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Little Ice Age Revealed in Tree-Ring-Based Precipitation Record From the Northwest Himalaya, India

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Key Points:

- Three distinct centennial scale phases have been identified in 635 years long precipitation record developed from the northwest Himalaya
- Stable precipitation during 1650s–1850s CE reveals clear evidence of Little Ice Age (LIA) for the north-western Himalaya
- High-magnitude droughts or low precipitation limit the LIA influence before 1650s CE

Supporting Information:

- Supporting Information S1

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Abstract The spatial and temporal span of hydrological impact of the "Little Ice Age" (LIA) in the north-western Himalaya is not well constrained due to data limitation. We evaluated a network of tree-ring chronologies from moisture-stressed ecological settings in Jammu and Kashmir to identify the impact of LIA over the western Himalaya. Our study reflects three centennial scale phases; the middle phase (1650s–1850s CE) with stable precipitation and in accordance with other hydrological records clearly demarcates the LIA impact over the Himalaya. However, high-magnitude droughts recorded in early (1383–1650s CE) and late phases (1850s–2017) underpin that the north-western Himalaya did not witness any LIA influence before 1650s.

Plain Language Summary Here, we present a 635-year long annual (prior year October to current year September) precipitation reconstruction from Kishtwar, Jammu and Kashmir. A network of 16 tree-ring chronologies of Himalayan cedar and neoza pine was used in the study. The reconstruction captured three distinct phases in precipitation regime from 1383–1650s, 1650s–1850s, and 1850s–2017 CE and among these, the middle phase (1650s–1850s) showed relatively prolonged pluvial phase with consistently stable precipitation advocating for the active LIA over the western Himalaya. The other two phases reflect high-amplitude droughts with intervening wet periods contrasting the existence of the LIA-induced wetting. To validate the reconstruction skill and the LIA effect over the western Himalaya and Central Asia, the present record was compared with the other available precipitation, river flow and hydrological proxy records which support the LIA influenced precipitation during 1650s–1850s CE.

1. Introduction

The Little Ice Age (LIA) is marked by the glacial expansion and widespread cooling in the Northern Hemisphere (Mann et al., 2009), while the timing of its advancement in different continents was spatially varied (Rowan, 2017). The continental scale temperature reconstructions (PAGES 2k Consortium, 2013) also recorded variable pattern in temperature in the last two millennia with distinct asynchronicity in multi-decadal warm and cold events, which could define Medieval Climate Anomaly and LIA worldwide. The LIA period is generally defined from fifteenth to nineteenth century with about 0.6°C temperature drop over the Northern Hemisphere (Bradley & Jones, 1993; Jones et al., 1998; Mann, 2002; Mann et al., 1998, 1999). However, Arctic Canada and Iceland ice-cap growth reflects the cold summer and ice growth started abruptly during 1275–1300 CE that coincided with the active volcanic period of the past millennium (Miller et al., 2012), whereas Europe was influenced largely during sixteenth to mid-nineteenth century (Mann, 2002). The LIA has major significance in the determination of global climate of the past millennium, but still controversies regarding its initiation, duration, and spatial advancements continue to exist across the globe. The one belief is that the LIA-induced glacial expansion occurred in north of 20°N areas which largely depends on the winter precipitation, while summer temperature was not the sole factor for LIA climate (Matthews & Briffa, 2005). However, another belief is that the glaciers expanded throughout the globe (Grove, 2001; Porter, 1981) and temperature fall had significant contribution in the LIA (Hughes & Diaz, 1994; Grove, 2001; Mann, 2002; Nesje & Dahl, 2003). Such anomalous results are likely due to a lack of precise environmental records from across the world restricting our understanding of LIA and its impact.

The Himalaya has the largest area of snow/ice outside the poles, but instrumental as well as proxy records are lacking to explain exact temporal and spatial influence of LIA. Although in recent decades, several specific studies on mass balance targeted to identify the past glacial history of the Himalayan glaciers have been utilized (Hedrick et al., 2011; Lehmkuhl et al., 1998; Kulkarni & Alex, 2003; Kulkarni & Rathore, 2003; Kulkarni et al., 2010; Murari et al., 2014; Owen et al., 2000, 2001, 2002, 2005; Rowan, 2017; Solomina et al., 2015). These studies also reflect variability in the timing and extent of glacial advance in the Himalaya during the LIA. A recent study (Managave et al., 2020) based on scPDSI denoting contrasting hydro-climatic trends in the western Himalaya and Karakoram region, revealed that the peak glacial activity occurred around 1300–1600 CE in the Lahaul region of the western Himalaya. However, a tree-ring-based glacial mass balance reconstruction from the Himalaya revealed significant mass loss during the LIA in the Himalaya (Shekhar et al., 2017). Such heterogeneity in proxy records highlights the role of regional characteristics of climatic phenomena in the orography-dominated Himalaya during the LIA. Although the highly dissected and orography-dominated Himalaya has large-scale spatial variability, inconsistent and patchy climatic records are inadequate to capture past climatic upheavals (Cook et al., 2010; Yadava et al., 2016).

The present study was carried out to investigate precipitation variability during the LIA in the western Himalaya. For this, tree-ring data from moisture-stressed sites in Jammu and Kashmir were used. The state of Jammu and Kashmir has large glaciated area where westerlies first strike the Indian subcontinent with moisture transported from the Mediterranean and Atlantic Ocean. Limited tree-ring-based hydrological studies have been carried out so far from Jammu and Kashmir (Ballesteros-Canovas et al., 2020; Borgaonkar et al., 1994; Hughes, 1992, 2001; Shah et al., 2018; Singh et al., 2017; Yadav et al., 2017). Here, we report a 635-year long precipitation record, the longest so far from this region, and highlight its linkage with the LIA over the western Himalaya.

2. Data and Methods

2.1. Tree-Ring Data

Tree-ring materials comprising 525 increment cores from 339 trees (356 increment cores from 212 neoza pine; *Pinus gerardiana* Wall. ex Lamb.) and 169 cores from 127 Himalayan cedar (*Cedrus deodara* [Roxb.] G. Don) were collected during three consecutive field excursions (2015, 2017 and 2018) from Kishtwar, Jammu and Kashmir. Sixteen (nine of neoza pine and seven of Himalayan cedar) homogeneous and moisture-stressed sites (Figure 1) were selected for the present study. Generally, two cores were extracted from each tree at breast height (~1.4 m) in the direction perpendicular to the slope and processed in the laboratory following the standard dendrochronological methods (Stokes & Smiley, 1968). The ring-width sequences were measured using the LINTAB (Rinntech) measuring machine, with a resolution of 0.01 mm (Rinn, 2003) and ring-width measurements of precisely dated samples were cross-checked in the COFECHA (Holmes, 1983) program. Strong correlation and high similarity in both species highlight the common climate forcing regulating the tree growth over the region. The method opted for chronology development and site details, number of samples, chronology span, and Expressed Population Signal are given in supporting information (Table S1). Out of the total 16 chronologies, one Himalayan cedar and four neoza pine chronologies are common in present and earlier studies (Singh et al., 2017; Yadav et al., 2017). High correlation and strong year-to-year coherence among all the chronologies for the common period 1842–2014 (Table S2) indicate the dominant influence of common climate forcing on tree growth over the study sites.

2.2. Climate Data and its Relationship With Tree-Growth

The instrumental records over the high-altitude Himalaya are very short and patchy. The available records show high spatial variability and therefore, single-station climate data are not usually suitable in dendroclimatic modeling (Singh et al., 2017; Yadav, 2011a, 2011b; Yadav et al., 2004, 2011, 2017). To minimize the effect of single-station data errors, seven meteorological station data were used to prepare regional precipitation series (Figure S1; Table S3). The first principal component of seven-station precipitation data (January–December) for the common period 1954–1994 explains 66% common variance and shows strong coherence (Figure S1; Table S4). The monthly precipitation data were normalized with respect to mean and standard deviation values of the common period and merged to prepare a regional series. The regional

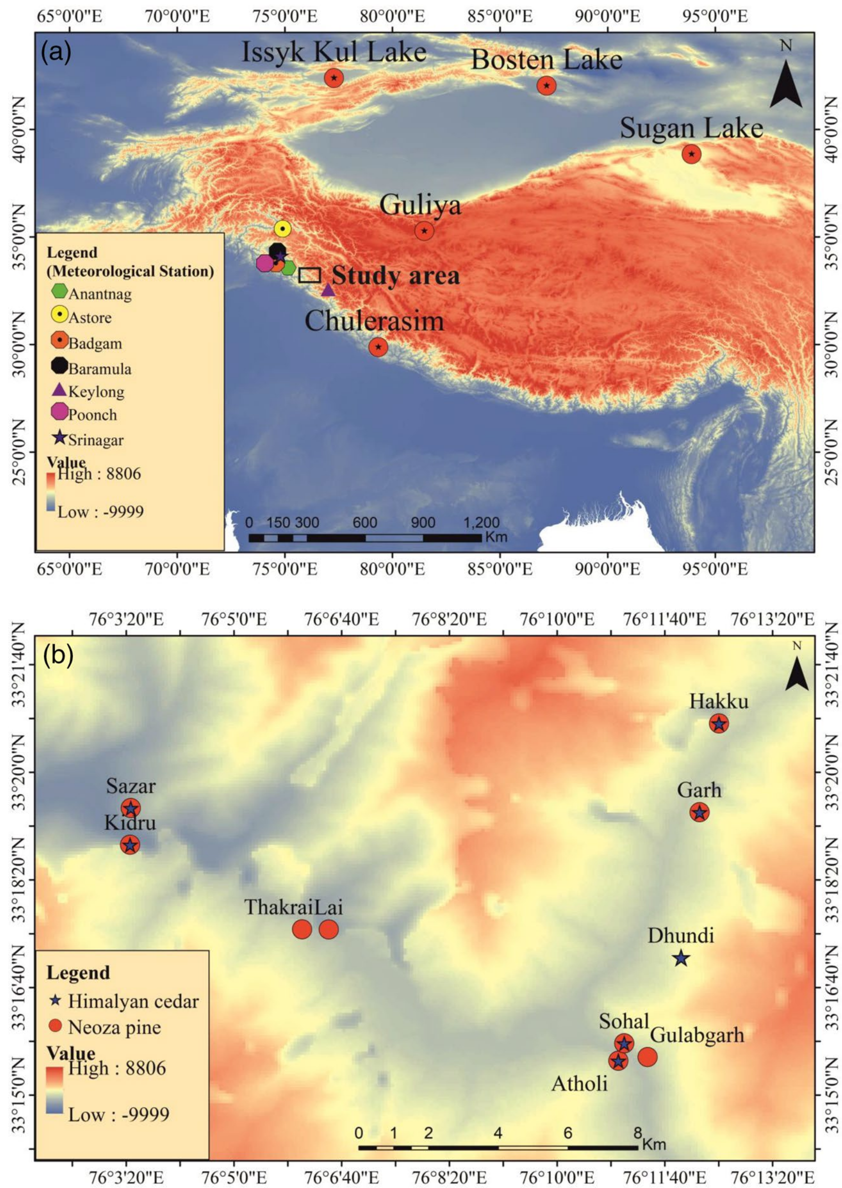

Figure 1. (a) General view of the study area with location of the meteorological stations and the hydrological proxy records used, (b) location of tree-ring sampling site over Kishtwar, Jammu and Kashmir.

precipitation series were then rescaled to the actual values relative to the mean and standard deviation of respective months of all the stations and used in dendroclimatic modeling. In the absence of temperature data from Kishtwar, Srinagar data (34°05′N, 74°48′E, 1585 m asl) ranging from 1893 to 2008 have been used to understand the climate and tree-growth relationship.

The correlation among climatic variables and first principal component (PC#1) of ring-width chronologies having eigenvalue greater than 1 that represents 84.28% variance of the chronologies for the common period 1842–2014 CE, showed positive correlation with precipitation from previous year October to current year September and negative correlation for the whole year temperature except current year September (Figure S2). The significant positive correlation in PC#1 and regional precipitation was recorded in December of the prior year and March, May and July of the current year, while for temperature significant negative correlation was found in October of the prior year and in January, March, April, May, June and July of the current year (Figure S2).

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2.3. Precipitation Reconstruction

Annual precipitation from prior year October to current year September (*p*O*c*S) was reconstructed using a network of 16 chronologies from Kishtwar, Jammu and Kashmir. To optimize the reconstruction length, the nested approach (Cook et al., 2003; Meko, 1997) was used in which the chronologies with decreasing length were removed from the pool of the larger set. Seventeen nested series were developed and the PC#1 of each nest was used in the calibration, verification, and reconstruction. The split-period calibration, verification for the two subperiods 1954–1973 and 1974–1994 using regional annual precipitation series and leave-one-out cross-validation method (Michaelsen, 1987) was performed to test the fidelity of calibration models used in the reconstruction. The statistical parameters in calibration and verification analysis such as reduction of error (RE), coefficient of efficiency (CE), Sign test and Pearson correlation coefficient (Cook et al., 1999; Fritts, 1976) were tested (Table S5). Positive values of RE and CE express the statistical skill in the annual (*p*O*c*S) precipitation reconstruction. The whole period calibration model 1954–1994 was used in the final reconstruction and mean series developed by combining the individual reconstructions. However, before averaging the values, the nested reconstruction series were scaled with mean and standard deviation of the most-replicated nest to minimize the artefact associated with the change in variance. The mean reconstructed precipitation series extends back to 1383 CE and revealed a significant correlation and close year-to-year similarity with the actual regional precipitation series (Figure S3; $r = 0.64$, $p < 0.0001$, 1954–1994).

3. Discussion and Conclusions

The reconstructed *p*O*c*S precipitation series (1383–2017 CE) reflects high year-to-year and interdecadal to centennial-scale variability (Figure 2). The most notable feature in the reconstructed 635 years data is three distinct centennial phases, early (1383–1650s) and late phase (1850s–2017) reflect relatively unstable and more turbulence but the middle phase (1650s–1850s) revealed stable conditions where the precipitation centered close to the long term mean. The middle phase reflects LIA-induced stable precipitation and its significant influence over the western Himalaya, while the high-magnitude drought or low precipitation periods in the early and late phases do not advocate for the LIA influence over the northwest Himalaya before 1650 CE. The low precipitation during the fifteenth and early-sixteenth centuries noted in the present reconstruction showed resemblance with the March–June precipitation record of the western Himalaya (Yadav, 2011a), where extensive dry periods were recorded during 15th and 16th centuries with 1410–1510 being the driest period. The extended low precipitation period also showed strong similarity with $\delta^{18}O$ tree-ring derived precipitation reconstruction from Karakoram, Pakistan (Treydte et al., 2006) in the 14th and 15th century and precipitation reconstruction for south-western Asia (Anderson et al., 2002). Besides, Anderson et al. (2002) also showed pluvial conditions in the mid-seventeenth to mid-nineteenth centuries consistent with the stable precipitation of present reconstruction.

Similarly, the western Himalaya temperature record (Yadav et al., 2011) also reflected 18th and 19th centuries being the coldest in last millennium when glaciers expanded over the region (Figure 2e). Based on the present study, we believe that cooling in the 18th and 19th centuries (Yadav et al., 2011) could be associated with the LIA-linked stable precipitation. The reconstructed *p*O*c*S precipitation series showed significant negative correlation with reconstructed temperature (Yadav et al., 2011) for the common period 1383–2008 CE ($r = -0.33$, $p < 0.0001$). Similar to the summer temperature, significant negative correlation was also observed with the spring (March–May) temperature (Yadav et al., 2004) of western Himalaya ($r = -0.416$, $p < 0.00001$, 1383–2000 CE; Figure S4). The cool periods during early-eighteenth to mid-nineteenth century were consistent with our data. Based on the glacio-archeological records, settled colonization has been identified within the glacial moraine complex of Tharang, Miyar basin, Lahaul Himalaya at more than 3,500 m asl during the late-tenth to early-nineteenth century (Saini et al., 2019). Saini et al. (2019) also marked the three sites of Tharang, Phundang and Patam (presently abandoned) showing settled agriculture coincident with warm temperature and limited snowfall. During 1300–1600 CE, there was no glacial expansion in the region and the period was generally warmer compared to the present day, which allowed permanent settlements within the end-moraine complex. However, the Miyar basin experienced glacial advances in the period of late-eighteenth and early-nineteenth centuries, which reflect close agreement with the present precipitation record and radiocarbon chronology (Saini et al., 2019). Climate proxies and map records revealed

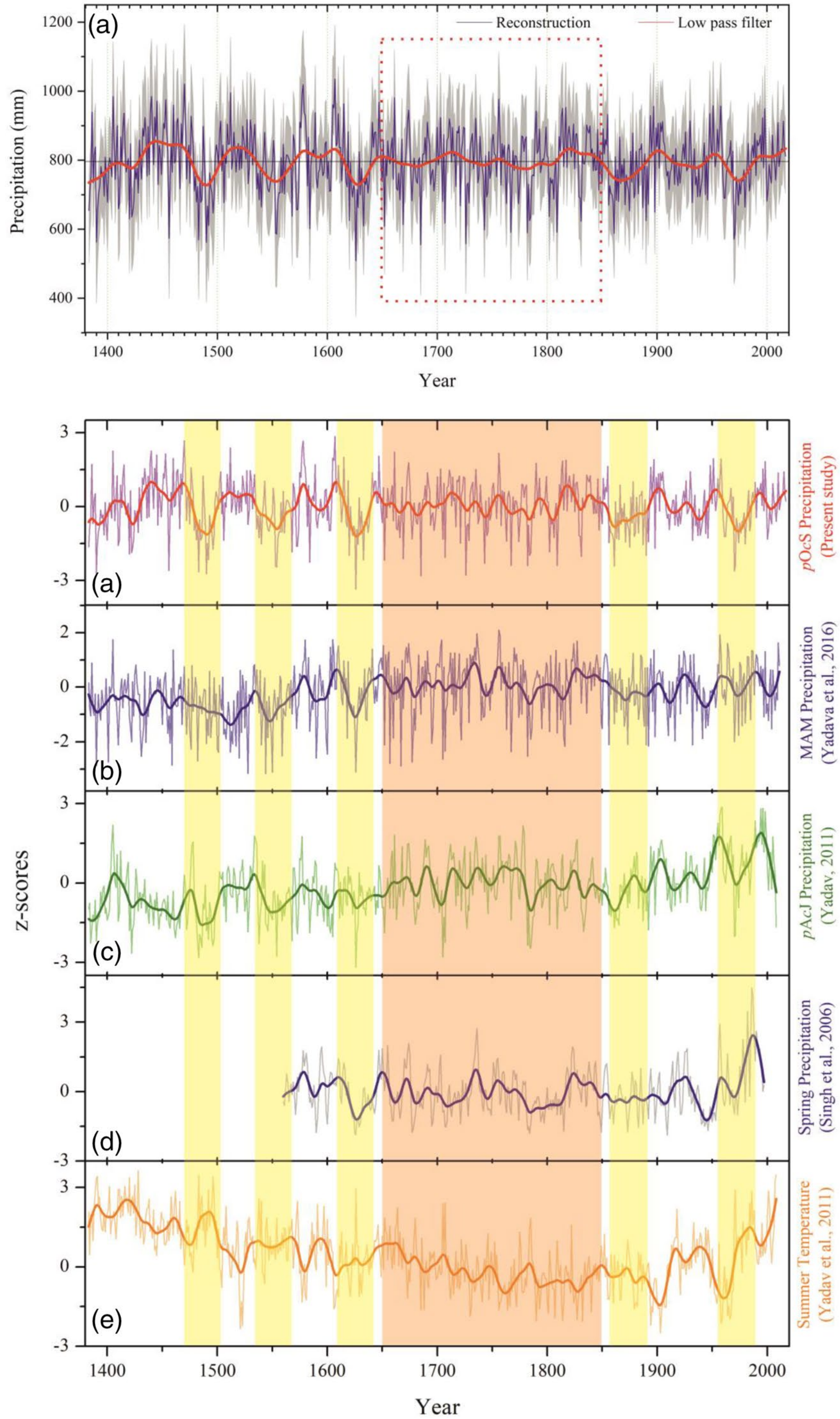

Figure 2. (a) *p*O*c*S precipitation reconstruction (1383–2017 CE) with 40-year spline superimposed and the shaded region is the prediction error. The rectangle shows the LIA influenced period of stable precipitation during 1650s–1850s. The comparison of (a) present reconstruction with tree-ring-based precipitation reconstructions of (b) Kinnaur, Himachal Pradesh, (c) Lahaul-Spiti, Himachal Pradesh, (d) Uttarkashi, Uttarakhand and (e) summer temperature of Lahaul-Spiti. All records were standardized with respect to mean and standard deviation of the common period, and stable and major low precipitation periods were highlighted by red and yellow vertical bars, respectively. LIA, Little Ice Age; *p*O*c*S, prior year October to current year September.

that the settlement abandonment occurred during late-eighteenth and early-nineteenth centuries due to reduced temperature and increased snowfall (Saini et al., 2019). The study of Qiao and Yi (2017) also found a significant role of precipitation in controlling the pattern of glaciation during the LIA over the Himalaya. The stable precipitation recorded in our study, in combination with other proxies, revealed that the LIA in the western Himalaya peaked during 1650s–1850s. Furthermore, the November–April, Snow Water Equivalent (SWE) record (Yadav & Bhutiyani, 2013) from the western Himalaya also revealed close similarity with present precipitation ($r = 0.621$, $p < 0.00001$, 1460–2008 CE; Figure S5). The low precipitation periods of early and late phases showed strong consistency with the SWE record (Yadav & Bhutiyani, 2013), while the SWE was relatively stable in the middle phase (1650s–1850s CE) similar to the present study.

The regional strength of our reconstruction was further tested by comparing it with other precipitation records of the western Himalaya. Three independent records, boreal spring precipitation (March–May) from Kinnaur, Himachal Pradesh (Yadava et al., 2016), annual precipitation (previous year August to current year July) from cold arid Lahual-Spiti, Himachal Pradesh (Yadav, 2011b) and spring (March–May) precipitation from Uttarkashi, Uttarakhand (Singh et al., 2006) were compared with present precipitation record (Figures 2a–2d). Strong and significant correlation with precipitation records; Yadava et al. (2016) ($r = 0.469$, $p < 0.00001$, 1383–2011 CE), Yadav et al. (2011b) ($r = 0.525$, $p < 0.00001$, 1383–2008 CE) and Singh et al. (2006) ($r = 0.346$, $p < 0.0001$, 1560–1997) endorse the strength of our reconstruction to capture regional scale features. The LIA-induced stable precipitation reflected in the middle part of the reconstruction was present over the whole western Himalaya (Figures 2a–2d).

To understand the past hydrological challenges and conditions, present precipitation reconstruction was also compared with tree-ring-based river flow records of Satluj (Misra et al., 2015; Singh & Yadav, 2013) and Indus (Rao et al., 2018; Figures 3b–3d). The Pearson correlation of present precipitation reconstruction with flow of Satluj (Singh & Yadav, 2013; $r = 0.467$, $p < 0.0001$, 1383–2005 CE), (Misra et al., 2015; $r = 0.566$, $p < 0.00001$, 1660–2004 CE) and Indus (Rao et al., 2018; $r = 0.24$, $p < 0.0001$, 1394–2005 CE), suggest synoptic scale variability in precipitation over the western Himalayan region that directly influenced river discharge. Furthermore, it has been clearly identified that similar to precipitation, river-flow records also showed lower flow in the early and late phases and stable discharge in the middle phase (1650s–1850s CE; Figures 3b–3d). In comparison to the low river flow, relatively stable river discharge in the middle phase also supports the LIA-induced stable precipitation at that time.

Present precipitation was also compared with tree-ring-based hydrological records of Jammu and Kashmir. In our earlier studies (Singh et al., 2017; Yadav et al., 2017), a standardized precipitation index (SPI8-May and SPI2-May) was developed for Kishtwar, Jammu and Kashmir region and among them, the SPI2-May record inferred severe dry climatic conditions for the region from 1439–1660s CE and wetter conditions from 1670s–2014 (Yadav et al., 2017). However, the pluvial condition from 1670s onwards was also interrupted by drier periods during 1850s–1870s and 1970s. These two drought periods, along with three other low-precipitation periods before 1650s also recorded in our data (Figures 3e and 3f) strongly support the finding of the present study. However, the SPI8-May record showed opposite trend with present precipitation during the late-eighteenth century (1760s–1790s CE; Figure 3g). This could be largely due to the use of single site Himalayan cedar chronology with low replication of samples in developing SPI8-May reconstruction (Singh et al., 2017). However, in the present study, we have used 16 chronologies and among them few chronologies, one of Himalayan cedar in SPI8-May and four of neoza pine with one Himalayan cedar in SPI2-May reconstruction are common. A comparison of the present reconstruction with April–May–June precipitation of Lidder Valley, Jammu and Kashmir (Shah et al., 2018) also revealed close similarity ($r = 0.493$, $p < 0.0001$, 1723–2010 CE; Figure 3h).

Apart from this, numerous societal challenges/consequences related to glacial advances in Jammu and Kashmir are reported to have occurred during the LIA period. For example, famines of 1814 and 1831–1833 in Kashmir (Anonymous, 1909; Bamzai, 1962; Koul, 1978) are associated with high precipitation and snowfall. While in the winter of 1841, devastating floods occurred over Indus and Kashmir (Anonymous, 1909). Jammu and Kashmir region experienced pluvial conditions during 1810s–1840s (Singh et al., 2017). A recent study (Ballesteros-Cánovas et al., 2020) revealed a number of recurrent flood events in 16th–18th century over the Kashmir region. Along with the increased flood events, the size of Wular Lake, Kashmir also increased to its maximum extent during the 18th and 19th century (up to about 200 km^2) reflecting

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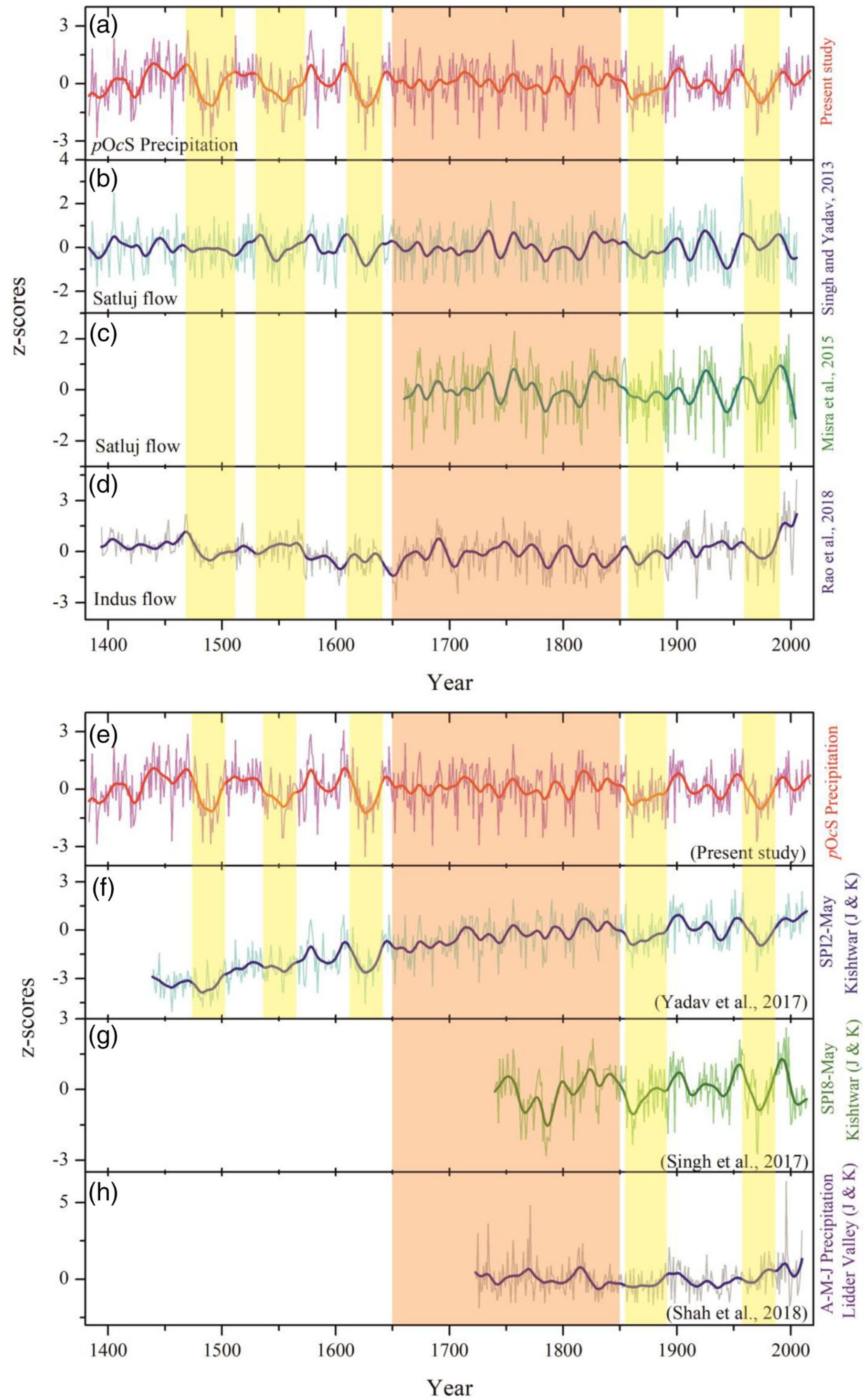

Figure 3. (a) Present precipitation reconstruction along with the western Himalayan river discharge; (b), (c) – Satluj flow, (d) – Indus flow in the upper half and lower half representing comparison of (e) present precipitation with hydrological records of Jammu and Kashmir, (f) SPI2-May, (g) SPI8-May and (h) April–May–June precipitation (data digitized from Shah et al., 2018). The stable precipitation along with relatively high-river discharge and low precipitation along with low river discharge is highlighted by red and yellow vertical bars, respectively. SPI, standardized precipitation index.

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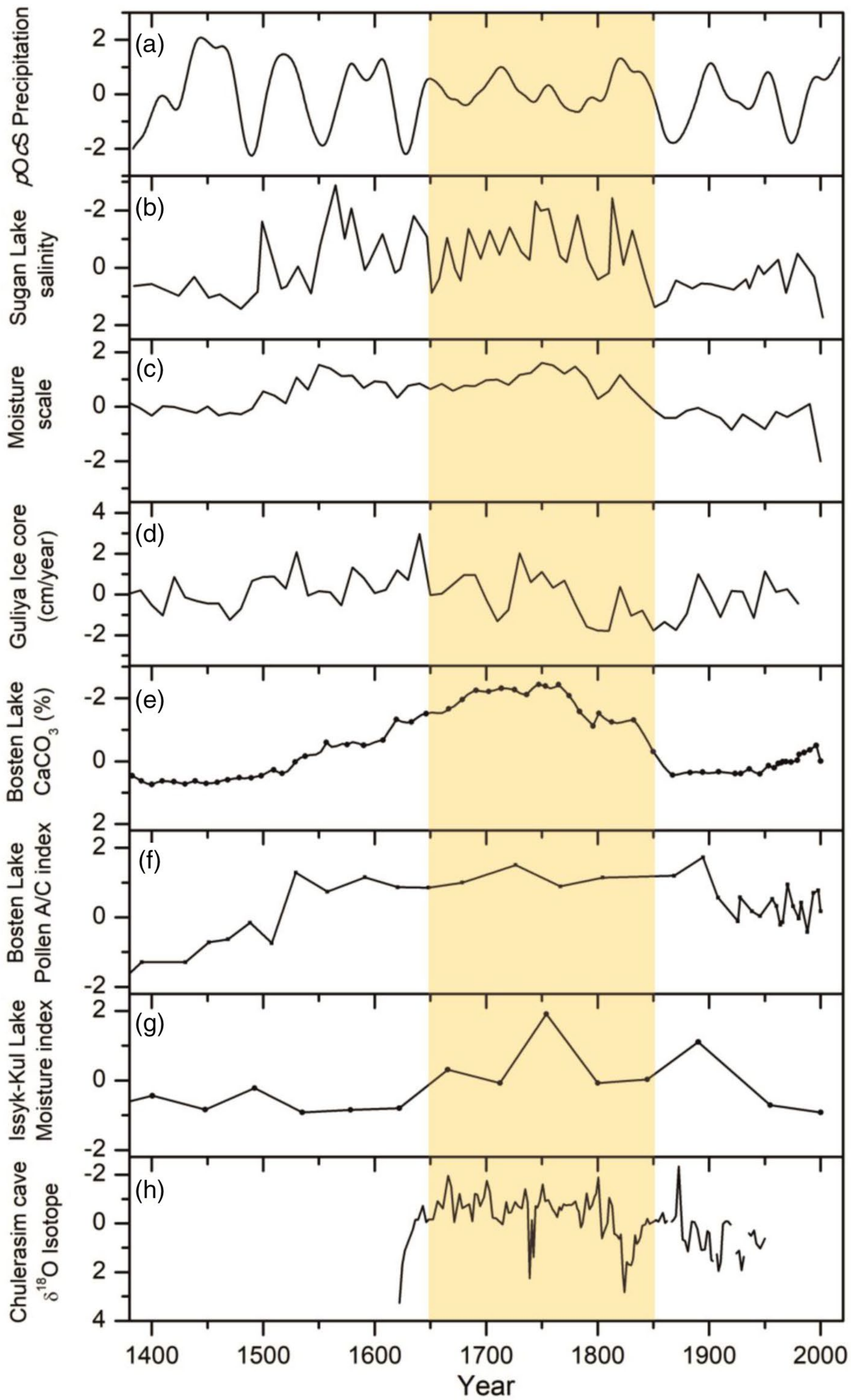

Figure 4. Comparison of (a) *p*OcS precipitation record with other hydrological proxy records, (b) Chironomid-based salinity from Sugan Lake, a direct measure of aridity (Chen et al., 2009), (c) Synthesized moisture data (Chen et al., 2010), (d) Guliya Ice core accumulation data from the western Kunlun mountains, Northwestern Tibetan Plateau (Thompson et al., 1995, 1997), (e) Bosten lake $CaCO_3$ content (Chen et al., 2006), (f) Bosten lake Pollen A/C (*Artemisia*/Chenopodiaceae) moisture index (Chen et al., 2006), (g) Issyk-Kul lake moisture index derived from *Artemisia*/*Ephedra* Pollen (Giralt et al., 2004) and (h) Chulerasim cave, $\delta^{18}O$ Isotope data, Kumaun Lesser Himalaya (Kotlia et al., 2017), of central Asia and the western Himalaya. The data (a)–(h) were normalized relative to the mean and standard deviation of the series and figures (e), (f), and (g) were digitized from published papers. The highlighted section shows the stable precipitation over the region. *p*OcS, prior year October to current year September.

LIA-induced pluvial conditions. However, the Wular Lake constricted in the sixth to seventh, sixteenth to seventeenth and in late-twentieth century (between 55 and 90 km^2), highlighting the stressed hydrological conditions before and after the LIA. All these records in combination with the present study suggest that the LIA was active during the mid-seventeenth to mid-nineteenth century over the western Himalaya, when maximum glacial advances and associated climatic events occurred due to consistently stable, good precipitation regime occurred over long period.

We further compared our present precipitation reconstruction with seven independent hydrological records available from the central Asia and Himalaya (Chen et al., 2010; Chen et al., 2009; Chen et al., 2006; Giralt et al., 2004; Kotlia et al., 2017; Thompson et al., 1995, 1997; Figure 4). As most of these proxy records have coarser temporal resolution compared to the tree-rings, a 40-year low-pass filter of tree-ring records was used to highlight low-frequency variations (Figure 4a). Hydrological records from diversified regions (Figures 4b–4h) indicate strong consistency with the stable precipitation during the middle phase and support the LIA influence. The low precipitation in the twentieth century also reflected in other proxy records (Chen et al., 2010; Chen et al., 2009; Chen et al., 2006; Giralt et al., 2004; Kotlia et al., 2017; Thompson et al., 1995, 1997) is consistent with the present precipitation reconstruction. The precipitation record was also compared with MADA (Cook et al., 2010) of a grid close to our study site (32°30′–35°N, 72°30′–75°E). The comparison revealed significant correlation ($r = 0.313$, $p < 0.0001$, 1383–2005) and showed its utility to understand the regional and seasonal hydroclimatic variability. Major drought periods recorded in the early and late phases of present study also showed consistency with the June–July–August PDSI (Cook et al., 2010) supporting our findings (Figure S6).

The *p*O*c*S reconstruction revealed five major low precipitation/drought periods in the 1470s–1500s, 1530s–1570s, 1610s–1640s, 1850s–1890s, 1960s–1980s CE (Figure 2) and out of these, three fall during 1383–1650 CE indicating dryness reflecting no impact of LIA during this period. The late-fifteenth century drought (1470s–1500s CE) was consistent with the tree-ring records from north-eastern Tibetan Plateau (Gou et al., 2010; Shao et al., 2005; Zhang et al., 2003), revealing a wide geographical extent of the high-intensity drought. Dry climatic conditions and low precipitation also prevailed in late-fifteenth to early-sixteenth century in Afghanistan (Beveridge, 1921; Yadava et al., 2016). Further, the early-seventeenth century droughts during 1610s–1640s CE were concurrent with the colder temperature and severe drought in the Late Ming period (1620s–1640s CE) over China, when agricultural production declined (Zheng et al., 2014). After the end of the LIA, two major drought periods (1850s–1890s and 1960s–1980s) were recorded in the precipitation reconstruction. The 1960s–1980s low precipitation events were coincidental with the change in Bosten Lake, where a 3 m drop in the lake level was observed during 1959–1987 CE, while the rising lake level was found since 1987 CE and exceeded the existing level of 1959 CE in 1999 CE (Chen et al., 2006). We are of the opinion that a more robust and strong network of proxy records would be needed to establish temporal and spatial extent of the LIA in global perspective.

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

The reconstruction data presented in the study can be found at https://www.ncdc.noaa.gov/paleo/study/32565.

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