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Lateral variations in vegetation in the Himalaya since the Miocene and implications for climate evolution

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ABSTRACT

The Himalaya has a major influence on global and regional climate, in particular on the Asian monsoon system. The foreland basin of the Himalaya contains a record of tectonics and paleoclimate since the Miocene. Previous work on the evolution of vegetation and climate has focused on the central and western Himalaya, where a shift from C3 to C4 vegetation has been observed at ∼7 Ma and linked to increased seasonality, but the climatic evolution of the eastern part of the orogen is less well understood. In order to track vegetation as a marker of monsoon intensity and seasonality, we analyzed δ^{13}C and δ^{18}O values of soil carbonate and associated δ^{13}C values of bulk organic carbon from previously dated sedimentary sections exposing the syn-orogenic detrital Dharamsala and Siwalik Groups in the west, and, for the first time, the Siwalik Group in the east of the Himalayan foreland basin. Sedimentary records span from 20 to 1 Myr in the west (Joginder Nagar, Jawalamukhi, and Haripur Kolar sections) and from 13 to 1 Myr in the east (Kameng section), respectively. The presence of soil carbonate in the west and its absence in the east is a first indication of long-term lateral climatic variation, as soil carbonate requires seasonally arid conditions to develop. δ^{13}C values in soil carbonate show a shift from around −10‰ to −2‰ at ∼7 Ma in the west, which is confirmed by δ^{13}C analyses on bulk organic carbon that show a shift from around −23‰ to −19‰ at the same time. Such a shift in isotopic values is likely to be associated with a change from C3 to C4 vegetation. In contrast, δ^{13}C values of bulk organic carbon remain at ∼ − 23‰ in the east. Thus, our data show that the current east–west variation in climate was established at 7 Ma. We propose that the regional change towards a more seasonal climate in the west is linked to a decrease of the influence of the Westerlies, delivering less winter precipitation to the western Himalaya, while the east remained annually humid due to its proximity to the monsoonal moisture source.

1. Introduction

The Himalayan belt has a major influence on global and regional climate, by acting as an orographic barrier for air masses and humidity (Boos and Kuang, 2010; Molnar et al., 2010). Modern climate shows significant east–west variation in the Himalaya: both mean-annual and winter precipitation on the plains and foothills are higher in the east, while the west is characterized by more pronounced winter aridity (Fig. 1; Bookhagen and Burbank, 2006, 2010). This variation is due to the two major atmospheric circulation systems influencing the climate of the Himalayan region: the Indian Summer Monsoon (ISM) and the Westerlies (Kotlia et al., 2015). The ISM takes up moisture in the Bay of Bengal and transports it towards the Himalaya during the northern-hemisphere summer months (e.g., Molnar et al., 2010), whereas the Westerlies bring moisture from the Mediterranean, Black and Caspian Seas and are most efficient in winter (Benn and Owen, 1998; Cannon et al., 2015). Generally, the influence of the Westerlies is greater in the western part of the Himalayan region (Cannon et al., 2015; Caves et al., 2015; Kotlia et al., 2015). The proximity to the moisture source in the Bay of Bengal makes the eastern Himalaya very humid (Bookhagen and Burbank, 2010).

These lateral variations in modern climate are linked to vegetation patterns, in particular the relative importance of C3 versus C4

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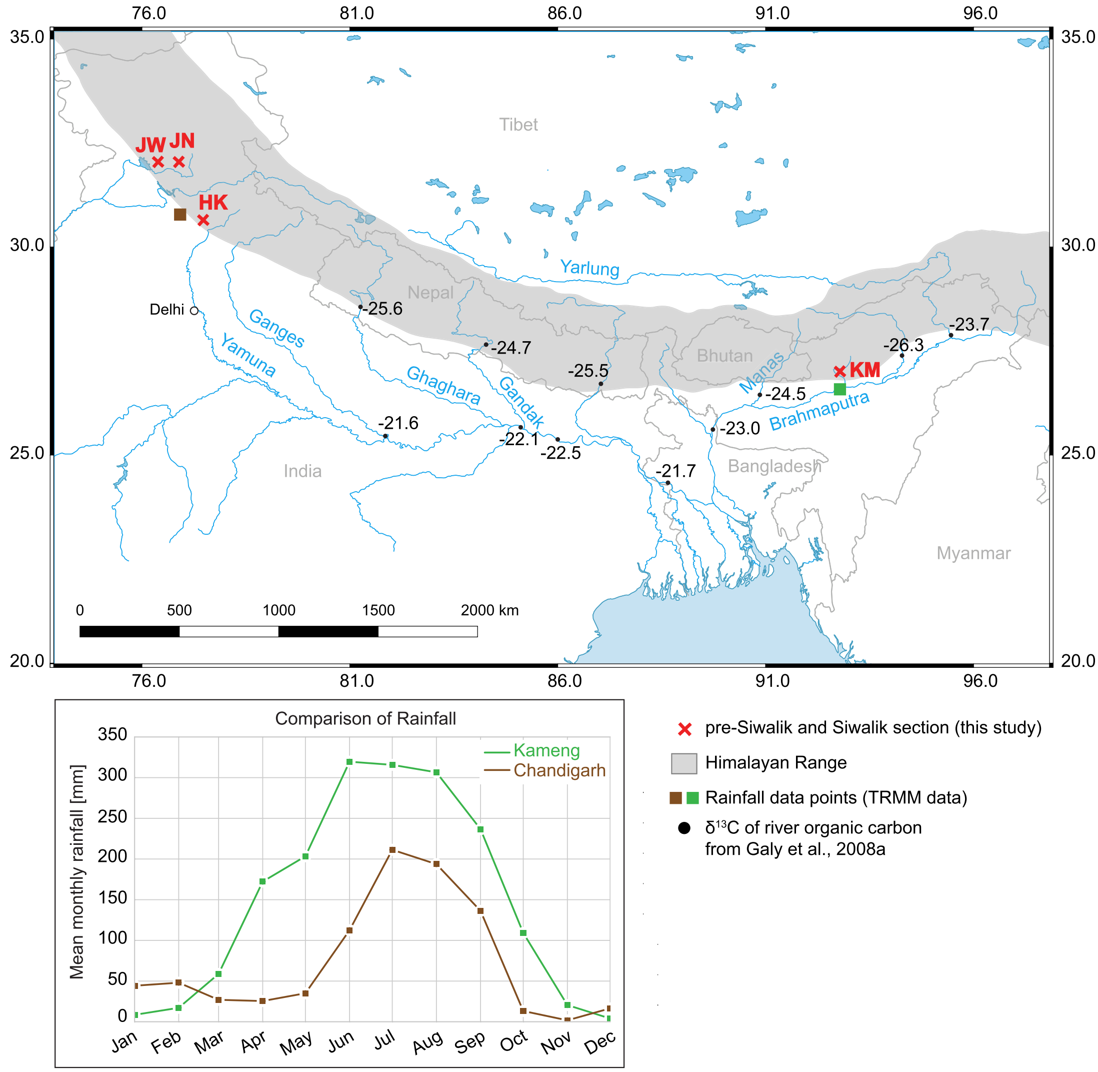

Fig. 1. Map of the Himalayan region, with δ^{13}C of modern river organic carbon from Galy et al., 2008a. The Himalayan range is indicated schematically in grey. Sections are indicated in red: JW: Jawalamukhi; JN: Joginder Nagar; HK: Haripur Kolar; KM: Kameng. Lower plot shows comparison of modern annual precipitation data (TRMM) in proximity to the sampled sedimentary sections in the west and east. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

plants. C3 plants are favored in a cool and humid climate, whereas C4 plants prefer intense light, warm and water-stressed conditions (Ehleringer, 1988). Thus, growing-season temperature and precipitation appear to be important factors influencing the evolution of C4 plants (Cotton et al., 2016). The distinct stable carbon-isotopic signature of C3 versus C4 vegetation allows paleo-vegetation to be tracked from the sedimentary record: pure C3 vegetation has $\delta^{13}C_{org}$ values between $-22‰$ and $-30‰$, whereas $\delta^{13}C_{org}$ values of C4 plants range from $-10‰$ to $-14‰$ (Cerling et al., 1997). The lateral variations in modern climate and vegetation are expressed by the signature of modern organic carbon transported in the foreland (Galy et al., 2008a; Fig. 1): sediments sampled from Himalayan tributaries at the mountain front have $\delta^{13}C_{org}$ values around $-25‰$, indicating dominance of C3 plants at higher elevations within the mountain belt. These values remain stable within the eastern Brahmaputra catchment, whereas they increase to values around $-22‰$ in the Western Ganga catchment (Fig. 1), implying laterally varying vegetation (from C4 in the west to C3 in the east) in the floodplain.

An important question is when and why the modern spatial patterns in climate and vegetation were established in the Himalayan foreland. The onset of the ISM is dated back to at least the middle Miocene (Dettman et al., 2001) and possibly the Late Eocene (Licht et al., 2014). Likewise, the Westerlies have been argued to influence Asian climate since the Eocene (Caves et al., 2015). However, the evolution of regional climate and vegetation patterns will depend on the relative strength of these two systems through time, which remains largely unknown.

The foreland basin of the Himalaya contains a sedimentary record of vegetation and paleoclimate since Miocene times, within the continental detrital pre-Siwalik and Siwalik Groups. The record of spatial and temporal variations in vegetation holds information on climate evolution, in particular patterns of atmospheric circulation, seasonality and the origin and transport of humidity (Hoorn et al., 2000; Sanyal et al., 2004; Gupta 2010, amongst others). Carbon and oxygen isotopic compositions of soil carbonates and soil organic matter from pre-Siwalik and Siwalik sediments in Nepal, Northwest India and Pakistan have been used to reconstruct changes in vegetation and climate during the Neogene (Quade et al., 1989, 1995a; Quade and Cerling, 1995; Sanyal et al., 2010; Singh et al., 2013). These records consistently show a shift in δ^{13}C values at ~7 Ma, which has been interpreted as a change from C3 to C4 vegetation, which was initially interpreted to be related to an intensification of the ISM (Quade et al., 1989). Steinke et al. (2010) suggest that this change was rather linked to an increase in aridity, and therefore a weakening of the ISM. A similar shift