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Vikram Singh [a], Ram R. Yadav [b,*], Anil K. Gupta [b], Bahadur S. Kotlia [c], Jayendra Singh [b], Akhilesh K. Yadava [a], Anoop K. Singh [c], Krishna G. Misra [a]

[a] *Birbal Sahni Institute of Palaeosciences, 53 University Road, Lucknow, India*
[b] *Wadia Institute of Himalayan Geology, Dehradun, India*
[c] *Centre of Advanced Study in Geology, Kumaun University, Nainital, India*

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ABSTRACT

Droughts in semi-arid and arid regions of the northwest Himalaya are very common causing distress to socioeconomic systems. Our understanding on natural variability in droughts in the northwest Himalaya in long-term perspective is limited largely due to paucity of observational and high-resolution proxy records. We developed a 275-years (A.D. 1740–2014) long Standardized Precipitation Index (eight months SPI of May, SPI8-May) reconstruction using ring-width chronology of Himalayan cedar (*Cedrus deodara* (Roxb.) G. Don) from Kishtwar, Jammu and Kashmir in the northwest Himalaya, India. The most conspicuous feature of reconstruction is pluvial 1950s, 1990s and dry 1970s. The wettest phase of 1990s is followed by a distinct drying since 2000s in Kishtwar. The reconstructed SPI8-May series showed very good consistency with tree–ring-based upper Indus basin discharge and gridded summer (June–July–August) PDSI data of the northwest Himalaya–Karakoram region. Such a consistency in SPI8-May, Indus discharge and summer PDSI in westerly dominated region of the Himalaya–Karakoram region underscores potential utility of SPI reconstructions in understanding climate change over the region in long-term perspective.

1. Introduction

Droughts are a frequently occurring phenomenon inflicting serious miseries to human societies almost every year in one or the other region of India (Shewale and Kumar, 2005). In recent years there is a growing concern globally on increase in frequency and intensity of droughts due to precipitation deficits that are amplified by ongoing increase in temperature (Dai, 2013). Deficient summer monsoon rainfall in western and central India consecutively in 2014 and 2015 caused serious water crisis, which worsened in early summer of 2016 and water trains were rushed to meet the civic water demands. Well developed surface transport system and infrastructure in plane areas of the country greatly help in mitigating the vagaries of such devastating droughts. However, coping with droughts in the Himalayan region is challenging as transport of water resources from one place to another, even in short distances, is very difficult due to highly dissected orographic terrains. Droughts occurring even for a short span of time cause drying of streams and aquifers in hilly terrains, which are the main source of water for agriculture and domestic needs. In view of this there is increasing need to understand natural variability in droughts in orography dominated regions of the Himalaya in a long-term perspective. In this line the Monsoon Asia Drought Atlas (MADA) developed by Cook et al. (2010) has shown the strength of tree–ring data networks in developing annually resolved spatial network of summer monsoon droughts in high Asia.

Droughts in the Himalayan region are caused by the reduction in precipitation brought by summer monsoon rains/western disturbances in monsoon/westerly dominated regions. Paucity of weather and high-resolution proxy records in the high elevation Himalayan region limit our understanding on hydroclimatic variability in long-term perspective. Tree rings have been widely used to develop annually resolved drought/hydrological records from

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* Corresponding author.
E-mail addresses: vnegi850@gmail.com (V. Singh), rryadav2000@gmail.com (R.R. Yadav), anil_k_gupta1960@yahoo.co.in (A.K. Gupta), bahadur.kotlia@gmail.com (B.S. Kotlia), singhwihg@gmail.com (J. Singh), akhilesh.k.yadava@gmail.com (A.K. Yadava), anoop1818@gmail.com (A.K. Singh), kgmisrabsip@gmail.com (K.G. Misra).

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semi-arid to arid regions of Asia (Sheppard et al., 2004; Davi et al., 2006; Li et al., 2006, 2007; Liang et al., 2006; Treydte et al., 2006; Yin et al., 2008; Cook et al., 2010, 2013; Shao et al., 2010; Zhang et al., 2011; He et al., 2012; Deng et al., 2013; Fang et al., 2013; Liu et al., 2013; Peng and Liu, 2013; Sun and Liu, 2013; Zhang et al., 2013, 2016; Bao et al., 2015; Yang et al., 2012, 2014a,b). But such studies in the Himalayan region are few and largely restricted to western part of the Himalayan region in Himachal Pradesh and Uttarakhand (Borgaonkar et al., 1996; Yadav, 2009, 2013; Shah et al., 2013; Singh and Yadav, 2013; Yadav et al., 2014, 2015; Misra et al., 2015; Yadava et al., 2016), Nepal Himalaya (Sano et al., 2011; Dawadi et al., 2013), eastern Himalaya (Shekhar and Bhattacharyya, 2015), and Bhutan Himalaya (Sano et al., 2013). Tree–ring studies in Jammu and Kashmir in the northwest Himalaya had a modest beginning in late 1980s with the investigation of ring-width, wood density (Hughes and Davies, 1987; Bhattacharyya et al., 1988) and isotope variations (Ramesh et al., 1985, 1986). The climatic reconstructions were restricted to the valley of Kashmir (Hughes, 1992, 2001; Borgaonkar et al., 1994; Ram, 2012). However, prior to the present study no attempt was made to develop dendroclimatic reconstruction from Jammu region in the northwest Himalaya, India. In the present study the main objectives of our research were i) establish the feasibility of climatic reconstruction especially concerning drought indices and ii) understand spatial patterns and regional hydroclimatic signatures in reconstructed drought indices from Kishtwar.

2. Data and methods

2.1. Tree–ring data

Himalayan cedar (*Cedrus deodara* (Roxb.) G. Don), a valued commercial timber tree in India grows in moist to semi-arid sites in monsoon and monsoon shadow zones of the western Himalaya at altitudes ranging from 1200 to 3300 m asl (Raizada and Sahni, 1960; Champion and Seth, 1968). Though it grows over a wide range of ecological conditions in the western Himalaya, its primary ecological requirements are a good amount of winter snowpack, not too heavy summer monsoon rainfall and well drained soils (Champion and Seth, 1968). The trees on moist sites usually grow faster and attain colossal girth in early age (Gamble, 1902); however, many of the thick trees growing on such sites usually do not attain long age largely due to common wood rot and other fungal/insect borne diseases. Himalayan cedar trees growing on semi-arid sites, where annual increment is low, attain longer ages. Ring-width series of Himalayan cedar (Singh et al., 2004) and other conifer species such as neoza pine (*Pinus gerardiana*) (Singh and Yadav, 2007; Yadava et al., 2016) and Himalayan pencil cedar (*Juniperus polycarpos*) (Yadav et al., 2006; Yadav, 2012) originating from semi-arid ecological settings in the western Himalaya, India have yielded long tree–ring chronologies extending over the last millennium. Thus far, most of the earlier tree–ring studies were restricted to Uttarakhand and Himachal Pradesh regions of the western Himalaya, India. The tree–ring studies of Himalayan cedar from the northwest Himalaya are of only exploratory nature (Bhattacharyya et al., 1988). To expand the tree–ring data network of this species in the Himalayan region we collected increment core samples of Himalayan cedar in July–August 2015 from semi-arid sites in Kishtwar located in the Middle Himalaya (Pir Panjal), Jammu and Kashmir, India (Fig. 1). Prior to our present study Bhattacharyya et al. in mid 1980s had collected Himalayan cedar samples growing in a moisture stressed site at Sashu in Kishtwar (33°20′N and 76°05′E, 1800 m asl) (Bhattacharyya et al., 1988). However, the sample replication in their collection was very low being restricted to 10 increment core samples from 3 trees only. Due to poor replication of tree core samples Bhattacharyya et al. (1988) did not attempt to identify the climate signal in tree–ring chronology. However, strong similarity in ring width pattern noted among trees and also consistency with growth pattern of neoza pine (*Pinus gerardiana*) growing over similar ecological settings in Kishtwar indicated common climate forcing (Bhattacharyya et al., 1988). In this study we present the analyses of increment core samples of Himalayan cedar collected from semi-arid locations in Kishtwar (Fig. 1). The sampling sites exhibited steep rocky slope with very thin soil cover, where trees are liable to suffer from moisture stress.

The growth ring sequences in increment cores were crossdated using conventional skeleton plotting method (Stokes and Smiley, 1968) and ring widths of precisely dated samples measured at 0.01 mm resolution using linear encoder (LINTAB) (Rinntech, Germany) coupled with personal computer. To assess dating quality, program COFECHA (Holmes, 1983) as well as matching of ring width measurement plots (Rinn, 2003) were used. Program COFECHA uses cross-correlation analyses in segmented blocks of individual tree-core measurement series with the master series prepared from all the series used in the analyses. Another important function of program COFECHA lies in assessment of the accuracy of ring-width measurements (Grissino-Mayer, 2001) by locating the 'outlier' ring-width measurements in any given year, which are flagged and listed in the output. These flagged measurements were carefully observed and re-measured to ensure if the original measurements were accurate.

Ring-width measurement series, in addition to climate forcing, are also influenced by various internal factors such as genetic constitution of trees, biological age and external factors like competition among neighboring trees and diseases. In dendroclimatic studies, these non-climatic trends inherent in ring-width measurement series are usually removed by curve fitting and detrending procedures referred as 'standardization' (Fritts, 1976). For standardization of ring-width measurement series we used 'signal-free' (SF) method (Melvin and Briffa, 2008), which is designed to enhance the preservation of common medium-to-low frequency variations ranging from timescales of decades to centuries in tree–ring chronologies. The signal-free method also mitigates the problem of 'trend distortion', which is most prevalent at the ends of the chronologies but can also occur anywhere in a tree–ring series as well, when flexible curve fitting methods are used (Melvin and Briffa, 2008). The signal-free method also has the advantage over conventional tree–ring standardization methods in mitigating the effects of 'segment length curse' (Cook et al., 1995) in preserving variability in excess of the lengths of tree–ring series used in development of the mean chronology. Using the signal-free method we detrended the raw ring-width measurement series of all the samples by applying a cubic smoothing spline (Cook and Peters, 1981) that preserved 50% of the amplitude over a wavelength of 67% of the series length. For standardization of the ring-width measurement series we used the program RCSsigFree_v45 provided by the Tree–Ring Laboratory, Lamont Doherty Earth Observatory (http://www.ldeo.columbia.edu/tree-ring-laboratory/resources/software). To stabilize the variance in heteroscedastic ring-width measurement series before detrending, data adaptive power transformation was applied (Cook and Peters, 1997). After detrending, the individual ring-width measurement series were combined to mean chronology (A.D. 1509–2014; Fig. 2) by calculating biweight robust mean (Cook, 1985). The expressed population signal (EPS) threshold of 0.85, considered to be reasonable for acceptance of chronology quality (Wigley et al., 1984) in

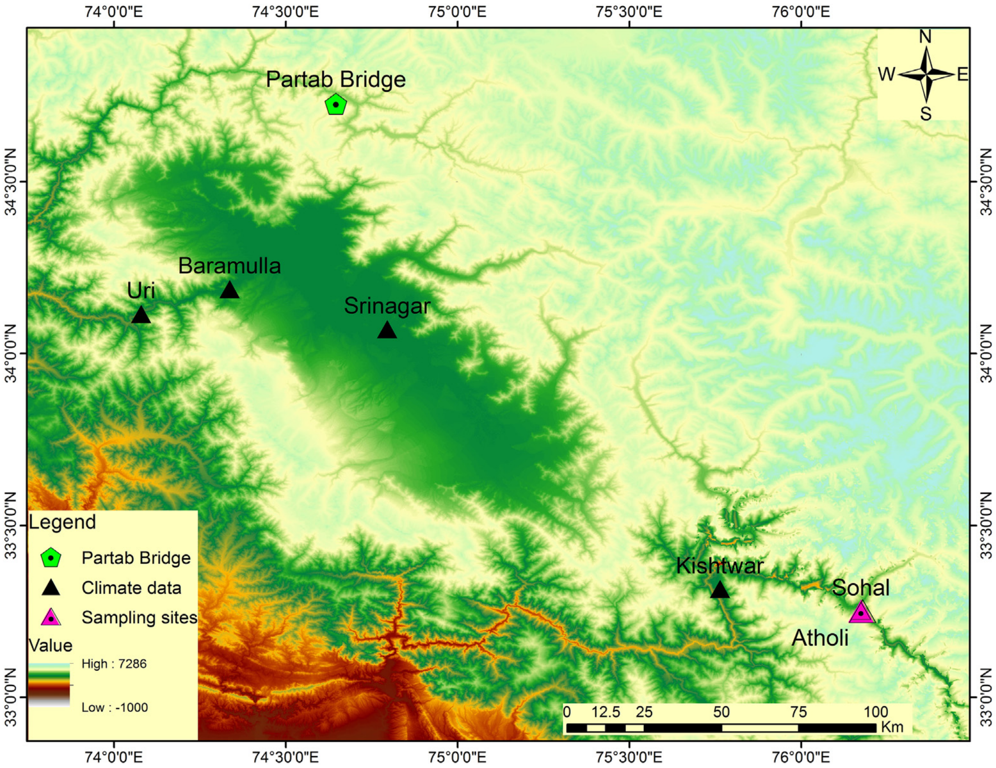

Fig. 1. Map showing the location of tree ring sampling site and meteorological stations used in this study.

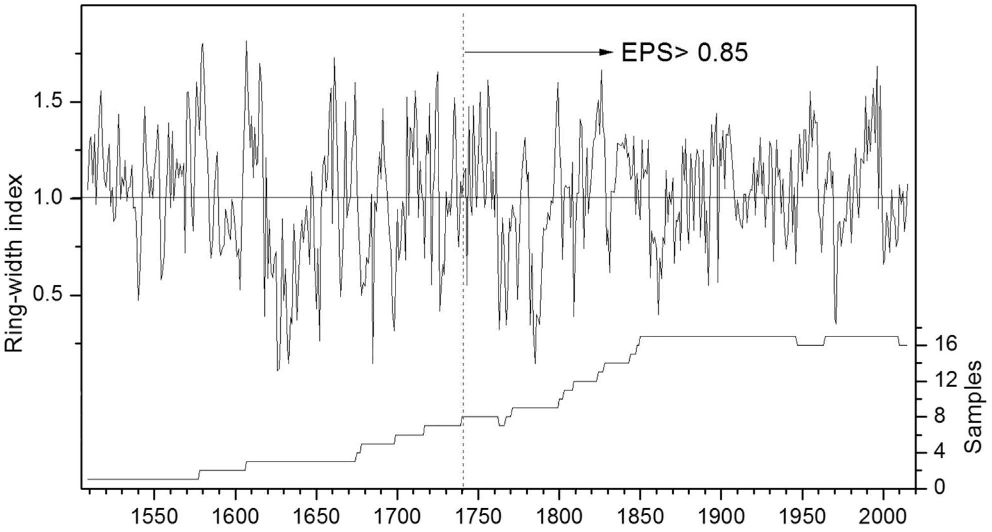

Fig. 2. Ring-width chronology of Himalayan cedar developed from Kishtwar, Jammu and Kashmir, the northwest Himalaya, India (A.D. 1510–2014). The vertical line at A.D. 1740 indicates the chronology after which EPS exceeds 0.85 threshold.

dendroclimatic studies was taken into account to truncate the chronology at A.D. 1740 for further analyses. Details of the signal-free chronology statistics viz., chronology span, number of samples used in chronology preparation, mean sensitivity, standard deviation and EPS threshold exceeding 0.85 are indicated in Table 1.

2.2. Climate data

In dendroclimatic analyses the climate data from stations close to sampling sites are useful for calibration of tree ring chronologies. But in orography dominated Himalayan region, as a whole, the

Table 1
Chronology statistics of Himalayan cedar from Kishtwar. EPS – expressed population signal, MI – mean index, MS – mean sensitivity, SD – standard deviation, AR1 – first order autocorrelation. The chronology statistics were calculated for A.D. 1740–2014 for which EPS exceeds 0.85 threshold.

Latitude (N)	Longitude (E)	Cores/trees	Chronology span A.D. (yrs)	Chronology with EPS >0.85 A.D.	MI	MS	SD	AR1
33°15′ 21″–33°15′ 55″	76°10′16″–76°10′57″	21/14	1509–2014 (506)	1740–2014	1.00	0.25	0.29	0.48

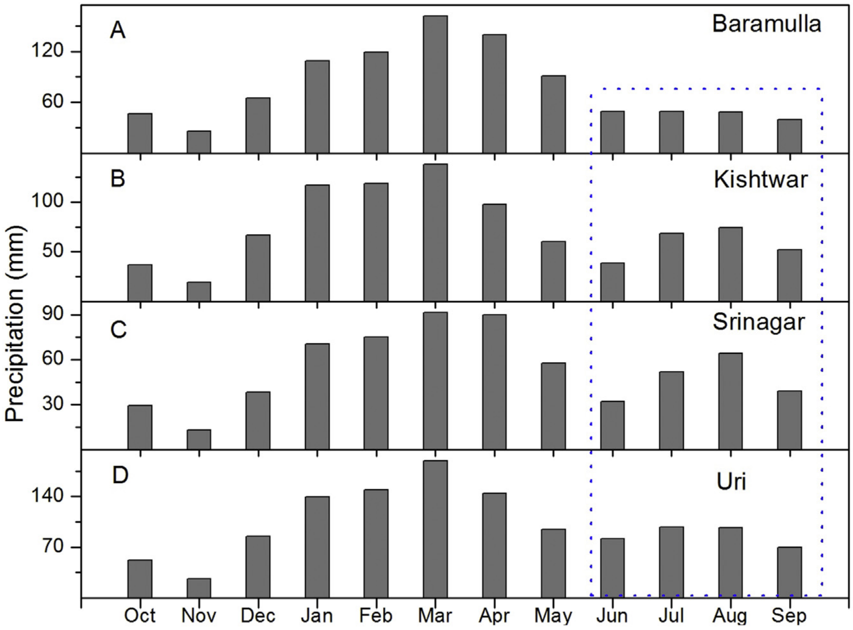

Fig. 3. Monthly precipitation pattern of meteorological stations used in the study: Baramulla (A), Kishtwar (B), Srinagar (C), Uri (D). Note that precipitation during summer monsoon season (June–July–August–September) over all the stations is low in comparison to winter and spring seasons.

meteorological stations with long, homogeneous data records are few and usually restricted to locations in valley floors far from the potential tree–ring sites. High variability in climate in the Himalayan region within short distances, mainly due to complex orography makes it unreasonable and also difficult to calibrate tree–ring chronologies with the meteorological data originating from stations away from the tree–ring sites. In our previous studies we observed this problem to be common with precipitation records largely due to orography forced high spatial variability in the Himalayan region (Yadav et al., 2004; Singh and Yadav, 2005; Singh et al., 2006, 2009; Yadava et al., 2016). Kishtwar has temperate climate and gets the lowest precipitation in entire Jammu and Kashmir region. The average annual rainfall in Kishtwar has been recorded as 822 mm (1901–1950 mean). Due to low average annual precipitation the whole of Kishtwar has been declared drought prone (Anonymous, 1909, 2014). The weather data records from the northwest Himalaya, in general, are very patchy and short, except the Srinagar meteorological station data, which extends back to the late 19th century (1893–2014). The geodesic distance between Srinagar and Kishtwar is ~122 km and both locations have a very similar precipitation regime. In view of the lack of weather data from any station close to tree–ring sites in Kishtwar, we prepared a regional precipitation data series using homogeneous data sets of four meteorological stations in the northwest Himalaya, India having similar climatic regime (Table 2). The precipitation of four meteorological stations selected in our study show weak summer monsoon rainfall contributing ~19% of the annual budget in Baramulla, ~27% in Kishtwar, ~16% in Srinagar and ~17% in Uri (Fig. 3).

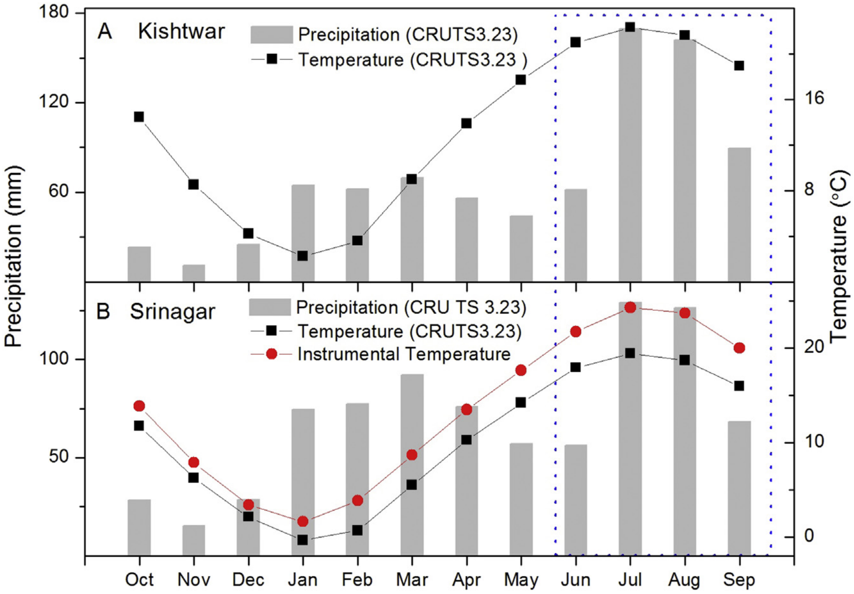

Fig. 4. Average gridded (CRU TS3.23; Harris and Jones, 2015) monthly precipitation and temperature data (1901–2014) close to Kishtwar (A) and Srinagar (B) showing relatively higher precipitation in summer, especially July–August. The instrumental temperature records of Srinagar (1901–2008) show pattern similar to gridded data (B).

Using precipitation data of these four stations (Baramulla, Kishtwar, Srinagar, Uri), we prepared a regional monthly data series by combining the z-scores calculated with respect to mean and standard deviation of the common period (1903–1947). The mean regional monthly precipitation series were then rescaled to total precipitation in millimetres with respect to the average of mean and standard deviation of respective months of all four stations. The regional average climate data series has the advantage over single station data in that it overcomes many problems associated with record in-homogeneities and differing station microclimates so that they can provide potentially more reliable data to calibrate tree–ring chronologies (Blasing et al., 1981; Jacoby et al., 2000).

Table 2
Precipitation data of meteorological stations used in the study.

S. no.	Station	Position	Altitude (m)	Length
1	Baramulla	34°12′N, 74°24′E	1590	1903–1970
2	Kishtwar	33°18′N, 75°42′E	1638	1901–1950
3	Srinagar	34°05′N, 74°48′E	1585	1893–2014
4	Uri	34°07′N, 74°00′E	1363	1901–1947

As the regional precipitation series prepared by us is limited to 1903–1947, we also tested if the available gridded precipitation and temperature data (CRU TS3.23; Harris and Jones, 2015) could be utilized for calibration of tree–ring chronology over the recent periods as well. For this, precipitation and temperature data available through the KNMI climate explorer (http://climexp.knmi.nl; Oldenborgh and Burgers, 2005) were downloaded for coordinates close to Kishtwar (33°–33°30′N and 75°–75°30′E) and Srinagar (34°–34°30′N and 74°–74°30′E). The gridded precipitation data (1901–2014; Fig. 4) showed dissimilar pattern compared to that displayed in the gauge-based observational precipitation data of Kishtwar and Srinagar (Fig. 3). The gauge-based observational precipitation records revealed major proportion of precipitation occurring in winter and spring seasons (Fig. 3). However, the gridded precipitation data showed higher proportion of annual precipitation occurring in summer monsoon months (June–July–August–September) (Fig. 4), i.e., Kishtwar (57%), and Srinagar (46%) compared to gauge-based observational precipitation data showing only 27% and 16%, respectively. Dissimilarity in observational and gridded precipitation data in the orography dominated Himalayan region endorses inherent difficulties in interpolation of gridded precipitation data, limiting its utility in tree–ring calibrations. In view of the existence of high dissimilarity in observational and gridded precipitation data we opted to use gauge-based observational weather data in our analyses. The data for the common period in all four stations, i.e., 1903–1947 as well as the data available from fewer stations from 1948 to 2014 (Table 2) were used separately in tree-growth climate relationship analyses.

Temperature records are also not available from any station close to the sampling locations in Kishtwar. In view of the existence of strong coherence in temperature variations over distant regions in the northwest Himalaya (Yadav et al., 2004) we used temperature records of Srinagar (34°08′N and 74°48′E, 1587 m asl; 1893–2008) in our present study. Srinagar temperature data show that July (24.2 °C) and January (1.5 °C) are the hottest and coldest months of the year, respectively (Fig. 4b).

2.3. Climate forcing on tree growth

To understand the climate signal in the ring-width chronology we performed bootstrapped correlation analyses between the chronology and available climate records (precipitation and temperature) using program DENDROCLIM2002 (Biondi and Waikul, 2004). The bootstrapped correlations were calculated for the period 1903–1947 for which regional precipitation series contained all four stations' precipitation data. The correlations were also calculated separately for 1948–2008, as temperature data were available only up to 2008. The monthly climate data for a window from October of the previous growth year to current year September were used in correlation analyses with the tree–ring chronology. The climate data of months prior to the growth year were included in correlation analyses as photosynthetic assimilates of the dormant season could also significantly contribute to the radial growth of trees. The correlations indicated that precipitation has a direct influence on tree growth and these were significant in previous year October and current year March, April and May (Fig. 5A). However, correlations with the mean monthly temperature were usually negative and significant in previous year October, current year April, May and June. The correlations calculated for the sub-period 1948–2008 (Fig. 5B) revealed similar results, but were weaker compared to that observed in the first sub-period 1904–1947.

We observed that the correlation of the ring-width chronology of Himalayan cedar with monthly precipitation and temperature variables nearly reflect the mirror image of each other (Fig. 5) endorsing that soil moisture availability is very important in modulating the annual growth of Himalayan cedar in semi-arid sites of Kishtwar. Considering these findings we studied the relationship between tree–ring chronology and commonly used drought indices, viz., Palmer Drought Severity Index (PDSI; Palmer, 1965), Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) and Standardized Precipitation Index (McKee et al., 1993). The drought indices PDSI (33°45′N–73°45′E) and SPEI (33°00′–33°30′N–75°00′–75°30′E) available for the grids closest to the tree–ring sampling location in Kishtwar were obtained from websites (http://www.cgd.ucar.edu/cas/catalog/climind/pdsi.html) and through the KNMI climate explorer (http://climexp.knmi.nl; Oldenborgh and Burgers, 2005), respectively. The multi-scalar SPEI data in time window of 4 and 8 months were used in the analyses. However, the Standardized Precipitation Index (SPI) in time window of 3–12 months were computed using the regional mean precipitation series from 1903 to 1947. The precipitation data from 1948 to 2014 were also used separately to compute SPI in similar temporal windows for correlation with the ring-width chronology. The SPI calculation involves fitting of a probability distribution to the long-term precipitation record, which is then transformed into a normal distribution so that the mean SPI for the desired period is zero (Edwards and McKee, 1997). Detailed methodology followed in calculation of SPI has been elaborated by Lloyd-Hughes and Saunders (2002). Positive SPI values indicate greater than median precipitation, and negative values less than median precipitation. A drought event occurs when the SPI is continuously negative and ends when the SPI becomes positive. In our earlier study (Yadav et al., 2015) we found that the use of SPI in dendroclimatic studies in the Himalayan region stands merit over the Palmer Drought Severity Index (PDSI, Palmer, 1965) and Standardized Precipitation Evapo-transpiration Index (SPEI, Vicente-Serrano et al., 2010) as it is based only on precipitation records, unlike PDSI and SPEI, calculation of which also requires many other variables, that in many cases are not available for the high-elevation regions of the Himalaya. The use of PDSI in the high Himalayan region is also limited for the snow dominated months as in its calculation precipitation is treated as rain and snowfall, snow cover, and frozen ground are not taken into account (McKee et al., 1995; Guttman, 1998).

2.4. Relationship between tree ring chronology and drought indices

Pearson Correlation Coefficients were calculated between ring-width chronology and drought indices i.e., monthly PDSI, SPEI and

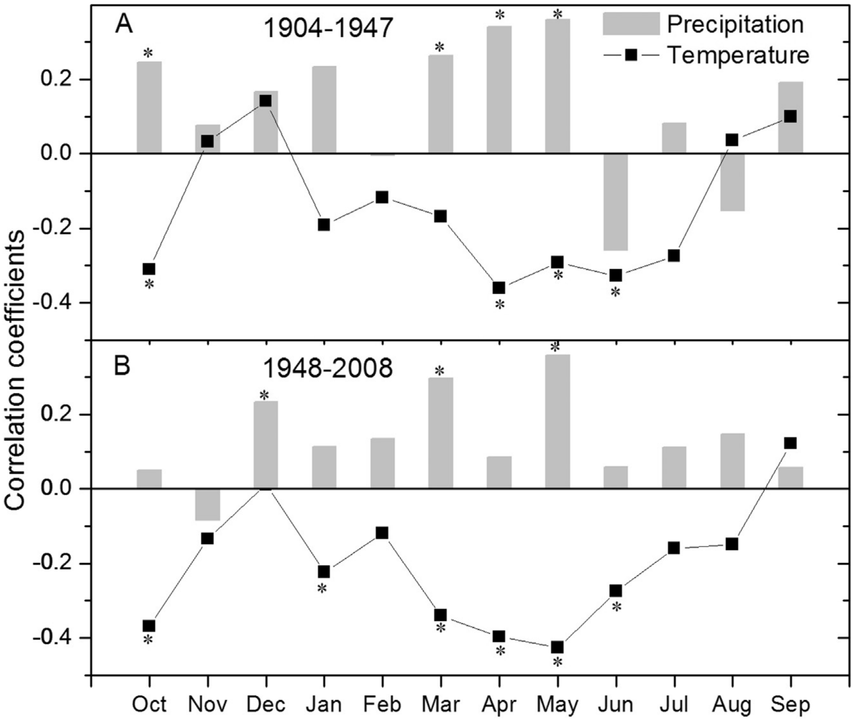

Fig. 5. Bootstrap correlation analyses between signal free chronology and monthly climate variables (monthly precipitation and temperature); A – 1904–1947; B – 1948–2008. The bootstrap correlations were calculated using DENDROCLIM2002 (Biondi and Waikul, 2004). Correlations significant at $p < 0.05$ are marked by an asterisk.

SPI. The multi-scalar SPEI values in time window of 4 and 8 months were used in correlations. To compare the relative strength of association between ring-width chronology and various drought indices, correlations were calculated over 1904–1947 for which SPI series consisted of 4-station precipitation data. The correlations between ring-width chronology and drought indices PDSI and SPEI were observed to be weaker in comparison to that with SPI. The SPI series in time-scale of 8 months, which showed stronger relationship with ring-width chronology, was selected for detailed study. The SPI series of 8 months time-scale developed using regional precipitation series as well as Srinagar precipitation alone were used in correlation analyses with ring-width chronology (Fig. 6). The highest correlation between ring-width chronology and 8 months SPI developed using regional precipitation series was noted for May (SPI8-May) ($r = 0.56$, 1904–1947). The correlations between ring-width chronology and SPI series of Srinagar

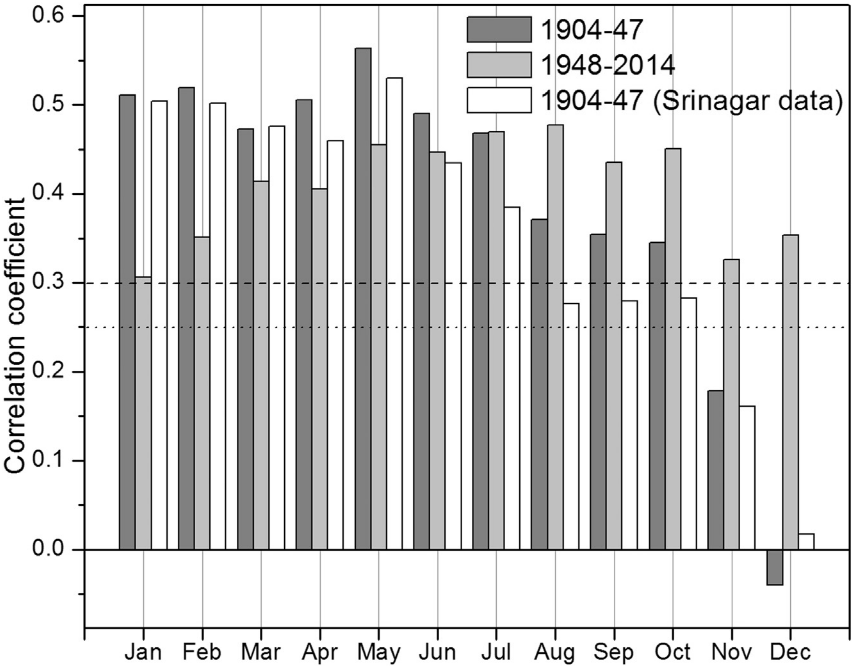

Fig. 6. Pearson correlation of the ring-width chronology of Himalayan cedar and SPI8-May calculated for 1904–1947 and 1948–2014 using regional and Srinagar precipitation series. The dashed and dotted lines show 95% confidence levels for two respective periods.

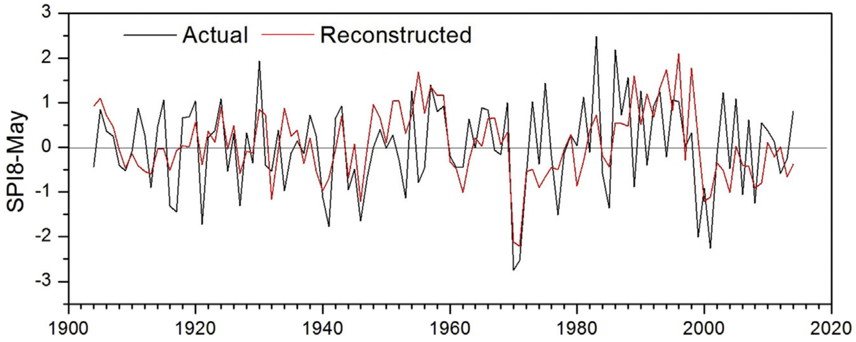

Fig. 7. Actual and reconstructed SPI8-May using calibration model 1904–1947 plotted together for comparison. The SPI8-May data for 1948–2014 were used in verification model.

precipitation data were relatively weaker in comparison to that observed with the regional SPI series (Fig. 6). In view of the existence of strong correlation between the tree–ring chronology and SPI8-May, we attempted to reconstruct SPI8-May for Kishtwar. The SPI8-May covering the cold period when precipitation largely occurs in the form of snow is expected to be very useful in understanding hydrological changes in the northwest Himalaya, where snowmelt water significantly contributes to the river flow.

2.5. Calibration, verification and reconstruction of drought indices (SPI8-May)

The correlation analyses of ring-width chronology with monthly precipitation as well as SPI indicated that moisture supply from previous year October to current year May plays an important role on radial growth of Himalayan cedar over semi-arid sites in Kishtwar. SPI8-May, which showed the strongest correlation with the chronology variable (t0), was taken for reconstruction. For this, we first performed calibration/verification tests using SPI8-May series prepared from regional mean precipitation data (1904–1947). The second sub-period 1948–2014 was used for verification of the calibration model. The calibration and verification were also performed using SPI data calculated from Srinagar data alone in two sub-periods (1904–1947, 1948–2014) to test the utility of regional series over the single station series. The calibration and verification statistics calculated for the two sub-periods (1904–1947 and 1948–2014) such as the reduction of error (RE), coefficient of efficiency (CE), Sign test, and Pearson correlation coefficient (Fritts, 1976; Cook and Kairiukstis, 1990) were used to test the fidelity of calibration models (Table 3). The robustness of calibration and verification models using different data sets is underpinned by positive values of both the RE and the CE, which are the most rigorous statistical test of model validation. The 1904–1947 calibration model using SPI8-May series prepared from regional mean precipitation data, which captured 30% of the variance in the instrumental SPI8-May data was used in reconstruction. The reconstructed series also revealed close year-to-year similarity and significant correlation with SPI8-May for the sub-period 1948–2014 ($r = 0.46$, two-tailed $p < 0.0001$) (Fig. 7).

3. Results and discussion

3.1. Ring-width chronology

The ring-width chronology of Himalayan cedar, involving 4666 ring-width measurements of 21 cores from 14 trees prepared for Kishtwar, spans from A.D. 1509–2014 (508 years) (Fig. 2). The chronology statistics (Table 1) for 1740–2014 span with EPS level >0.85 showed mean sensitivity 0.25, which is comparable to Himalayan cedar ring-width chronologies prepared from other moisture stressed sites in the western Himalaya (Yadav et al., 2004; Singh and Yadav, 2005; Singh et al., 2006, 2009). Statistically significant 1st order autocorrelation ($AR1 = 0.48$, 1740–2014) in the series shows the importance of previous year's growth on ensuing year. Prior to this study the lone chronology of Himalayan cedar prepared from this part of the northwest Himalaya (31°15′–31°20′ N and 76°05′–76°10′E, 1680–1800 m asl) based on 10 cores from only 3 trees extended from A.D. 1469–1983 (Bhattacharyya et al., 1988). We observed that in two independent studies authors were successful in getting considerably old trees of Himalayan cedar extending over 500 years age, underscoring the potential of developing long chronologies from this region of the northwest Himalaya for climate studies.

3.2. Interpretation of calibration results

While analysing the relationship between tree-growth indices, observational and reconstructed SPI8-May in the calibration period 1904–1947 we noted distinct mismatch in years 1904, 1911, 1917 and 1934. Calibration equation developed after removal of these years from the calibration model captured much higher variance (53%) in the SPI8-May series. Detailed analyses of SPI8-May series indicated drought conditions in 1904, 1917 and 1934 but the trees recorded higher growth, however, in 1911 when it was wet, trees recorded low growth. A careful study of the climate diagram of 1904, 1917, and 1934 form previous year October to current year September (Fig. 8) revealed that May experienced good amount of precipitation in all these years. The trees analysed in this study were found growing on steep rocky slopes with very thin soil cover. The moisture holding capacity of soil in such ecological settings is very low, making trees

Table 3
Calibration, verification statistics; $ar^2 - r^2$ adjusted after degrees of freedom, R – Pearson correlation, Sign test, RE (reduction of error) and CE (coefficient of efficiency). Calibration, verification statistics given in italics is based on observational data of single station precipitation data (Srinagar) (Fritts, 1976; Cook et al., 1999).

Calibration		Verification					
Period	ar^2 [%]	Period	R	Sign test	t Value	RE	CE
1904–1947	30.2	1948–2014	0.46 [$p < 0.0001$]	$44^+/23^-$ [$p < 0.0139$]	2.6919	0.08	0.05
1948–2014	19.5	1904–1947	0.56 [$p < 0.0001$]	$29^+/15^-$ [$p < 0.0488$]	3.0316	0.29	0.26
1904–1947	*26.3*	*1948–2014*	*0.45 [$p < 0.0001$]*	*$43^+/24^-$ [$p < 0.0271$]*	*3.0577*	*0.18*	0.06
1948–2014	*19.2*	*1904–1947*	*0.53 [$p < 0.0001$]*	*$31^+/13^-$ [$p < 0.0096$]*	*2.6175*	*0.24*	0.19

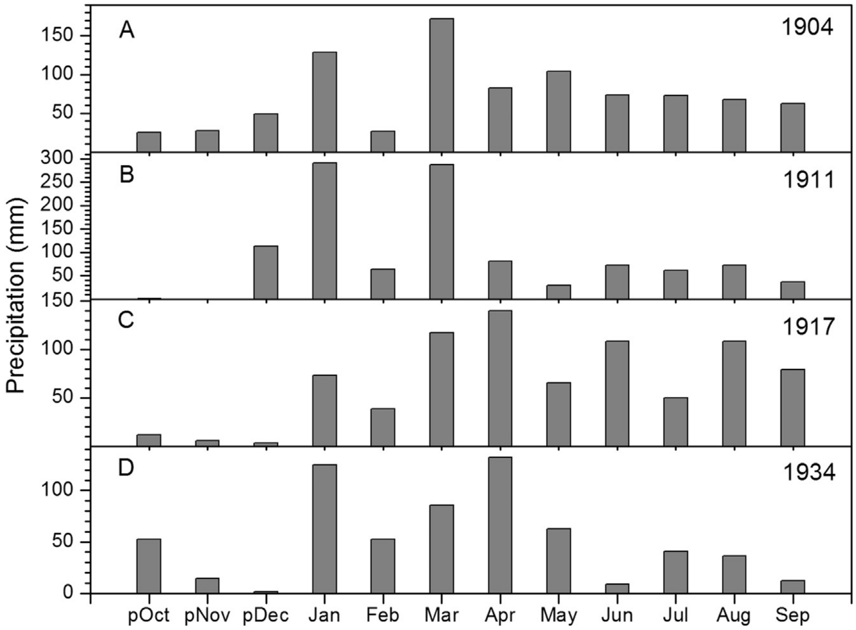

Fig. 8. Climate diagram of the years 1904 (A), 1911 (B), 1917 (C), and 1934 (D) when calibration model failed in capturing the observational SPI8-May data.

very sensitive to precipitation availability during the growing season. High precipitation in May, when vegetation growth is at its peak, resulted in enhanced radial growth of trees in 1904, 1917 and 1934. However, contrary to the above years the radial growth of Himalayan cedar was strongly reduced in 1911, when SPI8-May (1.11) indicated pluvial condition. The distribution of monthly precipitation values from previous year October to current year September (1910–1911) indicated very high precipitation in December, January and March, but May was extremely dry (29.0 mm precipitation) (Fig. 8). The dry conditions in May 1911 caused moisture stress, which led to a decrease of radial growth of Himalayan cedar. These findings clearly show that the tree–ring calibrations are much affected by the monthly distribution of precipitation rather than the cumulative amount of precipitation alone.

3.3. Analyses of reconstructed drought index SPI8-May

The SPI8-May reconstruction developed using Himalayan cedar ring-width chronology spanning from A.D. 1740–2014 for Kishtwar region revealed strong inter-annual to inter-decadal variability (Fig. 9; Table 4). The reconstructed SPI values showed 1785 (SPI −2.3), the driest year followed by 1971 (SPI −2.2) and 1970 (SPI −2.1) in the whole period of reconstruction. The reconstruction, consistent with the precipitation records of Srinagar, revealed paired droughts in 1970 and 1971 (mean SPI −1.6). The SPI values calculated using Srinagar precipitation data revealed that the drought of 1970–71 began to develop from November 1969 and continued until August 1972. In order to access the spatial extent of this drought we compared our reconstruction with other hydrological records available from the semi-arid regions of the western Himalaya (Yadav and Bhutiyani, 2013; Yadava et al., 2016). We observed that the droughts of 1970, 1971 were common over large parts of the adjoining cold semi-arid regions of Kinnaur (Yadava et al., 2016) and Lahaul-Spiti in Himachal Pradesh (Yadav and Bhutiyani, 2013) as well. Such an extended large-scale drought could have caused serious hydrological stress on socioeconomic systems in Kishtwar. The reconstruction further revealed that the long-term droughts observed in the late 18th (1760s–1790s) and

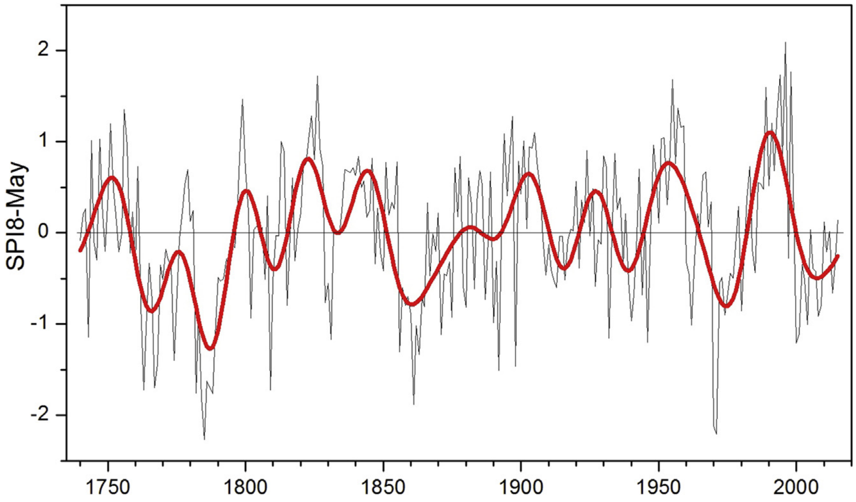

Fig. 9. SPI8-May reconstruction (A.D. 1740–2014) for Kishtwar overlaid with 20-year low pass filtered version (thick smooth line).

19th (1850s–1870s) centuries were also consistent with the low precipitation in spring season (March–May) in cold semi-arid region of Kinnaur, the western Himalaya (Yadava et al., 2016). In recent decade since 2000s, the increasing drought noted in present reconstruction has also been observed in large parts of the western Himalaya largely due to weakening of the westerlies (Yadav and Bhutiyani, 2013; Yadava et al., 2016). The observational records for the Pir Panjal region have also revealed decreasing trend in snowfall since 1990s (Shekhar et al., 2010) due to weakening of westerlies.

Table 4
Wet and dry periods reflected in reconstructed SPI8-May series. The non-over lapping 3-, 5- and 10-year wet, dry periods were calculated using running mean of the data.

3-year mean				5-year mean				10-year mean			
Wet		Dry		Wet		Dry		Wet		Dry	
Years	SPI	Years	SPI	Years	SPI	Years	SPI	Years	SPI	Years	SPI
1994–96	1.6	1784–86	−1.9	1992–96	1.3	1784–88	−1.8	1989–98	+1.2	1782–91	−1.4
1824–26	1.3	1970–72	−1.6	1955–59	1.2	1970–74	−1.3	1950–59	+0.9	1856–65	−1.0
1955–57	1.3	1787–89	−1.5	1822–26	1.1	1860–64	−1.2	1819–28	+0.8	1762–71	−0.9
1989–91	1.1	1861–63	−1.4	1987–91	0.9	1763–67	−1.1	1899–08	+0.6	1970–79	−0.8
1991–93	1.1	1766–68	−1.3	1903–07	0.8	2000–04	−0.8	1837–46	+0.6	2000–09	−0.7

The SPI8-May reconstruction indicated pluvial conditions centred in 1990s, 1996 being the wettest (SPI +2.1) followed by the other two wet years 1998 (SPI +1.8) and 1994 (SPI +1.7). The pluvial 1990s in the western Himalaya was also noted earlier in tree–ring based boreal spring precipitation reconstruction from Kinnaur in semi-arid region of the western Himalaya (Yadava et al., 2016). The SPI reconstruction further revealed a generally pluvial phase during 1810s–1840s with some intervening drought years. The Kashmir Valley had experienced devastating flood in the Indus during the winter of 1841 (Anonymous, 1909) encompassing the long-term pluvial phase in Kishtwar region. Similarly during the pluvial early 19th century, devastating famine due to heavy snow fall occurred in 1831–1833 (Anonymous, 1909). The 1893 great flood in Jhelum and heavy snow fall in 1902–03 in Kashmir Valley (Anonymous, 1909) occurred during the pluvial phase of 1890s–1900s noted in the reconstruction. The Jhelum flood of 1893 occurred largely due to incessant rains over three months, when Wular Lake, Jammu and Kashmir expanded to 266 square kilometres compared to its usual range of 32 square kilometres only (Anonymous, 1909).

3.4. Hydrological implications of reconstructed SPI8-May

Considering the temporal-scale of SPI data presented here we analysed its applicability in hydrological studies in the northwest Himalaya–Karakoram region where a major portion of annual precipitation occurs in winter and spring seasons. A comparison of SPI8-May reconstruction with boreal spring precipitation reconstruction from cold semi-arid region of Kinnaur, in Himachal Pradesh where major portion of annual precipitation occurs in winter and spring season due to mid-latitude westerlies revealed very close similarity on annual-to-inter decadal scale (r = 0.57, p < 0.0001, 1740–2011). The twenty year low pass filtered values of the two variables revealed very close consistency (Fig. 10). In monsoon shadow regions of the northwest Himalaya snowmelt water plays an important role in controlling the discharge of rivers as major portion of annual precipitation occurs in the form of snow during winter and spring seasons. The snowmelt water is known to contribute ~65% of discharge of the Indus River in the Karakoram (Bookhagen and

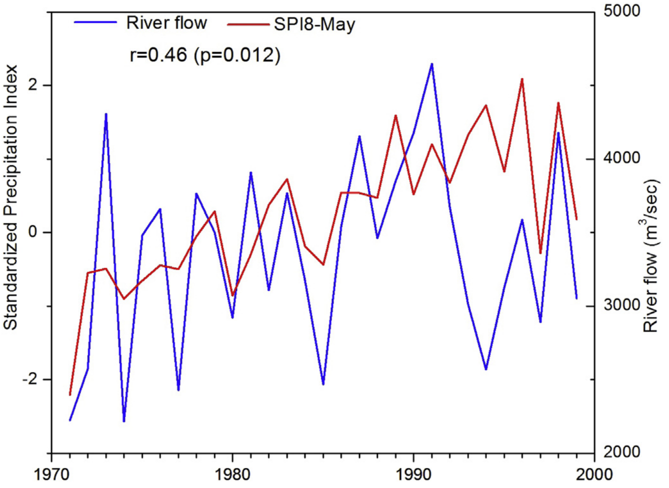

Fig. 11. Comparison of SPI8-May and Jhelum discharge at Akhnoor in Jammu region of the northwest Himalaya.

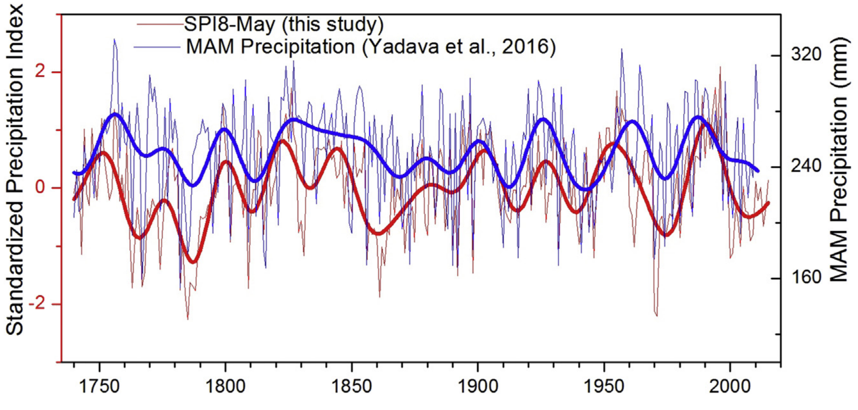

Fig. 10. SPI8-May reconstruction plotted together with boreal spring (March–April–May) precipitation reconstruction from summer monsoon shadow region of Kinnaur, a cold-arid region in Himachal Pradesh, the western Himalaya. Thick smooth lines represent 20-year low pass filtered data.

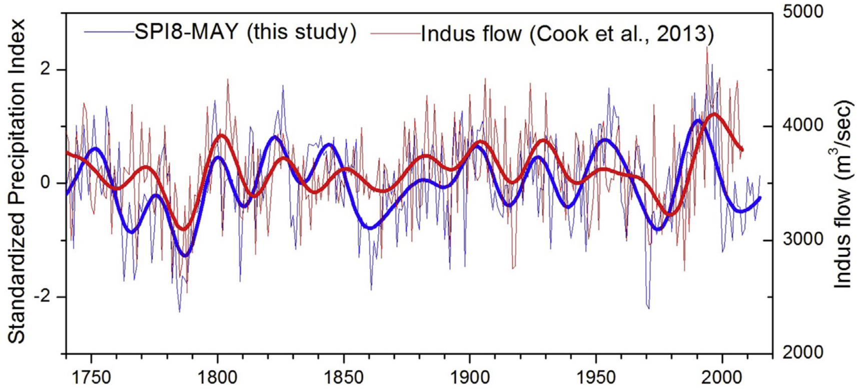

Fig. 12. SPI8-May reconstruction plotted together with Indus flow at Tarbela, north Pakistan (Cook et al., 2013). The 20-year low pass filtered data show very close consistency endorsing strong hydrological signal in SPI data.

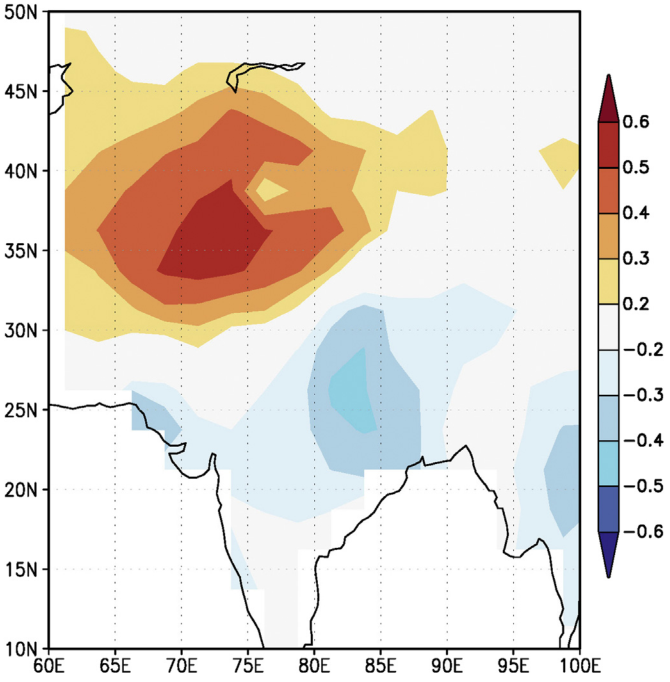

Fig. 13. Spatial correlation between reconstructed SPI8-May and gridded June–July–August PDSI of Monsoon Asia Drought Atlas (Cook et al., 2010). Correlations were calculated for the common period A.D. 1740–2005. The picture was generated using the KNMI Climate Explorer program (http://climexp.knmi.nl; Oldenborgh and Burgers, 2005).

Burbank, 2010; Cook et al., 2013). The Chenab River basin is snow covered to an extent of 70% of the area in March–April, which is reduced to nearly 27% in September–October (Singh et al., 1997). Such a vast difference in seasonal snow cover clearly indicates the role of snowfall amount in controlling the river discharge. In view of this, we compared our SPI8-May reconstruction with the Chenab River flow (1971–1999) at Akhnoor (32°54′N and 74°45′E) in Jammu and Kashmir, the northwest Himalaya. The reconstructed SPI8-May data showed significant correlation with the Chenab River flow of previous year October to current year May (Fig. 11; $r = 0.46$, two tailed $p = 0.012$), indicating the importance of SPI in driving the river flow. We also compared our SPI8-May reconstruction with the tree–ring derived discharge of Indus (Cook et al., 2013). The two records showed statistically significant Pearson correlation for the common period 1740–2008 ($r = 0.34$, two tailed $p < 0.0001$). A comparison of 20-year low-pass filtered SPI8-May and tree–ring derived Indus flow records showed very good consistency (Fig. 12). Such a strong temporal consistency noted in two independent tree–ring based records underscores the potential utility of SPI reconstructions from the northwest Himalaya to understand hydrological variations in long-term perspective.

3.5. SPI8-May reconstruction and regional droughts

Monsoon Asia Drought Atlas (MADA) developed by Cook et al. (2010) presents the comprehensive spatial network of drought index (PDSI) for June–July–August. To understand relationship

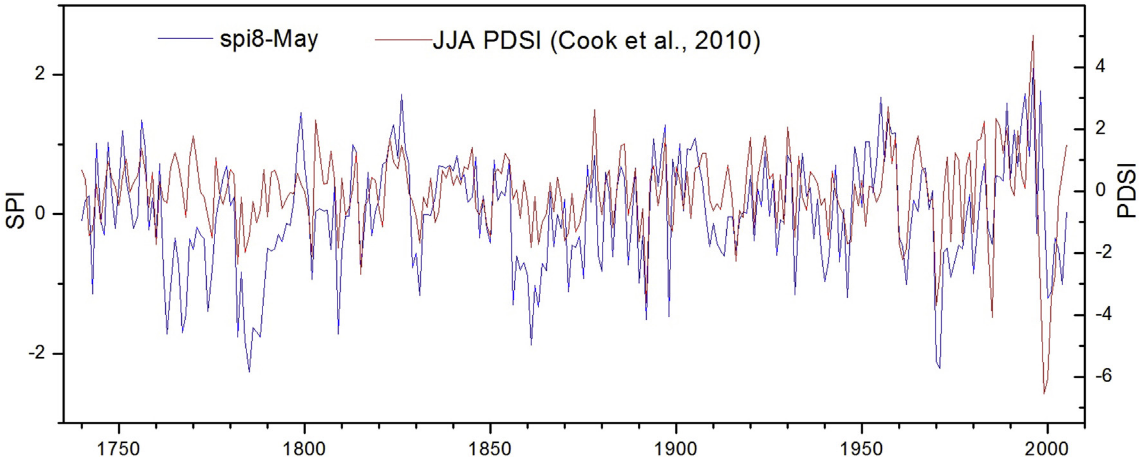

Fig. 14. SPI8-May reconstruction plotted together with June–July–August PDSI of Monsoon Asia Drought Atlas (Cook et al., 2010) available for the grid close to Kishtwar (32°30′–35° N and 72°30′–75°E).

between SPI8-May reconstruction and gridded JJA-PDSI data of MADA (Cook et al., 2010) we performed spatial correlation analyses using KNMI climate explorer (http://climexp.knmi.nl; Oldenborgh and Burgers, 2005). SPI8-May reconstruction from Kishtwar showed direct relationship with JJA-PDSI distributed over large part of the northwest Himalaya and Hindu Kush–Karakoram region (Fig. 13). However, the strength of correlation between SPI8-May and JJA-PDSI was noted to decrease with increasing distance from the site of SPI reconstruction. A comparison of SPI8-May reconstruction with JJA-PDSI of grid (32°30′–35°N and 72°30′–75°E) close to our study site showed very good year-to-year consistency (Fig. 14) and significant correlation ($r = 0.52$, 1740–2005, two tailed $p < 0.0001$). Such a relationship noted between SPI8-May and JJA PDSI endorses that the failure of precipitation in winter and spring seasons are closely associated with summer droughts in westerly dominated regions of the northwest Himalaya.

4. Conclusions

We developed a 506 years (A.D. 1509–2014) long chronology of Himalayan cedar using 4666 ring-width measurements of 21 cores from 14 trees sampled from moisture stressed sites in Kishtwar. The correlations between the tree–ring chronology and climate variables (monthly precipitation and temperature) revealed direct relationship between precipitation spanning from winter to spring seasons. The Standardized Precipitation Index (SPI8-May) showing the strongest relationship with the tree–ring chronology was reconstructed back to A.D. 1740, up to which sufficient replication of samples were available in the chronology. The reconstructed SPI data revealed 1990s, the wettest and 1780s the driest periods. The reconstructed SPI data revealed strong year-to-year to inter-decadal variability, which is consistent with the tree–ring-based hydrological records as well as JJA-PDSI of MADA from the northwest Himalaya–Karakoram region. Such a good consistency in tree–ring-based hydrological records and drought indices from the westerly dominated regions of the Himalaya–Karakoram region highlight the potential utility of SPI reconstruction from the northwest Himalaya to understand large-scale climate variability over the region in long-term perspective.

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