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Tree-ring footprints of drought variability in last ~300 years over Kumaun Himalaya, India and its relationship with crop productivity

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ABSTRACT

We reconstructed Standardized Precipitation Index (SPI), a metric of drought, using tree-ring width chronologies of Himalayan cedar (*Cedrus deodara* (Roxb.) G. Don) prepared from two ecologically homogeneous settings in the Kumaun Himalaya, India. The reconstruction employing first principal component of the two site chronologies in linear regression model helped in extending 7-month SPI of May (SPI7-May) back to 1720 CE. The calibration model capturing 60% of variance in the observed SPI series (1902–1967) is the strongest so far from the Indian region. On achieving such a robust tree-ring calibration we are of the opinion that SPI should provide a better option to develop long-term drought records for the data scarce Himalayan region. The SPI reconstruction revealed high year-to-year variability with 1816 (SPI −1.92) and 1737 (SPI +2.33) the driest and the wettest years respectively. The five year mean of reconstructed SPI revealed multiyear droughts in 1920–1924, 1782–1786, 1812–1816, 1744–1748, 1964–1968 and pluvial phases in 1911–1915, 1723–1727, 1788–1792, 1758–1762 and 1733–1737.

The SPI7-May was found to be significantly correlated with wheat-barley productivity data of Almora in Kumaun, close to our tree ring sites ($r = 0.60$, two-tailed $p < 0.0001$). However, we observed that the wheat-barley productivity data, to some extent, were better correlated with 7-month SPI of April (SPI7-April) ($r = 0.69$, two-tailed $p < 0.0001$). The difference in relationship of wheat-barley productivity and SPI of above two periods is largely due to the prevailing crop phenology in the region. The wheat and barley crops sown in October–November are usually harvested in May when the Himalayan cedar trees are in active vegetation phase of seasonal growth in Almora region. We observed strong and significant correlation in SPI7-May and SPI7-April ($r = 0.75$, two-tailed $p = 0.0001$) underpinning that the tree-ring derived SPI7-May could also be taken as a proxy of wheat-barley production in Almora region. This observation also stands for the past as we noted that most of the droughts recorded in our reconstruction (SPI <1) were associated with rabi crop failures in the Kumaun Himalaya. The findings of this study establish that the SPI7-May developed from tree rings should serve as an important base line data to quantify the impact of droughts on forest as well as rabi crop productivity in hilly terrains of the Kumaun Himalaya in long-term perspective.

1. Introduction

Drought is a naturally occurring subtle climatic phenomenon that may persist for a season or multiple years and affects more population than any other natural hazard (Wilhite, 2000). In India, National Commission on Agriculture (GOI, 1976) classified droughts in three categories as meteorological, hydrological and agricultural droughts. The agricultural drought is a situation when rainfall and soil moisture are inadequate during the crop growing season to support healthy crop growth to maturity. Recurring droughts in one or the other region of India are known to critically affect the livelihood of the vast majority of low income people whose sustenance is dependent on agriculture (Mishra and Singh, 2010; Gupta et al., 2011). Nearly 79.44 million ha of agricultural land area constituting ~57% of the cultivated area is rainfed and contributes 44% of the total food grain production in India (Anonymous, 2009). Such

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an extensive rainfed agriculture system practiced in India ranking first among the rainfed agricultural countries in the world, both in extent and value of produce (Aggarwal, 2013), makes economy of the country much dependent on seasonal distribution of rainfall. As nearly half of the total workforce in India (~52%) is still employed by the farm sector, severe droughts affecting agriculture productivity seriously hamper the developmental pathways of the country (Gadgil and Kumar, 2006). Such challenges are far bigger in the Himalayan region of India where drought impacts are high due to poor irrigation infrastructure facilities. The terrain constrains in the Himalaya hinder the development of sufficient crop irrigation facilities, making agriculture highly vulnerable to natural rainfall patterns. In view of this a better understanding of drought behaviour in long-term perspective is very important to develop appropriate climate adaptive measures.

The high-resolution proxy climate records used to extend the weather data back in the historical past provide valuable window to understand climate variability under the backdrop of anthropogenic changes (IPCC, 2013). The tree-ring records from moisture stressed sites in different parts of the world have been successfully used to understand temporal and spatial patterns of droughts (Woodhouse and Overpeck, 1998; Cook et al., 2004, 2007; Touchan et al., 2005, 2008, 2011; Esper et al., 2007; Stahle et al., 2007, 2013; Woodhouse et al., 2010; Burnette and Stahle, 2013; Griffin and Anchukaitis, 2014). Recently, a considerable progress has been also made towards this direction to develop annually resolved tree-ring-based drought/hydrological records for 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; Shao et al., 2010; Zhang et al., 2011; Ram, 2012; Sano et al., 2012; Yang et al., 2012, 2014a, b; Sun and Liu, 2013; Yadav, 2013). The age of many long living conifer species growing in semi-arid to arid regions of the western Himalaya are found to exceed over millennium (Esper, 2000; Cook et al., 2003; Singh et al., 2004; Yadav et al., 2006; Singh and Yadav, 2007; Yadav, 2012). Precisely dated annually resolved tree-ring chronologies of such old trees from semi-arid to arid regions of the western Himalaya should provide a valuable archive of drought variability in long-term perspective.

To understand the relative strength of droughts various types of indices have been devised over times (Keyantash and Dracup, 2002) and amongst these the Palmer Drought Severity Index (PDSI; Palmer, 1965) is widely used. However, realizing the fact that droughts vary over different timescales depending on the response times of different meteorological, hydrological, agricultural and socioeconomic systems, and PDSI having a fixed temporal scale, multi-scalar drought indices such as Standardized Precipitation Index (SPI; Mckee et al., 1993) and Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010) have come in to use recently. The SPI is being widely used to monitor short-term water supplies such as soil moisture which is important for agriculture production, as well as long-term water resources such as groundwater supplies, stream flow and reservoir levels (Mishra and Singh, 2010). However, in assessment of agriculture droughts the SPI has its own limitation as the availability of soil moisture is directly controlled by evapotranspiration, which is not taken into account in derivation of SPI. In spite of the above limitation we used SPI data in present study, as it was calculated from precipitation records available from weather stations close to our tree-ring sites in the western Himalaya. The SPI was also preferred for reconstruction over the other drought indices, viz., PDSI and SPEI as it showed statistically much robust calibrations with the tree-ring width chronologies of Himalayan cedar. Recently, the World Meteorological Organization in 2009 (WMO, 2012) also recommended that SPI, in addition to other drought indices, should be used as a drought metric by all National Meteorological and Hydrological Services around the world to characterise the meteorological droughts. The SPI reconstruction presented here-in is the first attempt to develop drought records for the Kumaun (Kumaon) Himalaya, India using tree-ring data of Himalayan cedar. The SPI records were also used to understand relationship with crop productivity in the rainfed agricultural region of Almora, adjacent to tree-ring locations.

2. Data and methods

2.1. Tree-ring data

Himalayan cedar commonly grows in semi-arid to arid regions of the Indian Himalaya. Good amount of winter snowpack, not too heavy summer monsoon rainfall and well drained soils are its primary ecological requirement. Over humid sites, the tree age is usually limited to only a few hundred years due to frequent wood rot, but in drier locations the age of many conifer species have been found to extend over the last millennium and even more (Singh et al., 2004). Due to the ecological preferences of Himalayan cedar for semi-arid and arid conditions the dendrochronological series of this species are found to be very sensitive indicators of variations in drought (Yadav, 2013). In the present study increment core samples of Himalayan cedar growing in Jageshwar and Gangolihat in the Kumaun region collected in May 2013 were used (Fig. 1). The Himalayan cedar in the Kumaun Himalaya is not native and was introduced in temple complexes several centuries ago depending on the establishment of religious shrines. The age of introduced Himalayan cedar in the Kumaun Himalaya using dendrochronological methods has been estimated back to the early 16th century CE (Yadav et al., 2014a, b). Due to suitable environmental conditions the Himalayan cedar introduced in the Kumaun region has completely naturalized and is showing very good regeneration. The sampled trees, used in this study, were found growing on sites with thin soil cover and variable slopes on northwest aspect where the ground water balance does not seem to have much impact on tree growth. Thin soil conditions and slope gradients favour fast run-off of the meteoric water to down streams making trees susceptible to soil moisture deficit. The increment core samples of Himalayan cedar collected from Jageshwar and Gangolihat sites in the Kumaun Himalaya (Fig. 1) were processed following conventional dendrochronological methods and growth ring sequences precisely dated to calendar year of their formation (Fritts, 1976). The ring widths of crossdated samples were measured to 0.01 mm resolution using linear encoder (LINTAB) coupled with personal computer (Rinn, 1996). To understand temporal growth dynamics in tree-ring series ring-width measurement plots from both the sites were carefully studied. The ring-width plots of tree samples from two sites revealed that the Himalayan cedar growth was influenced by stand dynamic features such as changing competition due to gap formations created by falling of adjacent trees. Therefore, to maximize the common signal in tree-ring-width chronologies, we detrended the measurement series by using 50-year cubic spline with a 50% frequency response function cut off (Cook and Peters, 1981). The ring-width series of individual tree samples were power transformed prior to detrending to stabilize variance in the heteroscedastic tree-ring-width measurement series (Cook and Peters, 1997). The growth trends were removed from the power transformed individual measurement series by subtraction that minimizes the end fitting-type bias as compared to the ratios (Cook and Peters, 1997). In order to reduce the influence of outliers the detrended ring-width measurement series of respective trees were averaged to a mean chronology (standard) by computing the biweight robust mean