virtually all the sites could be a lag effect. The soils at this time are dry (because no summer monsoon moisture reaches them) and normally the cooler temperatures are leading to the cessation of growth. However, if hot October temperatures occur this would promote continued growth but a lack of available water causes stress. The net outcome would be a reduction in reserves for growth the following year. Most species show a significant lag effect (Table 2).

Many of the tree-ring studies from the western Himalayan region within India have used the same species as reported here, so some brief comparisons are discussed. Singh et al. (2006) collected 13 *C. deodara* sites in the Western Himalayas of India that showed high inter-site correlations and was used to reconstruct spring (March–May) precipitation back to AD 1560. Their analyses also showed precipitation from the previous October–December had a positive affect on tree-growth, but this factor was not seen in our results (Table 3) where the emphasis was a late-winter and spring correlation. A noticeable feature of their climate correlations is the triple-month blocks of mirrored responses between temperature and rainfall (e.g., October–December, March–May and June–August; Fig. 2, Singh et al., 2006). In each triple-month block, when precipitation was positively associated then the temperature response was negative, and vice versa. This same feature is not observed by Borgaonkar et al. (2009; Fig. 5) who investigated
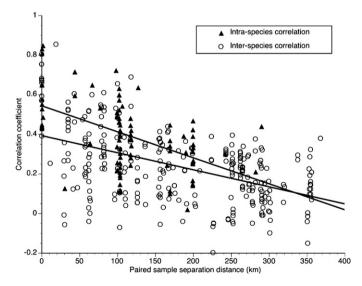

Fig. 3. Correlations between pairs of tree-ring sites compared to the their separation distance (note: $r^2 = 0.24$ inter-species comparisons, $r^2 = 0.27$ intra-species comparisons).

the response of three *C. deodara* sites to climate and glacier fluctuations in the same general vicinity of the western Himalayas. Neither is the same pattern reported in two other papers by Singh et al. (2004, Fig. 3 showing temperature; 2009, Fig. 5a1 showing rainfall) from *C. deodara* sites that appear only about 50 km from the earlier
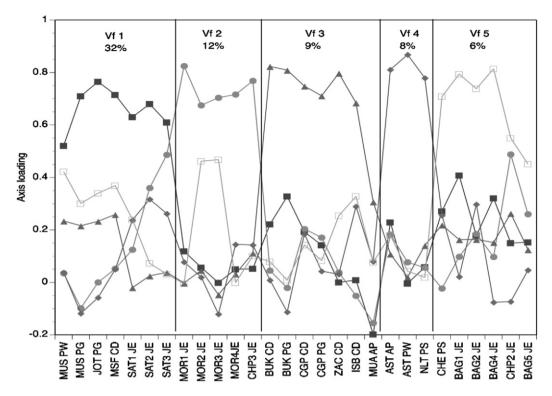
Fig. 4. Principal component analysis combined with site locations of the 28 tree-ring chronologies. 65% of the variance is explained by the 5 groupings.

mentioned cluster. Such differences perhaps question the extent of regional representation by the climate reconstructions.

Singh et al. (2009) concluded that there was a positive relationship of tree-ring index series with winter (December–February) temperature and summer precipitation but an inverse relationship to summer temperatures centered on May. Some similarity is seen to Table 3 but with changes in emphasis and timing in places. There is less of a positive association with winter temperatures and instead there is a strong negative correlation with previous autumn (October). The significant inverse relationship to late spring/early summer temperatures is identical. The rainfall pattern is also similar though the Pakistan sites appear to have stronger positive correlations earlier in the growing season (i.e., spring not early-summer) and as discussed earlier, we found there were no significant correlations to any summer rainfall months.

A multi-species temperature reconstruction was done from a network of 32 sites in Nepal that included *P. smithiana* and *P. wallichiana* (Cook et al., 2003) and this perhaps signals the prospect for a similar approach from the species collections presented in this paper. However, *P. smithiana* and *P. wallichiana* were the only species to show strong positive correlations to summer (June, July) temperatures (Table 3) with the other species highlighting the negative prior-autumn (October) and late spring (May) responses. Further collections of these two species are needed before perhaps a clearer pattern can be determined, but on the basis of the current collection the strongest grouping appears to be between *C. deodara* and *P. gerardiana* sites. The same pair of species were used by Singh et al. (2009) for a rainfall reconstruction with the recommendation of establishing wider networks.

Overall, the highly diverse range of inter-site correlations shown in Fig. 3 made the identification of possible clusters of similar sites difficult.

An attempt was made to identify broad groupings of the sites based on their ring-width patterns and locations using principal component analysis (Fig. 4). The results appear to confirm many

of the earlier observations and showed that a total of 65% of the variance was explained by five groupings. The strongest group, in terms of the amount of common variance explained (32%) consisted of a mixture of four species centered around two locations. One location contained the three juniper sites from near Skardu (sites [11–13] in Fig. 1 and Table 1; towards the east) and the other was over a wider area consisting of four chronologies (sites [19, 25, 26, 28]) from three species (CDDE, PIGE, PIWA) in the vicinity of the mountain Nanga Parbat (Fig. 1). The omission of the two stands from relatively close-by at Astore (sites [14,27]) from this group may at first seem surprising, but, as discussed earlier (Table 2), the chronologies cross-correlated poorly to other close locations indicating strong local climatic gradients. The two sites from Astore ended up being its own small group combined with only one other site, Nalter (site [22]; Vf 4 in Fig. 4). The same can be seen with the juniper sites tending to cluster into their own groups (i.e., Vf 2, Vf 5; Fig. 4). The last grouping (Vf 5) included the Cheras PCSM [21] site that supports our earlier observations (see Table 2) and the high elevation BAG5 [4] site appears only weakly associated. The CHP2 [6] site seems undecided between two groupings Vf 2 or Vf 5 perhaps again hinting at elevational driven differences. Another encouraging result was the Vf 3 grouping that primarily linked the six Chitral and Dir sites [16–18, 23–25] of two species (CDDE, PIGE) together. The inclusion of the moist temperate Murree-Ayubia site [15] in this "dry" western group was surprising and the values seem weak (Fig. 4) but may be driven by similar ring-width values for extreme years. Overall, the five groupings provide a basis for potential site and species clusters to develop climate reconstructions.

Conclusions

Northern Pakistan has a range of conifer species with potential for palaeoclimatic studies. Several species have trees around 700 years old but only *J. excelsa* attains ages significantly greater than a thousand years. An important conclusion from this study

has been the dramatic influence the mountainous terrain has on the correlations between different sample locations. This results in the situation where higher correlations are observed between two different species in close proximity to each other than between two sites of the same species but further apart. The results lend support to the use of multi-species climate reconstructions rather than the more conventional single-species network approach. The correlation functions to climate data failed to identify a summer monsoon rainfall response. The tentative explanation was that the sites either lie below the zone where residual monsoon rainfall reaches or further towards the west and beyond the extent of monsoon influence.

Acknowledgements

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