Past and the Present Climate of India

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Abstract

The Indian monsoon, which comprises the seasonal reversal of winds and implies rainfall on land, is a complex system. Given that the national economy depends critically on monsoon, its rigorous understanding it warranted. We trace here the geological history of monsoon and the present trends of its performance. The monsoon as it is now is about 10–8 Ma old. It has fluctuated around a mean value at all timescales due to the response of causative factors to various global forcings—the dominant being the Sun-Earth geometry and consequent asymmetric heating of land versus oceans. Whereas most regions show analogous responses to global forcings, significant spatial heterogeneities are seen on shorter timescales. Instrumental data suggest general weakening of monsoon system and at the same time an increase in extreme events. A broad brush scenario of the monsoon and its variability through geological time is presented.

Keywords

Monsoon • Droughts • Floods • El Niño • Geological records • Proxies • Marine records • Long-term trends

1 Introduction

The climate of the Indian subcontinent is dominated by the monsoons which are pronounced seasonal reversals of winds and transitions from drier to wetter regimes. During the summers, the southwesterly winds pick moisture from the northern Indian Ocean and drop this on the landmass, providing the summer rainfall that is critical to the survival of the Indian society and its economy. The winter winds blow from the northeast regions of the Asian continent and travel towards the Indian Ocean. This annual cycle of atmospheric circulation arises from interactions of the seasonal changes in solar insolation with the land-ocean distribution such that variations in the thermal fluxes produce differential warming between the land and the sea, leading to development of convective cells and consequent moisture transport and deposition (i.e. rain), inland.

The food grain production of India has a proportional relationship to the monsoon, with its critical dependence on the onset, duration and distribution of rainfall and the periods of break monsoon conditions. While the present monsoonal conditions are tracked using variety of instruments, its past history is studied using geological archives. Studies on the monsoon using such geological archives and instrumental record have now established the following (Singhvi and Kale 2009; Singhvi et al. 2010, 2012):

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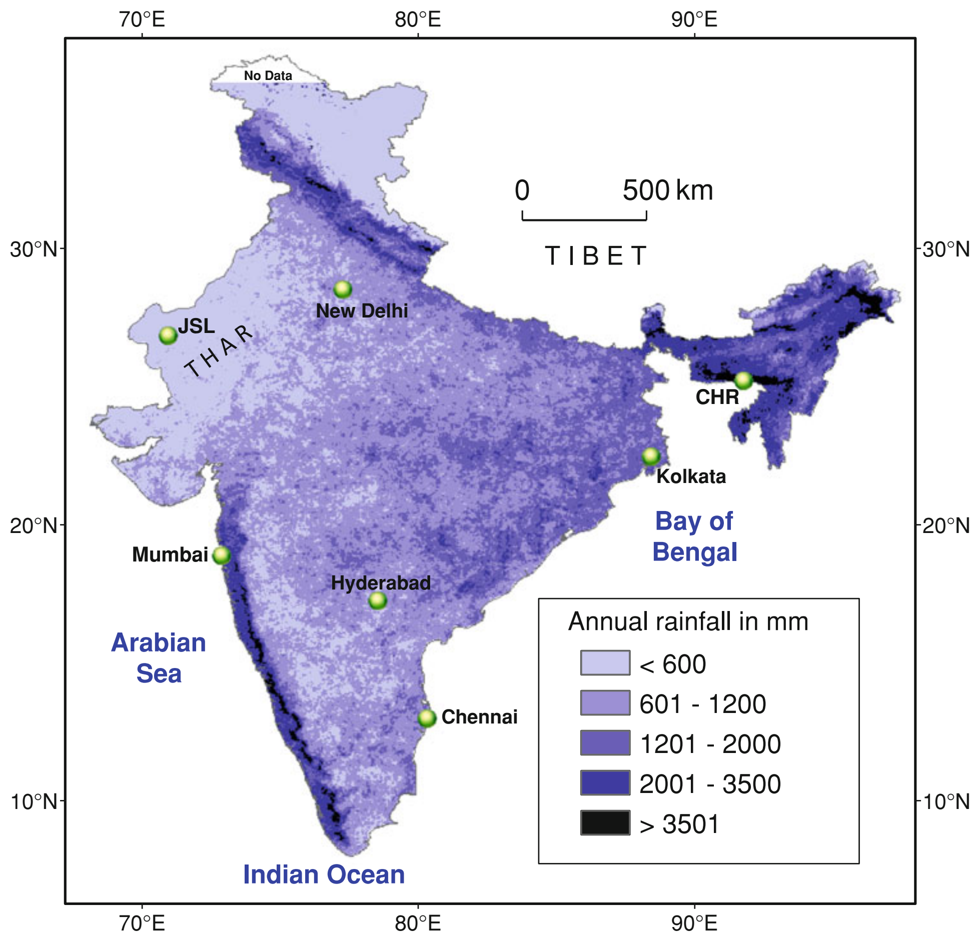

Fig. 1 Spatial distribution of annual rainfall over India. Two sites with extreme rainfall are Jaisalmer (JSL) and Mawsynram, near Cherrapunji (CHR). Average annual precipitation from TRMM satellite (*Data source* http://www.geog.ucsb.edu/~bodo/TRMM/)

1. As per the Climate Profile of India, published by the India Meteorological Department, the mean southwest monsoon (June, July, August and September) rainfall is 877.2 mm, which is about 74.2 % of annual rainfall (1,182.8 mm).
2. Monsoon is a stable atmospheric system, has never failed totally and has fluctuated around a mean southwest monsoon value of ~877 mm by about 20–30 %.
3. Significant spatial and temporal variability in monsoon rainfall exists (Figs. 1 and 2). However, the amount, intensity and distribution of rain through a season are highly variable. It is this variability that causes droughts and floods. Thus, in a region, 20–30 % lower rainfall implies drought and as much higher rainfall may imply floods. The long-term average of rainfall, however, remains nearly constant (Fig. 2).
4. The rainfall is spatially variable with the lowest average annual rainfall being ~130 mm at Jaisalmer and highest average annual rainfall being 11,410 mm at Mawsynrum (near Cherrapunji) in Meghalaya (Fig. 1). Despite this variability, it is expected that over a long term, the monsoon across the regions should have fluctuated analogously around their local means. Much of the moisture is derived from the oceans, particularly the Bay of Bengal, and is due to its thermal stratification with critical sea surface temperature for monsoon to establish being ~28 °C. The Arabian Sea being well mixed by

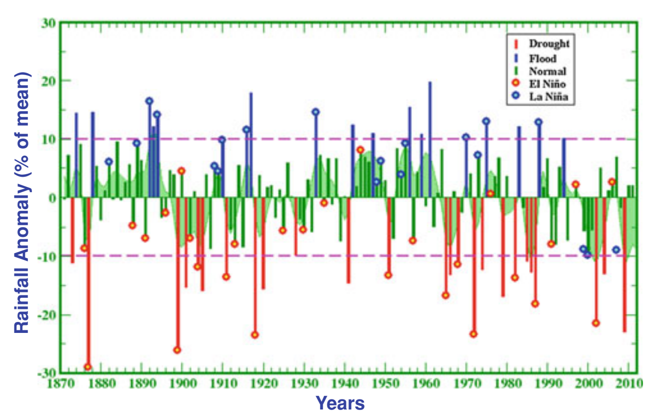

Fig. 2 Time-series of all-India summer monsoon rainfall anomalies expressed as percentage departure from normal for the period 1871–2011, based on IITM homogeneous Indian monthly rainfall dataset (*source* http://www.tropmet.res.in). Note that several instances of monsoon droughts have co-occurred with El Niño events; and conversely several excess monsoon rainfall years have co-occurred with La Niña events in the Pacific

wind fields has cooler waters and, hence, with the exception of western regions, it does not contribute much to the precipitation over the entire subcontinent.

5. Several factors, such as the Sun-Earth geometry, the condition in the North Atlantic Ocean, extent of snow cover in Eurasia, vegetation change, El Niño Southern Oscillation (ENSO), etc. contribute to rainfall in a given season, but an estimation of their exact influence and its long-term stability is difficult. The current rainfall forecast models use the following parameters; (i) NW Europe land surface temperature, (ii) Equatorial Pacific warm water volume, (iii) north Atlantic sea surface temperature, (iv) east Asian mean sea level atmospheric pressure, (v) central Pacific sea surface temperature, (vi) north Atlantic mean sea level atmospheric pressure, and (vii) north central Pacific winds, with statistically determined weightage for each of these (Kelkar 2009). Dependence of monsoon system on these parameters is not constant through time. Statistical considerations suggest that the predictability of monsoon system is 50 %, at the most. Thus, although good predictability is needed for water resources and agriculture, the prediction of key parameters like onset of rainfall, duration and intensity cannot be predicted with desired accuracy (Kelkar 2009).

This chapter reviews the present understanding of monsoon through geological time including the instrumental record. Direct measurement of rain and temperatures using instruments is ~150 year old. The pre-instrumental record of monsoon is deduced from geological archives such as tree rings, corals, speleothems, peat deposits, sediments from lakes, dunes, sedimentological character and style of deposition of sediments by rivers, sediments in lagoons and mangrove and their pollens, phytoliths, diatoms, geochemical changes, changes in isotopic ratios in specific fractions in them and, foraminifera from marine sediments. Being reconstructions, the geological records of monsoon are generally qualitative. Some efforts towards more quantitative reconstruction using annually laid archives, such as tree rings, have been made using statistical correlations of measured rainfall or temperature records and tree ring parameters. Each of the geological proxies records signatures of climate and monsoon signal in its distinctive manner and rate and this aspect has to be understood before interpreting them reliably. Sediment deposition on the land itself betrays a complex relationship of the rainfall and winds with endogenic processes like tectonics and, a proper care is needed in their interpretation. The response time to any given climate forcing is proxy dependent and the response time of proxies may range from being near instantaneous to millennia or even longer. This makes the interpretation and correlation of proxy records a non-trivial exercise (Singhvi et al. 2010).

2 Monsoon from Geological Records

Reconstruction of monsoon has been based on both the ocean and land based records. Preservation and issues arising from post-depositional diagenesis have implied that older Miocene to Quaternary records of climate are mostly available from ocean cores, whilst the younger records from the Quaternary are available both from the oceans and from land.

Changes in foraminiferal assemblages and their isotopic ratios in ocean bottom sediments, sedimentology and other attributes, provide a proxy for the monsoon winds and consequent changes in water masses due to wind induced upwelling. The land records on the other hand present a direct record of rainfall and associated changes in sediment production, transport, delivery and preservation. Such reconstructions use response of organic or inorganic system to rainfall. Sediment cores from the Bay of Bengal, the Indian Ocean and the Arabian Sea have provided records of changes in monsoon winds and water masses including sediment fluxes from rivers.

On the land, a considerable amount of long-term, chronometrically (age) constrained database comes from the Thar Desert and its margins (Singhvi 2004), the Ganga Plains (Singh 2005), Siwaliks and high altitude lakes. Such studies also used sedimentology, pedology, isotopic analysis and field correlations of sedimentary sequences besides isotope or relative chronology. Millennial scale to shorter term records have been reconstructed using sediments from rivers and lakes, chemical precipitates and tree rings across India and from ocean bottom sediments from Arabian Sea and the Bay of Bengal (Singhvi et al. 2012 and references therein).

2.1 Early History: Onset and Till 500 ka

Studies on sequences from the Vastan lignite mine near Surat in Gujarat, provided isotopic and pollen evidence of high precipitation in the tropical land mass during 56–52 Ma, the period of Paleocene-Eocene Thermal Maximum (PETM). Similar precipitation on the land must have existed even during earlier geological times. The only driving force would have been, accentuated greenhouse conditions and the temperature contrast between land and oceans. At this time period, India was far south than its present location and Himalaya was almost not even in existence (Samanta et al. 2013).

Establishment/intensification of present day Indian monsoon has been variously placed between 23 and 7 Ma, based on the type of evidence being examined and the age resolution of the archive. The exact origin of present monsoon is debated and suggestions range from its association to the rise of Tibet and Himalaya (to a height sufficient enough to block moisture laden winds), to its being a natural consequence of land-sea temperature contrasts. Differential heating of Tibetan Plateau and Bay of Bengal is considered as one of the driving mechanisms of the Indian Monsoon. A variety of marine records ranging from changes in sediment fluxes into the Bengal and the Indus Fans; foraminiferal abundances, and others indicate that the erosion of the Himalaya due to monsoon rain possibly began at around mid to late Miocene i.e. 10–8 Ma. The sediment records from Siwalik foreland basin and carbon isotope ratios provide a record of changes from tree dominated to grass dominated ecology around 7.5 Ma, which could have happened with the initiation of monsoon. Records from Arabian Sea using the foraminifer *G. Bulloides* suggest the initiation of upwelling around 8.5 Ma and this is also seen in the atmospheric modeling studies which place initiation of monsoon sometime during 10–8 Ma. The sediment transported by Luni River in western India varied from gravel bedload to sandbed stream to sheet flow, interspersed by deposition of aeolian sands and reflected changes in the river flow regime which in turn was related to monsoon rainfall. The gravel deposits had an estimated age bracket of late Miocene-Pliocene (~7–3 Ma). Thus, multiple evidences ranging from increased upwelling to rain induced erosion of the Himalaya, etc., converge to the inference that monsoon was initiated during the period 10–8 Ma. The monsoon was also intense and this intensification has been variously ascribed to the Tibet and Himalaya attaining a critical height or to the expansion of Antarctic ice sheets. It has also been suggested that vegetation change was in response to global changes in CO_2 budget. Though the rise of Himalaya began some 40–50 Ma ago, recent studies provide evidence that Tibet attained a height of around 1 km at 3.4 Ma, and was uplifted to 3 km at around 1.67 Ma. This implies that the height of Tibet and Himalaya possibly played only a subordinate role in the strengthening of the monsoon. Thus, the jury is still out on the possible causes, but the timing of initiation seems to be reasonably well bracketed.

Post 8.5 Ma, reduced upwelling phases around 5.5 and 1 Ma, indicating reduced monsoon strength, have been reported. The intensification of winter monsoon is placed at ~2.8–2.5 Ma based on micro-paleontological studies in the eastern Indian Ocean sediments. Results from a lake in China indicate monsoon was weak during 2.78–2.27 Ma, 2.61–1.44 Ma and 0.34–0.12 Ma and strong during 2.27–2.61 Ma and 1.44–0.34 Ma. This suggested that the monsoon fluctuated on millennium timescales. We refer to Molnar et al. (1993), Quade et al. (1989), Chao and Chen (2001), Gupta et al. (2004), and Clift and Plumb (2008) for more detailed account on monsoon, its initiation and later evolution.

In the Quaternary Period, most evidence on climate/monsoon is provided by calcretes, and fluvial and aeolian sediments of the Thar Desert. Radiometric ages and isotope geochemical analysis on these deposits indicate that the desert was well watered but had high seasonality with semi-aridity between 1.5 and 0.5 Ma and then for the past 0.5 Ma, the region has experienced increasing desiccation with interludes of phases with conditions comparable to the present. The sedimentation style and later cementation of fluvial sediments of Luni River also provide clues to changes in the monsoon and evidence of increasing desiccation is seen from 500 ka onwards till the present (Singhvi 2004).

2.2 Monsoon: 500–10 ka

Very few records for the earlier part of this period are available and the density of records increases with their proximity to the present. The sedimentation style and the sedimentology of river sediments have been interpreted in terms of river discharge such that normal monsoon implies conditions similar to the present, more intense monsoon conditions and drier conditions are then defined relative to the present. The records indicate periods of fluctuating monsoon in gross alignment with global climatic changes. Thus for example, records from the sediments of Luni, Ganga and Mahi Rivers and from the accreted dunes of the Thar Desert indicate that the period 150–100 ka was a period of monsoon, similar to the present with its later part being wetter (Fig. 3). The period 100–70 ka witnessed fluctuating condition followed by drier conditions from 70–60 ka. It was in this period, that the glaciers expanded and came down to ~2600 m a.s.l. as compared to the present elevation of ~3400 m a.s.l. in Himalaya. This was due largely to higher precipitation and lower temperature. The location of moraine deposits and their radiometric ages are the records of such changes.

A general phase of more humid condition is seen during 50–30 ka in a variety of records across the region. This is seen as red soils in Gujarat and Rajasthan, presence of elephants tusk and reddened horizon in Kalpi along Yamuna River in central India, the isotopic ratios of calcretes in Thar Desert, and the foraminiferal assemblages and salinity changes in the sediments from Bay of Bengal. The Bay of Bengal records suggest rapid fluctuation in monsoon during 75–15 ka and in this period, a phase of stronger monsoon during 60–40 ka. This has been linked to an internal feedback between snow and dust accumulation over Himalaya via albedo changes.

The monsoon was significantly weaker during the last ice age that peaked at ~21.4 ka (Last Glacial Maximum or LGM), and it was re-strengthened only around 13 ka attaining its full vigor ~11 ka. This evidence accrues from ocean upwelling records using foraminiferal assemblages,

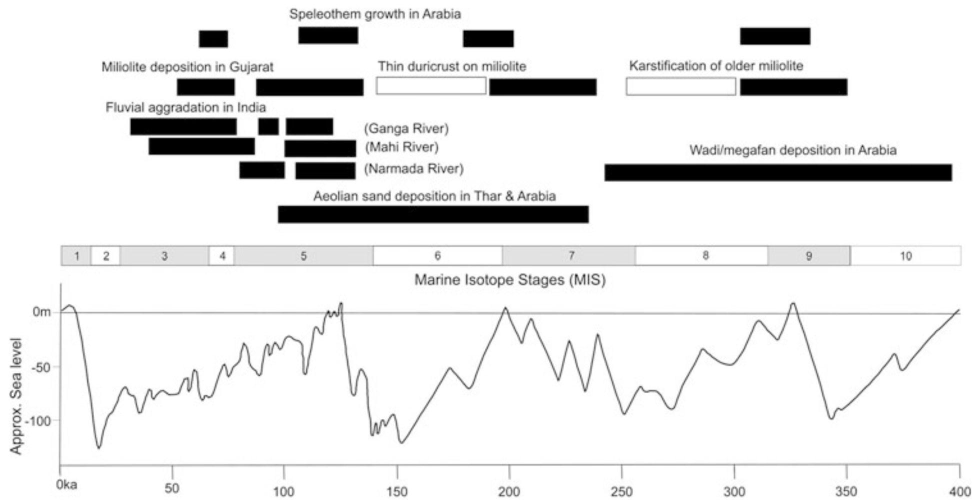

Fig. 3 Schematic of the major monsoon-controlled events during the past 500 ka. Global sea level changes and marine isotopic stages are also depicted. *Dark* and *white shades* respectively represent higher than and lower than normal monsoon. (Reproduced from Singhvi et al. 2012, with permission from Blackwell-Wiley, UK)

the trace metal records from the Arabian Sea and general absence of any geomorphic activity in the Thar Desert. During the LGM, the glaciers descended to lower elevation but the extent of descent was smaller compared to that during 70–60 ka. The descent during both time periods was due to lower temperature but at LGM still lower moisture availability implies lower amplitude of descent. Thus, despite favorable temperatures, the descent of glaciers was limited by the avalibility of precipitation. Several lines of evidence clearly suggest that the monsoon was weaker during the ice age that peaked at ~21.4 ka, the reduction in rainfall or associated winds is not yet established quantitatively. The difficulties in establishing this is compounded by a variety of factors including the presence of thresholds in each proxy. Interestingly, the desert sand from the margins of Thar Desert provides a good record of specific monsoon conditions that facilitate movement, deposition and preservation of sands over specific time windows. These time windows occur during transitional climate—from cooler to warmer. The sand accretion in Thar Desert is controlled by both wind and rain (i.e. vegetation limited) and its accretion followed by preservation occurs only over a short time window that occurs during a transitional regime from dry to wetter. The most recent window occurred around ~13 ka, when as per the oceanic records, the monsoon was re-establishing and the dune accretion and preservation across Thar was optimum. Summer winds (linked to southwest monsoon) were strong enough to move the sands and the moisture/vegetation was sufficient to trap the sand resulting in accretion. Prior to this window, the winds were weaker and moisture was absent to trap the sands, and after this window the vegetation was denser so that despite stronger winds associated with monsoon, sand migration did not occur. Extending this analogy to other episodes of regionally extended dune accretion in Thar, it is suggested that conditions of monsoon winds and rain that existed at around 13 ka should have also existed at 30, 60, 100 and 150 ka (Singhvi 2004). Beyond this time range, the dune accretion record is not accessible.

An external element of climate change in India was introduced by the explosive Toba Super Eruption at ~74 ka. Analysis of pollen from a core in Bay of Bengal led to a suggestion that the eruption was followed by cooling and prolonged desiccation which led to a decline in tree cover such that forests with trees were replaced by grasses and this resulted in a large-scale extinction of mammals (Williams et al. 2009). This indicates that even short-term abrupt events, like volcanic eruptions, could perturb monsoon dependent eco-system for an extended period to cause mammalian extinctions.

2.3 Past 10 ka

A large volume of data is available for this time period. Ocean bottom sediment records from the Arabian Sea suggest that the monsoon was fully established after the LGM, around 13 ka onwards. Sediment discharge from Ganga and Brahmaputra Rivers during 11–7 ka was twofold higher compared to the present flux, indicating that the monsoon and sediment availability in this time interval was stronger than the present. Pioneering work on the lakes of Thar Desert using the sediment character, evaporite mineralogy, and pollens indicated that the saline lakes fluctuated between—saline and freshwater condition during 12.8–6.5 ka, mostly fresh water during 6.3–4.4 ka and then experienced a extended dry phase at around 4 ka and then at 1 ka (Fig. 4) (Singhvi et al. 2012). This reconstruction is also generally borne by cave speleothem records from northwest Himalaya, record from rivers from Peninsular India and peat deposits in Himalaya and other studies (Fig. 4). An event of extreme dryness around 4 ka is seen in other records, which might possibly represent an extended period of droughts. Farther away but also dominated by the

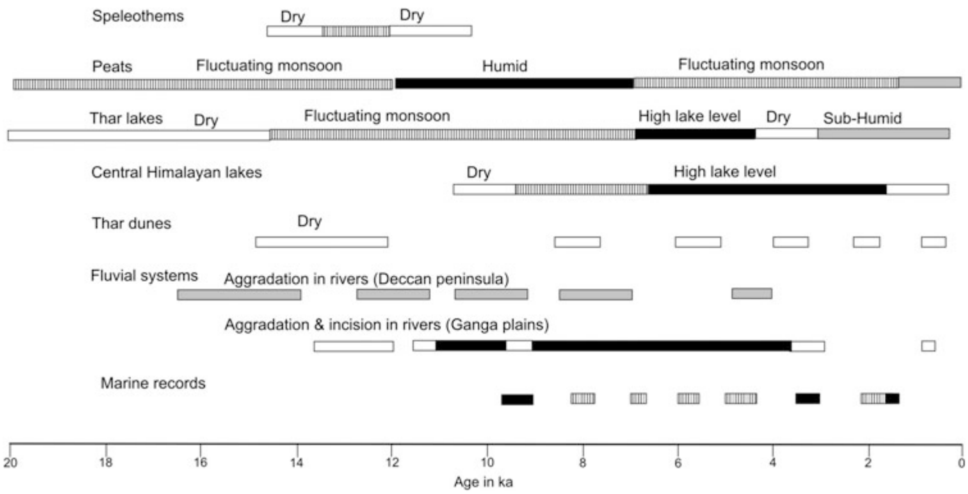

Fig. 4 Summary of geological data of changes in climate/monsoon over Indian subcontinent. (Reproduced from Singhvi et al. 2012, with permission from Blackwell-Wiley, UK)

southwest monsoon, the speleothem records from Oman indicate a phase of higher monsoon during 9–6 ka followed by a period of dryness 3–1 ka. A short lived drier/cooler event at 8.3 ka is also suggested.

An important lesson that accrues from the lakes in Thar Desert, which though indicate a similar patterns of change in their hydrology, yet show a time lag from the east to the western margins of Thar Desert, such that the lakes in western Thar Desert desiccated a thousand or more annum earlier than those in the east. This observation for the first time indicates the presence of spatial heterogeneity in geomorphic response for a given climate forcing and this to some measure reflects the changes in monsoon gradient through time. The dune record from Thar Desert also shows a similar response with geomorphic gradients, both from the east to west and from the south to north.

On a more recent timescale, reconstruction of palaeoflood records from slackwater deposits of rivers in central and western India, have provided evidence of changes in the frequency of large floods during past two thousand years (Kale 2012). Floods occur under specific rainfall conditions and are somewhat correlated to excess rainfall though floods occur in periods of overall low monsoon as well. Analysis of palaeoflood record indicated absence of large floods during 700–150 annum ago suggesting a period of low rainfall. Using oceanic records it was recently suggested that the monsoon winds strengthened during the past 400 years, however both the instrumental records and those from a first order Pennar River in Peninsular India, suggest that no increase in flood frequency is documented. This suggests the need to examine the relationship of the results from ocean upwelling and river floods in some detail.

Record from peats in Himalaya suggests a dry phase around 2 and 1.2 ka and a high rainfall phase around 600 years ago (Singhvi and Kale 2009). Around 2 ka, the dry phase is seen in dune migration rate in the Thar that was high at 0.9 cm/year around 2 ka reducing to 0.25 mm/ka during 1.5–0.6 ka and high during the past 200 years, this time due to human interventions. Slackwater deposits in Himalaya show 25 large floods during the past 1,000 years with 14 events between 1,000 and 700 years ago and 8 events between the last 700 and 200 years ago. In the recent flood in Kedarnath, palaeoflood studies along with sediment provenance using isotopes indicated the occurrence of large-magnitude floods over a few hundred year time-scale—an aspect that was totally ignored in the economic development of the region (Wasson et al. 2008). Studies on tree rings have also provided useful information such as; no significant change in temperature during the past 500 years, decadal scale fluctuation with decades of cool and warm periods. Thus, for examples, 1801–1810 was cooler with a temperature lowering of 0.31 °C and warming of 0.25 °C during 1978–87. Rainfall reconstruction also showed a similar decadal scale change. We refer to Singhvi and Kale (2009) and to the original papers cited therein for more details. Gupta et al. (2006) have discussed the relationship of proxy records and human adaptations.

2.4 Past 200 years: The instrumental records

(a) Observed changes during the 20th Century

Unlike the long-term warming signal in surface temperature data (Fig. 5), the summer monsoon precipitation on an all-India scale is characterized by significant inter-annual variations, but still does not exhibit any pronounced long-term trend (Fig. 2). However, on smaller spatial scales, some notable trends in the monsoon rainfall emerge. In particular, significant declining trends in the monsoon rains have been observed over the areas of Chattisgarh and Jharkhand in north-central India and in Kerala and parts of Western Ghat (Guhatakurtha and Rajeevan 2006; Krishnan et al. 2012 and references

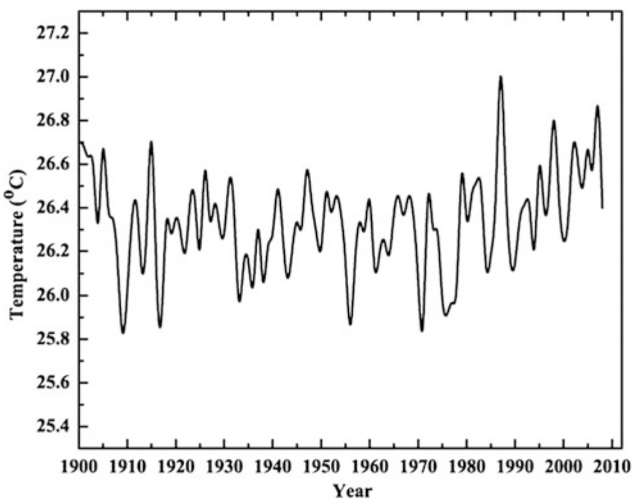

Fig. 5 Time-series of surface temperature (°C) averaged over India for the June–September season. The data are based on the global gridded surface temperature dataset from the University of Delaware (http://www.esrl.noaa.gov/psd/data/gridded/data.UDel_AirT_Precip.html)

therein) since 1950s (Fig. 6). In the recent three decades, the seasonal monsoon rainfall over Kerala has decreased by ~6 % and is supported by a consistent weakening trend of the summer monsoon circulation. Further, the period 1940–1960 and 1980–1990 experienced large floods when in general the monsoon system was inferred to be weakening (Kale 2012). Such an anti-correlation is intriguing and a possible reason could be the increased occurrence of extreme rainfall events that whilst have kept the average value nearly intact, nonetheless caused floods.

Studies on changes in the statistics of extreme precipitation events over central India during the last five decades suggest a significant increase in the frequency of very heavy rainfall events (>150 mm/day) and a reduction in the frequency of low and moderate monsoon rainfall days (Goswami et al. 2006; Rajeevan et al. 2008). Nandargi and Dhar (2012) analyzed rainstorms over northwestern Himalaya and noted that some of the most severe storms occurred during 1951–1975 and 1976–2000, but not during the recent decade (2001–2010). Overall these analyses present a somewhat counter intuitive-inferences, suggesting that we still do not completely understand all the internal feedbacks in monsoon system and their temporal evolution.

Two extreme episodes of abnormal precipitation in the recent times are the 26 July 2005 heavy rainfall event in Mumbai, and the 14–17 June 2013 multi-day event in Kedarnath, Uttarakhand. The Mumbai incident, which recorded 944 mm of rainfall in 24 hours, was associated with vigorous interactions of the large-scale monsoon circulation with embedded synoptic and meso-scale weather systems. The June 2013 Uttarakhand heavy-precipitation event was dominated by deep convection and repeated occurrence of cloud-bursts. Analysis of daily weather charts showed that the heavy rains in the Uttarakhand region were sustained by persistent interactions between the moist monsoonal circulation and anomalous southward intruding mid-latitude westerly troughs over northwest Himalayan region.

(b) Changing summer monsoon circulation

Using atmospheric wind data since 1950s, Joseph and Simon (2005) suggested a weakening trend in the summer monsoon low-level southwesterly flow. Long-term observed sea-level pressure records also indicate a weakening trend of the large-scale meridional pressure difference between the Indian monsoon trough and the subtropical southern Indian Ocean. It turns out that much of the decrease in monsoon orographic precipitation over the Western Ghat during the last 50+ years can be attributed to the weakening trend of the large-scale southwesterly monsoonal winds.

3 Understanding of the Monsoonal Trends in Recent Decades

In addition to changes in the seasonal mean monsoon, consistent long-term trends in the activity of monsoon synoptic systems and the intra-seasonal variations are seen. It has been reported that the frequency and intensity of prolonged monsoon "breaks" over India have increased during recent decades (Ramesh Kumar et al. 2009). Further, the frequency of the monsoon depressions, which are an important rain producing synoptic system forming over Bay-of-Bengal and propagating west-northwest into the Indian region, have significantly decreased during the last few decades (Dash et al. 2004). This decrease in the frequency of monsoon depressions is consistent with the weakening of the large-scale monsoonal flow, which is known to be important for the development of sheared instabilities in the summer monsoon environment (see Krishnakumar and Lau 1997).

A possible explanation for the recent weakening trend of the Indian monsoon has been the increasing concentration of anthropogenic aerosols (e.g., sulphates, black carbon, soot, etc.). Climate model simulations suggest that the radiative effects due to anthropogenic aerosols can modulate the tropical atmosphere-ocean coupled system and cause weakening of the South Asian monsoon circulation, leading to a decrease in precipitation (Bollasina et al. 2011 and references therein). Contrastingly, other climate modeling studies show that large-scale tropical atmospheric circulations can actually weaken in response to global warming alone i.e., purely from enhanced concentration of greenhouse gases,

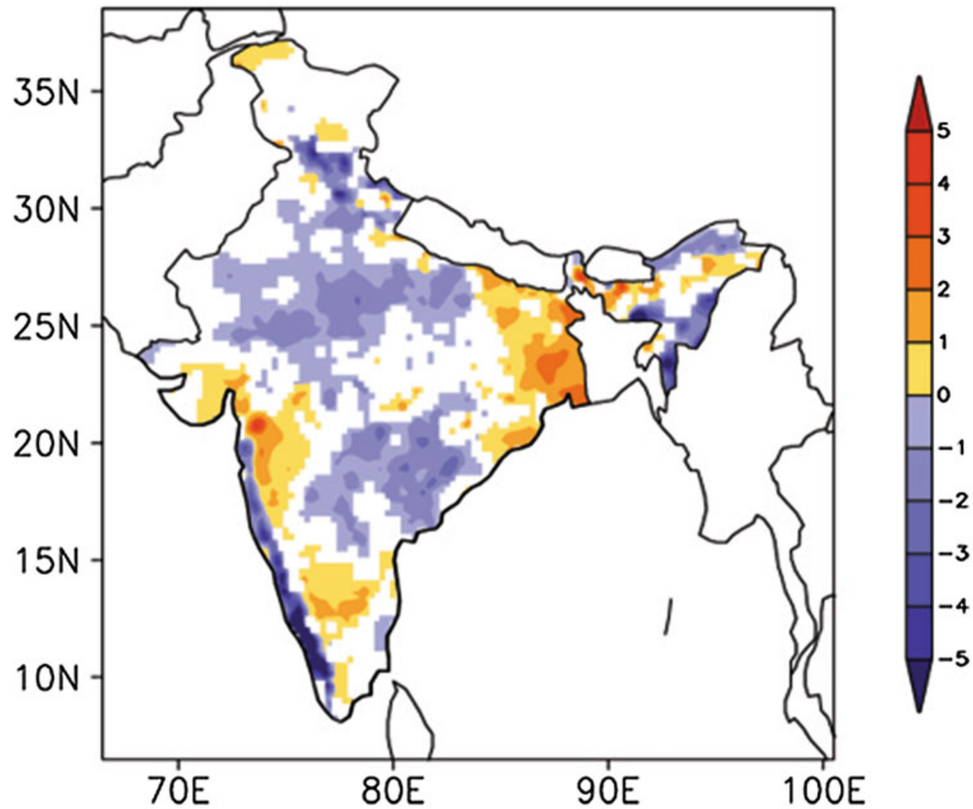

Fig. 6 Spatial map of linear trend of rainfall rate for monsoon season (JJAS) based on the APHRODITE rainfall dataset (1951–2007). The units are mm/day for the entire 57-year period. Values exceeding the 5 % level of significance have been shaded

even in the absence of anthropogenic aerosol forcing (Veechi et al. 2006). Very high resolution climate model simulation experiments show that global warming can lead to weakening of southwesterly monsoon flow and decrease of monsoon precipitation over the Western Ghat (see Krishnan et al. 2012).

Besides an increase in greenhouse gases and anthropogenic aerosols, the tropical Indian Ocean (TIO) has experienced rapid warming of sea surface temperature (SST) at a rate of 0.5–1.0 °C during the past five decades with the warming being strongest during the June-September (JJAS) summer monsoon season. The SST warming in the TIO is apparently related to the weakening of southwesterly monsoon winds (Swapna et al. 2013). Comprehensive modeling and observational studies will be necessary to unravel the details of the coupled interactions and quantify the influences of natural and anthropogenic forcing on the monsoon precipitation variations over the Indian subcontinent both in the historical past and the future.

4 Conclusions

This chapter has attempted to provide a general overview of the Indian monsoon and its variability through time. The monsoon has fluctuated on all timescales, yet it has been a stable system that has never totally failed. Given that historical records suggest that societal changes were largely driven by rainfall changes and not by temperature changes, it becomes imperative that the relationship of monsoon rainfall with temperature changes—both global and regional—need proper elucidation. The monsoon dynamics is complex and with a limit on its predictability makes it imperative to reconstruct robust palaeo records not only to further constrain the models but also provide palaeo-analogs of pristine Earth and its ecosystem so as to deduce the human impact aspects. We refer to Singhvi and Kale (2009) for more detailed discussion on these aspects and to Gupta et al. (2006) on human adaptation through times of climatic shifts.

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