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Evolution of the South Asian monsoon wind system since the late Middle Miocene

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ABSTRACT

The evolution and timing of the inception of the South Asian monsoon (SAM) has been one of the most debated climatic mysteries amongst climate workers. The Himalaya–Tibetan plateau (HTP) complex has been implicated as the main driver for SAM circulation. However, there are intense debates as to whether there was a critical elevation of the HTP complex that drove the SAM and at what time such a critical elevation was attained. Also, the role of the HTP complex in driving the SAM has been questioned in recent climate model studies. The model simulation suggests a major intensification of the SAM as early as ~30 Ma, whereas marine records from the Arabian Sea indicate a major strengthening of the South Asian summer or southwest monsoon winds between 10 and 8 Ma. The continental vegetation, on the other hand, captured a major transition from C_3 to C_4 type during 8–7 Ma but whether this change was local or global and whether this transition was driven by monsoonal precipitation is not unanimously accepted. Our new record from Ocean Drilling Program holes located off the Oman margin and on the Owen Ridge, western Arabian Sea shows appearance of monsoon wind proxy planktic foraminifer *Globigerina bulloides*, a significant increase in total organic carbon, and a negative shift in stable carbon isotope record of benthic foraminifera at ~12.9 Ma. These proxies indicate that present day South Asian monsoon wind system began to develop during the late Middle Miocene (~12.9 Ma) and summer monsoon was in its full strength in the late Miocene (~7 Ma). From 11 to 7 Ma, the summer monsoon was weaker when winter monsoon was stronger.

1. Introduction

Generally, in South Asia the term monsoon refers to the rains during the summer period, although mariners usually attach the meaning of the monsoon with winds (Cadet, 1979). The agricultural and drinking water needs of the South Asian region largely depend on South Asian summer monsoon precipitation. For instance, nearly 80% of India's total annual rainfall is received during the summer or southwest (SW) monsoon season (June–September) which is the main component of the annual rainfall in the country (Parthasarathy, 1960). The South Asian summer monsoon is an important conveyor of interhemispheric exchange of energy and moisture (Clift and Plumb, 2008; Denton et al., 2010).

Monsoon inception in South Asia, the sudden arrival of rainy season after a period of hot and dry weather, has been an age-old mystery in the geophysical dynamics of the tropical meteorology (Chao, 2000). Normally, the SW monsoon moist winds touch the India's western shore by May 31st or June 1st every year owing to sudden changes in the lower troposphere over the Indian Ocean that intensify the southeast (SE) trade winds leading to the establishment of cross-equatorial flow of trade winds and resultant low-level Somali or Findlater jet (Fieux and Stommel, 1977) (Fig. 1). The Findlater jet and cross-equatorial transport of the SE trade winds strengthen the summer monsoon circulation (Findlater, 1969). The SE trade winds are drawn by the continental low pressure zone located over Central India and get deflected by the Coriolis force after crossing over the Equator, giving rise to the SW monsoon and associated precipitation (Cadet and Desbois, 1979).

The Findlater jet drives maximum cross-equatorial moisture transport along the Somali (East African) coast (Cadet, 1979) that may modulate summer precipitation over India since a correlation has been observed between the strength of the Findlater jet and amount of rainfall over the western coast of the Indian landmass (Findlater, 1969). Due to the Coriolis force, water is piled up to the south of the Findlater jet (deep thermocline) but upwells to the north of it (shallow thermocline) (Cadet, 1979). The cross equatorial winds are stronger during a good monsoon year than during a weak one (Cadet and Desbois, 1979). The cross-equatorial flow is established within a few days as a result of a rapid increase in the wind speeds of the Findlater jet leading to the abrupt onset of the South Asian summer monsoon (Fieux and

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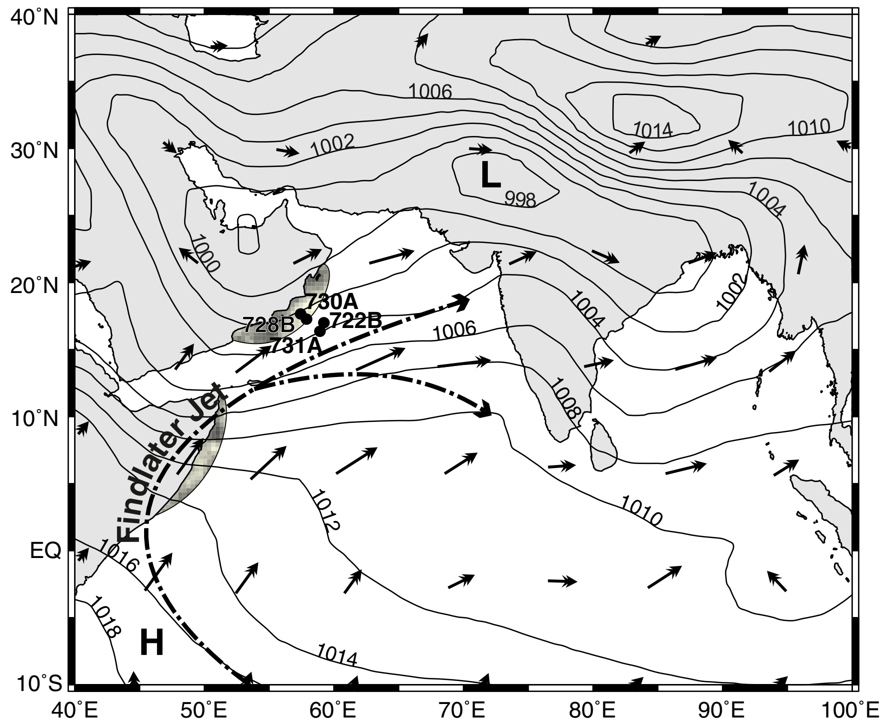

Fig. 1. July 2014 sea-level pressure (mbar, thin contours), wind direction, cooling of the Arabian Sea due to upwelling (dark shades off Oman and Somali coasts). Location of ODP Sites 722, 728, 730 and 731, off Oman margin and on Owen Ridge (black circles). H, high pressure; L, low pressure. (Source: NOAA-NCEP).

Stommel, 1977). The speed of the Findlater jet is closely related to the strength of the Southeast Trade winds (Fieux and Stommel, 1977). Average jet speed over a period of 27 years indicates complete development of the Findlater jet in less than two weeks (Boos and Emanuel, 2009). The South Asian monsoon (SAM) is therefore a unique inter-hemispheric atmospheric feature of both societal and academic importance.

In the geological record, the inception and development of the SAM system brought major changes in the fauna, flora and sedimentation in the region during the Miocene (Quade et al., 1989; Badgley et al., 2008). Numerous studies have highlighted the potential importance of this major climatic event on global climates (France-Lanord and Derry, 1994). The Miocene onset or intensification of the SAM has been linked to the phased uplift of the HTP complex (Zhisheng et al., 2001), uplift of HTP combined with Antarctic glaciations and global climate changes (Gupta et al., 2004), as well as movement of the Inter Tropical Convergence Zone (ITCZ) with respect to the Indian Plate (Armstrong and Allen, 2011). Several studies fix the timing of monsoon intensification between 30 and 7 Ma (Quade et al., 1989; Ramstein et al., 1997; Fluteau et al., 1999; Clift and Gaedicke, 2002; Spicer et al., 2003; Gupta et al., 2004; Rowley and Currie, 2006; Clift et al., 2008), although a few records suggest major intensification of the SAM at roughly the same time as the "biogenic bloom" during the late Miocene (Chen et al., 2003; Gupta et al., 2004).

The sedimentation rate dropped, while the clay mineralogy shifted to the smectite–kaolinite assemblage at all the holes of ODP Leg 116 at ~7 Ma indicating a warmer and more humid climate with increased chemical weathering (France-Lanord et al., 1993). The Sr flux to the Bay of Bengal also decreased at ~7 Ma resulting from declining erosion rates in the Himalaya (Derry and France-Lanord, 1996). A decrease in sedimentation rate at ~7 Ma was related to increased vegetation and/or a period of tectonic quiescence in the Himalaya. Alternatively, the sediments were stored in the Siwaliks (France-Lanord et al., 1993). A marked vegetation change took place in the Nepal Himalaya during 8–6.5 Ma, characterized by a replacement of subtropical and temperate vegetation by pioneering grasslands (Hoorn et al., 2000). There was a major setback to the frugivorous and browsing mammals in the Siwaliks across this climatic transition (Badgley et al., 2008).

However, some of these earlier observations have been challenged by the later studies. For example, recent study of $\delta^{18}O$ from pedogenic carbonates and mammalian teeth suggests an increase in temperature, a decrease in precipitation since ~9 Ma, which have been related to the onset of the SAM (Quade and Cerling, 1995; Badgley et al., 2008). The late Miocene vegetational transition represents a change from a wet monsoonal forest before 8.5 Ma to a dry monsoonal forest at 7 Ma to savannah at 6 Ma (Badgley et al., 2008). Carbon isotopic profiles of mammalian faunas also document this shift in vegetation during the late Miocene. These propositions are in contrast to the earlier interpretations implicating vegetational change from C_3 to C_4 to wetter conditions in the late Miocene (Quade et al., 1989). Changes in $\delta^{18}O$ values of equid tooth profiles from the Siwaliks indicate a substantial decrease of annual rainfall during 10–6.3 Ma (Nelson, 2005). Environmental and vegetational changes from dominant C_3 to dominant C_4 are not restricted to Asia (Steinke et al., 2010). Globally, various regions of the world experienced major changes in the late Miocene. C_4 grasslands were spreading in the Americas and Africa, indicating a global trend toward drier conditions during the late Miocene (e.g., Cerling et al., 1997; Keeley and Rundel, 2005; Badgley et al., 2008). Hay et al. (2002) suggested that expansion of C_4 grasslands has changed hydrological cycle and atmospheric transport mechanisms in the late Miocene.

In recent years, questions have been raised about the timing of the origin, character and evolution of the present day SAM in the geological past (e.g., Quade et al., 1989; Kroon et al., 1991; Gupta et al., 2004; Huang et al., 2007; Clift et al., 2008). As for the East Asian monsoon (EAM), a consensus is emerging to place its origin in the early Miocene (Sun and Wang, 2005; Clift et al., 2008), yet there is no unanimity on the timing of inception of the SAM. Evolution of the SAM has long been related to the uplift of the Himalaya–Tibetan plateau (HTP) complex as elevated heat source of the Himalaya and the Tibetan plateau is believed to be vital for the establishment and maintenance of the Indian summer monsoon circulation through mechanical and thermal factors (Molnar et al., 1993). However, there are debates as to whether there is any