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Long-Term Climate variability and change over monsoon Asia

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INTRODUCTION

The knowledge of climate variability over the period of instrumental records and beyond on different temporal and spatial scale is important to understand the nature of different climate systems and their impact on the environment and society. Most of the observational and numerical simulation studies on climate are based on the instrumental records of about a century which are aimed at the understanding of the natural variability of climate system and to identify processes and forcings that contribute to this variability. This is essential if we are to predict global and regional climate variations, determine the extent of human influence on the climate and make sound projections of human induced climate change. The large variability in the Asian summer monsoon rainfall on both space and time scales (Table 1) is well-known, which accentuates the critical dependence of the regional economy on the water received from the monsoon rainfall.

The monsoon system operates via connections between atmosphere, land and ocean systems, through fluxes of heat, moisture, and momentum between them and the loss of heat to outer space (Webster et al. 1998). Besides possessing the largest annual amplitude of any tropical or subtropical climate feature, the monsoons also exhibit considerable variability on a wide range of time scales.The monsoon system is potentially sensitive to changes in radiative forcing resulting from changing concentrations of long-lived greenhouse gases and aerosols, as well as through changes in boundary conditions such as sea surface temperature and land surface conditions such as snow and vegetation cover. While the terrestrial ecosystems are known to be sensitive to monsoon variability, modeling reveals that large-scale, sustained modification of ecosystems and vegetation cover has significant effects on the monsoon (Wei & Fu 1998).

Though the palaeorecords of monsoons over India and other parts of Asia are not systematically synthesized, some studies based on different proxy sources, scales and resolutions have been able to bring out a few prominent features of long-term climate change. Well-established time series of Indian monsoon rainfall from instrumental record prepared from a dense network of meteorological stations covering a period of more than a century is available on regional scale as well as for India as a whole[1] (Parthasarathy et al.1995). Surface air temperature data over the country has been documented for about a century and analyzed to see the trend of temperatures, particularly for the last two decades (Hingane, Rupa Kumar & Raman Murty 1985; Rupa Kumar, Krishna Kumar & Pant 1994). All these studies indicate a highly variable but trendless behaviour of the Indian summer monsoon rainfall with a prominent epochal nature of variability (Fig.1). However, it has been reported that there do exist some smaller sub-regions with statistically significant increasing and decreasing trends (Fig.2; Pant & Rupa Kumar 1997). The surface temperature over the Indian region shows increasing trend of about 0.4°C/100 years. The increasing tendency of mean

Table 1. Temporal scales of monsoon variability.

Scale	Intraseasonal	Interannual	Decadal and Century	Millennia and longer
Features	Active and break-monsoon phases; 30-50 day oscillations	Droughts and floods	Changes in the frequency of droughts and floods	Changes in the areal extents of monsoons
Factors	Atmospheric variability; tropical-midlatitude interactions; Soil moisture; Sea surface temperatures	Atmospheric interactions; El Niño/Southern Oscillation; Top layers of tropical oceans; Snow cover; Land surface characteristics	Monsoon circulation variations; Deep ocean involvement; Greenhouse gases increase; Human activities; Biospheric changes; Volcanic dust	Global climate excursions; Ice ages; Warm epochs; Sun-earth geometry

1 Regional means of monthly mean rainfall (1871-2000) and surface air temperature (1901-90) can be downloaded from the official web site of the Indian Institute of Tropical Meteorology (http://www.tropmet.res.in).

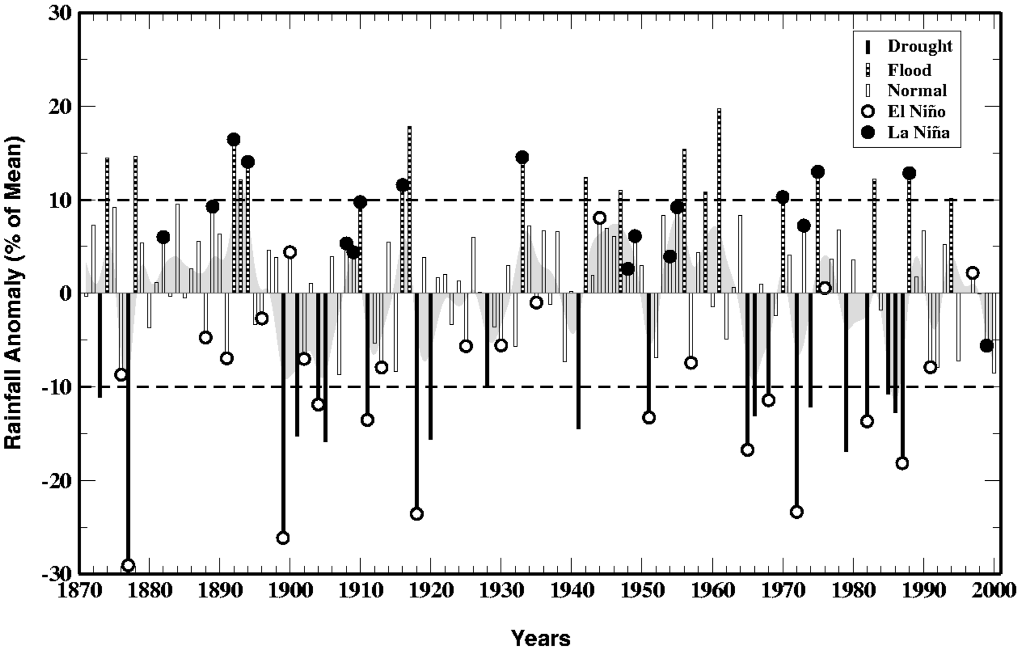

Figure 1. All-Indian summer monsoon rainfall during 1871-2000 (based on IITM Homogeneous Indian Monthly Rainfall data set).

temperature is mainly contributed by the maximum temperature, as the minimum temperature is trend less during the current century (Rupa Kumar, Krishna Kumar & Pant 1994).

The aforesaid studies are based on the climatological data excluding the Himalayas. However, the understanding of climate variability over the Himalayas is especially important, being the greatest mountain barrier on the earth, where polar, tropical and Mediterranean influences interact. The Himalayas play a prime role in maintaining and controlling the monsoon system over the Asian continent. The common limitation of many of the climate variability studies over the Himalayan region is the lack of sufficient climate data from high altitude locations.

It is clear that information about climate based on instrumental records has both spatial and temporal limitations, providing only a small window to the gamut of various climatic processes on a wide spectrum of spatio-temporal scales. Therefore, it is imperative that we should try to deduce climatological information through some indirect sources. Fortunately, nature has plenty of climate-sensitive materials which contain reliable signatures of past climates; highly sophisticated methods are involved in the identification, collection, analysis and reconstruction of past climates from such "proxy" sources. These techniques have proved to be invaluable tools in our quest to unravel the mysteries of climate system. Monsoon Asia, though replete with a variety of proxy climatic sources and has been the scene of some of the oldest civilizations of the world, is yet to be comprehensively explored in terms of its past climatic variations. In this lecture, I wish to provide a glimpse of the various palaeoclimatic approaches that have been recently used to understand the past climates over monsoon Asia.

HISTORICAL CLIMATE RECORDS

Historical evidences are very important to get some information about contemporary climate change. However, these evidences are generally found scattered in many places and languages with varied interpretation, information is vague and fragmentary. A systematic and logical approach in interpreting historical evidences is crucial to extract valuable information on past climate. Historical records in India and China are relatively long compared to other parts of Asia and provide informative evidences of past climate.

In India, the monsoon and related events find an important place in folklores and written documents. Ancient literature is replete with references to monsoons and the famines which occurred due to the failure of the monsoon (e.g., Yaksha's *Nirukta*, Valmiki's *Ramayana*, *Jataka* series of the Budhists, Chanakya's *Arthasastra*, etc.). *Meghdoot* by the famous Sanskrit scholar Kalidas is a legendary epic describing the Indian monsoon clouds and the onset of the monsoon over Central India which is said to be occurring over the region in the middle of June. This also describes the monsoon current as a messenger from the peninsula to the Himalayas at low levels returning at the higher levels.

There are indications that the northern, desert-margins-edge of the monsoon, in the northwest part of South Asia, underwent wide fluctuations leading to the appearance and disappearance of human civilizations in the region. The *Harappan* civilization of the Indus valley flourished during the period 2300 to 1700 BC, the *Painted-Gray-Ware* culture between 700 and 300 BC, and the *Rangamahal culture* between 100 and 200 AD. Ramaswamy (1968), commenting on the good monsoon regimes in northwest India, has postulated that during the period 2000-500 BC deep troughs in the upper westerlies may have extended into Pakistan more frequently than now, causing monsoon depressions to curve to the north or northeast, leading to active monsoon conditions over the entire Indus valley.

Historical climate evidences are mostly related to monsoonal rain, for example, occurrence of drought or flood, no harvesting due to lack of rain or good grain production and so on. Pant et al. (1993) made systematic efforts to extract climate related information for the last 1000 years from historical records of various climatic zones of India. Many historical evidences are indicative of droughts and floods leading to famine conditions. Relatively low frequency of occurrence of droughts was observed during AD 900-1600. This may be due to less availability of related historical information that accounts only for severe and significant events. Since AD 1600 frequency is relatively higher and drought events are more or less randomly distributed.

DENDROCLIMATIC STUDIES

Many long-lived trees grow with annual ring structure. Climatic information recorded by trees growing in stressful forest environments can be extracted from the size, structure and chemical composition of these annual growth rings. The precisely dated tree-ring series from such trees provide a wealth of information about climatic and environmental changes over the past few centuries with an interannual resolution. When a large number of tree-ring chronologies are available for a region and they are demonstrated to represent the effect of specific climatic variables like temperature, rainfall and humidity, these parameters can be reconstructed backward. The spatial anomalies in tree growth/climatic elements may be mapped and used to deduce climatic anomalies over a wider geographical region. Tree-ring data also show a potential source of information on severe floods, earthquakes, volcanic eruption, glacier advance and retreat, ecological disturbances (e.g., fire and outbreaks), etc.

In India extensive work has been carried out to understand the dendroclimatic potential of Himalayan conifers (*Pinus*, *Picea*, *Cedrus*, *Abies*, etc.) and tropical trees (teak, toona, etc.). Ringwidths and densities are the most widely used variables for studying the tree growth-climate relationships. Temporal variations of isotopic ratios in tree-rings of the Himalayan conifers are also good indicators to deduce high-resolution palaeoclimatic history.

Dendroclimatic analysis using a wide network of tree-ring chronologies and monthly as well as seasonal data of temperature and precipitation anomalies over western Himalaya indicates a significant relationship between pre-monsoon climate and tree growth. A strong association of pre-monsoon climate with tree

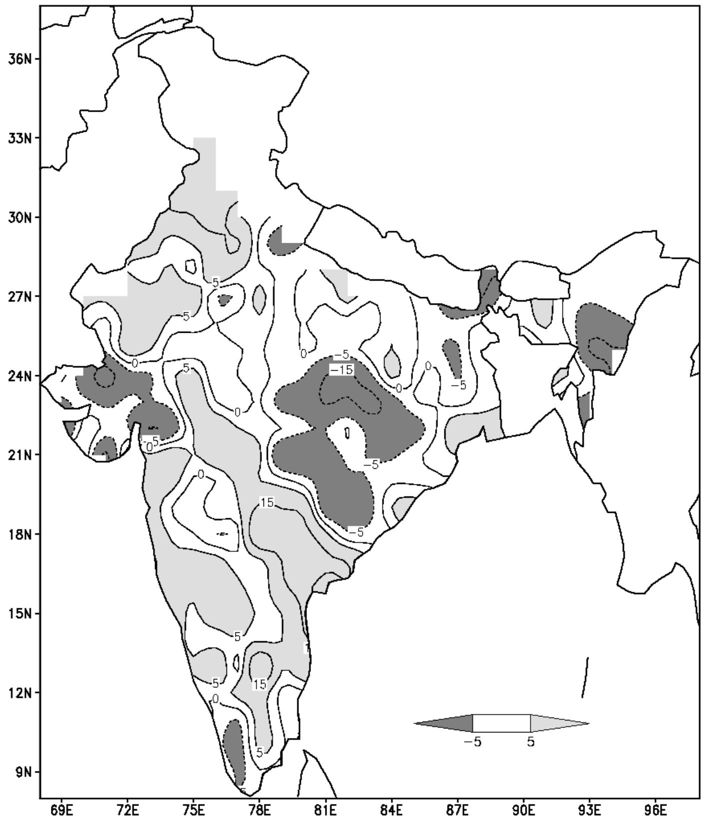

Figure 2. Spatial patterns of linear trend (% of mean/100yrs) in the Indian summer monsoon rainfall.

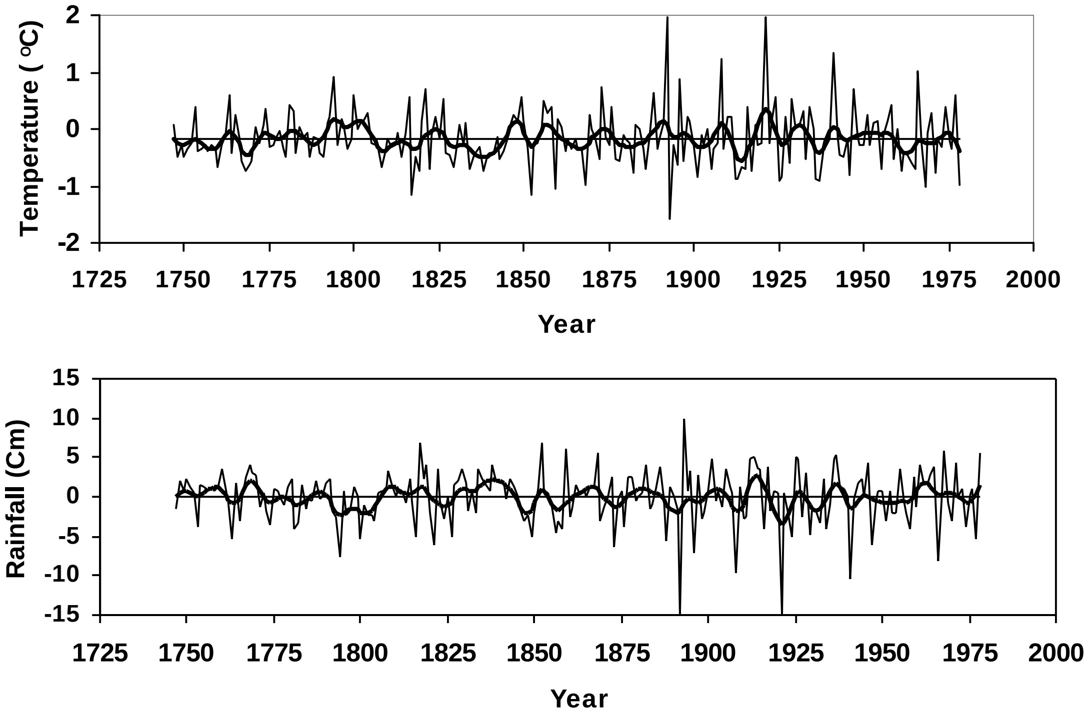

Figure 3. Reconstrcted pre-monsoon (March-April-May) temperature and rainfall anomalies since AD 1747 over the western Himalaya using tree-ring chronology network. Smooth lines indicate low-frequency variations.

growth is mainly due to severe moisture stress conditions occurring during these months (Borgaonkar, Pant & Rupa Kumar. 1994, 1996, 1999; Pant et al. 2000). Ramesh, Bhattacharyya & Gopalan (1985) studied the isotope ratios of the tree rings and Hughes (1992) studied the tree-ring density variations, over the western Himalaya. Figure 3 represents the reconstructed pre-monsoon temperature and precipitation from tree rings based on this relationship, going back to AD 1747. Either temperature or precipitation series do not show any long-term trend. The reconstructions also reveal that the pre-monsoon climatic conditions during past 250 years were not significantly different than the present climatic conditions. Reconstructions cover the later part of the Little Ice Age. It is observed that this phenomenon is not prominently reflected in the tree-ring variations over the western Himalaya.

In tropical region of south and southwest Asia number of groups have been working to establish good quality tree-ring data network to understand monsoon variability and related global parameters (e.g. ENSO) in the recent past. In this context, teak (*Tectona grandis*) from Indonesia, Thailand, Java, India have been demonstrated as a potential source for high resolution spatial reconstruction of climate (e.g., D'Arrigo, Jacoby & Krusic 1994; Pant & Borgaonkar, 1983; Ramesh, Bhattacharyya & Pant 1989; Bhattacharayya et al. 1992). These studies indicate good potential of *Tectona grandis* in the reconstruction of monsoon precipitation. However, a large temporal and spatial network of tree-ring chronologies in this region is needed to understand past variations of monsoon and related parameters.

Pant, Rupa Kumar & Borgaonkar (1988) attempted to reconstruct the variability of all India summer monsoon rainfall (AISMR) since last 400 years, using an indirect dendroclimatic approach, based on the fact that the Southern Oscillation (SO) is strongly related to the Indian summer monsoon rainfall. The data of Wright's Index of SO reconstructed back to AD 1602-1960 using tree-ring chronologies from both western-north America and the Southern Hemisphere (Lough & Fritts 1985) have been used to estimate AISMR back to AD 1602. The actual and estimated AISMR series during the calibration period (Figs 4a,b) indicate good agreement with each other. The reconstructed AISMR for the period AD 1602-1960 is represented in Fig. 5. The smooth line is low-frequency variation based on cubic spline filtering. An excess rainfall epoch is observed during AD 1610-1635. Other less prominent epochs are also seen in the series which reflect the basic nature of the instrumental rainfall series (e.g. occurrence of different epochs, Mooley & Parthasarathy 1984). Major drought events noted from historical and other sources during 19th century by Mooley & Pant (1981) have also been matching with the reconstructed series as low precipitation years.

GLACIO-CLIMATIC STUDIES

Vast snow cover over Asian mountainous region provides valuable information of past climatic fluctuations. Glacier movements (advancement, stationary and retreating phases), chemical and physical properties of ice cores are useful parameters to investigate the spatial variability of climate in this region. The wide spread

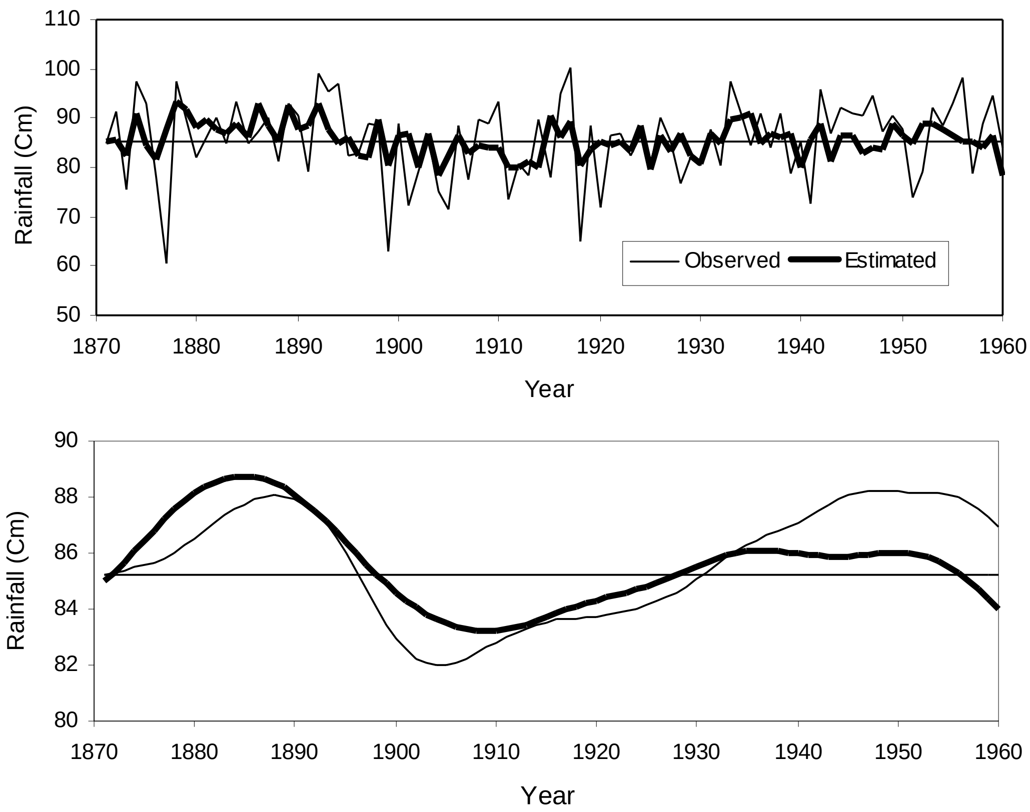

Figure 4. Estimated and observed all India summer monsoon rainfall (a) interannual variations, (b)low-frequency variations using cubic spline smoothing. The estimated values are based on indirect dendroclimatic reconstruction using southern oscillation index.

occurrence of glaciers in the mountains of central Asia provide variety of sites from which multi-parameter ice core records can be recovered. Table 2 represents glacierized surface area in central Asia (Haeberli et al. 1988).

Table 2. Glacierized area in central Asia

China	56,500 km^2
India/ Pakistan	40,000 km^2
Kazakhstan. Tajikistan & Khirgizstn	18,200 km^2
Nepal/ Bhutan	7,500 km^2
Afganistan	4,000 km^2

Studies of modern glacier fluctuations in the mountains of central Asia have been limited to general observations of advance or retreat of the snout. Very few studies (Mayewski & Jascjke 1979; Mayewski et al 1980) are available which indicate glacier fluctuations since the beginning of nineteenth century in terms of absolute time scale. They reported the glacier fluctuations on the basis of percentage of advancement, retreating and stationary positions of several glaciers across the Himalaya on yearly scale since AD 1812. These records indicate the fluctuations in dominancy of advance and stationary positions of glacier till AD 1870. During AD 1870 to 1940 random fluctuations in dominancy of retreat, stationary and advance regimes were observed followed by retreating phase in present decades. Mayewski et al. (1980) also discussed the relationship between glacial advances from 1890 to 1910 in the Trans-Himalaya and strengthened monsoon circulation pattern.

Evidence of long-term glacier fluctuations in Lahul-Spiti Himalaya (Owen et al. 1995, 1996) is attributed to an increase in aridity throughout the Quaternary due either to global climatic change or uplift of Pir Panjal ranges to the south of Lahul which restricted the northward penetration of south Asian summer monsoon. Studies on movement of glaciers in Nepal during last four decades, in general, indicate receding phase, the rate of recession has increased during the 1980's. South facing glaciers in the Langtang region of Nepal were stationary over the past 10 years, while north facing glaciers advanced.

Glacio-climatic investigations of Tibetan Plateau also reveal some information on the extent of ice at the Last Glacial Maxima (LGM) and their implications for constructing the palaeomonsoon. It has been argued that the whole of the Tibetan Plateau was covered by a single ice sheet, though this feature is yet to be reliably established.

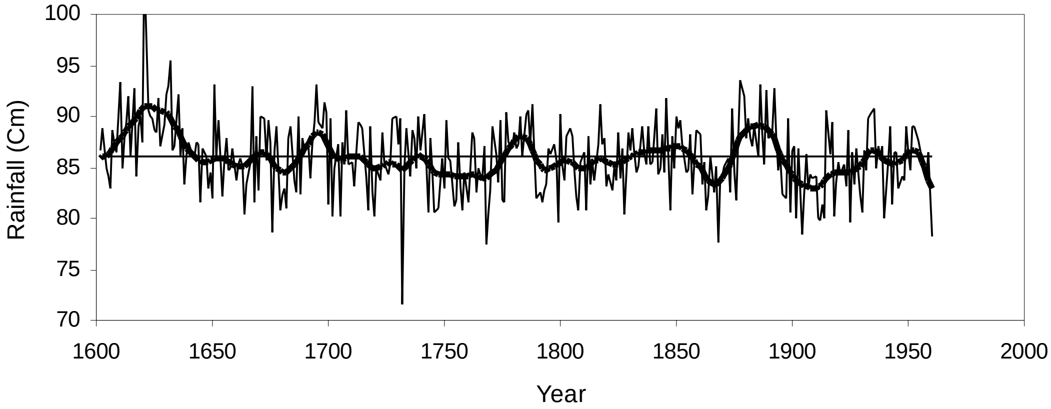

Figure 5. Reconstructed series of all India summer monsoon rainfall since AD 1602; the dark line indicates low-frequency variation.

ICE CORE INVESTIGATIONS

Analysis of physical and chemical characteristics developed from ice cores provide high resolution and direct view of palaeo-atmosphere of the time scales of decades to hundreds of thousands of years. Over Indian as well as central Asian region ice core palaeo-climatic investigation is limited compare to the wide scale studies in the polar regions. Glacio-chemical analysis on vast region of central Asia (Wake et al. 1993, 1994) indicates that glaciers adjacent to large arid regions (such as those of the northern and western margins of the Tibetan Plateau) contain high concentration of ions and dust particles due to incoming strong dust flow from nearby sources. Glaciers more distance from dust source regions show intermediate levels of major ions and dust, while southern slope glaciers of eastern Himalaya are relatively free from the influence of desert dust. These dust free ice records may have good potential associated with inter-annual and longer scale variability of Indian and Plateau monsoons. Ladakh Himalaya ice cores (Mayewski, Lyons & Ahmad 1983; Mayewski et al. 1984) indicate significant shift in chemical composition of monsoon water on seasonal to multi-annual scale. Short-term climatic and environmental informations since last 2000 years have been derived from isotopic and chemical studies of five glaciers in the Indian Himalaya (Nijampurkar et al. 1982,1985; Nijampurkar & Bhandari 1984; Nijampurkar & Rao 1992).

The $\delta^{18}O$ series and concentration of micro-particles analysed from ice core studies of Dunde Cap, northeastern margin of Tibetan Plateau (Thompson et al. 1989) indicates the climatic condition during Holocene and Late Glacial Stage. They suggested colder and wetter climate of Late Glacial Stage than Holocene period as revealed from more negative $\delta^{18}O$ ratio, increased dust content and decreased soluble aerosol concentration during Late Glacial Stage. The transition period is marked by decreasing dust particle content, less negative $\delta^{18}O$ ratios and higher concentration of aerosol around 10,000 years ago. During early Holocene, the region experienced less precipitation. Little Ice Age was not as cold as expected. The period AD 1000 to 1200 was found to be coldest from the study of couple of ice cores over Tibetan Plateau (Thompson et al. 1995; Yao et al. 1995).

The best high-resolution evidence for climate change in South Asia over the last millennium comes from the high-altitude (7200 m) ice-core record from Dasoupu, Tibet (Thompson et al., 2000). Changing dust and chloride concentrations in the core give a precise record of decadally changing South Asian monsoon intensities from 1000-1440 AD. From 1440 onwards the resolution is annual. The greatest recorded failure of the monsoon and occurrence of drought in the last thousand years was from 1790 to 1796. Less severe monsoon failures took place in the 1640s, 1590s, 1530s, 1330s, 1280s and 1230s events. During the drought of 1790-1796 at least 600,000 people died of starvation in just one region of northern India in 1792 alone. The consequences on the whole region over the entire drought would have been catastrophic. The twentieth century increase in anthropogenic activity in India and Nepal, downwind from the Dasoupu site, is recorded by a doubling of chloride concentrations and a fourfold increase in dust. Like other cores from the Tibetan Plateau, the Dasoupu data suggest a large-scale warming trend that appears to be amplified at higher elevations in the high mountain terrain (Thompson et al. 2000).

LONG-TERM CLIMATE CHANGE: MULTIPROXY STUDIES

Physical and Chemical characteristics of lake sediments, ocean sediments, peats, loess, speleothem are potential proxies which offer important information on long-term climate variability of Holocene and beyond. Holocene variations in monsoon rainfall over northwest India have been discussed by Bryson & Swain (1981), Swain, Kutzbach & Hstenrath. (1983); Singh, Wasson & Agrawal (1990), etc. using pollen sequences and lake level data. Hyper-arid condition was observed from Last Glacial Maxima (LGM) to c. 13,000 years BP. This dry climate might be due to low precipitation of summer monsoon and higher winter precipitation than that at present (Singh, Wasson & Agrawal 1990). They also pointed out that the cause of such situation might be because of westerly circulation moved farther south along with weak summer monsoon circulation. Studies of Van Campo et al. (1982) of deep sea cores from Arabian Sea also indicated weak monsoon circulation during LGM. Early Holocene (c. 9300-7500 years BP) monsoon precipitation indicates increasing trend and mean annual precipitation during the mid-Holocene (c. 7500-6000 years BP) was about double the modern value (Swain, Kutzbach & Hastenrath 1983; Singh, Wasson & Agrawal 1990). The intensity of monsoon as well as winter precipitation declined after c. 6500 year BP A decreasing trend continued till further to present level.

Similar patterns of LGM climate have been shown by Sukumar et al. (1993) using $\delta^{13}C$ measurements in peat from Nilgiri Hills, southern India. The changes in vegetation type revealed from the $\delta^{13}C$ series corresponds to a specific climate regime. Predominance of tropical grass type vegetation during 20-16 K-years BP clearly indicates a very arid phase during LGM as this type of vegetation grow favorably under low aridity and low soil moisture. This also points to a period of weak southwest summer monsoon during LGM. Spreading of dicotyledonous forest and temperate grass around 11 K-yeas BP may be the cause of strengthening of summer monsoon circulation. The data also indicate dry condition around 6000 years BP.

Oxygen isotopes from Arabian Sea sediment cores indicate lower salinity and weak upwelling during the last glacial maximum and reverse conditions during interglacial phases (Cullen 1981; Duplessy 1982). Lacustrine pollen sequences from northwest India suggest a cold and dry period with weak monsoon activity during the last glacial maximum at around 18 ka (Singh et al. 1974). Increased moisture from about 10ka to 5ka has been inferred from mesic pollen and high lake levels in northwest India, Kashmir, Nepal and the southwest of the Tibetan plateau (Singh et al. 1974; Swain, Kutzbach & Hastenrath 1983; Wasson, Smith & Agrawal 1984) and from increases in monsoon-transported pollen found in Gulf of Aden and Arabian Sea ocean sediment cores (Van Campo et al., 1982; Van Campo, 1986).

Multidisciplinary evidence from the northwestern parts of South Asia shows that the Holocene climate from 10 - 4.5 ka was warm and humid and associated with vegetation rich in grass, poor in halophytes and experiencing a relatively high frequency of floods as the intensity of the summer monsoon increased after 18 ka (Pant & Maliekal 1987). Sediment cores from the Arabian Sea indicate that the continental heat low was strongest around 8 ka, when the southwest monsoon probably reached its northernmost position (Sirocko et al. 1993). The period thereafter, until about 5 ka, was marked by fluctuating precipitation and lake levels (Swain, Kutzbach & Hastenrath 1983; Prasad Kusumgar & Gupta 1997). The period 4.5-3.5ka experienced fewer extremes, but increased rainfall, swamp vegetation and mesophytic dominance. Evidence of human interference increased in later times. Around 3.5ka, a trend towards aridity set in over the entire northwest, with a total absence of preserved pollen in Rajasthan lakes and increased sand mobility. inferred from Pollen data from the Central Himalayan region suggests that that the period 4-3.5 ka represents the weakest phase of the monsoon during the Holocene (Phadtare 2000). After 3.5 ka a the present climate, with its frequent droughts and seasonal extremes, became established and the current vegetation was fixed (Pant & Maliekal, 1987). Recent high-resolution studies, clearly suggest that short-term oscillations in the Indian monsoon occurred within the Holocene, with the possibility of tropical soil hydrology and continental vegetation playing a role in driving high-frequency variations (Overpeck 1996; Thamban et al. 2001).

The palaeoclimate of the Himalaya on different time scales has been studied by various workers. The north-west Himalaya and Kashmir valley received particular attention and were studied using different techniques like lithostratigraphy, magnetostratigraphy, palaeobotanical data, pollen evidences, diatom studies and stable isotopic ratios. Some clues from vertebrates from the sediments were also used to frame the Cenozoic climatic changes of the region. The climatic record of Kashmir valley for the past four million years is well preserved in the Karewa sediments, having an estimated thickness of 1000 meters. Most of the exposures of the Karewas in the valley were fully mapped and their mutual correlations were studied. A reasonable chronological framework of these sequences is now available, having a satisfactory convergence between the different climatic parameters within the limitations of the dating resolution (Agrawal et al. 1989). Up to 3.8 M years the climate seems to be warm temperate. From 3.7 to 2.6 Myears BP, there was a transition from a sub-tropical type of climate to a cool temperate type, and with some variation in precipitation, cool temperate until 2.2 M years BP Between 0.6 and 0.3 M.years, there are three relatively long cold periods. This evidence is based mainly on pollen data but is also supported by stable isotopic and faunal data.

Loess is unstratified, homogeneous, porous calcareous silt generally wind deposited in periglacial environment and represents cold arid conditions. Palaeosols or buried past soils are generally indicative of warm and humid climate. These loess-palaeosol layers are very good continental palaeoclimatic indicators. These deposits provide climatic information of past 2,00,000 years. There are evidences of 10 palaeosols during this period, out of which 3 palaeosols show greater weathering and may therefore reflect warmer/humid conditions compared to the others. Between 10,000 years BP and present, the pollen profiles show a cold temperate-warm temperate-cool temperate cycle. However, a warming of the valley is indicated around 17,000 years BP. Recent study of Mazari (1995) based on bog, lake and fluvial sediments in the Spiti valley, Western Himalaya indicate warm and moist phase at 6880±45, 5390±95 and 3150±05 year BP Around 990±70 and 460±210 years BP similar patterns were observed. Cold and dry phases occurred mostly in the intervening time in the mid-Holocene, and also around 1830±140 and 300 years BP In the valley, human settlements thrived only during periods of climatic amelioration. Around c.18,000 years BP there was an Upper Palaeolithic culture; at c.5000 years BP, Neolithic cultures; at c.1800 years BP a Kushana culture; and at c.1000 years BP historical dynasties (Agrawal et al. 1989). On the whole, the climatic pattern of Kashmir and western part of the Himalaya follows a global trend: the warming up of the Pliocene, the glacial and interglacial oscillations of the Pleistocene etc. However, the Pleistocene cooling was not abrupt but very gradual (Agrawal 1985).

Palaeoclimatic studies in the central part of the Himalayan ranges, comprising the Nepal Himalaya and Tibetan plateau, have been carried out by Fort (1985) using the analysis of sedimentary and geomorphic data. He concluded that, on the northern side of the Nepal Himalayan Range, warm and alternatively dry/humid climates of late Cenozoic period (~10 M years BP) are progressively replaced by cold climates, which lead to the development of glaciation. Occurrence of first glacial remnants took place fairly late, around middle Pleistocene (1 Myears BP), at a time when the range reached an altitude high enough to lie above the snow line. Increasing dryness of this Tibetan side is due to the range uplifting, still active, blocking the advance of monsoon moisture. On the southern side of the Nepal Himalaya, warm climates prevailed all the time, but slight nuances occurred due to rising (temperate tendency) and proximity to relief (increasing contrasts). Rapid strengthening of summer monsoonal circulation was observed around 10.-9.5 K years ago from multiproxy data from two lakes of western Tibet (Gasse 1991; Fontes 1993) resulting wet-warm conditions which is further changed to long-term aridity around 4.3 K years ago.

MODELLING STUDIES

Monsoon, a component of global circulation system, has been a dominant part of the climate over the Indian subcontinent since geological times. It is believed that four monsoon maxima occurred during interglacial conditions over the past 150,000 years, owing to changes in orbital forcing and solar radiation and changes in surface boundary conditions (Prell & Kutzbach, 1987). General Circulation Models (GCM) studies reveal that with interglacial orbital configurations, increasing northern hemisphere radiation strengthens seasonal land-ocean temperature gradients and the monsoon circulation over South Asia (Dong, Valdes & Hall 1996). In general the model showed that cold periods in the past are characterized by strengthened winter-like circulation, whereas warm periods are associated with strong summer monsoon flow. Observations support the model findings.

Studies based on (GCM) give better understanding of past monsoon variability and its relationship to various forcing factors (Bryson 1989; Rind & Overpeck 1993). The role of Tibetan Plateau in relation to monsoon circulation is very important. The uplift of Tibetan Plateau has led to the evolution of a complex monsoon circulation pattern (Ruddiman & Kutzbach 1987). Some GCM studies indicate the major role of astronomical forcing in Asian monsoon variability (Kutzbach & Street-Perrott, 1985; Prell & Kutzbach 1987; Clemens & Oglexby 1992; Wasson 1995). Climate model analysis of Hansen et al. (1988) and Meehl & Washington, (1993) indicate that the Tibetan Plateau is likely to warm significantly in response to elevated atmospheric trace gases concentration and this could give rise to stronger summer monsoonal circulation.

Modeling of climate variability on inter-decadal to century time scale is a major research area in the field of climatology. The shortness of instrumental climate records that cover the past 100 years at most, make the study difficult. In the Himalayan/ Tibetan Plateau region the problem is more severe due to lack of long instrumental records. A well dated high resolution palaeoclimatic data offer a means of extending the climate record back in time. conclusions

For a better understanding of climate variability at different time scales, it is important to expand the geographical coverage of palaeoclimatic records. The sources of these records include tree-rings, ice-cores, speleothems, historical records and lake-sediments. By understanding the past monsoonal variability and its relationship to various forcing factors, it is possible to improve our fundamental understanding of the dynamics of the systems. This will be helpful to develop more reliable predictive models of Asian monsoon variability. The South Asian region has a vast unexplored potential in terms of a variety of proxy climatic indicators, which, when subjected to a concerted and coordinated study, can provide vital clues to the monsoon variability. Further, the simulation of the monsoon circulation has been posing a tough challenge to global climate modelling efforts, and the palaeoclimatic evidences of monsoon changes can be of great utility in improving the formulations of monsoon-related aspects in the climate models.

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