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Leaf physiognomy records the Miocene intensification of the South Asia Monsoon

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A B S T R A C T

Our understanding regarding the onset and development of the modern South Asia monsoon (SAM) is still incomplete due to its complex nature and differing views about its relationship with major orographic features such as the Himalaya and Tibetan Plateau. Climate data derived from some terrestrial and marine sediments from the Neogene suggests the onset and intensification of the SAM to a near-modern state occurred during the Miocene, while modelling and other terrestrial proxies point to a much earlier origin for the proto-East Asia monsoon (EAM) and proto-SAM. Angiosperm leaves, particularly dicot leaves, provide a good indication of prevailing climatic conditions as a result of key adaptations in their leaf structure. Here we use Climate Leaf Analysis Multivariate Program (CLAMP) in conjunction with general circulation models to decode the Lower (~13–11 Ma) and Middle (9.5–6.8 Ma) Siwalik climate signal inherent in the physiognomy of fossil leaves. The reconstructed climate data indicates that the Middle Siwalik was warmer and wetter than the Lower Siwalik, particularly in the cooler part the year. The leaf physiognomy of Lower and Middle Siwalik assemblages is indistinguishable to that of the modern leaf assemblages, which are influenced by today's SAM climate. This shows that the SAM was already well established as an independent domain during the late middle Miocene (~13–11 Ma) and has remained nearly the same from the perspective of leaf adaptations since then. A quantitative monsoon intensity index indicates an intensified monsoon during the late Miocene (9.5–6.8 Ma), a finding replicated by climate modelling.

1. Introduction

Globally, monsoonal climates today encircle the low latitudes and can be subdivided according to their location and individual characteristics into the South Asia Monsoon (SAM), Western North Pacific Monsoon (WNPM), East Asian Monsoon (EAM), Indonesia-Australian Monsoon (I-AM), North American Monsoon (NAmM), South American Monsoon (SAmM), North African Monsoon (NAfM) and South African Monsoon (SAfM) (Yim et al., 2014; Wang et al., 2017) (Fig. 1). In simple terms, the monsoon is defined by seasonal reversals of surface winds, but these reversals are often associated with distinct rainy summers and dry winter seasons (Webster, 1987; Wang et al., 2017). Of the eight regional monsoons listed previously, those that affect Asia, the SAM, EAM and WNPM (Wang et al., 2017), collectively form the Asia Monsoon System (AMS), which is the largest and strongest monsoon system in existence. The SAM and EAM are continental monsoons, while WNPM is an oceanic monsoon (Wang et al., 2017).

Predicting the future characteristics of this AMS is complex (Goswami and Krishnan, 2013; Wang et al., 2015) yet vitally important because the AMS supports the lives and livelihoods of millions of people in Asia (Gadgil and Rupa, 2006). To better understand the complex future behaviour of the modern AMS we have to understand its evolution, and tease out its underlying mechanisms and dynamics in deep time. A range of studies using different approaches have been undertaken to try and understand the evolution of the AMS (Quade et al., 1989; Prell et al., 1992; Dettman et al., 2001; Zhisheng et al., 2001;

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