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Hydroclimatic variability and corresponding vegetation response in the Darjeeling Himalaya, India over the past ~2400 years

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ABSTRACT

To understand the present day climate change impacts on ecosystem, knowledge of the rapid climatic events occurred within the last few thousand years is crucial. Indian summer monsoon (ISM) dominated eastern Himalayan vegetation is sensitive to even a minor change in climate parameters, hence suitable for studying climate-plant interactions. We reconstruct a ~2400 years climatic history of the Darjeeling area, eastern Himalaya combining pollen, phytoliths, non-pollen palynomorphs (NPPs), $\delta^{13}C$ signatures, sediment texture and total organic carbon (TOC) records from a lacustrine deposit to explore ecosystem response to climate change and to understand the possible forcing mechanisms behind it. This study is centred on two northern hemispheric late Holocene climatic events namely Medieval Warm Period (MWP) and Little Ice Age (LIA). Although considerable variations exist globally for these warm (moist) and cool (dry) periods with respect to their timing, duration, and hydroclimatic dynamics, our results identify a humid climatic phase at the beginning of the last millennium, a pre-MWP less humid phase, while MWP was wetter than the former phase and a wet LIA in the Darjeeling Himalaya. Our results indicate that this climatic variability also induced changes in the regional vegetation. During 364 BCE to 131 CE, the region was humid harbouring a dense broad-leaved evergreen forest; a comparatively drier condition prevailed between 131 CE and 624 might be the reason behind the thinning in the forest cover. A wet phase is observed during 1118 CE. A further increase in monsoonal strength is apparent between 1367 CE and 1802. Considering the available records from the eastern Himalaya and peninsular India it is inferred that centennial scale variations in frequencies of "active dominated" and "break-dominated" periods govern the internal dynamics of the ISM, and considered to be the key forcing mechanism behind the differential behaviour of the ISM over these regions.

1. Introduction

The nature and causes of rapid climatic changes (RCCs) during the late Holocene remain controversial due to disparity in their timing, duration, magnitude and dynamics among different regions of the globe. These inconsistencies may be attributed to sensitivity of the proxies used, time lag factor among different proxy parameters, regional climatic differences and their forcing factors and sometimes chronological constrains (Mayewski et al., 2004). Two significant late Holocene climate events spanning the last millennium a cool-dry phase known as 'Little Ice Age' (LIA), a period approximately ranged between ca. 1400 to 1850 CE (Mann, 2002a) preceded by a contrasting warm-moist phase known as Medieval Warm Period (MWP) spanning between ca. 900 to 1300 CE (Mann, 2002b) have shown considerable global as well as regional variations both in time span and in magnitude. Signatures of 'MWP' and 'LIA' are most prominent in the Northern Hemisphere where these phases are manifested by corresponding warming and cooling trends respectively. Although MWP displayed a warming trend that matches or sometimes exceeds that of the past decade in some regions, but are comparatively lower than the recent global levels (Mann, 2002b). However, during LIA, a cooling over the extratropical Northern Hemisphere continents is noticed (Mann et al., 2009). These phases are less reliable in the Southern Hemisphere, especially in the extratropics. In the monsoon dominated tropical regions, these temperature anomalies also influenced monsoon as expressed by regional hydroclimatic variations, though heterogeneity exists in timing and extent of these RCCs (Mann et al., 2009; Wanner et al., 2008).

A good number of proxy- records have reconstructed the nature and

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magnitude of the late Holocene climate variations in centennial- to millennial-scale (and some even up to decadal scale) from different parts of the geographically and climatically varied Indian subcontinent (for example, Agnihotri et al., 2002; Berkelhammer et al., 2010, 2012; Bhattacharyya et al., 2007; Chauhan and Quamar, 2010; Demske et al., 2016; Dixit and Bera, 2013; Gadgil et al., 2005; Kotlia et al., 2012, 2014, 2016; Kotlia and Joshi, 2013; Liang et al., 2015; Menzel et al., 2014; Mishra et al., 2015; Phadtare, 2000; Prasad et al., 2014; Quamar and Chauhan, 2012, 2014; Rühland et al., 2006; Shankar et al., 2006; Sinha et al., 2007, 2011a, 2011b, 2015 and Tripathi et al., 2014). In most of these records, variations in the Indian summer monsoon (ISM) was emphasized as it supplies nearly 80% of the annual precipitation over the Indian subcontinent as the JJAS (June–July-August-September) seasonal precipitation vital for the agrarian-based Indian socio-economy. Records exhibit conspicuous climatic variations in the Indian subcontinent in the last two millennia. Identification of the forcing factor(s) behind this regional inconsistency is an urgent need to understand the pattern of variability and to enhance the future climate predictability.

Earlier asynchronous behaviour of the ISM is also observed during the MWP and LIA in India. For example MWP in general is observed as an interval of strong monsoonal period (Dixit and Tandon, 2016 and references therein), but high resolution speleothem oxygen isotopic ($\delta^{18}O$) records from Dandak Cave, central-eastern India (Sinha et al., 2007) and Dharamjali Cave, Central Kumaun Himalaya (Sanwal et al., 2013) inferred that droughts occurred frequently on either side of MWP. Furthermore, records from the Indian core monsoon zone (CMZ) suggest that the entire span of the LIA was punctuated by episodic and widespread reoccurrences of monsoon megadroughts (Sinha et al., 2011b), while from a general cool-dry trend, departures are observed in the central Himalaya and in the northeast India, where signatures of a wet LIA was evident (Sinha et al., 2011a; Sanwal et al., 2013; Dixit and Tandon, 2016 and references there in). In their multi-proxy study and model simulations, Polanski et al. (2014) have showed that heterogeneity exists among different regions within the Indian subcontinent regarding the summer and winter moisture anomalies, where western and central Himalaya are influenced by variations in intensity of extra-tropical Westerlies during winter. Variations in thermal gradient between the Bay of Bengal and the Indian subcontinent as well as the zonal band of strengthened ISM–EASM (East Asian Monsoon) link influence the eastern Himalayan region while, the summer moisture anomalies of the Central India are affected by the SST (sea surface temperature) pattern in northern Arabian Sea. More studies from comparatively underexplored regions of this vast subcontinent may improve our understanding of these late Holocene RCCs and identify the nature and possible forcing factors of these multi-century climatic variations.

The 'eastern Himalaya' may serve as an excellent archive for studying past monsoonal impacts on vegetation, as this highly precipitated region is exclusively influenced by the Bay of Bengal branch of the ISM with a rich and diverse flora. Moreover, from this geographically and floristically vast region, very little is known on the late Holocene monsoon variability and its ecosystem impacts. Available records inferred asynchronous monsoon trends in the eastern Himalaya in the last few thousand years (Chauhan and Sharma, 1996; Sharma and Chauhan, 2001; Bhattacharyya et al., 2007; Agrawal et al., 2015). One of the reasons may be the age uncertainties of these records attributable to poor age resolution. Besides, possible forcings behind this asynchronous behaviour of the ISM are not even considered in these studies. Our aim behind this multiproxy study is to identify the trends of past changes in vegetation distribution with reference to climatic forcing over the last ca. 2400 years in the Darjeeling area, eastern Himalaya and to discuss the possible underlying mechanisms. We have used pollen grains as one of the proxies as they depict a picture of both the local (herbs and azonal elements) and regional vegetation (due to their long distance wind transport). While, large proportions of the phytoliths recovered from ancient sediments represent a highly localized, *ín situ* deposition. Due to their durable nature and distinctive shapes phytoliths can identify plants up to family, generic or sometime even specific level also, and thus help in reconstruction of past vegetation (Piperno, 1988). Moreover, phytoliths also can distinguish grasslands from woodlands, C3 from C4 grasses in an assemblage and among the C4 grasses dominance of mesophytic from xerophytic grasses (Pearsall, 2000). However, a certain amount of phytoliths in assemblage may also be contributed due to their long-distance transport (Piperno, 1988). The combination of dry season winds and arid vegetation with bare ground cover are the two factors that favour long-distance phytolith transport, which is not the case for the forested Darjeeling Himalaya. Hence, phytoliths recovered in ancient sediments will reflect mostly the local vegetation scenario. Non-pollen palynomorphs (algal, fungal and zoological remains) may also provide useful information on local ecological characteristics of a site due to their definitive ecological preferences. They are widely used in reconstructing vegetation dynamics, land-use and hydrological changes (Barthelmes et al., 2012; Cugny et al., 2010; Dietre et al., 2012; Feeser and O'Connell, 2010; Ghosh et al., 2017; Wünnemann et al., 2010). Stable carbon isotopic signature preserved in organic matter associated with soil/sediments (SOM) is another tool frequently used in palaeovegetation as well as palaeoclimate reconstructions (Meyers, 1994). It is a reliable proxy to discriminate past distribution of C3 and C4 plants. Environmental factors like the temperature and precipitation influence carbon isotopic fractionation in both C3 and C4 plants and alter the $\delta^{13}C$ values of these plants. C3 plants adapted to humid climatic conditions show a large range in $\delta^{13}C$ values (−20‰ to −34‰, VPDB), while C4 plants adapted to less humid conditions show a range between −9‰ to −19‰ (O'Leary, 1988; O'Leary, 1981; Sage, 1999; Agrawal et al., 2012; Basu et al., 2015). A minor variation in temperature–-rainfall gradients significantly alter $\delta^{13}C$ values of C3 and C4 plants, which is reflected in $\delta^{13}C$ value of SOM (Deines, 1980; O'Leary, 1981; Farquhar et al., 1989). Hence, together all these proxies may provide insights into long term changes in climate, vegetation and land-use.

2. Study area, climate and vegetation

The Darjeeling Himalaya bounded by Sikkim in the north, Nepal in the west and Bhutan in the east is a part of the eastern Himalayan mountain ranges. Samples for the present study were collected from a 70 cm deep profile dug out at the bed of a small, dried lake located at an elevation of 1943 m a.s.l. (above sea level) (27°01′45.24″N; 88° 19′18.71″E) of the Darjeeling Himalaya. Today the surface area of the dried lake is only about 35 × 30 m and situated about 15 km southeast from Darjeeling Township at the Sixth Mile area of the Darjeeling district (Fig.1). Presently this dried lake is located at the temperate vegetation belt of the Darjeeling Himalaya, surrounded by an open wood land.

The region is influenced by the Bay of Bengal branch of ISM. Between 1500 and 3000 m a.s.l. a warm-temperate humid climate prevails, where a warm summer and a dry winter characterize the region (as per Köppen-Geiger climate classification, Peel et al., 2007). Annual mean temperature of the area is about 14.7 °C. Mean temperature of the summer months reaches to 21.3 °C, while mean temperature for the winter months goes down to 4.5 °C. Though snowfall is not a common feature in Darjeeling town, but sometimes may takes place once or twice in a year between January and February. However, high elevated sites of the Darjeeling Himalaya get plenty of snow between end of December and February. From the gridded climate data, the mean annual rainfall of the area is estimated to be about 2716 mm (Hijmans et al., 2005). Maximum extent of rainfall takes place between the months of June and September.

The dominant forest type of the study area falls under east Himalayan wet temperate forest. Higher stretches of the temperate vegetation belts are occupied by oaks (*Quercus* spp.) and chestnuts