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Tree rings reveal recent intensified spring drought in the central Himalaya, Nepal

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ABSTRACT

To better understand long-term drought variations in the central Himalaya, we developed new tree-ring width chronologies of Himalayan spruce (*Picea smithiana* (Wall.) Boiss.) from three sites in the north-western Nepal. The local site chronologies showed high cross correlations and similar growth-climate responses to regional spring drought variability. We thus combined all site chronologies into a regional composite (RC) standard chronology that spans 516 years (1498–2013 CE). The RC chronology showed significant positive (negative) correlations with spring (March–May) precipitation (temperature) variability. Meanwhile, RC chronology showed the highest correlation with spring self-calibrating Palmer drought severity index (scPDSI, $r = 0.652$, $p < 0.001$), indicating that radial growth of *P. smithiana* is strongly limited by spring moisture availability. Using RC chronology, we reconstructed the spring drought variability for the period 1725–2013, which explained 42.5% variance of the actual scPDSI during the calibration period 1957–2012. Our reconstructed spring drought variability in the central Himalaya showed consistent wet-dry episodes with other regional drought and precipitation reconstructions from the Himalaya and nearby regions. Spectral peaks and spatial correlation analysis indicate that spring drought variability in the central Himalaya may be linked to large scale climatic drivers, mainly Atlantic Multidecadal Oscillation activities due to sea surface temperatures variation in the Atlantic Ocean. Our reconstruction revealed a continuous shift toward drier conditions in the central Himalaya since early 1980s that coincide with continental-scale warming and reduced spring precipitation in the central Himalaya.

1. Introduction

The high mountains of Himalayas in south Asia are warming at an alarming rate of 0.6 °C per decade, which is considerably higher than the global average (Shrestha et al., 1999, 2012; IPCC, 2013). Increasing sea surface temperatures (SSTs) concurred with global warming and resulted in unusual El Niño–Southern Oscillation (ENSO) extreme events in the late 20th century (Li et al., 2013). Repeated ENSO events have contributed to mega-drought events over Asia due to failure of south Asian summer monsoon (SASM) (Cook et al., 2010; Sano et al., 2012). An overall weakening trend of monsoon precipitation have been revealed on global scale (Wang and Ding, 2006; Zhou et al., 2008; Li et al., 2010) as well as in the Himalayan region (Davtalab et al., 2015). The climate conditions in the central and western Himalaya is dominated by the SASM during summer, and the mid-latitude north-westerly disturbances during winter and spring. Increasing drought in the recent decades has been observed in the central Himalaya due to decreasing boreal winter and spring precipitation (Wang et al., 2013; Cannon et al., 2015; Gaire et al., 2017), and summer precipitation (Sano et al., 2012; Xu et al., 2017). However, the heterogeneous behavior of drought variability in the central Himalayan region and its teleconnection to the global climate variability needs to be investigated in a long-term perspective.

Drought records are of utmost important in the ecologically sensitive regions of the Himalaya (Yadav, 2013). The drought combined with increasing temperature not only alters regional hydrological regimes, but also triggers forest mortality and vegetation die-off (Martínez-Vilalta and Lloret, 2016). Better understanding about the underlying causes of historical droughts can provide deeper insight on possible effects of climate change and vulnerability of human societies to future droughts (Cook et al., 2010). The paucity of long-spanned and spatial representative instrumental records in the Himalayas requires the study of climate history from high-resolution proxy data like tree-rings (Cook et al., 2003, 2010; Sano et al., 2012). Tree-ring data have

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been used to reconstruct historic droughts and precipitation in the western Himalayan regions (Singh et al., 2009; Yadav, 2013; Yadav et al., 2014; Yadava et al., 2016). However, dendroclimatic reconstructions for the central Himalaya are rather scarce (Cook et al., 2003; Sano et al., 2012; Thapa et al., 2015; Gaire et al., 2017). Cook et al. (2003) established the most comprehensive tree-ring network from 46-sites throughout Nepal and reconstructed February–June and October–February Kathmandu temperature based on multi-species tree-ring chronologies. Sano et al. (2012) reconstructed a summer drought index based on tree-ring $\delta^{18}O$ isotope variations from *Abies spectabilis* and found increasing aridity due to a weakening of SASM over the central Himalaya since past two centuries. Thapa et al. (2015) reconstructed spring temperature from *Picea smithiana* in the western part of the central Himalaya, Nepal and revealed increasing spring temperature since the 1980s. Gaire et al. (2017) reconstructed tree-ring based March–June precipitation and found decreasing spring precipitation in the north-western part of the Nepal since mid-1970s. Other studies disclosed the importance of spring moisture availability on tree growth (Dawadi et al., 2013; Liang et al., 2014) and highlighted the opportunity to reconstruct historic spring drought events in the central Himalaya (Liang et al., 2014).

Spring moisture availability plays a crucial role for vegetation growth, agricultural production, forest productivity and ecosystem functions. Therefore, study on long-term perspective of spring drought variability and its teleconnection to the ocean-atmospheric circulation is a relevant issue. In this study, we developed a series of new tree-ring width chronologies of Himalayan spruce (*Picea smithiana*) in the central Himalaya, north-western Nepal and we aimed: 1) to identify the dominant climatic factors limiting radial growth of high-elevation Himalayan spruce, 2) to determine historical drought variations in the central Himalaya, and 3) to evaluate the teleconnections of spring drought variability with the global climatic drivers.

2. Materials and methods

2.1. Study area

The study area is located at Rara National Park (RNP) and adjacent forests in the north-western part of the central Himalaya, Nepal (Fig. 1, Table 1). Regional climate is warm and wet during summer, but rather cold and dry during winter, and warm and dry during spring (Putkonen, 2004; Ichiyanagi et al., 2007). Monsoonal air masses originating from Indian Ocean flow north to the Himalayan Mountains and cause summer monsoon rainfall from June to September (Barry, 2008). In contrast, boreal winter and spring precipitation is caused by disturbances of the mid-latitude north-westerlies (Bräuning, 2004). The east-west running main Himalayan massifs block monsoonal air masses from flowing northward, creating a rain shadow zone with less precipitation and semi-arid site conditions (Bräuning, 2004; Barry, 2008) in our study area. According to the meteorological records from Jumla station (situated at 29.27°N, 82.18°E, 2366 m a.s.l.), the total annual precipitation is 797 mm, 66.5% of which fall in summer (June to September) (Fig. 2a). Although spring (March–May) precipitation (141 mm) contributes only 17.65% of total annual precipitation, it plays a crucial role for vegetation growth, biomass gain and crop cultivation in the Himalayas.

The average annual maximum, mean, and minimum temperatures at Jumla are 20.6 °C, 12.7 °C, and 4.8 °C respectively, with a mean temperature of 20.2 °C in July and 4.2 °C in January (Fig. 2a). Significant increasing trend was observed for mean annual temperature (0.26 °C/decade) and spring temperature (0.31 °C/decade) of Jumla station (Fig. 2b) during 1969–2013. Spring and annual precipitation showed no significant trend during the entire period 1957–2013 (Fig. 2c). No significant trend has been observed for regional self-calibrating Palmer drought severity index (scPDSI) from 1957 to 2013, however both spring and annual scPDSI has been decreased since early 1980s (Fig. 2d).

2.2. Tree-ring data

Picea smithiana (Wall.) Boiss. (Himalayan spruce) is a native species in the central and western Himalayas from Afghanistan to central Nepal, and mostly grows on lithosol soils within an elevation belt of 2500–3300 m. The species is cold tolerant and either forms pure forest stands on steep slopes or associates with various conifers, e.g. *Abies* spp., *Pinus wallichiana*, and *Juniperus indica* or broad leaved trees such as *Betula utilis*, *Quercus semecarpifolia*, and *Juglans regia* (Miehe et al., 2015).

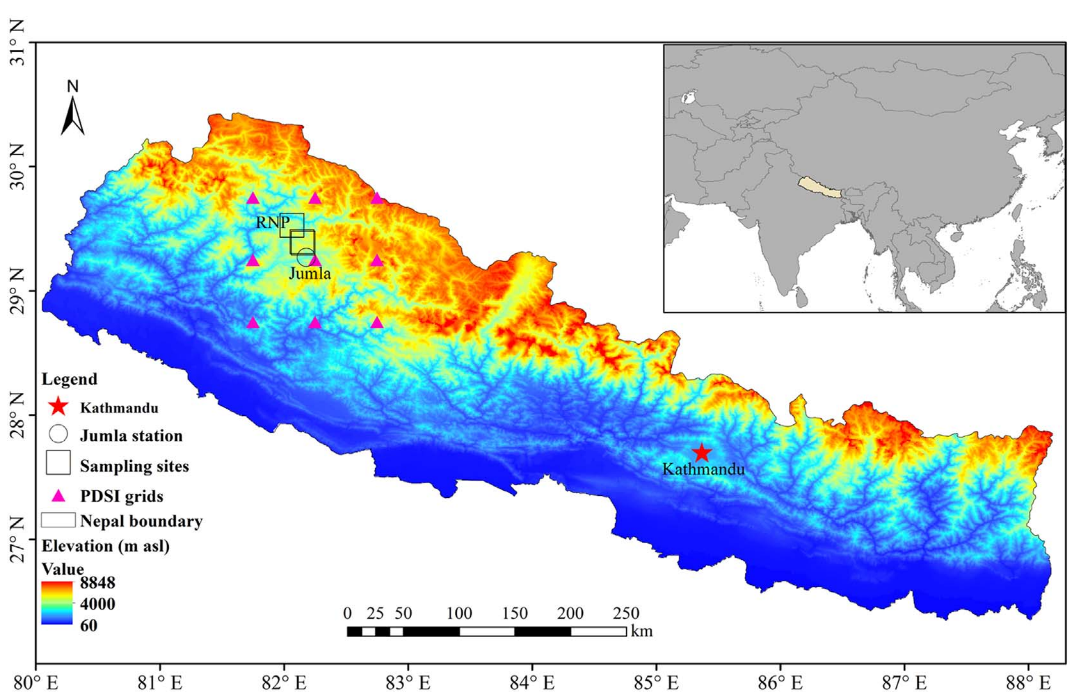

Fig. 1. Map of the study area showing sampling sites of Himalayan spruce, Jumla climate station and CRU scPDSI grid points in the central Himalaya, Nepal.