Long-term tree-ring variations in *Juniperus* at the upper timber-line in the Karakorum (Pakistan)

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Received 30 April 1998; revised manuscript accepted 25 July 1999

A HOLOCENE RESEARCH PAPER

Abstract: Ring-width series of *Juniperus excelsa* M. Bieb and *Juniperus turkestanica* Kom. from six different sites, in the Hunza-Karakorum, were used in reconstructing modes of regional climate over the past 500 years. All reconstructions were derived from trees growing close to the upper timber-line (approx. 4000 m a.s.l.). Standardized site chronologies, derived from ring-width measurements, display common low- and high-frequency variation that is synchronous between all sites. Since the documented increase in atmospheric CO_2 loading, roughly 150 years ago, Hunza-Karakorum trees are not growing as well as they were previously. From the mid-nineteenth century to the present, these trees appear to be alternating between states of more extreme favourable and unfavourable growth periods of different amplitude and duration. Maximum (favourable) variations occurred between AD 1579 and 1603, whereas minimum (unfavourable) variations occurred between AD 1825 and 1850.

Key words: Tree-rings, *Juniperus*, dendroclimatology, climatic variations, standardization methods, Karakorum, Pakistan.

Introduction

Recent discussion of climate patterns and their variability focuses on medium- to long-term changes rather than short-term variations (e.g., Bradley and Jones, 1992; Eddy and Oeschger, 1993; Jones *et al.*, 1996). Many studies investigate low-frequency signals in tree-rings worldwide in order to understand the climate of the past 1000 years (e.g., Cook *et al.*, 1991; Luckmann and Innes, 1991; Schweingruber and Briffa, 1996). Tree-ring growth integrates many different environmental influences at one time. In order to deal with climatic questions the number of environmental factors affecting tree growth must be limited. Climatic influences are isolated by careful site and sample selection. Sampling along species distribution boundaries is most instructive, since here the number of climatic factors controlling ring width decreases (Fritts, 1976; Schweingruber, 1996). Consequently, boundary environments provide the highest potential for reconstructions from tree-rings. If changes in temperature or precipitation are to be derived from tree-ring proxy data the strength and influence of these climatic variables, on tree growth, must be analysed first. To answer questions of how forest populations respond or ecosystems adapt to climate change, reconstructions of temperature and precipitation are less informative than the data provided by the trees themselves.

The purpose of this study is to analyse climatically induced, long-term fluctuations of radial growth over the past 500 years in northern Pakistan. Ring widths of *Juniperus* trees growing on different sites, close to the upper timber-line, in the Hunza-Karakorum region were examined. Samples were taken exclusively from living trees with ages between 165 and well over 1000 years. A simple statistical method was used to extract the low-frequency signal sought and to minimize the biological, as well as site-related, signals within each sample.

Study area and *Juniperus* tree-ring material

The Hunza-Karakorum region (35°50′–37°00′N/74°00′–75°30′E) is part of a high mountain range including the second highest peak in the world, K2 (8611 m a.s.l.). From the Hunza River to the top of Mt Rakaposhi (7788 m a.s.l.) relief rises nearly 6000 m over a horizontal distance of only 11 km (Weiers, 1995). Global radiation is extremely high in the upper elevation of this subtropical region. Up to 95% of the solar constant may be reached along the upper timber-line during high-radiation days (Cramer, 1994). Owing to geography, southern exposures are more arid than northern.

Radiation gain on these high slopes (reaching well into the upper atmosphere) produces an inner-mountain slope wind circulation system that locally modifies the overlaying large-scale synoptic precipitation gradient (Schweinfurth, 1956; Troll, 1952).

0959-6836(00)HL384RP

Clouds condense above the upper slopes and ranges, while the valley bottoms stay dry. Precipitation down on the valley floors may average 132 mm yr^{-1} (Gilgit 1432 m a.s.l.), while the amount of rain and snowfall above 3500 m a.s.l. has been estimated at 600 mm yr^{-1} and more (Weiers, 1995).

Annual variability of air temperature shows a single maximum. For example, in January 1991 the average temperature in Bagrot Valley (3780 m a.s.l.) was −12°C and +12.2°C in August (Cramer, 1994). Forests do not establish below 2600 m a.s.l. (too dry) and cannot exist above 4000 m a.s.l. (too cold) (Schickhoff, 1995). *Juniperus excelsa* M. Bieb and *Juniperus turkestanica* Kom. are the only tree species able to grow on southern exposures and cover large areas with sparse populations (< 10 % coverage). In the northeastern Hunza-Karakorum, *Juniperus* forests replace moist-temperate, coniferous forests of *Picea smithiana* (Wallich) Boiss. and *Pinus wallichiana* A.B. Jackson, even on northern exposures (Figure 1).

Increment cores, from trees growing on different exposures, at five phytosocially homogeneous locations, were collected according to the criteria of Schweingruber *et al.* (1990b) (Table 1: Chap and Mor 1 to 4). In addition, five trees, scattered over the entire study area, were sampled (Hun). All sites lie close to the upper timber-line between 3600 m a.s.l. and 3900 m a.s.l. Under cold-wet conditions *Juniperus* grow extremely slowly and reach ages over 1000 years.

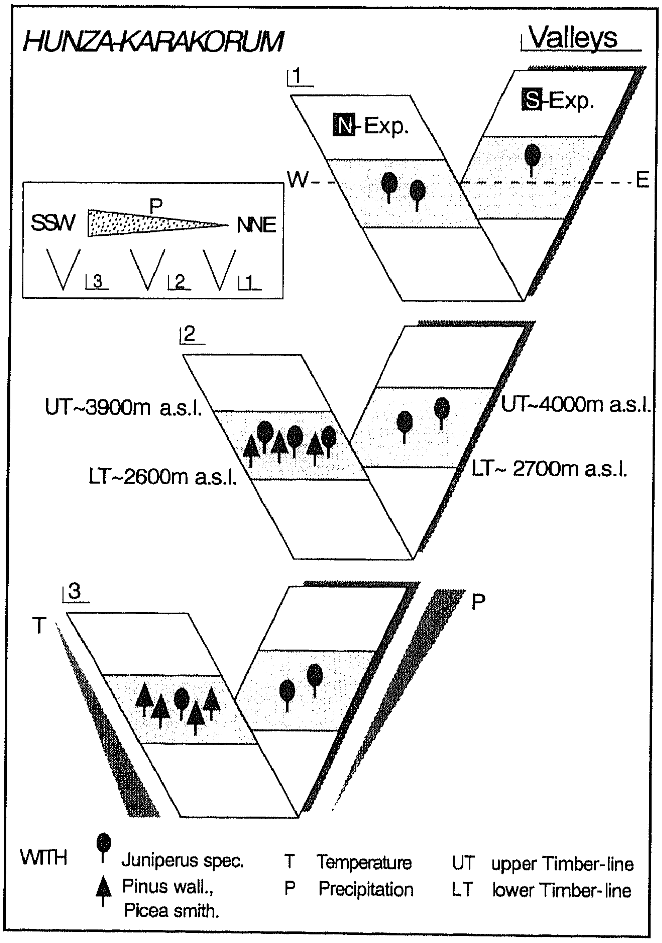

Figure 1 Sketch of ecologically relevant parameters in the Hunza-Karakorum. A negative, synoptic gradient of precipitation, oriented SSW to NNE, is shown above the Hunza-Karakorum. Global radiation, as well as the distribution of rain and snow, controls the distribution of vegetation by exposure and altitude. Forests do not establish below 2600 m a.s.l. On northern exposures of the SSW, communities of moist-temperate, coniferous forests are common; in the NNE *Juniperus excelsa* M. Bieb and *Juniperus turkestanica* Kom. are the only tree species able to survive on any exposition.

Star-shaped cross-sections are typical of *Juniperus*. This condition develops when the cambial activity along some radii is reduced while that of adjacent radii continues (Figure 2). Missing rings are also common in trees growing along the upper timber-line as well as periods of 20 to 50 years with a growth rate less than 0.05 mm yr^{-1}. Within these portions of dramatically suppressed growth it is nearly impossible to resolve individual rings. The only way to develop a continuous, dated, time-series of ring-width measurements is by cross-dating each radius using a catalogue of pointer years (Esper *et al.*, 1995; Schweingruber *et al.*, 1990a). Strip-bark growth forms (Ferguson, 1968; Fritts, 1969; Graybill and Idso, 1993; Kelly *et al.*, 1992; Wright and Mooney, 1965) also appear in older *Juniperus* trees. This condition develops as the cambium is damaged locally and will no longer be overgrown. Mechanical damage by rockfall seems to be the principal stimulus for cambial dieback and unilateral growth. In extreme cases only a narrow strip on the stem is still active, creating these eccentric growth forms. Owing to a predominance of these eccentric star-shaped cross-sections, cores were drilled at chest height from only the living part of the stem, the so-called 'lobes' (Figure 2).

Standardization methods

Standardization is the process of removing the geometric and age-based growth trend in annual ring-width series. Each ring width is divided by the model estimate of tree growth for each year. The resulting indices are dimensionless, homoscedastic, and may be averaged with index series from other trees to produce a mean, site, index chronology. The choice of model used in the standardization procedure determines the relative signal frequency retained or removed from the original time-series (e.g., Bräker, 1981; Briffa *et al.*, 1996; Cook *et al.*, 1995; Fritts, 1976). Tendency to overfit the original ring-width series closely will result in preservation of high-frequency variation, while the opposite will retain predominantly low-frequency variation. The degree to which standardization is performed on a tree-ring series is constrained by the questions asked of the data.

Figure 3A illustrates the individual raw ring-width measurements from two trees growing on a site located in the Chaprot Valley (series Chap 1 and Chap 18; Table 1). Both trees vary in age and are growing at distinctly different levels until 1790. Prior to 1790 the amplitude of mid-frequency modulations is dramatically different. After 1790, Chap 1 increases its growth level as Chap 18 drops to nearly the same level. From 1830 onwards both series share very similar low-frequency variation, a condition they did not share prior to 1790. An average ring-width series from these two trees would eliminate many of these inherent differences and would not be interpretable vis-à-vis a common climate signal.

In order to meet the demands of emphasizing common and minimizing uncommon variation, standardization becomes necessary. Selection of the proper standardization method to be used in this study was constrained by the following requirements:

- comprehensibility;
- lowest alienation;
- consistent calculation of single series;
- maximum comparability of single series;
- suitability to the time-series and the questions asked of the data.

Figure 3 (B–D) shows the results of standardization on the two raw ring-width series Chap 1 and Chap 18 by three methods: (B) division by the series mean [AD]; (C) division by simple linear regressions [LD]; and (D) division by a 101-year digital filter (MD). The smoothed series values (101-year filter) are based on a weighted kernel estimation for optimal nonparametric regression

Table 1 Location of the sites and essential statistical values. Four of the five homogeneous sites lie within the Morkhun Valley (Mor 1 to 4), and one is located in the Chaprot Valley (Chap). They are situated on different exposures in tributary valleys to the Hunza Valley (Hun)

	Chap	Mor 1	Mor 2	Mor 3	Mor 4	Hun
Longitude/latitude	36°20'N/74°02'E	36°35'N/75°05'E				–
Elevation in m	3900	3900	3800	3600	3900	–
Exposition	S	SW	ENE	ENE	SSE	–
Soil	Inceptisols					–
No. of trees	18	7	9	14	8	5
Max. age	~ 1000	~ 1350	~ 1100	~ 1450	~ 1000	~ 1000
Mean growth rate	0.42 mm	0.28 mm	0.25 mm	0.26 mm	0.24 mm	0.28 mm
t-Value	17.4	22.7	32.3	36.5	19.8	20.5
Sign test in %	73.5	78.6	80.0	83.7	74.9	72.6
Autocorr. Chrono Lag=1	0.76	0.78	0.6	0.63	0.73	0.76
Autocorr. Chrono Lag=10	0.36	0.54	0.27	0.44	0.42	0.49

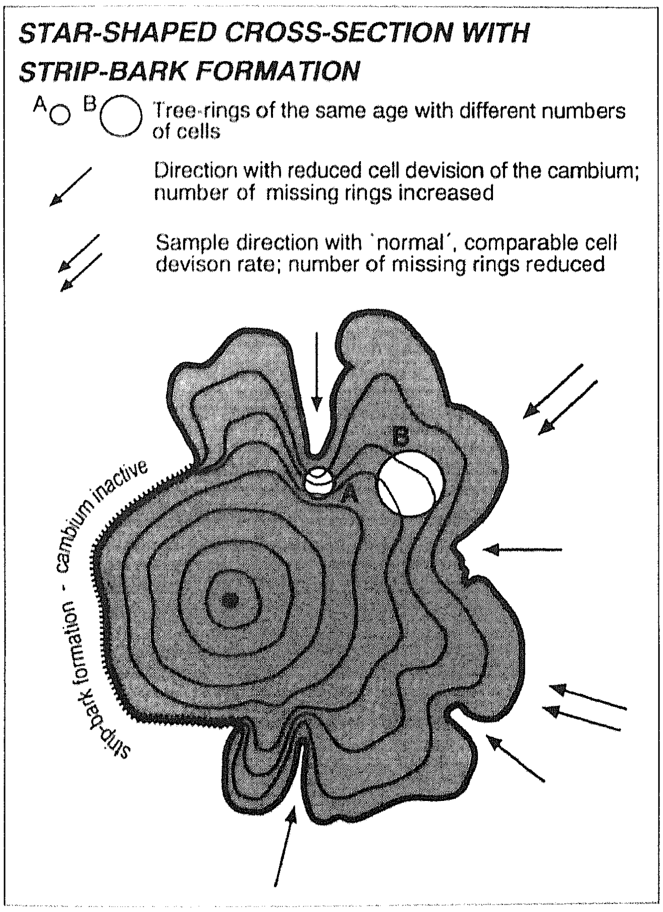

Figure 2 Sketch of a typical star-shaped cross-section including strip-bark formation found in an old *Juniperus* tree. For unknown reasons cambial activity is locally reduced creating radii with increasingly smaller tree-rings. Old *Juniperus* trees frequently produce strip-bark formation. Here the growth persists in one direction on one side of the stem owing to a lack of cambial activity elsewhere.

functions. The weight array equals an arithmetic moving average, the weights being derived from a Laplace function. They allow calculation of a regression function with the statistical properties of a spline. Smoothing the data works like an arithmetic weighted filter with the benefit of not cutting the extremities of the series. For details, see Gasser and Müller (1984).

Each method produces dramatically different results. Indices derived by method AD are still noticeably heteroscedastic and continue to retain much of the original data's growth trend. In this example both series start and end on different levels. Although between 1796 and 1839 the computed indices are synchronous, they eventually spread apart. While Chap 18 shows an increased index until 1795, after 1835 it is Chap 1 that has higher values. Many of the original growth characteristics in both series have been either modified or completely reversed, and too little of the inherent age-size related growth trend has been removed thus preventing any objective comparison of the two series.

Standardization using linear regression models (LD) brings Chap 1 and Chap 18 closer together, although remarkable differences appear between 1773 and 1795, as well as between 1878 and 1909 (Figure 3C). From 1804 to 1818 both index series exhibit maximum. Small variations in the early portion of Chap 1 were enlarged owing to the models' positive trend possessing minimum values in the early years (1494–1502 = 0.08 mm). This is a typical feature of the end effects that often occurs with linear detrending. If a tree maintains low growth rates only in the mid-section of a series (e.g., 1700–1800), but significant higher growth before and after it, then the variations of the index-values will stay small.

Of the three methods tested, standardization by a low-pass, 101-year moving average (MD) appears to be the best. Though differences between the two example series are still recognizable (e.g., 1773–1795, 1878–1909), much of the common low-frequency variation has been retained (Figure 3D). Differences of this kind should be indicated as a scatter in a chronology (Figure 5). Second, the overall mean and variance of the indices have been stabilized.

How will the site chronology appear, however, if AD, LD and MD are used on all 18 single series from Chaprot Valley (Chap)? The resulting averages are shown in Figure 4. Although there are remarkable differences among the standardization methods (Figure 3) the average curves fit close together. The individual differences are minimized by averaging, so that in AD different low-frequency signals eliminate each other. This effect correlates with the number of single series combined. But the scatter of the single series can no longer be distinguished in the average curve. The calculated total standard deviation (at AD = 44.6, at LD = 39.5, and at MD = 30.9) points to the heterogene collective of single indexed series in LD and especially in AD.

When the 101-year digital filter is used to standardize all radii from all sites it produces the best index series of stable variance and maximum comparability. The moving average emphasizes centenary trends and reduces the serial-correlation toward the raw ring-width data from 0.76 to 0.53 (Chap, Lag = 1). Within nine years the mean autocorrelation of a site falls below zero, while

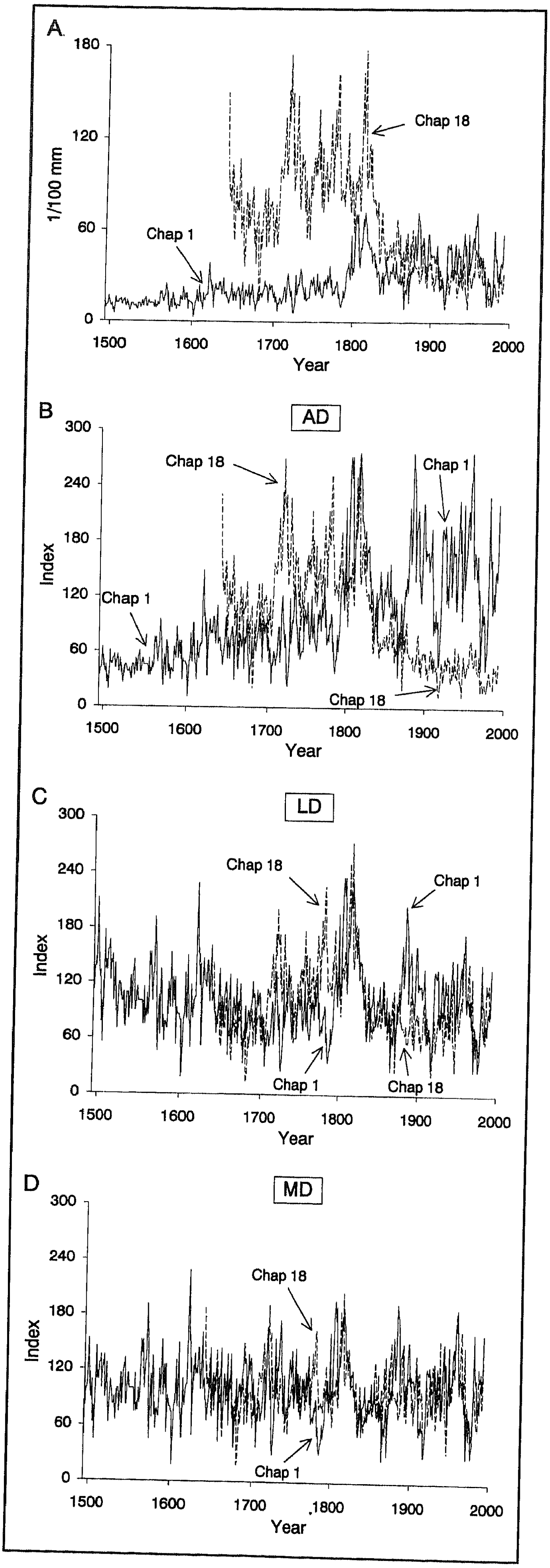

Figure 3 The effect of three standardization methods on two single ring-width series (Chaprot Valley: Chap 1 and Chap 18). (A) The raw ring-width series in 1/100 mm. (B) The ring widths divided by the series mean (AD). (C) The series after being divided by simple linear regression (LD). (D) Division by a 101-year moving average (MD). In MD the differences between Chap 1 and Chap 18 are minimized and most of the common low-frequency variation has been retained. After the division each value has been multiplied by 100.

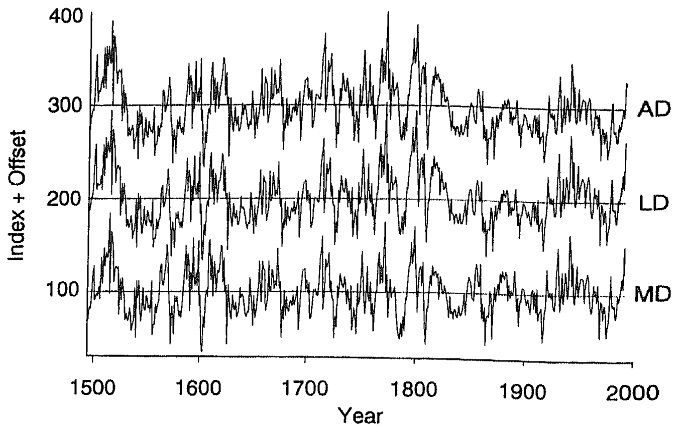

Figure 4 Comparison of standardized chronologies from a site in the Chaprot Valley (Chap), using all three standardization methods. (AD = division by the series mean; LD = division by the simple linear regressions; MD = division by 101-year moving averages). The chronologies are plotted with an offset of 100 points.

serial persistence in the average raw ring-width series, at lag 9, is still 0.38.

Prior to creating a site chronology using the MD method, each standardized single tree-ring series was examined for site coherency. If an individual curve fit followed an opposite tendency to the collective tendency in a site, then the uncommon period was removed from the individual record before inclusion into the average site index chronology. These departures from the norm were deemed non-climate-induced trend departures. Deviations of this kind could be explained by the influence of anomalous, non-concentric ring form found in the cross-sections of *Juniperus* trees (Figure 2). For each instance where the standardized curve suggests an anomalous, non-climatic departure, the original wood sample was visually inspected to confirm the decision to remove that portion of the tree's index series. This a-priori selection was employed to maximize the total common variance within a site and minimize randomly distributed uncommon variation. However, it only influences the scatter of the single series combined to site chronologies. The behaviour of the chronologies themselves is only slightly affected.

500-year long-term fluctuations

The yearly growth rate of *Juniperus excelsa* M. Bieb and *Juniperus turkestanica* Kom. along the upper timber-line is extremely small. Growth fluctuates between 0.24 and 0.42 mm yr^{-1} (Table 1). Trees from Chaprot Valley grow significantly faster than all other sites. The prevailing synoptic precipitation gradient (Figure 1) creates an ecological background which is expressed in the mean cambial activity of the valleys (Chaprot Valley SSW-situated, Morkhun Valley NNE-situated). Though there are differences in the growth rate, every site is located in an extreme environment along a temperature-limited timber-line. Here the climate is still the most controlling factor that synchronizes growth, both in the high- and low-frequency domains, regardless of site or exposition.

The average sign test is an expression of common signal within a site, particularly in the high-frequency domain (Hollstein, 1980). The summarized averages of all Hunza-Karakorum sites in this study lies above 70% pointing to a high year-to-year synchronicity (Table 1). The computed t-values express the absolute level of the sign test significance. All the averaged t-values are higher than 17.4 (Chap), reaching a maximum of 36.5 (Mor 3).

Demonstration of the climatic sensitivity of *Juniperus* in the NW Karakorum has been given in detail by Esper *et al.* (1995). Beside the analysis of the high-frequency signal, Figure 5 also shows the synchronicity of the low-frequency signal among the sites. The total of all single series (n = 61) lies so close together that it appears as an average in one figure. The deviations show how small the variability of the single series is. The deviation amplitude varies from s = 19.0 in 1838 to 65.3 in 1585 (where s equals the standard deviation for all populations).

Standardization, using a 101-year moving average filter, optimizes centenary-level trends. Therefore, it is necessary to determine just how much biological, or possibly climatic, trend is retained or lost by the process. Figure 6 is a plot of all the 101-year filters from each tree, from each site. The analysis of the filter's performance follows the criteria of disorder. In other words, if the filters at one site show a chaotic picture, the danger of losing climatic information is small. Conversely, if the tendencies, or long-term wave forms, are synchronized, then the danger of losing climatic information is high.

This is obviously the case in Hun, Mor 2 and Mor 4 (Figure 6). Here the filters show an unsorted, partly chaotic picture. No synchronized inclinations appear in any period over the past 500 years which are not interrupted by some, or at least one, filter's curve. At first sight the situation at Chap seems to be different. In the middle of the figure, between 1700 and 1800, many filters indicate a maximum followed by a negative decay into the nineteenth century. However, not all trees share this pattern. These are the slow-growing trees with a growth rate of less than 0.25 mm yr^{-1}, whose filters are horizontal.

Positive trends can be found in a third of the filters from Mor 1, though differentially strong. From the late nineteenth century until 1990, a systematic trend of increasing growth rates has been eliminated. This has to be considered during the discussion of the resulting site chronologies (Figure 7A). Although this is a very low-frequency signal of only a few series, the trend is not confirmed at the other sites.

In Mor 3 the summarized filters show a striking synchronicity, which has been systematically removed in all single series. In the centre of the figure, between 1700 and 1760, the old trees climb from a rate of constantly below 0.25 mm yr^{-1} to a persistently level. This trend has been confirmed by almost every filter at this site. It can not be denied that right here a common climatic signal has been eliminated. The MD standardization method has raised the resulting site chronology in Figure 7A to higher values before 1700 and depressed indices to lower levels after 1760.

After all the raw ring-width series from each site were standardized using the MD method, and anomalous period departures due to extremely suppressed growth removed, averaged, standardized site chronologies were developed (Figure 7A). The process of detrending and transforming the ring width variables into dimensionless indices of stabilized variance emphasizes the low-frequency signal and eventually leads to maximum comparability of the sites. No different curve signatures are used in the figure because the six chronologies lie close together.

Common high-frequency signals of different amplitude as well as common low-frequency signals of different range and amplitude, so-called long-term fluctuations, become clearly visible in this composite illustration. The site chronologies follow small-scattering long-term waves and document favourable and unfavourable growing conditions over the past 500 years. Even though the averages are composed of trees from sites on different exposures they all show the same low-frequency signal. Maximum synchronicity is maintained until 1606, between 1635 and 1695, 1725 and 1780, 1790 and 1808, 1830 and 1842, and after 1865 until 1990. However, there are a few periods which show some degree of uncommon signal for a couple of decades.

The period from 1790 to 1867 has a key position. After high growth rates until 1810 and 1814 the indices become significantly smaller at two sites, whereas the other chronologies persist on a higher level. Finally, the deviating chronologies also react to the increasingly unfavourable climate conditions, making the values of every site small after 1831 until 1841. At the same time there is a minimum scatter. After 1841 the *Juniperus* trees experience a marginal regeneration but then again show a significant decline from 1860 to 1867. Only one site is not affected by this second depression. Periods of widened scatter are not clearly understood.

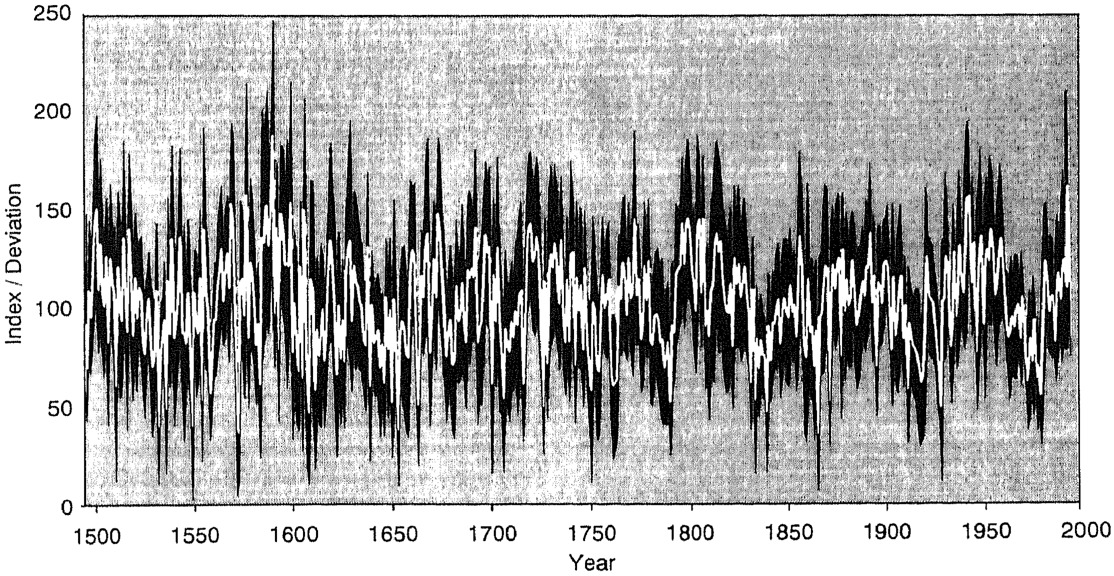

Figure 5 MD-indexed chronology of all *Juniperus* (n = 61) (white curve) and standard deviation. The standard deviation is shown as a black strip. Timespans of small and large variance can be identified.

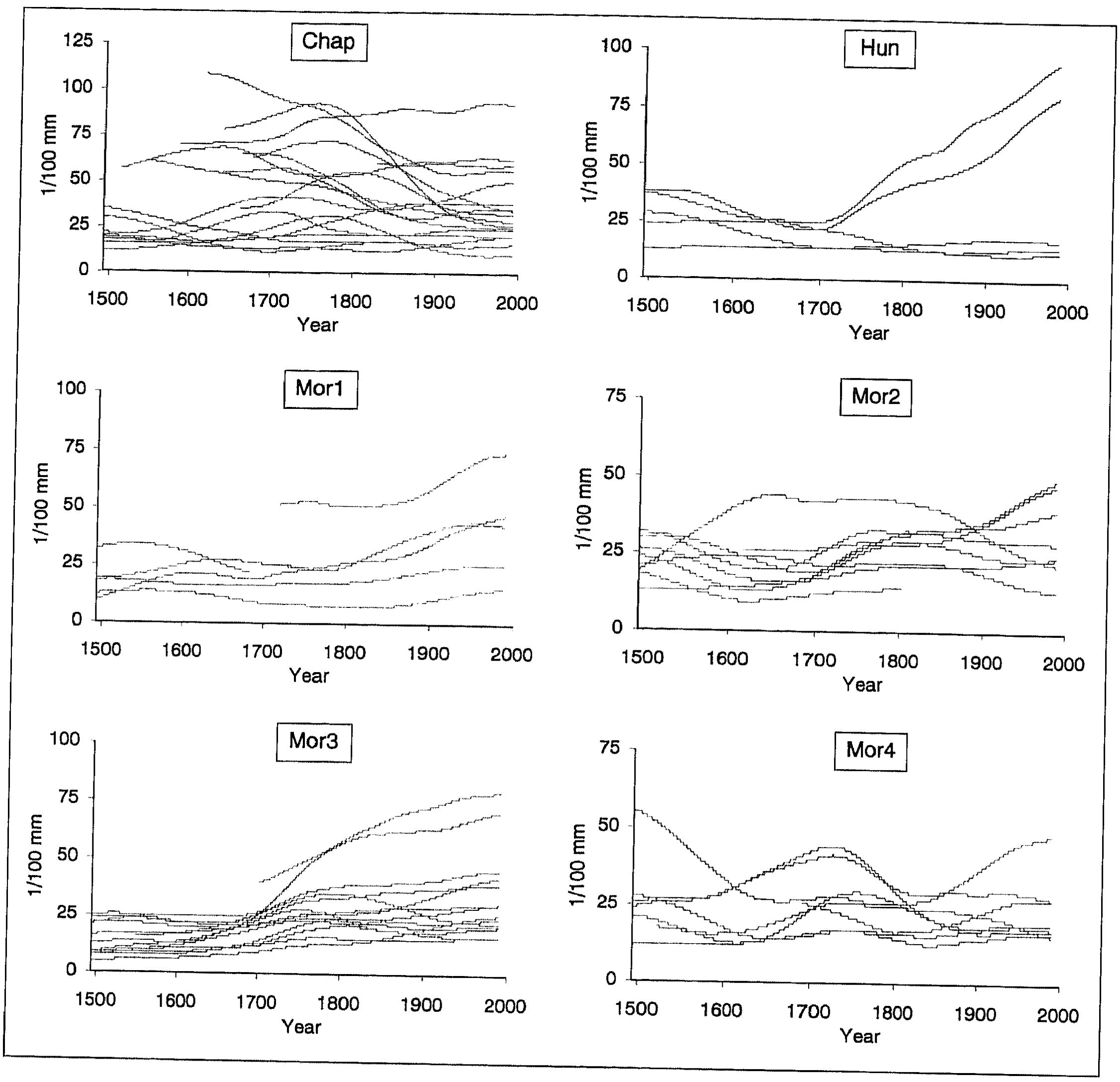

Figure 6 101-year filters used with the MD standardization method (division by moving averages). The centenary very low-frequency signal is eliminated by standardization. No systematic (climatic) information is lost if the filters are unsorted and unsynchronized as in Chap, Hun, Mor 2 and Mor 4.

Whether the scatter is a result of the site ecology or climate requires further research.

Figure 7B combines the information from all site chronologies in 7A and emphasizes the climate-induced long-term fluctuations. It is a plot of the positive (favourable) and negative (unfavourable) departures about the total mean of the site chronologies. This curve has been smoothed by a 13-year filter, then again by a second five-year filter. All site chronologies have an equal influence on the figure, because of the unweighted combination. Both amplitude and frequency of the fluctuations vary. In the tree-ring widths of *Juniperus* no centenary trend has been recorded that can be related to the documented increase in atmospheric CO_2 loading.

Periods of significantly favourable growing conditions are: 1560–1603, 1792–1824, 1871–1904 and 1933–1963. Slightly favourable periods are: 1500–1521, 1662–1700 and 1715–1743. The years 1662 to 1700 were interrupted by a growth reduction from 1679 to 1684. Periods of significantly unfavourable growing conditions are: 1522–1559, 1604–1661, 1825–1870, 1905–1932 and 1964–1984. 1604–1661 is divided into two parts by clearly positive indices (1624–1635) and 1825–1870 by slightly positive indices. Slightly unfavourable periods are: 1701–1714, 1744–1767 and 1779–1791.

Maximum amplitudes are reached from 1579 to 1603 (favourable) and from 1825 to 1850 (unfavourable). 1662–1791 is a period of more balanced growth. After 1970 a period of increasing cambial activity starts. Amplitude and speed of reaction or the graph's inertia correlate with the underlying filter.

A multivariate time-series approach to test the influence by a single climate variable did not seem appropriate using meteorological station data from Hunza-Karakorum. The only long-term station record is from Gilgit (1432 m a.s.l.). This single-station data does not satisfactorily represent the upper timber-line closely enough to calculate regression models (Esper *et al.*, 1995). Studies to understand the important linkages between trees from drier sites along elevational gradients are in progress.

Sampling the upper timber-line only does not satisfactorily capture the vertical hydrothermal gradient and the horizontal hydrologic gradient in the Hunza-Karakorum. Therefore positive deviations from the mean value function of the standardized growth chronology in Figure 7B are considered 'favourable climatic conditions', and negative deviations considered 'unfavourable climatic conditions'. The striking similarity of information between all sites points to a single controlling factor – climate.

Discussion

In living *Juniperus* trees, 165 to over 1000 years of age, from the upper timber-line in the Hunza-Karakorum (northern Pakistan), a 500-year record of climate-influenced variation has been recorded. Periods of different length and amplitude have been pointed out representing radial growth above or below average. These long-term fluctuations reflect climatic variability since 1494.

The suitability and applicability of various statistical methods were tested. Isolation of the common low-frequency signals using

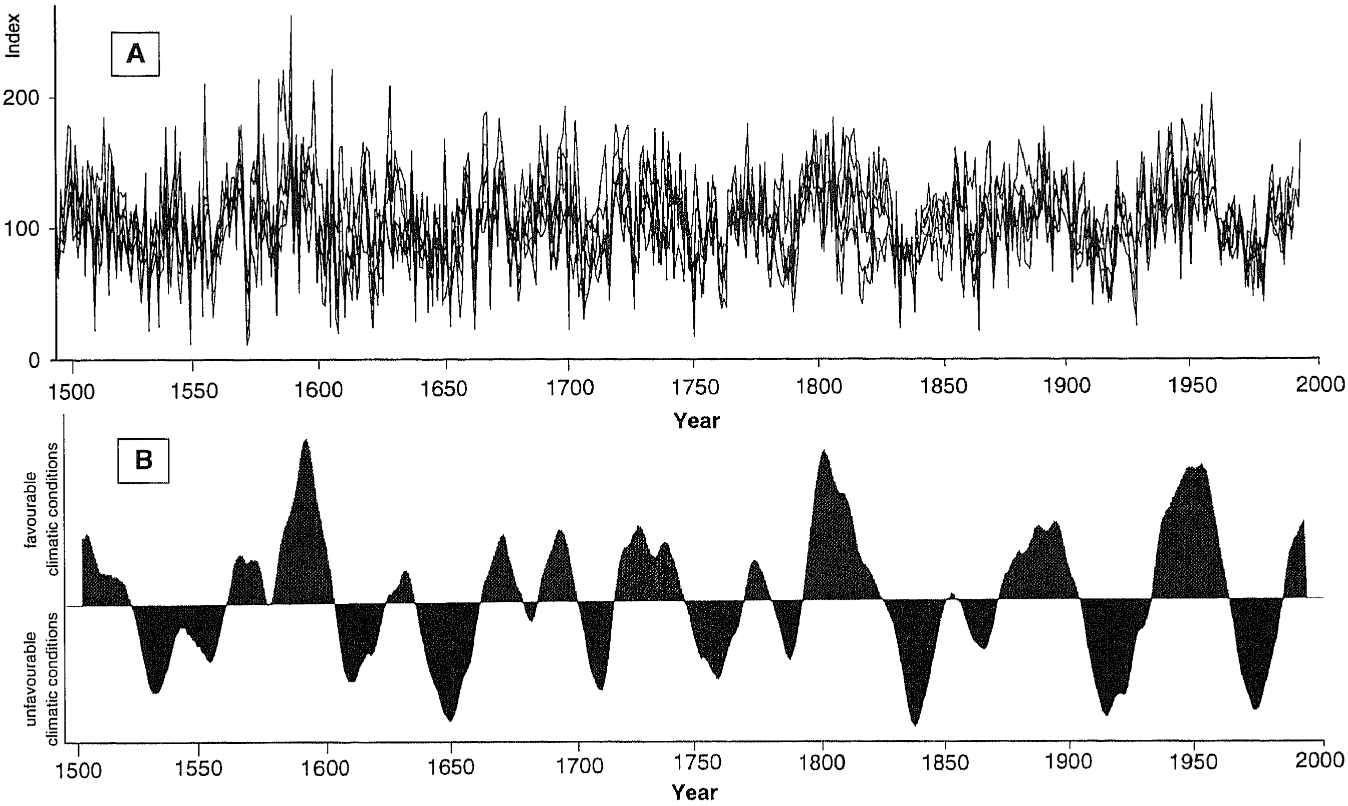

Figure 7 (A) Six standardized site chronologies (Chap, Mor 1 to 4, and Hun) resulting from the division by 101-year filters (MD) and (B) unweighted chronology, smoothed and shown as positive and negative deviations from the total average. The synchronicity of the site chronologies is almost continuous. Significant inhomogeneities can be found at 1781–1789 and 1810–1830 (A). Averaged and smoothed (in two steps: (1) by a 13-year running mean; (2) by a five-year running mean) the sites close to the upper timber-line show favourable and unfavourable climatic periods of the past 500 years (B).

a specific collection of chronologies proved somewhat problematic due to age and site-related growth differences.

From the dendrochronologic point of view, the NW Karakorum is comparatively poorly represented, and understood (Ahmed, 1989; Ahmed and Sarangezai, 1991; Bilham *et al.*, 1983; Esper *et al.*, 1995). Dendroclimatological studies exist in monsoonally influenced N India (e.g., Bhattacharyya *et al.*, 1988; Hughes, 1992; Pant *et al.*, 1990) and extended *Juniperus* chronologies are found in Kirgistan (Graybill *et al.*, 1992; Mukhamedshin and Sartbaev in Zheng *et al.*, 1982) and eastern Tibet (Bräuning, 1994a; 1994b; Bräuning and Lehmkuhl, 1996). Many investigations verify a cooling period around 1850 (e.g., Graybill *et al.*, 1992; Haserodt, 1989; Hughes, 1992; Kick, 1996; Mayewski *et al.*, 1980; Röthlisberger and Geyh, 1985; Shroder, 1993), that can be found in a decreased growth rate in every tree of the studied sites in the Hunza-Karakorum. All trees grow in extreme conditions almost along the upper timber-line. The hypothesis for further research is that low-frequency signals in *Juniperus* ring width basically reflect temperature variations.

Acknowledgements

This study has been financially supported by the DFG (German Science Foundation, DFG grant No. Wi-937-1/5) within the framework of the CAK project (Culture Area Karakorum). I wish to express my appreciation to Professor F.H. Schweingruber and Professor M. Winiger for their scientific support and advice. I would like to thank Dr O.U. Bräker, P. Krusic, L. Lachlan and E. Stein for the scientific discussion and assistance.

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