Twentieth century as the wettest period in northern Pakistan over the past millennium

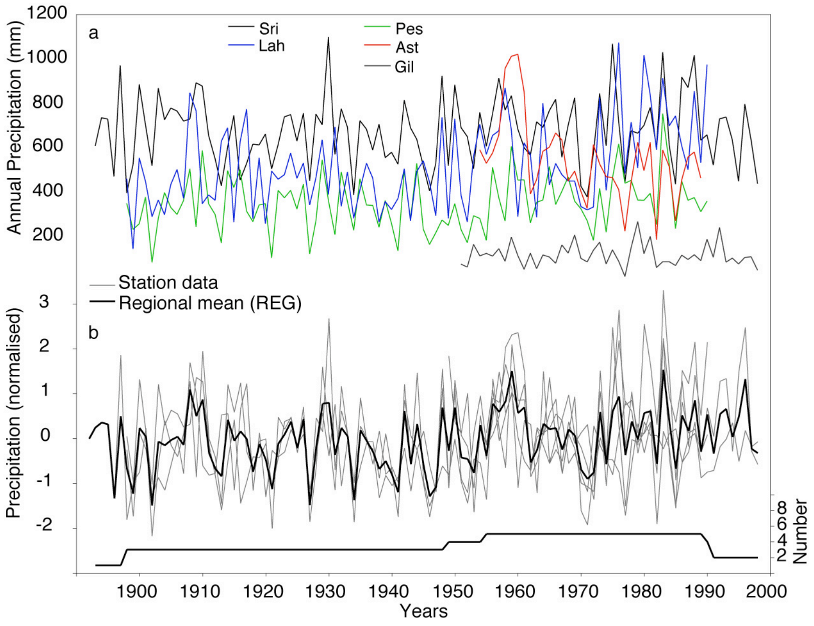
Supplementary tables, figures, legends, notes and references

Site name	**Coordinates**	**Altitude (m)**	**Exposure**	**Species**	**Number of trees/samples**	**Period**
Ram-high	35°22'N 74°52'E	3600	S	*Juniperus turkestanica*	4/8	1900-1998
Bag-high	36°02'N 74°35'E	3800	S	*Juniperus turkestanica*	4/8	1900-1998
Bag-low	36°02'N 74°35'E	2900	S	*Juniperus excelsa*	5/10	1900-1998
Mor-high	36°35'N 75°05'E	3900	SE	*Juniperus turkestanica*	7/14	826-1998

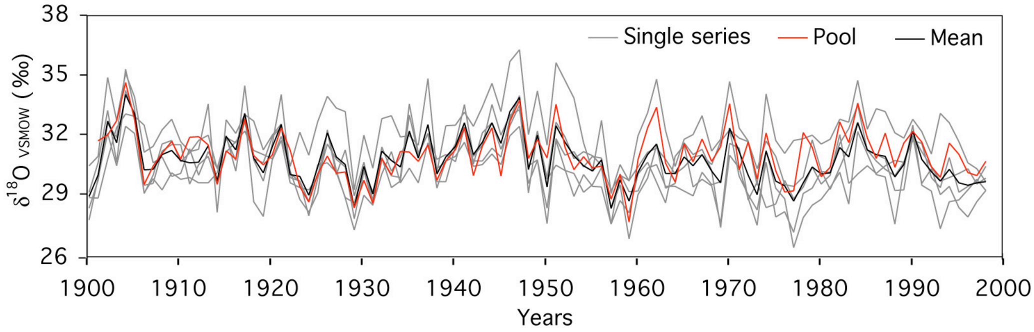
Supplementary Table 1: Sampling site information

O-s	Sri	Pes	Lah	Ast	Gil
				Temperature	
Sri		**0.73**	**0.63**	**0.74**	**0.53**
Pes	**0.47**		**0.83**	**0.60**	**0.41**
Lah	**0.50**	**0.44**		**0.54**	0.29
Ast	*0.35*	0.25	0.07		**0.74**
Gil	**0.33**	0.27	0.08	0.27	
	Precipitation				

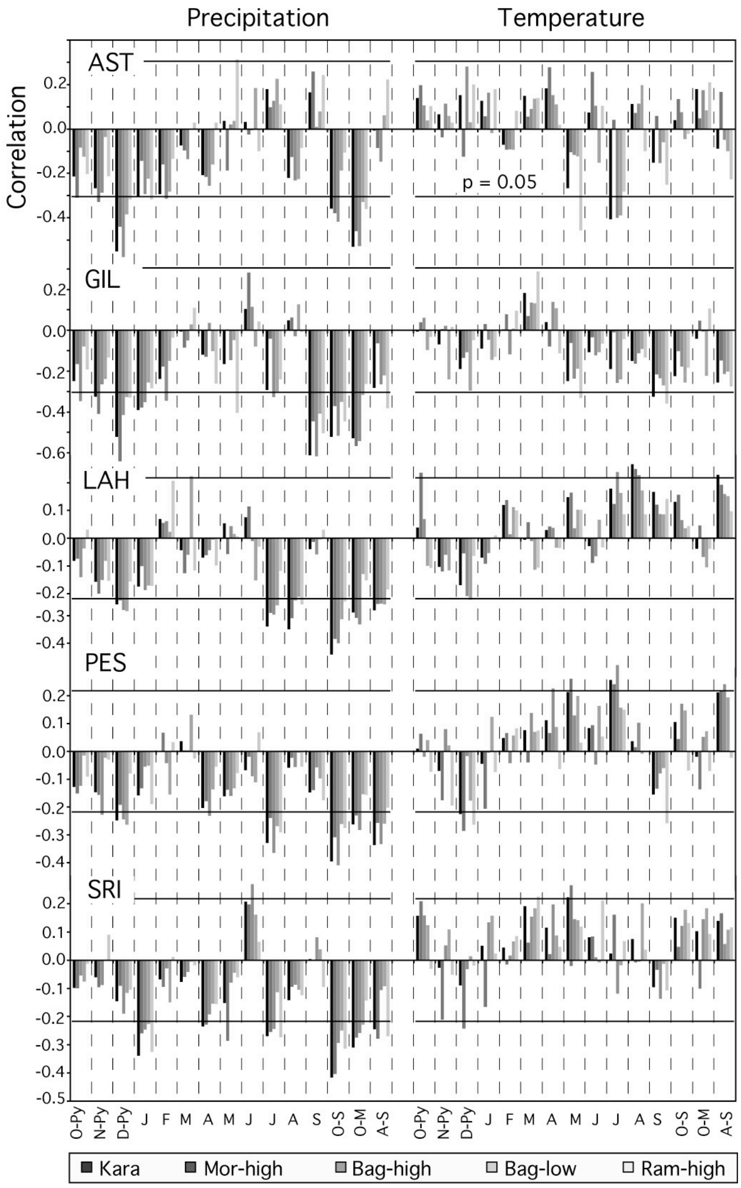
Supplementary Table 2: Inter-station correlations using annual (October-September, O-S) means of temperature (upper right) and normalized precipitation (lower left). Correlations are based on the common period AD 1954-1989. SRI=Srinagar, PES=Peshawar, LAH=Lahore, AST=Astor, GIL=Gilgit. Bold: $p<0.05$, italics: $p<0.01$.



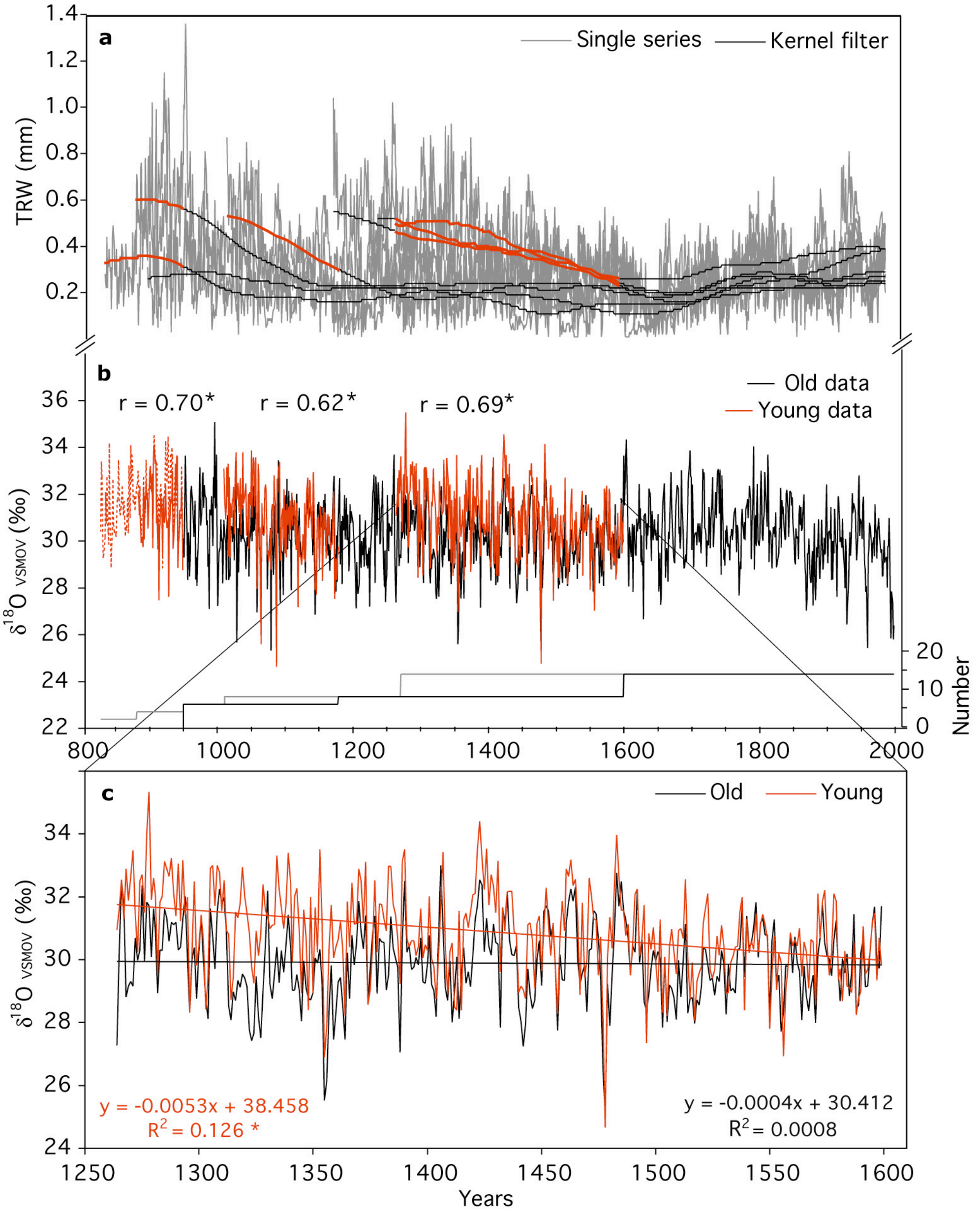
Supplementary Figure 1: Annual (October to September) precipitation data from Srinagar (SRI), Peshawar (PES), Lahore (LAH), Astore (AST) and Gilgit (GIL); **a** precipitation means; **b** data normalized over individual series lengths, the mean of these series and also the number of series contributing to the mean.



Supplementary Figure 2: δ^{18}O measurements from five single trees at Bag-low, their arithmetic mean, and the δ^{18}O curve obtained from pooling the rings of the same trees before single-series-measurements. The series are homoscedastic with no spread-versus-level relationship, as is generally the case with tree-ring width measurements[1]. The mean inter-series correlation of 0.62 is highly significant ($p<0.001$). The arithmetic mean of the five series (black) correlates at 0.85 with the pooled record (red), validating the pooling method.



Supplementary Figure 3: Correlations between tree-ring δ^{18}O and normalized precipitation and temperature data for each of the five meteorological stations; correlation coefficients are shown for each of the four tree sites and their variance adjusted mean (Kara) from October of the previous year (Py) to September of the current year (O-S), winter half year (October-March, O-M) and summer half year (April-September, A-S). The climate signal, seen when calibrating against the regional mean series REG (Fig. 2b, main text) is supported by the results using single station data. AST and GIL are situated within the study region, and are most representative for the tree sites despite elevational differences of about 1000 m. Both validate the winter precipitation signal being dominant. LAH, PES and SRI highlight spring and summer conditions also being of importance suggesting integration of whole year conditions. As discussed for REG, only weak and heterogenous correlations are found with summer temperature conditions.



Supplementary Figure 4: Potential age-related biases in ring-width and $\delta^{18}O$ measurements. **a** Ring-widths of seven trees used for isotope analyses at Mor. 101-year smoothing Kernel filters indicate, that the early segments (red), showing systematically wider rings, are biased by age-related effects commonly known as age-trend. **b** Pooled oxygen record (black) using cellulose from only “old” rings versus shorter segments (red) using only “young” rings. “r” is the correlation for the periods 881-950, 1077-1178, and 1264-1599. The record for the latter period is derived from pooling the three younger trees. Bottom: Numbers of samples combined in the long record using only the old (black) and all data (gray). **c** Least-square linear fits to the $\delta^{18}O$ time-series from young and old data over the 1264-1599 period show that there is a significant long-term $\delta^{18}O$ trend in the records containing juvenile rings but none over the same time period from records composed only of older rings.

Notes to supplementary figure 4:

Ring-width measurements from our 1000-year old living juniper trees (Mor) are strongly biased by non-climatic, age-related trends, commonly found in growth proxy data (ring-widths, wood density)[1]. In these junipers, the age-trend and long-term temperature changes tend to mimic each other during the cooling from the Medieval Warm Period (MWP) into the Little Ice Age (LIA)[2,3], making unbiased estimates of past climate challenging. To date, such biases have not been reported for oxygen isotopes. We tested the age-level relationship in $\delta^{18}O$ time-series over the past millennium using cellulose from “old” and narrow rings, and comparing this record with three shorter segments composed of “young” and wide rings (Supplementary Fig. 3b). These segments all correlate >0.62 with the long record, thus demonstrating a common signal in the mid-to-higher frequencies. However, linear fits to the young and old data over the 1264-1599 period, during which the growth rate differences between both are maximum, indicate a significant trend ($p<0.001$) for the time-series from young rings but no trend from the old rings (Supplementary Fig. 3c).

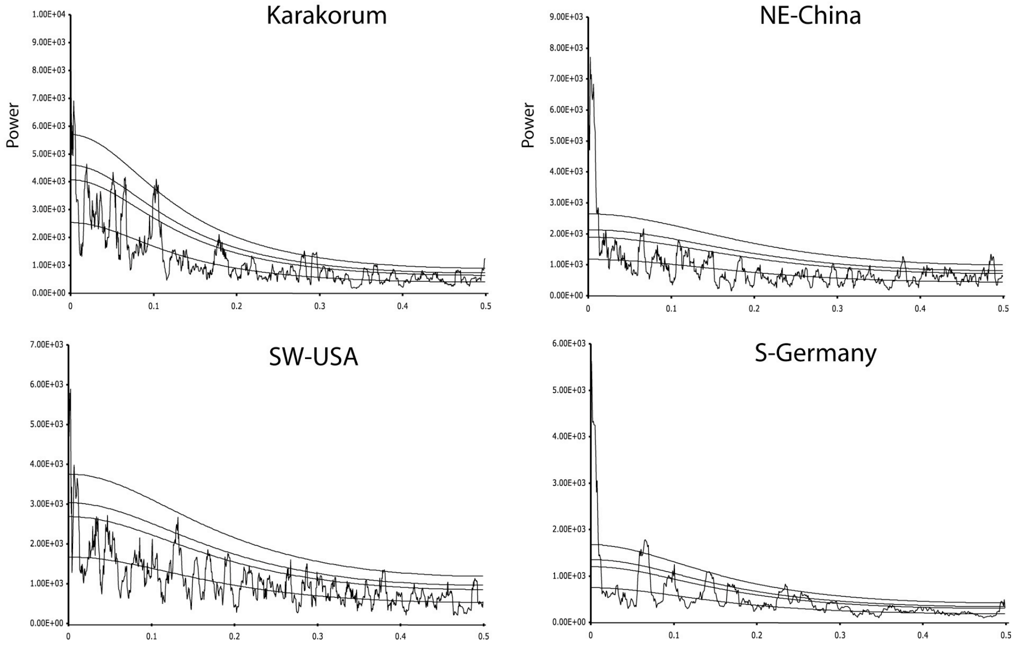
For the first time, these results suggest that long-term age-related effects could exist in $\delta^{18}O$ measurements. Several factors could account for the observed age-related

$\delta^{18}O$ decrease found in young juniper trees. Based on tree physiological considerations, we here present two possible explanations.

(i) $\delta^{18}O$ variations in up-taken water are the baseline for variations in tree ring cellulose. Although young and old trees originate from the same site, they might access different source water. Because of a their shallow root system, young trees take up relatively more of water from the upper soil. Due to evaporative effects, this water has up to 6‰ higher $\delta^{18}O$ values than water deeper in the soil[4, 5].

(ii) The differences in $\delta^{18}O$ of tree ring cellulose between young and old trees might additionally be caused by differences in ^{18}O enrichment of leaf water. Evapotranspiration enriches leaf water because the heavier $H_2{}^{18}O$ vapour has a lower vapour pressure than $H_2{}^{16}O$, and $H_2{}^{18}O$ diffuses more slowly than $H_2{}^{16}O$. The extent of ^{18}O enrichment depends on the leaf-to-air water vapor pressure gradient. Trees grown in humid conditions show generally lower $\delta^{18}O$ values than those grown in dry conditions[6]. In the open juniper stands, considered here, air humidity can assumed to be the same for young and old trees. However, a less developed root system with slightly inferior water supply could lead to a higher leaf-to-air water vapor pressure gradient with higher ^{18}O enrichment in young trees as compared to old trees.

The presence of age-related $\delta^{18}O$ trends would have significant implications for preserving long-term variability in the millennium-long chronology and more generally for all $\delta^{18}O$ tree-ring applications. Hence, in the main paper we show the long reconstruction using all tree-ring data together with results obtained by excluding young-ring cellulose (fig. 3b, main text).



Supplementary Figure 5: Power spectra (multitaper method[7]) of the four annually resolved precipitation reconstructions shown in fig. 4 of the paper. Smoothed curves are 50%, 90%, 95% and 99% red noise significance levels. All spectra tend to be consistent towards the red noise component with substantially more variance in the decadal to centennial time scales than at higher frequencies.

References

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