

Asian Monsoon Variability, Cyclicities, and Forcing Mechanisms

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Introduction

The summer monsoon is the dominant climatic feature of the Indian Ocean tropics and the adjacent continent. Boreal summer is characterized by high solar radiation that causes intense sensible and latent heating over northern India and Tibet Plateau. This pattern of heating causes ascending air flow and the development of an intense low pressure cell that is centered over Asia around 30°N (Figure 1). The atmospheric pressure gradient between the Asian Continent and the cooler southern Indian Ocean induces large scale meridional overturning with the lower circulation limb being the strong low-level southwesterly summer monsoon winds of the western Indian Ocean. The convergence of these air masses and their uplift due to heating and orographic steering cause seasonal monsoon rains (Figure 2). By contrast, the winter season of the Asian sector is characterized by low solar radiation, cold temperature, and northeasterly winds, which flow from the cold Asian continent towards the Arabian Sea. These continental winter monsoon winds carry little moisture and have relatively low velocity. Monsoon rainfall in India is highly variable. The northeastern region, the western slopes of the Western Ghats and parts of the Himalayas have very high rainfall of around 2000mm annually. The eastern part of the peninsula extending up to northern plain receive around 1000 to 2000mm rainfall, while the area from western Deccan up to the Punjab plain gets around 100mm to 500mm rainfall. Thus the unique monsoon circulation in the Indian Ocean and associated rainfall over Asia thus has a fundamental impact on two aspects: i) socio-economic and agricultural development in the densely populated Asian countries and, ii) the biogeochemistry of the Indian Ocean sediments.

Evolution of Asian Monsoon

To track the evolution and variability of monsoon beyond the historical times one needs to depend the monsoon proxy records which are preserved in the marine and terrestrial records. Here emphasis will be laid on the monsoon reconstructions mainly based on the marine proxies.

Long-term variations of proxies of monsoonal intensity tracers, especially the species diversity of calcareous nannofossil species, and the abundance of the planktonic foraminifera *Globigerina bulloides* and the radiolarian *Actinomma* spp. (upwelling indicators) show that the evolution of the Asian monsoon started in the late Miocene, at about 9.5Ma (million years ago).

Between 9.5 and 5Ma the monsoon increased noticeably in strength, with smaller fluctuations in monsoonal intensity from 5 to 2Ma. Uplift of the Himalayas and the Tibetan Plateau occurred coeval with the increase in strength of the Asian Monsoon between 9.5 and 5Ma.

Variability of monsoon on glacial and interglacial time scale

Multi proxy based monsoon variability from the western Arabian Sea reveal that in general monsoons were stronger during interglacials (warm periods) and weaker during glacial period (cold periods) (Fig.3). Scientific consensus exist that most of the monsoon variability during glacial and interglacial were caused due to Earth's orbital parameter changes. However, high-resolution studies on monsoon variability questions the linear linkages between monsoon and insolation changes caused due to Earth's orbital changes and proposed that air temperature changes in the Arctic and Greenland play an important role in controlling the monsoon variability.

Variability of Monsoon during Holocene

After a weak summer monsoon activity during the last glacial maximum, the initiation of strengthening monsoon activity began around 15 kyr which coincides with the northern hemisphere deglaciation. Monsoon activity further increased from 12000 years BP and reached maximum intensity between 9000 and 6000 years BP. Thereafter, it decreased from 5000 to 1200 years BP (Fig. 4). As a consequence strong monsoon rainfall the out flow of the rivers draining the Himalayan Mountains increased at the end of the deglaciation, and it was larger than today during the lower and mid Holocene. About $5 \times 10^{12} \text{m}^3$ of sediment was deposited in the Bengal Basin from 11,000 to 7000 years BP when the southwest monsoon was strong. Further more the development of Ganges-Brahmaputra River Delta began 11,000 years BP, when rising sea level flooded the Bengal Basin, thereby trapping most of the river discharge on the inner margin.

Ultra high-resolution record of monsoon variability during the time span of 1000 years reveals that monsoon wind strength increased during the past four centuries as the northern hemisphere warmed. This suggests that the warming trend may directly affect the monsoon and the observed link between Eurasian snow cover and the southwest monsoon persists on a centennial scale.

Cyclicality of Monsoon

Paleomonsoon records show periodicity of SW monsoon at 100, 41 and 23 kyr corresponding to Earth's orbital changes of Eccentricity, Obliquity and Precession, respectively. In addition, high-resolution monsoon variability exhibit sub-orbital periodicities of 2200, 1700, 1500, and 775 years. The cross spectral analyses between the orbital parameters and monsoon proxies demonstrate varying degree of coherence. Strong coherencies are recorded over the precession band (23 kyr), moderately strong coherencies are recorded over the obliquity band (41 kyr), and moderate to weak coherencies are recorded over Eeelectricity band (100 kyr).

Forcing Mechanism of Monsoon

Much of the variability occurs at orbital periodicities, and all of the paleoclimatic time series show maximum intensity of monsoon that occur during

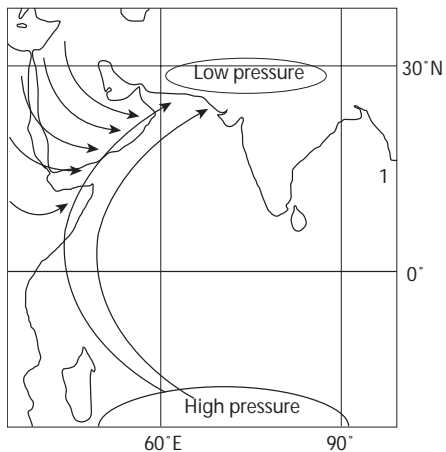


Fig.1. Atmospheric circulation during northern hemisphere summer

interglacials and coincide with precession maxima and maxima of northern hemisphere summer radiation.. During glacial conditions, paleoclimatic records are less distinct and show more individual monsoon variability. Such pattern of monsoon variability on glacial and interglacial time scales appears to be driven by orbital variations of Earth in association with albedo changes in the Tibet Plateau. The synchronous changes documented between the high latitude climate and Indian Ocean monsoon records at millennial time scale poses new challenge to address the monsoon variability issue. However, it is not clear yet whether monsoon triggers the high latitude changes or high latitude air temperature changes initiates monsoon changes in the tropics.



Figure 2. Pattern of rainfall during peak summer monsoon in the Western Ghats of India

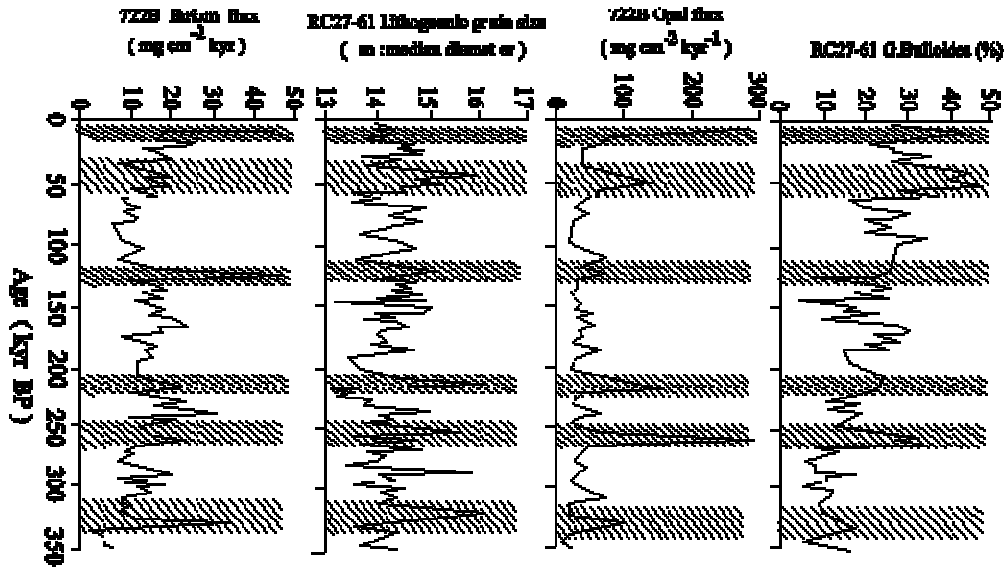


Fig. 3. Multi proxy monsoon reconstructions show that summer monsoon strength was stronger during interglacials (shaded intervals) as compared to glacials

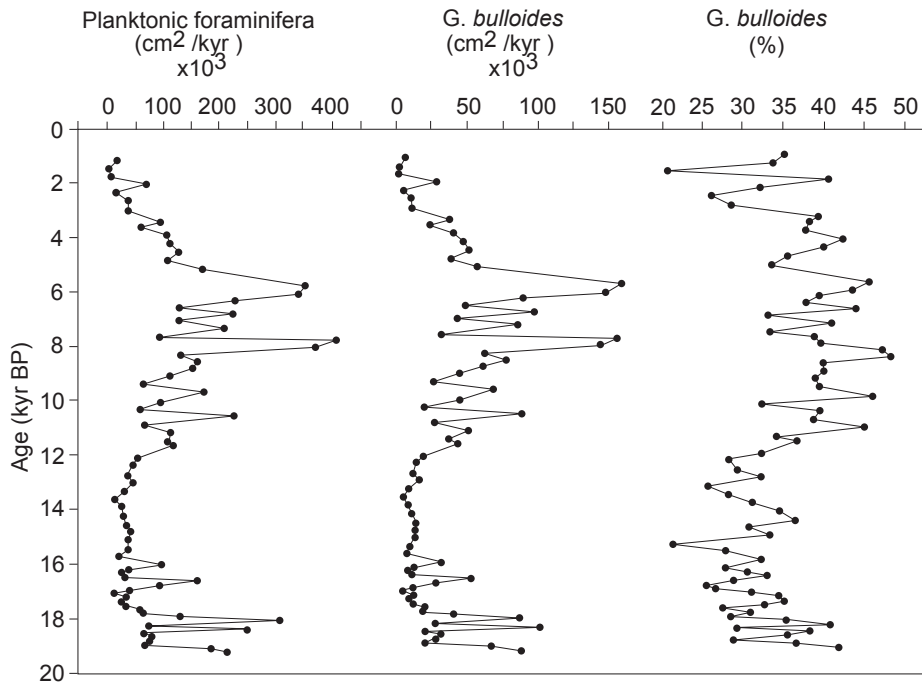


Fig. 4. Variability of monsoon during last glaciation and Holocene