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A modern pollen–climate dataset from the Darjeeling area, eastern Himalaya: Assessing its potential for past climate reconstruction

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ABSTRACT

Relying on the ability of pollen assemblages to differentiate among elevationally stratified vegetation zones, we assess the potential of a modern pollen-climate dataset from the Darjeeling area, eastern Himalaya, in past climate reconstructions. The dataset includes 73 surface samples from 25 sites collected from a c. 130–3600 m a.s.l. elevation gradient along a horizontal distance of c. 150 km and 124 terrestrial pollen taxa, which are analysed with respect to various climatic and environmental variables such as mean annual temperature (MAT), mean annual precipitation (MAP), mean temperature of coldest quarter (MTCQ), mean temperature of warmest quarter (MTWQ), mean precipitation of driest quarter (MPDQ), mean precipitation of wettest quarter (MPWQ), AET (actual evapotranspiration) and MI (moisture index). To check the reliability of the modern pollen-climate relationships different ordination methods are employed and subsequently tested with Huisman–Olff–Fresco (HOF) models. A series of pollen–climate parameter transfer functions using weighted-averaging regression and calibration partial least squares (WA-PLS) models are developed to reconstruct past climate changes from modern pollen data, and have been cross-validated. Results indicate that three of the environmental variables i.e., MTCQ, MPDQ and MI have strong potential for past climate reconstruction based on the available surface pollen dataset. The potential of the present modern pollen-climate relationship for regional quantitative paleoclimate reconstruction is further tested on a Late Quaternary fossil pollen profile from the Darjeeling foothill region with previously reconstructed and quantified climate. The good agreement with existing data allows for new insights in the hydroclimatic conditions during the Last glacial maxima (LGM) with (winter) temperature being the dominant controlling factor for glacial changes during the LGM in the eastern Himalaya.

1. Introduction

To develop a better understanding of climatic variability and its ecosystem impacts, quantitative climate data from natural archives beyond the temporal range of instrumental records is an essential prerequisite (Herzschuh et al., 2010). Mountain ecosystems containing a series of climatically very different zones within a short elevational range are best suited for such studies. The combined effects of climate and topography lead to a range of micro-habitats supporting a rich and diverse biota (Körner, 2004), which are also very sensitive to climate changes (Xu and Wilkes, 2004; Körner, 2004). Altitudinal shifts in the tree line, changes in species composition and succession are the most common responses of vegetation to climate changes in any mountainous region (Ramakrishna et al., 2003) and impinge upon the reliability of plant-based paleoclimate reconstructions. The Himalaya, serve as a natural laboratory to test plant-based palaeoclimate proxies. However, the paucity of long, reliable and uninterrupted

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instrumental climate data from the region has imposed challenges to the researchers. Reliance on proxy based studies from natural archives is a necessity. Tree ring records to some extent have filled the gap but only for durations extending back over the last two millennia (Bhattacharyya and Shah, 2009; Yadav, 2012). In contrast to the western and central Himalaya, the eastern Himalaya having more humid conditions due to the influence of the Bay of Bengal branch of ISM, is characterized by only few quantitative climate data for the Late Quaternary to Holocene (Ghosh et al., 2014, 2015). The available tree ring data cover even a shorter time span of c. 500 a BP in comparison to other parts (Chaudhary et al., 1999; Chaudhary and Bhattacharyya, 2000; Bhattacharyya and Chaudhary, 2003; Bhattacharyya and Shah, 2009; Shah and Bhattacharyya, 2009; Sano et al., 2013; Shah et al., 2014; Shekhar and Bhattacharyya, 2015; Yadava et al., 2015).

Pollen grains have long been used as proxies for quantitative paleoclimatic reconstructions (Davis, 1978; Birks, 1981), but quantitative relationships between modern pollen rain and climate have never been studied in the Himalaya. Hence, a composite quantitative method is required which may help to understand the relationships between modern pollen rain and contemporary climate crucial for estimating paleoclimatic conditions based on fossil pollen data (Shen et al., 2006).

Widely used quantitative methods for the Quaternary paleoclimate reconstructions are transfer functions (Webb and Bryson, 1972; Birks, 1995), response surfaces (Bartlein et al., 1986; Webb et al., 1993a, b; Markgraf et al., 2002), and the best modern analogues (Overpeck et al., 1985; Guiot, 1987, 1990). However, both for the response surfaces and best modern analogues, a large number of surface samples (usually > 500 samples) distributed over a wide environmental range are preconditions for reliable reconstructions (Birks, 1995, 2003). In most cases these modern datasets include c.1000 to 3600 (e.g. Cheddadi et al., 1997; Tarasov et al., 1999; Cao et al., 2014; Peyron et al., 2017) pollen surface samples from a wide eco-climatic and orographically varied region. On the other hand, transfer function method can reconstruct past environment and climatic change reliably with a comparatively low number of training data sets. Even from regionally restricted pollen-climate calibration sets, a site-specific reconstruction can dependably be made using this method (Birks et al., 2000; Lotter et al., 2000; Seppä and Birks, 2001, 2002; Bigler et al., 2002; Seppä et al., 2002; Heikkiä and Seppä, 2003; Herzschuh et al., 2010). Therefore, considering the surface pollen sample size, location and climate, we adopt the transfer function method for establishing a quantitative, pollen-based climate reconstruction model in the Darjeeling part of the eastern Himalaya. The interplay of climate and orography creates numerous microclimates in mountainous regions and in such a high rainfall region like the eastern Himalaya with high species diversity, complex plant-climate relationships exist with rising elevation. Along with a south to north declining temperature gradient, here also exists an increasing rainfall gradient from west to east. Within the eastern Himalayan sectors (i.e., Darjeeling, Sikkim, Bhutan and Arunachal Pradesh) the richness, diversity and composition of the flora also vary. So, every sector is unique for both its climate and flora. Here we aim to develop and test the efficacy of a modern pollen-climate calibration set to reconstruct the Late Quaternary climatic condition of the Darjeeling Himalaya and so generate a baseline for future studies from other sectors of the eastern Himalaya.

Our objectives are: 1. to identify the climate variables most influential in determining the differential plant distribution in the Darjeeling Himalaya and to establish and assess the relationships between modern pollen and climatic variables, and (2) to test the performance of pollen–climate transfer functions by numerical cross-validation with modern climate data, and by applying our transfer functions to Late Quaternary pollen spectra for which quantitative climate data are already available.

2. Study area: climate and vegetation

The hilly terrains of the Darjeeling district (26° 31′–27°13′N and 87° 59′–88°53′E), located in the north-western part of the state West Bengal, India, are known as the ‘Darjeeling Himalaya’. These hills are parts of the Lesser and Sub-Himalayan belts of the eastern Himalaya (Fig. 1) and are eco-climatically unique. In the north, Sikkim Himalaya bounds the region, the Nepal Himalaya in the west and the Bhutan Himalaya in the east. A highly degraded platform of terrace deposits extending along the east-west axis demarcates the southern foothill zone. This foothill zone, alternatively known as ‘Terai’ is regarded as one of the low lying belts of the country and traversed by a number of rivers and streams flowing between hills and the ridges where the elevation varies between 90 and 150 m a.s.l. A ridgeline stretching from the Darjeeling in the west to Kalimpong in the east is defined as the inner mountain belt. Here a series of lofty ridges containing deep valleys are formed by the hills. Singalila ridge is the highest point here, where elevation reaches up to c. 3636 m a.s.l. Monsoon, the distinct seasonally varying hydrological regime generated from the seasonal shift of the major pressure cells over Asia and the adjacent oceans accompanied by changes in large-scale circulation patterns, controls the climate of the entire Himalayan Arc (Schickhoff et al., 2015). The climate of the Himalaya is strongly modified on regional and local scales by its pronounced topography. In all the eastern Himalayan sectors, including the Darjeeling Himalaya, windward sides of the slopes receive summer precipitation (June–September) that amounts up to 5000 mm due to the south-westerly flowing ‘Bay of Bengal branch’ of monsoon generated as a result of the strong establishment of the Asian Heat Low. However, the leeward sides in general receive precipitation between 2000 and 2500 mm. More than 80% of annual rainfall is received during summer season (June–September) along the eastern Himalaya. Dry conditions characterize the transitional seasons, while on south-facing slopes infrequent convective precipitation events occur (Romatschke et al., 2010). A warm tropical climate throughout the year characterizes the foothill region of the Darjeeling Himalaya and a temperate climate is seen at the summits. In the plains (i.e. the foothill region) mean annual temperature is about c. 24 °C, which drops to c. 5–6 °C at the ridges. Mean summer temperature at the ridges varies between 11 °C–12 °C, while in the foothills between 27 °C and 28 °C. Winter (December–February) is extremely cold at the ridges where mean temperature even drops to 0 °C, while temperature varies between 15 and 17 °C in the foothills.

Unique topographical features of the hills and moisture-laden monsoonal winds from the Bay of Bengal greatly influence the vegetation of the region. Following the forest type classification by Champion and Seth (1986) and Negi (2002), five vegetation zones along rising elevations are identified in the Darjeeling Himalaya i.e. 1. tropical semi-evergreen forest 2. tropical moist deciduous forest 3. sub-tropical forest 4. wet temperate forest and 5. sub-alpine forest (over 3000 m a.s.l.). Details of the forest types with dominant plant species are described in the supplementary information.

3. Methods

3.1. Pollen sampling, extraction and study

The modern pollen dataset used here consists of a total number of 73 surface samples from 25 sites along an elevation range c. 130–3600 m a.s.l. covering all the above-mentioned vegetation