Review Article

Late Quaternary to Holocene Southwest Monsoon Reconstruction: A Review Based on Lake and Wetland Systems (Studies Carried Out During 2011-2016)

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(Received on 10 April 2016; Accepted on 25 May 2016)

The recent trends in Late Quaternary researches, particularly, for the Holocene period is mainly focused on reconstructing the past climate dynamics, fluctuations in the intensity of the southwest monsoon (SWM) and applications of these datasets for predicting future trends. During the years 2010-2015, the published data, although shows chronological constraints, by covering different physiographies of India, which presently display a highly variable climate from hot to cold desert and from high to low rainfall region. An integrated multidisciplinary, multiproxy data provide a comprehensive understanding of the trend in climate change, from moist mid-Holocene to dry Late Holocene conditions from the Indian subcontinent although with a slight variation in time brackets which is attributed to external forces responding to varied landscape, geographical setting and altitudinal changes. Most of the lake records show a decline in SWM since the middle Holocene with intermittent intense wetter conditions. This allowed the lake margins to shrink and expand. Some lakes hold the signatures of abrupt and extreme events such as the 8200 yr BP solar insolation event, 4200 extreme aridity, 3800 dry and warm conditions, Medieval warm period (MWP) and the Little Ice age (LIA) events. Till date, however, these data are few and far in between and the need of the day is to rigorously generate quantification of SWM intensity using lake sediments and compile the dataset for climatic modeling such as the Regional Climate Models (REGCMS) to predict future climate change if any with greater degree of correctness.

Keywords: Lake Sediments, Southwest Monsoon, Extreme Events, Vegetation, Dry and Warm Periods

Introduction

The nation's economy is largely dependent on food and agricultural production and food security. Monsoon dependent countries such as ours, the monsoonal rains are looked forward to with great anticipation and hence it is important to understand and evaluate meteorological data for future predictions with high accuracy. Climate models such as general climate model (GCM) and regional climate models (REGCM) for long term prediction are carried out using various parameters as its data input and the amount of rainfall (past and present) records are vital parameters. Varied past environmental conditions have left geochemical signals in the sediment records that can be used to interpret paleo-ecological and paleoenvironmental

histories (Meyers and Teranes, 2001). Physical and chemical characteristics of lakes and ocean sediments, peat bogs, loess, and speleothems have been used as important proxies for reconstructing long-term climate variability of the Holocene period and beyond. However, the reconstruction of the past monsoonal record is not accurate as there are discrepancies in analytical precision and resolution.

Instrumental and historical information and records about climate conditions of the past are restricted to the last few centuries and millennia, respectively. For this purpose lake sediments are often used as one of the important proxies for the reconstruction of paleoenvironments because they can demonstrate continuity in environmental and seasonal

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sensitivity, therefore providing high resolution paleoenvironmental and climatic information (Zhang *et al.*, 2004; Hodell *et al.*, 1999; Harrison *et al.*, 1993; Street-Perrott and Harrison, 1985). As the formation and deposition of lacustrine sediments are dominantly controlled by climate processes and catchment geology, the analysed sediment properties, referred as 'palaeoclimate proxy data' are used as indicators of the variability of past environmental conditions as well as of the impact of human influences on lake systems and their catchment areas. Numerous lake catchments and their hydrologic settings in industrialized countries have witnessed strong anthropogenic impacts during the last ca 150 years (Zolitschka *et al.*, 2015). The deposition of sediment incorporates environmental information as proxies relating to sedimentary structure and composition. Each sedimentary column represents a paleoenvironmental archive that requires a measure of depositional age (i.e. a chronostratigraphy) to yield a meaningful time-series of their proxies. Whilst both natural climate change and human-influenced environmental changes are likely to be recorded in Holocene sediments (Shen *et al.*, 2005), it is critical to evaluate the influence of human activities on the reliability of sedimentary proxies in inferring the past climate change (Yang *et al.*, 1997; Zhang *et al.*, 2010). Lakes are major sinks not only for sediment deposition in a closed system, but also are major sinks for carbon, carbon sequestration and also hold signatures for reconstructing paleoenvironments.

Elemental and isotopic analyses of sediments provide useful information regarding provenance and climate change, either as an independent method (Robinson, 1994; Piovano *et al.*, 2004; Ng and King, 2004; Yanes *et al.*, 2006; Ruiz-Fernandez *et al.*, 2007; Tanaka *et al.*, 2007; Xue *et al.*, 2007; Minyuk *et al.*, 2007) or associated with pollen and isotopic data (Osborne *et al.*, 1993; Goslar *et al.*, 1999; Brauer *et al.*, 2000; Mingram *et al.*, 2004; Dressler *et al.*, 2006; Parker *et al.*, 2006; Schettler *et al.*, 2007). The determination of mineralogical composition of lake sediments is another useful tool for paleoenvironmental reconstruction of the area around the lake catchment and wetland ecosystems (Luque and Julia, 2002; Sakai *et al.*, 2005; Fagel and Boes, 2008; Fagel and Mackay, 2008). These researches show an integration of various disciplines with multi-proxy study and interdisciplinary approach, which has

become necessary for a spatio-temporal comparisons. In the last five years use of proxies like-sedimentology, mineral magnetism, phytoliths, palynology, diatoms, thecamoebians, geochemistry, radioisotopes and application of various dating techniques has been extensively used to address issues related to paleoclimate, paleovegetation, paleoprecipitation, possible climate-culture relationship, abrupt climatic events etc. The archives used are mainly lacustrine and wetland sediments, although a few fluvial, aeolian and coastal wetland records are available.

The Holocene period began approximately ~11500 yrs ago and this period is marked by the evolution and decline of human cultures and establishing agriculture practices (Possehl, 1994). Relatively warm and cooler conditions during this period are also characterised by marine transgression and regression which has resulted in shifting of the coastlines world over impacting human settlements/migrations. Such oscillations resulted in geomorphological changes, sedimentation patterns in coastal plains and inland areas, forming back waters, estuaries, formation of marine-terraces, spits, sand barriers, beach ridges and shifting of river courses (Wolf *et al.*, 2008).

Precession of the earth's orbit around the sun has been attributed to cause significant changes in the seasonal distribution of surface heating during the Holocene period (Maher and Hu, 2006). For the North African and Southwest Asian monsoons, a wealth of proxy data reveals major northward expansion of monsoonal rain in the early and mid-Holocene period (Maher and Hu, 2006). Lake level data from the North African region show that the lacustrine deposition was initiated at around 14500 yr BP, which is the onset of the 'African Humid Period' (Street and Grove, 1979; Street-Perrott and Harrison, 1984; Gasse, 2000). A high-resolution, well-dated deep sea sediment record of aeolian flux studied from the ODP site 658C, Mauritania) corroborates well with the onset of humid conditions and dates which is reflected by a steep rise in biogenic carbonate, opal and a decrease in terrigenous flux. The high terrigenous flux at the ODP site 658C indicate increased monsoonal intensity and precipitation from the end of the younger Dryas to around 5500 yr BP that is when the African Humid period came to an abrupt end (deMenocal *et al.*, 2000). Lake level data, also collate

well for the mid-Holocene (around 6000 yr BP) indicating conditions were still wetter than present day across North Africa, East Africa, The Arabian Peninsula (Jolly *et al.*, 1998; Maher and Hu, 2006). Across this monsoonal belt, the major fluctuation from wetter to arid conditions has been dated to between 5000 and 6000 yr BP and is also associated with the ongoing decline in the boreal summer insolation (deMenocal *et al.*, 2000; Maher and Hu, 2006).

Parallel patterns in the SWM intensity have been recorded in the Qunf cave/Oman/Arabian sea and Tibetan regions. For example Fleitman's *et al.* (2003) $\delta^{18}\text{O}$ data of the speleothem samples from Qunf Cave, Oman, indicates peak precipitation from around 10000 to ~5000 yr BP with a stepped decline from ~8000 yr BP. For Tibet, Gasse *et al.* (1996) and van Campo *et al.* (1996) provide multiproxy records (pollen, radiocarbon, stable isotopes) from two sets of Holocene lake sequences (lakes Sumxi and Bangong). They identified major strengthening of the summer monsoon around 11500 yr BP with rainfall maxima from 10800 to 9600 yr BP and 8200 to 7200 yr BP, separated by an arid interval centered around 8800 yr BP. The trend towards long term aridity is observed after 6800 yr BP. These authors further conclude that the paleoenvironmental fluctuations in western Tibet are in phase with those of North Africa.

In comparison, during the Holocene period, most part of the southern Indian peninsula was vulnerable even to the slightest rise in sea level in response to the natural short term extreme events. An increased understanding of the temperature record in the few past years through a multi-proxy studies have strengthened our confidence in assessing the middle Holocene warming trend associated with the rise in sea level to reduced precipitation/regression in shoreline which is primarily the result of human activities since the last 3000 to 2000 yr BP. A considerable high resolution regional paleoclimate data are now available for a comprehensive integration with archaeological data in order to manage the vulnerable areas that may be a subject of immediate concern for the welfare of mankind, for economic and societal benefits in the future (Brock and Wikler, 2006). A compilation of paleoclimate data generated from the high altitudinal and tropical lakes of Indian and sites elsewhere are presented in Tables 1 and 2.

In this paper, we present a review of work that describes the recent trends in paleoclimate studies carried out in different parts of India based on lacustrine and paleolake deposits. These climate records are concerned with changes in regional and local climate, monsoonal shifts, past environmental and tectonic changes. For convenience, we have discussed the work and findings under six headings: a) palaeoclimatic records from the Himalayan zone, b) the Ganga Plain, c) the Central India, d) the Western region, e). the southern India and f) the coastal and wetland region (Fig. 1).

Late Quaternary-Historical Climatic Records from the Himalayan Zone: The Present Scenario

Several high resolution and well-dated records of Late Quaternary climatic variations are documented from the Himalayan region both from the northeast and northwest. Lake deposits from all these regions have provided continuous and high-resolution record of the past conditions (Das *et al.*, 2010). The most commonly used proxies are pollen, stable isotopes ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$), ostracods, grain size, mineral magnetism and various geochemical variables.

The high altitude moraine dammed lake Paru Co provided an 11,000 yr BP perspective record of local and synoptic-scale of the SWM variability and fluctuations in the lake levels. The sedimentological data indicate that the SWM was considerably weaker between 10,900 and 10,700 yr BP, but rapidly ameliorated to maximum intensity by 10,100 yr BP (Bird *et al.*, 2014).

Kar *et al.* (2015) reported modern pollen assemblages from Hamtah and Chhatru glaciers, Lahaul-Spiti. Wünnemann *et al.* (2010) studied the Tso Kar lake (Ladakh), to reconstruct the possible monsoonal impact on the hydrology of the lake basin during the last 15,000 yr BP using geochemical, mineral composition, aquatic pollen and non-pollen palynomorphs. The maximum glacier advance was observed between the LGM and ca 15,000 yr BP while considerable summer monsoon moisture supply occurred in the periods around 12,500 yr BP and between ca 11,500 and 8,600 yr BP. The maximum lake level rise occurred around 11,800 yr BP with a maximum extent between 8,500 and 7,000 yr BP under warm-moist climate conditions. Weakening in summer monsoon after 8,000 yr BP caused shrinkage of the

Table 1: Paleoclimate records of the lake sediments from India and world high altitude lakes

S.No.	Country and lake name depth	Altitude/	Protocols used	Inferences	References
1.	Tso Moriri Lake (Ladakh)	4600 m	Stable isotope	This region experienced increasing Indian Summer Monsoon (ISM) precipitation between ca. 13.1 and 11.7 cal ka and highest ISM precipitation during the early Holocene (11.2-8.5 cal ka)	Mishra <i>et al.</i> , 2015
2.	Lake Towuti (Indonesia)	293 m	Magnetic measurements	Magnetic parameters are controlled not only by detrital influx, which usually correlates with climate, but also by in situ geochemical processes, which do not always correlate directly with climate	Tamuntuan <i>et al.</i> , 2015
3.	Nainital and Sattal lakes (India)	1938 m and 1,370 m	Major oxides and phosphorus fractionation	High concentration of P and S in Nainital lake shows that it is affected both by natural and anthropogenic activities. The biogenic silica is high in Sattal when compared with other lakes	Purushothaman <i>et al.</i> , 2015
4.	Lake Tota (Colombian Andes)	3015 m	AMS ¹⁴ C radiocarbon	A period of high lake level is observed at Tota Lake from 4000 to 3620 cal. yrs BP	Cardozo <i>et al.</i> , 2014
5.	Wular Lake (India)	1580 m	Textural and geochemical studies	Sediments indicate low (recent) to moderate (past) chemical weathering of the source rocks, which are consistent with the prevailing climate in the area. It is a well-established fact that in cold climatic regions, chemical weathering is less when compared to physical weathering, thus this study presents a classical example of climate control on weathering	Rashid <i>et al.</i> , 2013
6.	Lake Blanc Huez (French)	2543 m	AMS ¹⁴ C, ²¹⁰ Pb dating and TOC	According to the available core chronologies, higher glacial activity may have occurred during the 3600-3300 cal. BP colder event and during the more recent Little Ice Age	Garçon <i>et al.</i> , 2012
7.	Northern Andes	2540 m	XRF Geochemical analysis (Lake Fúquene)		Bogotá <i>et al.</i> , 2011
8.	Lake Pumoyum*	~5030 m	¹⁴ C dating	Changes in organic matter sources in the sediment cores from the last glacial to the Holocene (after ~19 cal ka BP) were estimated by ¹⁴ C measurements of TOC and plant residues in three sediment cores	Watanabe <i>et al.</i> , 2010
9.	Lake Respomuso (Spain)	2130 m	XRF and XRD	The distribution of trace elements (As, Cd, Ni, Cu, Cr, Co, Mn, Pb and Zn) and their relationships with the major elements and mineral components evaluated by PCA showed that the metals are of geogenic origin	Zaharescu <i>et al.</i> , 2009
10.	Lake Titicaca (tropical Andes)	3810 m	Diatom biostratigraphy	During the mid-Holocene (6000-3500 cal yr BP), the abundance of the saline taxon <i>Chaetoceros muelleri</i> , coupled with high abundances of epiphytic and epipelagic diatoms, indicates maximum salinity and lowest lake levels in the entire 30 000 year record	Tapia <i>et al.</i> , 2003

Table 2: Paleoclimate records of India and Tropical lakes of the world

S.No.	Country and lake name	Depth	Protocols used	Inferences	References
1.	Lake Kivu (East Africa)	1463 m	XRF and High-resolution seismic	The onset of carbonate preservation since the 1970s that is currently observed in the sediment could indicate that hydrothermal discharge has recently increased in the lake	Ross <i>et al.</i> , 2015
2.	Pookot Lake (India)	775 m	Magnetic susceptibility & AMS	The vegetation history and climate for the past ~3100 years.	Veena <i>et al.</i> , 2014
3.	Lake McKenzie (SE Queensland)	85 m	Microfossils and geochemistry	A slowing or ceasing of sediment accumulation occurred during the time period from ca. 18.3 to 14.0 cal kyr BP	Atahan <i>et al.</i> , 2014
4.	Vembanad lake (India)	-	Physical and geochemical parameters	Vembanad Lake have indicated the chances of chemical transformation of mercury and the potential hazard if the deposited mercury fractions are remobilized	Mohan <i>et al.</i> , 2014
5.	Yanchi lake (NW China)	1195 m	Grain-size, mineral composition and geochemical proxies	The depositional environment is stable and the lake level is relatively high during the Late Glacial and the early Holocene	Yu <i>et al.</i> , 2013
6.	Bera lake (Malaysia)	25-30 m	Radioisotopes and sediment quality indices	Aquatic life threatens by the some toxic metals especially by As, Fe, and Cr metals	Gharibreza <i>et al.</i> , 2012
7.	Lake Valencia, Venezuela	400 m	AMS & Geochemical	From the latest Pleistocene to the earliest Holocene, total organic carbon (TOC) substantially increased from 2.2 to 10%, while total organic carbon over total nitrogen (TOC/ TN) decreased from as high as 34 to as low as 10	Xu and Jaffe (2008)
8.	Lake Naivasha, Kenya	-	Numerical and statistical analyses	Within-lake variability of surface sediment chironomid assemblages in the fairly large (~100-170 km ² since 1983) and shallow (Z _{max} = 5-8 m) fluctuating tropical lake	Eggermont <i>et al.</i> , 2007
9.	Lago Verde (Mexico)	149 m	Limnology	The highest anthropogenic impact was reached by ca. 1988	Caballero <i>et al.</i> , 2006
10.	Lake Abiyata (Ethiopia)	1577 m	Diatoms and pollen	The drastic drought of the end of the 19th century (around 1890 AD; 68-66 cm), or the deforestation and reforestation of the escarpments in the early 1970s	Legesse <i>et al.</i> , 2002

Fig. 1: Map showing some important lakes sediment cores that were used for paleoclimate reconstruction studies (Modified from Keerthi 2014)

lake to its lowest stand at about 4,200 yr BP, with the return of permafrost activity (Fig. 2). Three major lakes occurred due to deglaciation after the Last Glacial maximum (LGM) and Holocene warming (Phartiyal *et al.*, 2013; Nag and Phartiyal, 2014) along the 136 km stretch of the present day Indus River valley that existed around 17,000-13,000 yr BP (Rizong paleolake) occupying 35 km of the valley length, 14-5 yr BP (Khalsi-Saspol paleolake) 55 km and between 12,000-1,000 yr BP (Spituk-Leh paleolake) 40 km length. Phartiyal *et al.* (2015) recorded the changing depositional regimes since the last 48,000 yr BP from the Tangtse Valley with varied sedimentary architecture, fluvial episodes, lacustrine pulses, flood events, colluvial and Aeolian sediments. The site was located near the vicinity of the Karakorum Fault. They also pointed out sixth lake basin of Pangong Tso towards the west, occupying the present day Tangtse Valley, that existed between 9,000-5,000 yr BP coinciding with periods of high lake levels in Tibet and China. The data generated indicated monsoon

Fig. 2: (A) Represents the CWI and CaO/MgO graph of the Pookode lake in correlation with the graphs plotted following Ponton *et al.* (2012). The CWI values show good relation of warm and arid climate around 3800 and 1700 yrs BP. This also indicates drought in the southern region during the late Holocene 1700 yr BP, which also coincides well with the tank construction, (B) represent the $\delta^{13}\text{C}$ values of the leaf wax record from 16A sediment core off the Godavari river mouth, (C) calibrated radiocarbon ages of the sediment core 16A, (D) $\delta^{18}\text{O}$ measured on *Globigerinoides ruber* from 16 A sediment core, (E) Number of settlements based on archaeological data expressed as totals over culturally defined time intervals (see auxiliary material). In solid gray, sites from the Deccan Plateau (Andhra Pradesh, Karnataka, Maharashtra). In solid black, Indus (Harappan) sites from the dry Baluchistan, Sindh, Gujarat, Cholistan and lower Punjab. In dashed black, sites from rainier upper Punjab and Haryana following Ponton (2012)

intensification over the Indian subcontinent around 48,000 yr BP followed by drier and arid conditions around 30,000–21,000 yr BP.

Mishra *et al.* (2014) studied the hydrochemical, geochemical, mineralogical and sedimentology of the Tso Moriri Lake (Ladakh) sediments, isotopic composition ($\delta^{18}\text{O}$ and δD) of the inflowing stream water and the data indicated that Tso Moriri Lake is an evaporative lake with contributions from both westerly source (snow melt) and Indian summer monsoon precipitation. The lacustrine sediment variables from Lake Bhimtal, (Uttarakhand) studied by Choudhary *et al.* (2013) presented the 100-year record of paleo-productivity and changes in organic matter in lake revealing a sharp increase in lake productivity over the last two decades. However, anthropogenic influences in the catchment area point to a recent increase in the trophic circumstances of the lake.

The tectonically and structurally controlled Badanital Lake dated from ~5,100 yr BP to present revealed major climatic phases, especially pertaining

to 4,200 yr BP event, MWP (920–440 years BP), LIA (440–160 years BP) and 20th century warming trend (Kotlia and Joshi, 2013). On the other hand, a variance in the intensity of SWM for the past 6,500 yr BP based on the isotopic measurements of aragonite gastropods and lake sediments collected from the Kotla Dahar lake located in the northwest Himalaya, was presented by Dixit *et al.* (2014) (Fig. 3). The data revealed a sharp reduction in the SWM intensity and a peak in the E/P ratio in the lake catchment around 4,100 yr BP and suggested that the climate played an important role in the Indus de-urbanization. The 4,200 yr BP aridification event is regarded as one of the most severe climatic changes in the Holocene that affected several Early Bronze age sites.

An overview of available Late Pleistocene–Holocene records of the past vegetation *vis-a-vis* climate based on the latitudinal subdivision of the northeast region was presented by Mehrotra *et al.*, (2014). The study reveals a broad spectrum of the past climate in terms of humid/dry, warm/cold inferred based on the variations of some key pollen or group

Fig. 3: This panel depicts the vertical variations in (A) $\text{CaCO}_3\%$ (Kotla Dahar lake, Dixit 2014), (B) C/N ratio from the Nal Sarovar lake (Prasad and Enzel, 2006), the grey horizontal bar in C/N indicates drier events, (C). Variations of Organic Matter in Paru Co Tibetan Lake (Bird *et al.*, 2014) and concentration of the *Globigerina bulloides* % from the Arabian Sea (Gupta *et al.*, 2003), (D) Weight percent of calcium carbonate from the paleolake Rewasa sediments versus calibrated ages (Dixit *et al.*, 2014), (E) Nam Co Lake, Tibet (Doberschütz, 2014). The bar denotes climate transition at 2000, 4100, 7100–8000 yr BP and 9400 to 10300 yr BP wetter conditions and periods of high lake stands and or strengthened ISM rainfall

of pollen taxa depicted diagrammatically, thereby providing a glimpse of spatio-temporal vegetation *vis-a-vis* climatic changes using sub-surface samples also. Paleoclimate data based on pollen analysis of the last 3,000 yr BP from the Merbeel Swamp, Dibrugarh District, Assam, exhibits three climatic phases, i.e., relatively cool and dry (3,000-2200 yr BP), the onset of warm (2.2-0.85,900 yr BP), and an increased warm and humid conditions after 800 yr BP (Bera and Dixit 2011). A 1760 yr BP palaeovegetation record from the Mothabeel and Dangrithan reserve forests (Bera *et al.*, 2011) and a pollen analysis from Deosila Swamp, Rangjuli Reserve, Assam, revealed several stages of development and history of *Shorea robusta* forest and climate shifts since the last 6340 yr BP (mid Holocene) (Dixit and Bera, 2011). Their data reveal less cool and dry climatic conditions that prevailed during 6340-2970 yr BP followed by warm and humid climate that occurred during 2970 to 1510 BP. An increased SW monsoon and a more warm and humid climate prevailed from 1510 to 540 BP; becoming warmer and dry around 540 yr BP. This was probably due to the weakening of the monsoonal rains, and increased anthropogenic activities.

Bhattacharyya *et al.* (2014) carried out an analysis of vegetation cover and climate change of the Ziro Valley, Arunachal Pradesh since the late Quaternary period. Dixit and Bera (2012a,b,c) showed the development of tropical mixed deciduous forest since 14,120 cal BP using sedimentary record from the Dabaka Swamp in Nagaon District, Assam. Evidence for high energy fluvial activity during 14,120-12,700 yr BP preceded by the occurrence of tropical tree savanna vegetation under cool and dry climate was recorded between 12,700 and 11,600 yr BP. The Younger Dryas is recorded with less cool and dry climate around 11,600-8310 yr BP. Recurrence of intense fluvial activity between 8310-7100 yr BP and subsequent occurrence of tropical mixed deciduous forest under a warm and humid climate between 7100-1550 yr BP, coinciding with the peak period of the Holocene Climatic Optimum (HCO) was recorded. The tropical mixed deciduous forests continued to prevail under the increased warm and humid climates to 768 yr BP. However, since then the forest began to deteriorate under a warm and relatively dry climatic regime, accelerated by human settlement and forest clearance. Similar human settlement events since 560 BP are also described by Dixit and Bera (2011). A

similar trend in the Late Quaternary pollen/vegetation/climate relationship in and around the Chayagaon swamp, Kamrup District, Western Brahmaputra flood plain of Assam were reported by Bera and Dixit (2011) and Dixit and Bera (2012b).

There are only a few records available based on palynological studies from Meghalaya (Basumatary and Bera 2010 and Basumatary *et al.*, 2014a, b). Detailed pollen studies conducted by Basumatary and Bera (2010) on the Garobadha swam, West Garo Hills, Meghalaya, described the changing vegetation and climate scenario in the region since 1300 yr BP. Three climatic regimes: onset of warm and humid (1300 yr BP), increasing warm and humid (~752 yr BP), and warm and dry (~322 yr BP) are recorded. A detailed palynological analysis of the subsurface sediment from Srinagar, southwest Tripura, was carried out by Bhattacharyya *et al.* (2011) and their studies revealed that the climate during 7000-3000 yr BP in that region was dominantly warm and humid between 6800~3800 yr BP. The probable evidence of the beginning of rice cultivation during the mid-Holocene in the region came from the large-sized grass pollen, that occur since 5700 yr BP.

Ghosh *et al.* (2015) and Bera *et al.* (2015) submitted a ~50,000 yr BP record of monsoonal variability in the Darjeeling foothill region of the eastern Himalayas. Pollen, phytoliths and $\delta^{13}\text{C}$ signatures of the soil organic matter from the two fluvial sedimentary sequences of the Darjeeling foothill region, eastern Himalayas portray palaeoclimatic oscillations and their impact on regional plant communities over the last ~50,000 yr BP (Ghosh *et al.*, 2015). Quantitative paleoclimate estimation using the coexistence approach on pollen data and other proxies indicates significant oscillations in the precipitation during the late part of MIS 3 (46,400 to 25,900 yr BP), early and middle part of MIS 2 (25,900-15,600 yr BP) and 5,400 to 3,500 yr BP. Middle to late MIS 3 (ca 46,400-31,000 yr BP) was characterized by a comparatively low monsoonal activity and slightly higher temperature than that during ca 31,000 yr BP onwards. Simultaneous expansion of deciduous trees and chloridoid grasses also imply a drier and warmer phase. Between 31,000 and 22,300 yr BP (late MIS 3 to mid-MIS 2), higher precipitation and a slightly cooler temperature led to an increase in evergreen elements over deciduous taxa and wet-loving panicoid grasses

over dry-loving chloridoid grasses than earlier. After ca 22,300 yr BP, shrinking of forest cover, expansion of C4 chloridoid grasses, Asteraceae and Chenopods in the vegetation with lowering of temperature and precipitation characterized by the onset of the LGM which continued till 18,300 yr BP. Restoration in the forest cover and increase in the temperature and precipitation regime occurred by the end of LGM. However, since 5,400 to 4,300 yr BP, intense monsoonal activity supported a dense, moist evergreen forest cover that subsequently declined during 4,300 to 3,500 yr BP. A further increase in the deciduous elements and non-arboreals was a consequence of reduced precipitation and higher temperature during this phase.

Although a good data set is available on the late Quaternary paleoclimate from the Himalayan states of India, there is still a dearth of complete quantitative inferences and/or climate reconstruction models based on the present records and climate data and this creates a gap in our understanding of the late Quaternary paleoclimate and vegetation scenarios (Mehrotra *et al.*, 2015). Moreover, there is a paucity of well exposed Quaternary lithosections or lake deposits as the region is often subjected to natural hazards, degradation of vegetation and sediment cover due to anthropogenic activities and local urbanisation.

Historical Culture-climate Data from the Ganga Plain

Ganga Plain, one of the biggest alluvial tracts of the world, is about 1000 km long and 200-450 km wide. The thickness of the alluvium in the Ganga Plain is about 3000-5000 m towards Himalaya and 200-300 m towards the Peninsular Plateau. Several tributaries of the Ganges river form a dense network over the Gangetic plain providing a freshwater, which is the main reason of it being one of the most polluted regions of our country. Apart from the river network several, lakes, ponds and low lying areas are spread over that have been used for reconstructing the late Quaternary palaeoclimatic and geoarchaeological research. Several sites have been excavated and researched since 2010-2015 and some of the interesting results are presented below:

Stable oxygen isotope record from the biogenic carbonates analysed from the Rewasa Lake (Haryana) sediments provided the first terrestrial

evidence of the 8.2 kyr drying from the Indian subcontinent (Dixit *et al.*, 2014) (Fig. 3) and a history of the Indian Summer Monsoon from <“11000 to 6000 yr BP. Saxena *et al.* (2013) identified five wet phases alternating with four dry phases since the past 10,600 yr BP. The phytolith assemblage and Phytolith index of the Lahuradewa lake sediments revealed a dry phase between 5300-4100 yr BP. A multi-proxy study, including pollen, sediment texture and organic/inorganic carbon analyses of the Chaudhary-Ka-Tal (UP) revealed that around 8470-6422 yr BP grasslands thrived in the region under a warmer and moderately-humid climate conditions than today (Saxena *et al.*, 2015). The appearance of cerealia pollen ~7500 yr BP indicated incipient agrarian practice and the period between 6422-3150 yr BP, a warm and more-humid climate attributed to the strengthening of the SW monsoon was recorded.

Trivedi *et al.* (2011) studied the lake sediments from Ropan Chhapra Tal, Deoria district (UP) and suggested that between 1350 and 600 yr BP, open grassland vegetation with sparse trees grew under a dry climate with moderate monsoon rainfall. A brief spell of pluvial environment occurred between 600-425 yr BP with a sharp reduction in trees from 425 yr BP onwards and the expansion of grasses denoted the onset of relatively drier climate, probably in response to a reduction in the monsoon rainfall. Trivedi *et al.* (2013) studied the Jalesar Lake (UP) sediments and based on multiproxy data demonstrated that prior to 42,490 until 13,560 yr BP; the Central Ganga Plain supported grassland with scanty trees under a cool and dry climate. The upwarping phase of the Ganga Plain occurred during 13,560-5260 yr BP and that between 5260 and 4760 yr BP the establishment of forest groves under an ameliorating climate thrived. However, around 4760-3260 yr BP, the forest groves diversified and the margins around the lake expanded and acceleration in agricultural practices was observed. Between 3200-1200 yr BP climate became less humid and since 1200 yr BP weak SW monsoon was recorded. Singh *et al.* (2015) reported a 400 to 1200 AD record of the Ropan Chhapra Tal in the Central Ganga Plain using sedimentology, environmental magnetism, and stable isotope of oxygen for SWM variability. Their study revealed that during 400-900 AD, humid to warm, dry conditions favoring stronger SWM seasonality; intense SWM at ~480 and ~540 AD with flooding around ~700 AD and a weak

monsoon in 580 and 740 AD, with drought at around 500 AD occurred. The multiproxy record suggests that during ~900–1200 AD intense summer monsoon was synchronous with the Medieval Warm Period (MWP), whereas after 1200 AD, weak monsoon phase coincided with the onset of the Little Ice Age (LIA).

However, the statistical analysis and modeling of Indian Monsoon variability during the past millennium was primarily focused on Medieval climate anomaly (MCA) and the LIA (Polanski *et al.*, 2014). The paleo-hydrological changes depict a dipole pattern between Himalaya and Central India between the LIA and the MCA. Palynological and sedimentological studies also revealed that the LIA was not continuous but interrupted by the short duration of the warmer periods (Achyuthan *et al.*, 2013).

Climate and Precipitation Fluctuations from the Central India

Various well-dated multi-proxy studies have been carried out in the Himalaya and Central Indian lakes (Mishra *et al.*, 2015; Polanski *et al.*, 2014; Anoop *et al.*, 2013). Chauhan *et al.* (2013) studied the palynology, texture, mineralogy, geochemistry, and magnetic susceptibility from Padauna Swamp, (MP) and inferred a warm and relatively less humid climate between 8600–7500 yr BP. However, between 7500–6250 yr BP in response to the onset of a warm and humid climate, the tree-savannahs succeeded by open mixed deciduous forests with the invasion of a few more trees. The period between 6250–2800 yr BP reflected warm and more-humid climate probably due to the invigoration of southwest monsoon. A warm and more-humid climate, including the timely arrival of SW monsoon was observed since 2800 yr BP.

Tripathi *et al.* (2014) discussed a pollen database synthesis of the palaeovegetation and climate oscillation of western Odisha. Quamar and Bera (2014a, b) described vegetation (modern pollen-vegetation) and climate change during the mid and late Holocene in northern Chhattisgarh, central India inferred from pollen records. The Late Holocene paleoclimatic studies based on palynological analysis of Talbehat, Madaura and Dhaura sediments near Jhansi revealed a shift in vegetation depicted in three distinct pollen zones since 4000 years BP to 1400 years BP (Farooqui and Sekhar, 2011) being Moist

Deciduous Forest at around 4000 yrs BP to Mixed Deciduous Forest at around 2000 yrs BP and finally to Dry Deciduous Forest since ~1400 yrs BP. This study, in particular, showed that during this time the vegetation succession was in equilibrium with the climatic fluctuations and the agricultural expanse was very limited also due to undulating terrain. When compared to the vegetation succession recorded from the Gangetic plain, it was in contrast, as the Gangetic plain during this period was greatly under the influence of anthropogenic activity with extensive agricultural expanse.

Climate-culture, Historical Records from the Western and Northwestern India

Prasad *et al.* (2014) adopted a multi-proxy approach, using palynology, phytoliths, sedimentology, clay mineralogy, carbon isotopes and magnetic mineralogy analyses of Wadhvana (Gujarat) lake sediments to determine the mid-Holocene climatic fluctuations, and surmised that the urbanization in the Harappan civilization in northwest India was coincident with the initial phase of drastic decline in the rainfall during mid-Holocene. The emergence of cultural complexity of Harappan civilization was an initial adaptation to the earliest phase of environmental deterioration during this period. The subsequent decline of the Harappan civilization is probably linked to the changing seasonality pattern and excessively dry climate of later phase (~4200–4255 yr BP) of the mid-Holocene. Raj *et al.* (2015) based on a multiproxy study of the Pariyaj Lake archive, studied the Holocene climatic fluctuations of the Gujarat alluvial Plains.

Coastal archaeological sites serve as potential archives of past climate-culture and vegetation relationship, responding to the relative sea level changes during the Holocene. Most of the Harappan dwellers along the coastal region largely depended on perennial or monsoon-driven river systems for fresh water requirements for the agriculture based sustenance. The period since 4000 yrs BP witnessed climatic amelioration from warm and humid (high precipitation) to dry and arid (low precipitation). Consequences of climate change evolved the vegetation from evergreen moist deciduous to dry deciduous as number of dry months per annum increased. The palynological results from Bet Dwarka, Bokhira (Porbander) revealed absence of vegetation,

although fresh water thecamoebians and few marine palynomorphs indicated the relative extent of fresh water and marine water incursion (Farooqui and Gaur, 2013). Results from the Kodinar (Kaj and Kanjetar) revealed a significant abundance of evergreen and moist deciduous vegetation around 4000 yr BP, which gradually declined and was replaced by dry deciduous vegetation by around 2000 yrs. BP (Farooqui *et al.*, 2013). The present day hinterland vegetation in these areas and adjacent northeast Gir Forest is largely represented by dry deciduous plant taxa except for mangrove in coastal areas. The overall results show that the dry and arid climate reached its climax in Bokhira and Porbander (22°-22° 30' N Latitude) around 4000 yr BP while in Kodinar (21°-21° 30' N Latitude) it reached its climax around 2000 yrs. BP. Thus, the climatic climax of dry and arid conditions shifted from North to the southern region of Saurashtra. The fragments of ancient potteries and other artefacts recovered from the lower sediment layers provide evidences of Sorath-Harappan colonization in the vicinity which was not an urban site.

The abundant cyanobacterium remains, low terrigenous organic matter, aquatic pollen and low thecamoebians in lower sediment layers point to low precipitation and arid climatic conditions ~2000 BC (Farooqui *et al.*, 2013). During this period the dominance of evergreen and moist deciduous arboreals from both the sites does not show equilibrium with the prevailing dry/arid climate and therefore, the pollen assemblage here represents the remnants of wetter middle Holocene vegetation in the region. Phytoliths of drought tolerant summer season crops also reflects here changes made in the agricultural strategy by the Harappans in response to climate (Enzel *et al.*, 1996; Giosan *et al.*, 2012; Ponton, *et al.*, 2012; Rashid *et al.*, 2011; Madella and Dorian, 2006; Possehl 2002; Staubwasser *et al.*, 2003). The increase in deciduous arboreal pollen since the last 2000 years represents equilibrium with the dry/arid climate (Madella and Dorian, 2006; Farooqui *et al.*, 2013). But, enhanced limnic conditions recorded due to the occurrence of thecamoebians during this period are attributed to changes in wetland configuration induced by hydrostatic changes in the river mouth. This was also largely defined by the dynamics of sediment deposition through rain-fed rivers/streams in the region (Farooqui *et al.*, 2013).

Ponton *et al.* (2012) reconstructed the Holocene paleoclimate in the core monsoon zone (CMZ) of the Indian peninsula using a sediment core recovered offshore from the mouth of Godavari River. Carbon isotopes of sedimentary leaf waxes proved to be a useful tool for an integrated and regionally extensive record of the flora in the CMZ and they documented a gradual increase in aridity-adapted vegetation from ~4,000 until 1,700 years ago followed by the persistence of aridity-adapted plants after that. The oxygen isotopic composition of planktonic foraminifer *Globigerinoides ruber* detected an unprecedented high salinity events in the Bay of Bengal over the last 3,000 years, and especially after 1,700 years ago, which indicated that the CMZ aridification intensified in the late Holocene through a series of sub-millennial dry episodes. Cultural changes occurred across the Indian subcontinent as the climate became more arid after <4,000 years. Sedentary agriculture took hold in the drying central and southern India, while the urban Harappan civilization collapsed in the already arid Indus basin. The establishment of a more variable hydroclimate over the last ca. 1,700 years may have led to the rapid proliferation of water-conservation technology in south India (Giosan *et al.*, 2012 and Ponton *et al.*, 2012).

Late Quaternary Records from the Southern India

The lake sediment retrieved from southern Indian lakes has largely been studied for reconstructing the fluctuations in the intensity of the SWM. The late Quaternary studies of the Vembanad Lake peat deposits indicated arid climate prior to 40,000 yrs BP humid climate. Detailed pollen studies revealed the existence of mangrove vegetation and evergreen forest, suggesting a humid climate and high intensity of SWM during that period (Nair *et al.*, 2010; Padmalal *et al.*, 2014; Nair *et al.*, 2014). The occurrence of a peat sequence in the sediments in the low-lying area around the Vembanad Lake supported by radiocarbon dates showed that their formation was from the submerged coastal forests, especially of mangrove vegetation (Nair *et al.*, 2014). The palynological study of the late Quaternary evolution of Ashtamudi–Sasthamkotta lake systems of Kerala reveals that a marine transgression occurred at ~6000yrs BP coupled with heavy rainfall in the hinterlands that was responsible for faster sedimentation in the region (Nair *et al.*, 2010).

Fig. 4: Compilation of the late Quaternary to Holocene paleoclimate reconstructed from different lakes adopting multi proxy analyses

The recent studies in the Pookode Lake, Kerala, analyzing the multi proxies, such as sediment texture, radiocarbon dating, phytolith, diatoms, spores and pollen revealed a change in the hydrological conditions as well as shallow of the lake since the last 6000 yr BP (Veena *et al.*, 2014). The lake sediments have preserved the evidence of the Medieval Warm Period (MWP) and the Little Ice Age (LIA). Textural analysis, geochemistry and palynology revealed the occurrence of a warm and dry period that prevailed during 6,200 to 420 yr BP and were interrupted by the wet phases between ~ 3,900 to 1,900, 1,400 to 760, 420 to 140 yr BP due to strengthening of SWM, rise of water level, and the expansion of the Pookode lake margin (Veena *et al.*, 2014; Nair *et al.*, 2014) (Fig. 4).

Further corroborating the data of the Pookode Lake; a detailed limnology of the Kukkal lake sediments revealed a continuous sediment record since the Early Holocene to the present (9000 yrs BP to present). The present lake situated at an elevation of

~1887m.a.s.l., is a small basin that appears to have alternated between lacustrine and wetland deposition. Climate proxies including sediment texture, TOC, TN, C/N, pollen and geochemical composition indicate a steady progression to wetter conditions, with two stepwise changes at about 8000, and between 3200 and 1800 years BP. The change at 8000 BP appears to correspond to a brief (100-150 years) dry spell recorded elsewhere in India. The change at 3200-1800 BP consisted in a rapid intensification of the southwest monsoon, and may correlate with the initiation of the Roman Warm Period. There is no clear evidence of changes at the times of the Medieval Warm Period and the Little Ice Age. The C/N ratio of the sediments ranges from 14.02 to 8.31 indicating that the organic matter originated from a mixture of lacustrine algae and vascular plants. Chemical weathering indices (CIA, CIW and PIA) are consistent with extreme silicate. Pollen data show an evolution from savanna vegetation prior to about 8000 years BP, followed by grassland with palms, the appearance of spore-bearing plants just prior to 3200

years BP, and the reestablishment of 'Shola' forest between 3200 and about 1800 BP (Vijayraj *et al.*, 2016).

Similarly, another sediment core raised from the Parson's valley, Ooty, was Radiocarbon dated. The ages range from ~22,470-1240 yr BP. The C/N value varies from 10.30 (21,810 yr BP) to 22.45 (1240 yr BP) reflecting mixed (terrestrial and aquatic) origins of the organic carbon since the late Marine Isotope Stage 3. The sediments are mostly silt (84%), with minor amounts of clay and sandy silts. The $\delta^{13}\text{C}$ values exhibited major shifts from -17.6 to -14.0‰ around 22,470 yr BP to 19,100 yr BP and -16.9‰ to -3.8‰ around 1240 to 820 yr BP is reflecting drier conditions due to decrease in the intensity of both the monsoons (Priyanka *et al.*, 2016). A shift of $\delta^{13}\text{C}$ from -14.7‰ to -16.5‰ (around 15,900 to 2820 yr BP) points to ameliorate monsoon conditions. Absence of coarser sediments indicates reduced terrestrial flux due to the decrease in monsoonal runoff, dry climate or thick vegetation canopy around the lake since 19,100 yr BP (Priyanka *et al.*, 2016).

Basavaiah *et al.* (2015) employed mineral magnetic, geochemical, and textural parameters to elucidate the climate and sea level change signatures from Kolleru lake sediments representing the inter-deltaic part of the Krishna-Godavari sedimentary basin (KG basin). The various mineral magnetic parameters, c and S -ratio along with major elemental concentrations of Ti, Al, Fe and Zr show signatures of an arid event before 10,000 yr B, between 9,000-8,000 yr BP periods and during the last 5,500 yr BP. The overall climate of warm and humid type was inferred from 10,000 to 9,000 yr BP, which correlates with Early Holocene Optima and 6,000 to 5,500 yr BP of Middle Holocene. The presence of evaporite crystals in the lower layers of the sediment core corroborated by mineral magnetic and geochemical proxies indicates sub-aerially weathered facies during the arid Late Pleistocene. Similarly, the peat layers rich in mangrove pollen indicate sea level changes between 10,000 yr BP and 6,000 yr BP. The sub-surface position of the Pleistocene weathered layer and the Holocene peat layer suggests tectonic subsidence of the area, which is situated over the basement graben, known as Gudiwada sub-basin.

Recent work on the Vellayani lake, carried out by Veena *et al.* (2015), suggested that the humans

have continuously changed the landscape and vegetation cover of the earth, including deserts and lake margins. Vellayani Lake, Kerala, is being severely affected by human activity in the catchment basin. Population increase, leading to increased demand for agricultural land and water, is driving a positive feedback loop resulting in the accelerating siltation of the lake and lowering of water levels. A 145 cm sediment core has represented deposition since 3000 years BP, but at least half of the sediment has been deposited since 1650 AD, possibly since 1950 AD. The sediment stratigraphy was disturbed, most likely by slumping since 1970, of an unstable sediment accumulation near the lake margin. The disturbance precludes detailed interpretation of paleoenvironmental proxies, textural variation, chemical weathering index, pollen and phytolith assemblages. The proxies provided evidence of drier climate up to 3000 years BP, and wetter conditions at about 1210 years BP. Low frequency of phytoliths morph types indicated reduction in vegetation cover and a significant increase in grassland since 2300 yrs BP due to climate warming, weakened southwest monsoon, deforestation reclamation of the lake margins for intensive agricultural practices. Occurrence of diatoms and sponge spicules indicated shallowing of the lake from 2300 yrs BP onwards. Occurrence of charcoal pieces post 3,000 yrs BP represented human impact along the lake margin. Integration of all the results showed that the Vellayani Lake contracted because of a weakened Indian southwest monsoon since 3000 yrs BP, intense human impact in the form of deforestation, irrigation and agricultural practices.

Climate Induced Relative Sea Level Fluctuations from the Southern Coastal Zone

A complex interplay of riverine and marine processes has shaped the deltaic areas of the Indian peninsula in space and time. Most of rivers/streams that join the Bay of Bengal in the east and the Arabian Sea in the west traverses a long distance and are monsoon driven. Therefore, the palynological succession reconstructed from sediments deposited in coastal wetlands largely depict the changes in Indian monsoon. In India, the coastal wetlands sustain millions of people and are more vulnerable to the effects of a rise in Relative Sea level (RSL) and changes in marine ecosystems. The sediment depositional environments varying from lacustrine to fluvial, fluvio-marine to

purely marine depends upon the geomorphology and related shoreline fluctuations. The deltaic dynamism is largely influenced by monsoon driven active channels, tectonic nature of the basin, sea-level changes, relief of the drainage basin and climate. The analysis of delta building process through time and the dynamics of the coastal wetlands are essential to predict the future changes, especially in context of sea level rise and coastal erosion. Land subsidence in modern coastal or deltaic plains is a common process. Sea water invasion and loss of deltaic land have been reported in Krishna-Godavari delta (Nageshwara Rao *et al.*, 2013; Farooqui, 2013; Ranjana and Farooqui 2015; Farooqui *et al.*, 2016).

The consequences of climate change and land subsidence are often related to sea level rise/fall. Mangroves, its extinction and migration through time was assessed through palynological studies in two sediment cores from Kanuru (500 cm deep) and Machilipatnam (118 cm deep), Krishna delta, India. Four Units were identified on the basis of marine/terrestrial palynomorphs. In Unit 1, the marine palynomorphs indicate palaeoshoreline in Kanuru from 8420-8300 yr BP, which is now ~4-5 kms inland from the present shoreline. After a short span a retreat in sea level took place between 8300-7040 yr BP. Subsequently, about 3-4 short-term intermittent rise/fall in RSL were recorded in Unit 2 between 7040 and 3980 yr BP in Kanuru and between 5225-3240 yr BP in Machilipatnam. The Unit 3 is characterized by non-estuarine sediment deposition since 3920-240 yr BP in Kanuru and since 3240-950 yr BP in Machilipatnam. The Unit 4 reveals a rise in RSL in both the studied sites which began much earlier in Machilipatnam than in Kanuru. Loss of mangrove diversity and dominance of salt tolerant mangroves was recorded in Unit 4. Results indicate climate induced RSL fluctuations highlighting the event of 8200 yr BP from Kanuru site and duration of the intermittent rise/fall of RSL during the Middle Holocene transgression. The rate of sea level rise during the period was not continuous but interrupted by 3-4 retreats (Farooqui, 2013) suggesting neotectonics. Overall the results reveal that Middle Holocene warming and sea level rise was not continuous but fluctuated with intermittent short duration before the weakening of monsoon was set in during the late Holocene (~3000-2500 yr BP).

Similar trends in climate induced relative sea level changes were recorded from the Pichavaram estuary, Tamil Nadu. The pollen and sedimentology results reveal a climate shift from warm and humid with the strengthened monsoon (3630-3190 BP) to dry and arid (~2750-760 BP). Since the last millennium (~760 BP), Pichavaram estuary has been influenced by a similar cyclicity but with a less wet and humid climate due to weakened northeast monsoon conditions. The ecological changes, in turn, affect the relative sea level rise and fall, which is reflected by the variability/extinction of freshwater and marine palynomorphs (Srivastava *et al.*, 2013). The palynological reconstruction of sediments deposited between (2,500-4,000 yr BP) reveals fluvio-marine deposition and a good percentage of diverse mangrove species, indicating comparatively strengthened monsoon condition (warm and humid climate) along with adequate seawater ingress through tidal inlets which favoured the estuarine ecosystem. During this period the stability of relative sea level is recorded due to the consistency recorded in the mangrove pollen percentage and other terrestrial and marine palynomorphs (Srivastava *et al.*, 2011, 2012, 2013; Srivastava and Farooqui, 2013). The overall results from coastal wetland archives also conform with the records of climate changes documented on land in different parts of India.

Climate Induced Vegetation Changes During the Late Pleistocene: Evidences from the West Coast

Neogene rain forest flora recorded earlier from the Varkala Formation and the present record of its existence since MIS-6 in the region indicate that the monsoon circulation over the southern India was similar since the Middle Miocene Climate Optimum and the flora in the South-Western Ghats is a fossil ecosystem and a relic of the Tertiary period (Farooqui *et al.*, 2014).

The southwestern Ghats region of the Indian Peninsula is unique for its extant endemic rainforest flora supported by high rainfall throughout the year. The record of tropical rainforest corresponding to the dynamic series of Pleistocene interglacial/glacial cycles is poorly known from peninsular India. The palynological study of organic matter (OM) deposits (>40,000 yr BP) in two well sections (Chaganachery, Kerala) from the Indian Peninsula (west coast) were

carried out. A rich archive of tropical rainforest pollen/spores and marine dinoflagellate cysts indicates anoxic fluvio-marine/estuarine deposition environments during warmer climate with an intensified Asian monsoon. The geochemical fingerprinting of glass shards indicates the presence of Youngest Toba (YTT) ash of ~74,000 yr BP from northern Sumatra, and therefore establishes a time-controlled stratigraphy. The depositional time period of the OM is related to the sea level highstand of Marine Isotope Stage 5.1 (~80,000 yr BP) which was the host to the YTT shards. The Late Quaternary pollen/spores diversity suggests that the modern climatic conditions in the southwestern Ghats have facilitated the conservation of moist evergreen rainforest and dry/moist deciduous forest. The pollen grains show its lineage with the extant flora and some of the fossil pollen recorded during the mesic Tertiary period from the Indian peninsula. Thus, it appears that the tropical rainforest survived here as 'Plant Refugia' in xeric (glacial) Quaternary periods, perhaps as riparian vegetation, and was rejuvenated during the Holocene as modern extant flora (Farooqui *et al.*, 2010).

Further, a palynochronological study of a 552 cm deep sediment core from the southeastern Arabian Sea covered a time span of ~1,40,000 yr BP. The age estimate is based on oxygen isotopic data of planktic foraminifera. Six zones were identified on the basis of palynology covering partially MIS-6 and MIS-5 to MIS-1 (Marine Isotope Stages). The interglacial period (MIS-5) reveals high rate of sedimentation corresponding to the high percentage of terrestrial rain forest pollen. The palynological study reveals highstand and intense rain forest vegetation during MIS 5a, which corresponds to the similar earlier records of estuarine ecosystem on land in Kerala. The relative sea level rise and fall since ~1,40,000 yr BP have been inferred through quantitative estimate of marine versus terrestrial palynomorphs. The terrigenous non-pollen forms comprised abundant Neogene extinct nanoplanktons (*Discoaster* spp.) until MIS-3 and was transported from the Varkala Formation (highlands of the Kerala coast). The pollen assemblage is comparable to the present day flora in Kerala therefore, the provenance of pollen recorded in the studied core is Western Ghats of India. High percentage of planktic foraminifera and dinoflagellate cysts throughout the core indicates high productivity that suggests upwelling induced by seasonal reversals

in the monsoon winds even during the glacial periods. *Botryococcus* remains, and poaceous leaf cuticles dominated by the *Pooideae* group in the marine realm also point towards active winter monsoon. Considerable fragmentation of rain forest took place post 74,000 yr BP and during the LGM as the sea retreated to its maximum which resulted into the vast exposure of land favoring the expanse of grassland with pockets of rainforest "plant refugia" on land.

Lastly, substantial records of modern pollen studies and vegetation distribution in terms of surface pollen records are available (Basumatary and Bera, 2010; Bera and Dixit, 2011; Dixit and Bera, 2011, 2012a, b, c; Bera, *et al.*, 2011; Basumatary and Bera, 2012; Achyuthan *et al.*, 2013). However, for the reconstruction of paleoenvironments, there is a need for the detailed quantification of the surface pollen data, modern pollen rain which represent the modern climate. These data supplemented by fossil pollen records can be calibrated to develop a transfer function model (Guiot, 2011) which then can be used to quantitatively reconstruct paleoclimates with a greater degree of confidence. There is a need for such climatic reconstruction, which has not yet been attempted.

Conclusions

Several studies through different proxies show the sensitivity of biotic forms which correspond to more or less well defined climatic fluctuations in most of the studied areas in India. The duration of the climatic events and its intensity, however, varied from region to region depending on the local landscape and geographical location. Following points emerge from this review study based on the reconstruction of southwest monsoon and climatic conditions since the late Quaternary depicted using multi-proxy studies involving sedimentology, geochemistry, pollen/spores, phytolith, etc.

1. It is noted that through the late Quaternary to the Holocene period the intensity of SWM declined, but was interspersed with short intervals of high rainfall. This allowed the margins of the lake to shrink, but increased during the short periods of high rainfall. There was a gradual vegetation evolution by a reduction in the percentage of evergreen forest to semi-evergreen or to mixed moist deciduous forest

and these changes occurred in most of the areas in the Indian sub-continent.

2. Moderate to low rainfall areas in India reveal a drastic change from moist deciduous forest to dry deciduous forest since the last 5000 to 4000 yr BP. These changes are interrelated to three main factors such as the influence of extra-tropical Westerlies in western and central Himalayas, the summer temperature gradient between Bay of Bengal and Indian subcontinent along with Indian East Asian Monsoon affecting the eastern Himalayas. The central India is affected by summer sea surface temperatures of the Arabian sea influenced by Indo-Pacific warm pool that modulates the Indian monsoon.
3. The lake records irrespective region in India, few of them hold signature of the 8200 solar insolation, 4200 arid environment, 3800 warm and dry periods, MWP and LIA events. The overall results from coastal wetland archives also conform to the records of climate changes documented on land in different parts of India.

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Acknowledgements

In this review, we have considered all the published data till date, if we have missed any, this was inadvertent. We acknowledge all the researchers who have published their work. We are grateful to Prof. A.K. Singhvi, PRL, Ahmedabad, for inviting us to write a review on the reconstruction of Late Quaternary to Holocene past climate based on lake sediments. Gopal V and Lone A thank the UGC, New Delhi for the Dr DS Kothari Postdoctoral Fellowship (No.F. 4-2/2006(BSR)/ES/14-15/0020) and Anna Centenary Research Fellowship, Anna University, Chennai, respectively. We thank the reviewers for their encouraging comments that helped in the presentation of the data and the manuscript.

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