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Journal of Climate Change, Vol. 3, No. 2 (2017), pp. 11–23.
DOI 10.3233/JCC-170011

Deciphering the Past Climate and Monsoon Variability from Lake Sediment Archives of India: A Review

Om Kumar[1,2*], Rahul Devrani[1] and AL. Ramanathan[1]

[1]School of Environmental Sciences, Jawaharlal Nehru University, New Delhi – 110067
[2]Department of Geology, Centre for Advanced Studies, University of Delhi, Delhi – 110007
✉ omkrs007@gmail.com

Received June 14, 2017; revised and accepted July 22, 2017

Abstract: With a view to get a broader picture of paleoclimate/paleomonsoon variability we have selected 30 lakes with reliable chronologies from the climatically sensitive regions of India. An integrated review of different climate proxies i.e. grain size, C/N ratio, pollen, $\delta^{13}C$ and $\delta^{18}O$ and mineral magnetism on a radiocarbon dated sediment cores is carried out for present study. Here we present a climate-proxy record of monsoon variability over the past ~50,000 yr from monsoon and non-monsoon dominated regions. Our results based on multiproxy sediment records of lakes reveal that India experienced different climate and monsoon variability throughout geological past. Paleorecords give an insight of two climatically significant periods in this study area. A high monsoon activity has been noticed during the time resolution of 13 ka to 8 ka while a short dry period has prevailed during 5 ka-4 ka that is concurrent to the offset of Harappa civilization. Importantly, majority of paleoclimate records demonstrate that a Younger Dryas (12.9 ka-11.5 ka) records are not well preserved in lacustrine archives.

Keywords: Monsoon variability; Paleoclimate; Non-Himalayan lakes, India.

Introduction

Paleoclimatic studies play an important role in improving understanding of past climate variability on longer time scales. Various records viz. lacustrine (Anoop et al., 2013; Dixit et al., 2014; Juyal et al., 2004; Prasad et al., 2014; Rajagopalan et al.,1997; Sarkar et al., 2014), marine (Gupta et al., 2003; Ponton et al., 2012; Stubwasser et al., 2003; Trauth et al., 2003), speleothems (Burns et al., 2002; Kotlia et al., 2015; Lachinet et al., 2004; Sinha et al., 2011; Yadav et al., 2005), tree rings (Borgaonkar et al., 2011; Yadav et al., 2011) and ice cores (Jouzel et al., 2007; Lorius et al., 1985; Petit et al., 1999) have been used to document climate variability during late Quaternary period in many parts of the world. Lacustrine deposits are one of the important terrestrial archives to study climatic change and can be used to decipher past climatic oscillation in different time scale. Many workers have used lacustrine deposits to decipher paleoclimatic information and past monsoon variability in India (e.g. Anoop et al., 2013; Dixit et al., 2014 and references therein; Menzel et al., 2014; Prasad et al., 2014; Rajagopalan et al., 1997; Sarkar et al., 2014).

The lacustrine deposits have proved to be high resolution paleoclimatic archives as they are governed by paleohydrological changes. Using lacustrine sediments, several proxies are widely applied to re-construct past climate and monsoon variability. These proxies include mineral magnetism, speleothems, isotope geochemistry, pollen, noble gas and grain size. The environmental magnetism in lacustrine sediments have been widely used to study paleoenvironmental and paleoclimatic changes in India (e.g. Shankar et

*Corresponding Author

al., 2006; Warrier and Shankar, 2009); and other parts of world (Duan et al., 2014; Oldfield et al., 1978; Peck et al., 2004). High magnetic susceptibility values refer to warm and/or wet periods whereas low values denote cold and/or dry periods (Evans and Heller, 2003; Vlag, 1999). However, in particular cases, high susceptibility signify cold, glacial periods while low values indicate interglacials (i.e. Evans and Heller, 2003). Pattern of particle size distribution and variation is widely used by researchers to determine paleoclimate/paleoenvironmental condition, mainly due to its high sensitive to climatic changes (Conroy et al., 2008; Peng et al., 2005; Warrier and Shankar, 2009). Sediment grain size is an useful indicator of energy conditions referring to the intensity of water current or turbulence level (Folk, 1966) and water depth (Campbell et al., 1998); wherein finecoarse grained sediments are deposited in a low/higher energy condition. The stable carbon isotopic composition of organic matter ($\delta^{13}C$) from the lacustrine sediments has been widely used to reconstruct and paleoenvironmental changes and paleovegetation in India and different parts of world (Meyers, 1997). In addition, the paleolake level fluctuation and source of organic matter also can be estimated by $\delta^{13}C$ value of organic matter present in lacustrine sediment. The C3 plants are more abundant during wet conditions whereas C4 plants usually spread during phases of dry climate (Tieszen et al., 1979).

By utilizing multi proxy data, it is possible to obtain paleoclimatic/paleomonsoon records beyond the range of instrumental observations. Hence, proxy reconstructions are therefore needed in order to study climate of the past and paleomonsoon variability. The paleoclimatic and paleomonsoon variability are of a great interest to the scientific community to understand and enhance the reliability of future climate models. Systematic studies regarding climate and monsoon variability during late Quaternary of India are mostly qualitative; however, in order to develop futuristic models for monsoon variability, quantitative reconstructions are needed. As of now, the quantitative data sets of past monsoon variability are still in embryonic stage.

The lacustrine deposits in India preserve high resolution records of past monsoon variability, climatic oscillations and the paleovegetational history. The present study is an attempt to review the variability of the Indian Summer Moonson (ISM) on temporal and spatial scale. The present review is based on a set of 30 lake records from Indian Summer Monsoon (ISM) and non-monsoon dominated region of India (Figure 1). In present study, we present a synthesis of the past climate and monsoon variability in India inferred from available proxy records from non-Himalayan regions.

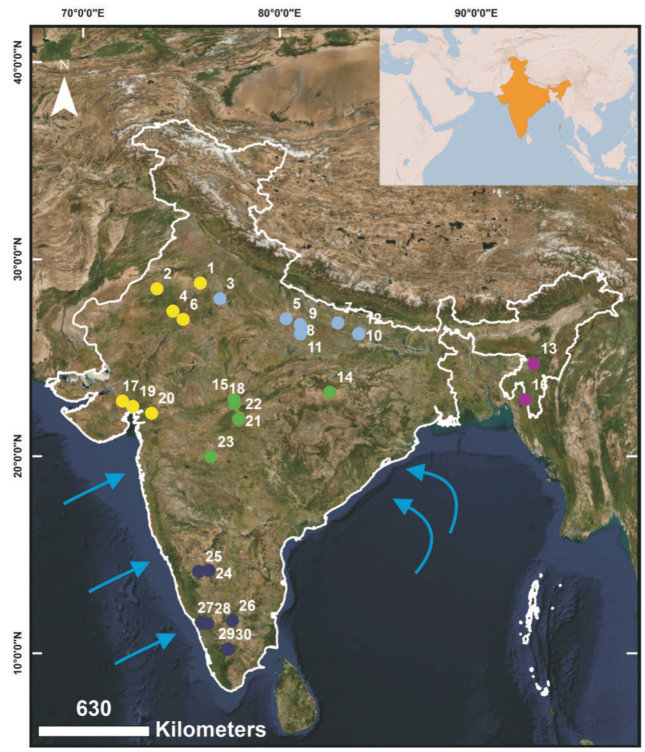

Figure 1: Points represent geographical location of the selected lakes in India. Dark Blue, Green, Yellow, Light Blue and Deep Purple colour points represent lakes from Southern India, Central India, Western India Ganga Plain and Northeast India. The numbering of the lakes is based on descending order of the latitude of the lake; 1 – Riwasa Lake, 2 – Lunkaransar Lake, 3 – Kotla Dhar Lake, 4 – Didwana Lake, 5 – Jalesar Tal Lake, 6 – Sambhar Lake, 7 – Lahuradewa Lake, 8 – Karela Lake, 9 – Choudhary ka-Tal Lake, 10 – Ropan Chpra Tal Lake, 11 – Sanai Lake, 12 – Nikahari Tal Lake, 13 – Loktak Lake, 14 – Matijharia Lake, 15 – Kachia Jhora Lake, 16 – Demagiri Lake, 17 – Nal Sarovar Lake, 18 – Nitaya Lake, 19 – Pariyaj Lake, 20 – Wadhwana Lake, 21 – Sapna Lake, 22 – Khedla Quila Lake, 23 – Lonar Lake, 24 – Thimmannanayakanakere Lake, 25 – Shantisagara Lake, 26 – Ennamangalam Lake, 27 – Pookot Lake, 28 – Nilgiri Peat, 29 – Konalar Lake, 30 – Berijam Lake.

Methods

Paleoclimatic data sets for this review have been considered on the basis of following important factors i.e. (1) time period (50-0 ka), (2) chronology, (3) non-Himalayan lakes and (4) geographic distribution. For the convenience of discussion, thirty lakes (and one peat) were organized on the basis of major geographical zones in India viz. Southern India, Central India, Ganga Plain, Western and Eastern India (Figure 1). To organize the dataset, lakes in the geographical zones were further arranged latitudinal i.e. from south to north, as the advancement of monsoon also vary spatially. Detailed information of paleorecords is listed in Table 1.

Documentation of Spatial and Temporal Variability of Past Climates and Monsoon

Southern India

Berijam Lake: Bera et al. (1996) have reconstructed the last 20,000 yrs BP of paleoclimatic and paleoenvironmental history for Berijam Lake by using pollens (Figure 1). Based on the pollen proxy records they have categorized the paleoclimate of the area into six phases: (i) (20 to 17 ka), phase (ii) (17 to 14.5 ka), phase (iii) (14.5 to 7 ka), phase (iv) (7 to 4 ka), phase (v) (4 to 2 ka) and phase (vi) 2 ka to present. Their study suggested that lake preserved the climatic oscillations, showing a dry spell (phase i) followed by wet phases (phase ii, iii, iv, v and iv). Phase (i) is characterized by grassland vegetation under cold and dry climate followed by wet phases ii to vi showing dominance of shrub savanna, grass and arboreal under humid climate. (Figure 2).

Konalar Lake: Bera and Farooqui (2000) have studied the last 4000 yr paleovegetational history from Konalar Lake in Palni Hills (Figure 1), by using pollen. The paleoclimate history was divided into four phases: phase (i) (4 – 3.46 ka), phase (ii) (3.46 – 2.3 ka), phase (iii) (2.3 – 1.15 ka) and phase (iv) ~1.1 ka to present. The vegetation during phase (i), a wet phase, was abundant with poaceae (51-60%) and increase of shrubs followed by phase (ii) with predominance of non-arboreal under humid climate. While during phase (iii), poaceae was in maximum percentage i.e. 79%-85%, marking it as a dry phase followed by phase (iv) which depicts of poaceae (65-73%) and other ephemerals (*senecio, artimicia*) with amelioration of climate.

Nilgiri Peat: Rajagopalan et al. (1997) reconstructed the climate history of last 40 kyr by using stable carbon isotopes analysis of organic matter. The variation in $\delta^{13}C$ (-14 per mil to -19 per mil) before 40 kyr BP to until 28 kyr BP reflects the dominance of C3 plants and moist conditions. Again little changes were observed in $\delta^{13}C$ of -19 to -18 per mil during period 28-18 kyr BP. During the last glacial maxima or after (about 16 kyr BP) sudden changes in $\delta^{13}C$ value a peak -14.7 per mil reflects dominance of C4 plants related to arid conditions. C3 plants grow in higher precipitation and soil moisture, whereas C4 plants prefer the regions of low moisture content and aridity. Sukumar et al. (1993) used $\delta^{13}C$ proxy in the Nilgiri peats, and reconstructed past 20 ka paleoclimatic oscillation. They suggested three phases of paleoclimate variability on the basis of $\delta^{13}C$ variation. Phase (i) (6 to 2 ka) and phase (iii) (~20 to 16 ka) showing arid climate; whereas phase (ii) (10 to 6 ka) with $\delta^{13}C$ range of -17 to -22‰.

Pookot Lake: Sandeep et al. (2015) and Bhattacharya et al. (2015) have reconstructed the paleoenvironmental/ paleovegetational history of Pookot lake using multi-proxies like pollen, grain size and rock magnetic parameter of last 3100 yrs (Figure 1). Their study shows variability in monsoon strength during the first phase (i) (~3.1 to 2.5 ka) showing high catchment erosion and detrital flux indicating a strong monsoon (Figure 2). Second phase (ii) (~2.5 to 1 ka) reflects brief interval of strong monsoon and frequent drying up of the lake (Figure 2). During phase (iii) (~1 ka to present) luxuriant vegetation, high magnetic susceptibility and catchment erosion reflects strong monsoonal conditions (Figure 2). Sandeep et al. (2015) also suggested a connection between monsoonal rainfall and solar irradiance; the abovesaid region is influenced by solar activity; periods of high irradiance shows high rainfall.

Ennamangalam Lake: Basu et al. (2016) retrieved a 1.65 m core to reconstruct the past vegetation pattern and paleoclimatic condition during 4.8 ka (Figure 1). They used lipid biomarker, isotopic composition proxies to infer the source of organic matter. The study shows high terrestrial versus aquatic ratio (TAR) values reflect increased precipitation in the region after ca. 3 ka (Figure 2). TAR have been used to reconstruct paleohydrological condition, hence the TAR value suggests alteration in monsoon activity during mid-late Holocene.

Shantisagara Lake: Sandeep et al. (2017) used multi-proxy to reconstruct the past monsoon variability presented a 11 ka records from Southern Peninsula of Indian Summer Monsoon (ISM) variability by using environmental magnetism, grain size, organic geochemical and stable carbon isotope (Figure 1). Climatic and monsoon variability have been characterized by five diffferent phases (i) (11-10.7 ka) with weak monsoon and phase (ii) (10.7 to 8.6 ka) with intensified ISM (Figure 2). The phase (iii) (8.6 to

Table 1: List of lakes with paleomonsoon/paleoclimate records shown in Figures 1 and 2

S.No	*Lake name*	*Latitude*	*Longitude*	*Proxy*	*References*
1	Riwasa Lake	28.789	75.958	AMS-^{14}C, $\delta^{18}O$, Ostrocod	Dixit et al. (2015)
2	Lunkaransar Lake	28.500	73.750	^{14}C, $\delta^{13}C$, water chemistry and sediment geochemistrty	Bryson and Swain (1981), Swain et al. (1983)
3	Kotla Dhar Lake	28.003	76.955	AMS^{14}C, Ostrocod, $\delta^{18}O$	Dixit et al. (2014)
4	Didwana Lake	27.369	74.563	Pollen, AMS^{14}C	Bryson and Swain (1981), Singh et al. (1990), Singh et al. (1972)
5	Jalesar Tal Lake	26.979	80.320	AMS-^{14}C, pollen	Trivedi et al. (2012)
6	Sambhar Lake	26.945	75.089	AMS^{14}C $\delta^{18}O$, geochemistry, pollen	Sinha et al. (2006)
7	Lahuradewa Lake	26.767	82.950	AMS^{14}C, pollen	Saxena et al. (2013)
8	Karela Lake	26.682	81.027	Pollen	Chauhan et al. (2015)
9	Choudhary ka Tal Lake	26.480	81.144	Grain size, pollen, AMS^{14}C	Saxena et al. (2015), Trivedi et al (2016)
10	Ropan Chpra Tal Lake	26.218	84.028	AMS^{14}C Stable, $\delta^{18}O$, magnetic	Singh et al. (2015)
11	Sanai Lake	26.207	81.050	AMS^{14}C, pollen, geochemical	Sharma et al. (2006), Sharma et al. (2004)
12	Nikahari Tal Lake	26.206	84.007	Pollen, grain size, AMS^{14}C	Saxena et al. (2016)
13	Loktak Lake	24.700	92.917	AMS-^{14}C, pollen, geochemical	Nautiyal and Chauhan (2009)
14	Matijharia Lake	23.250	82.550	Pollen, ^{14}C	Quamar et al. (2014)
15	Kachia Jhora Lake	22.874	77.667	Pollen, AMS^{14}C	Quamar et al. (2015)
16	Demagiri Lake	22.867	92.467	AMS -^{14}C, fungal	Mandaokar et al. (2008)
17	Nal Sarovar Lake	22.800	72.000	AMS^{14}C, $\delta^{13}C$, grains size, $\delta^{15}N$, C/N	Prasad et al. (1997)
18	Nitaya Lake	22.667	77.700	^{14}C, pollen	Quamar et al. (2012)
19	Pariyaj Lake	22.530	72.520	AMS^{14}C, pollen, phytoliths, sedimentology	Raj et al. (2015)
20	Wadhwana Lake	22.183	73.483	AMS^{14}C, pollen, phytoliths, sedimentology, clay mineralogy, carbon isotopes, magnetic mineralogy	Prasad et al. (2014)
21	Sapna Lake	21.880	77.910	Pollen, AMS^{14}C	Chauhan et al. (2012)
22	Khedla Quila Lake	21.880	77.910	Pollen, AMS^{14}C	Quamar et al. (2014)
23	Lonar Lake	19.967	76.500	AMS^{14}C, $\delta^{13}C$, grains size, $\delta^{15}N$, C/N, AMS -^{14}C, $\delta^{18}O$, $\delta^{13}C$	Menzel et al. (2014), Anoop et al. (2013)
24	Thimmannanayakanakere Lake	14.200	76.400	MS, grain size, carbonate, AMS^{14}C	Shankar et al. (2006), Warrier et al. (2014)
25	Shantisagara Lake	14.143	75.882	AMS^{14}C, stable carbon isotope, mineral magnetism	Sandeep et al. (2017)
26	Ennamangalam Lake	11.648	77.589	Lipid biomarker, carbon isotope	Basu et al. (2016)
27	Pookot Lake	11.542	76.027	AMS^{14}C, rock magnetism, stable carbon isotope, pollen	Sandeep et al. (2015), Bhattacharyya et al. (2015)
28	Nilgiri Peat	11.500	76.333	AMS^{14}C, $\delta^{13}C$	Rajagopalan et al. (1997)
29	Konalar Lake	10.213	77.367	AMS^{14}C, pollen	Bera and Farooqui (2000)
30	Berijam Lake	10.185	77.395	^{14}C, pollen	Bera et al. (1996)

4.5 ka) showed weakened summer monsoon, followed by phase (iv) (4.5 to 3.3 ka) reflecting fluctuating monsoon conditions (Figure 2). Finally, in phase (v) (3.3 ka to present) there is increase in ISM (Figure 2). The high value of χ_{ld}, χ_{fd}, χ_{ARM} and SIRM mirrors strong monsoon, whereas low value reveals weak monsoon during Holocene.

Thimmannanayakanakere Lake: Shankar et al. (2006) used magnetic susceptibility (χ_{lf}) to reconstruct the past rainfall variability from paleoarchive of Thimmannanayakanakere lake (Figure 1). A good correlation was observed between magnetic susceptibility (χ_{lf}) and rainfall. The correlation was used to reconstruct paleorainfall for last 3700 years of Chitradurga region (Figure 2). Warrier et al. (2009; 2014) used grain size and carbonate as a proxy to reconstruct paleorainfall variation and this study supports the work of previous workers. The high value of sand and carbonate period between 3.7 ka and ~2 ka suggests arid climatic conditions.

Central India

Lonar Lake: Several workers have used different climate proxies like mineralogy geochemical, isotopic ($\delta^{18}O$, $\delta^{13}C$) to get the high-resolution paleoenvironmental/ paleoclimate records from Lonar lake (viz. Anoop et al., 2013; Menzel et al., 2014; Prasad et al., 2014 and Sarkar et al., 2014) (Figure 1). The highly positive correlation between $\delta^{18}O$gy and $\delta^{13}C$gy inferred from the sediment core indicates evaporation is major controlling factor of isotopic enrichment. Two dry phases were given by Anoop et al. (2013) for the region i.e. phase (i) (4.63 - 3.89 ka) and phase (ii) (2.04-0.560 ka) (Figure 2).

Khedla Quila Lake: Quamar and Chauhan (2014) retrieved a 2 m sediment core from the Khedla Quila Lake and reconstructed the late-Holocene vegetational history of Madhya Pradesh, using pollen proxy (Figure 1). The proxy records provide information on how vegetation pattern has changed during the three distinct phases of climate: phase (i) (1.416-0.506 ka BP), phase (ii) (0.506-0.120 ka BP) and phase (iii) (0.120 ka-present). While phase (i) shows moderate precipitation, phase (ii) represents intense precipitation, followed by phase (iii) showing weakening of monsoon. The presence of plant species *Madhuca indica, Sapotaceae, Holoptelea, Acacia* and *Schleichera* under warm and humid climate is shown (Figure 2).

Sapna Lake: A 1.5 m sediment core was recovered from Sapna Lake by Chauhan and Qumar (2012) (Figure 2). The authors demonstrated that between 3.8 and 2.7 ka, an open Acacia-dominant scrub forests interspersed with stretches of herbaceous vegetation under dry climate existed in the region. Around 2.7 to 1.26 ka, the Acacia-dominant scrub forests were replaced by mixed deciduous forests. Three phases were observed, phase (i) (3.8-2.25 ka), phase (ii) (2.25-1.26 ka BP) and phase (iii) (1.26 ka to present). Phase (i) shows weak monsoon, phase (ii) represents intensified monsoon and phase (iii) represents medium monsoon (Figure 2).

Nitaya Lake: Quamar and Chauhan (2012) used pollen record of a 2.4 m thick sediment profile from lake deposit in Nitaya Lake. Their study displayed high resolution record of vegetation, climate and monsoon variability of last 12,700 years. Based on paleovegetation pattern and monsoon oscillation, five climatic phases were identified. Phase (i) (12.7-7.150 ka) represents dry period, phase (ii) (7.2-4.66 ka) shows intense monsoon, phase (iii) (4.7-2.9 ka) shows weak monsoon, phase (iv) (2.8-1.1 ka) again represents intense monsoon and phase (v) (1.1 ka to present) suggests moderate monsoon.

Kachia Jhora-Lake: Kachia Jhora-Lake, southwestern Madhya Pradesh (India) has displayed last 3300 yr paleovegetation and monsoon alteration record (Quamar and Chauhan, 2012) (Figure 1). The phase (i) (3.35-2.25 ka BP) displays moderate precipitation followed by phase (ii) (2.25-0.8 ka), with increased monsoon strength and last phase (iii) (0.8 ka BP - present) end with weakening of monsoon activity (Figure 2).

Matijharia Lake: Quamar and Bera (2014) have recovered a 1.8 m deep sediment core from Matijharia Lake to investigate the paleovegetation and climate during the period of mid- to late-Holocene (Figure 1). The study surmised that a warm and relatively more humid climate dwelled in the region coupled with expected increment in monsoon precipitation. The assessment of undertaken study demonstrates the consequent changing pattern of vegetation as against the scenario of climate change and human activities at Baikunthpur region of Koriya District from mid-late Holocene. The authors have further divided the study into three phases: phase (i) 6.41- 4.25 ka), phase (ii) (4.25 -1 ka) and phase (iii) is 1000 to present (Figure 2); highlighting moderate, weak and strong monsoon phases. Quamar et al. (2017) has unfolded the Palaeovegetational history of late Holocene (~4 ka) using pollen proxy near Martijharia lake. Their study reveals three wet phases; phase (i) (~3.7 ka to ~2.42 ka) characterized by moderate precipitation followed by phase (ii) (~2.4 ka to ~1.43 ka). The diversity of forest increases reflects increased monsoon precipitation and phase (iii) (~1431 cal yr BP to present) reveals less diversity of forest under warm and less humid climate.

Ganga Plain

Nikahari Tal: A 90 cm short core was recovered from the Ganga plain to understand the paleomonsoonal and vegetation history by Saxena and Singh (2016) (Figure 1). They have suggested that there was a shift in the vegetation pattern that gradually started around 1350 AD. During ~1420-1620 AD, the region had abundance of shrubs, marshy taxa and the lake also reached highest level, reflecting strong monsoon. Between 1620 and 1900 AD, an increase of silt and clay percentage in lake sediments have been interpreted as weak monsoon. The Little ice age signal is also recorded during 1620-1700 AD, displaying decreases in arboreal diversity and increased percentage of clay reflecting weak monsoon during LIA (Figure 2).

Saini Lake: Sharma et al. (2006) reconstructed the monsoon variability of Pleistocene-Holocene period in the Ganga plain. Their study reported two dry spells and one humid period in the region (Figure 2). The dry periods were inferred during 15-13 ka and 5 to 2 ka, followed by a humid climatic condition or wet period. They have also reported dry spell conditions corresponding to the younger events from periods of 11.5-10.5 ka (Figure 2). During the Younger Dryas cold event (12.9 -11.5 ka) northern hemisphere experience weakening of monsoon strength.

Ropan Chhapra Tal Lake: Singh et al. (2015) used multiple climate proxies like grain size, mineral magnetism and stable oxygen isotopes to reconstruct the monsoon variability (Figure 1). They observed higher δ^{18}O and higher clay percentage values in years 500, 580 and 740 AD, which indicates warm and arid climate in the said time periods; whereas lower δ^{18}O values were observed around 480, 540, 700 A.D. and during 900 to 1200 AD (Figure 2), representing warm and humid climatic conditions due to strong ISM.

Choudhary ka Tal: Saxena et al. (2015) have reported a rich diversity of forest groves in the Choudhary ka Tal Lake and suggested that the Ganga Plain has experienced a warmer and moderately humid climate than today during ~8.6 to 6.4 ka. This was followed by a humid and warm climate as compared to the earlier phase during ~6.4 to 3.15 ka.

Karela Lake: Paleovegetation and climate history of central Ganga plain has been demonstrated by Chauhan et al. (2015). The paleonological data along with geochronology of sediment profile has been addressed. The pollen records reveal five phases whereby two phases ((i) (~14 ka to 12.5 ka BP), Phase (v) (2 ka BP to present)) are featured as dry and the remaining three phases are contrarily presenting a humid climate (Phase (ii) ~12.5 to 8.7 ka BP; phase (iii) (~8.7 to 4.8 ka BP) and phase (iv) (~4.8 to 2 ka BP). The presence of abundant grassland indicates dry phase (i and v) and wet phases evidenced by the dominance of forest grooves. The aforementioned dry climate characterized by grassland and wet phase. During period between 14 ka and 12.5 ka BP, scanty vegetation (grassland, *Holoptelea integrifolia* and *Oroxylum*) was present under cool and dry climate in Karela Lake (Chauhan et al., 2015) (Figure 1). The presence of forest groves ~4.8 to 2 ka BP indicates a warm and more humid climate with the increase of Indian summer monsoon (ISM) (Figure 2).

Lahuradewa Lake: Saxena et al. (2013) used phytholith morphotypes to reconstruct the climate variability of Holocene in the Lahuradewa Lake (Figure 1). They found the dominance of phytholith morphotypes of grasses belonging to subfamilies Panicoidae, Chloridoidae and Festucoidae. The pollen proxy investigation of lake records have allowed the authors to document five dry phases and four wet phases. Identified dry phases are: phase (i) (10.3-9.2 ka), phase (ii) (5.3-4.1 ka), phase (iii) (1.65-1.2 ka) and phase (iv) (0.95-0.7 ka). From identified dry phases, phase (ii) (5.3-4.1 ka BP) was the most prominent dry phase (Figure 2).

Jalesar Tal: The pollen records of Jalesar tal contribute salient picture of vegetational and climate history of the Ganga plain (Trivedi et al., 2012). The proxy records reveal two dry phases, phase (i) (42.5 to 13.6 ka) and phase (vi) (1.2 ka to present) characterized by the abundance of non-arboreals (Poaceae, Cheno/Am, Tubuliflorae etc.). And four wet phases: phase (ii) (13.6 to 5.3 ka), phase (iii) (5.3 to 4.8 ka), phase (iv) (4.76 to 3.2 ka) and phase (v) (3.2 and 1.2 ka). The period between 4.76 and 3.2 ka shows high organic carbon value, suggesting forest became diversified with onset of warm and humid climate in response of active climate monsoon. Forest grooves became sparse owing to reduced monsoon precipitation between 3.2 and 1.2 ka (Figure 2).

Kotla Dhar: Dixit et al. (2014) recovered 2.88 m sediment core from paleolake Kotla dhar and reconstructed the monsoon history (~6.5 ka), by using hydrological proxies aragonite ($\delta^{18}O$) and $CaCO_3$. The Kotla dhar record implies relatively high lake level phase (i) (6.5 to 6.0 ka) and phase (ii) (5.8-4.2 ka) with increased $\delta^{18}O$ interpreted as weakening of summer monsoon and $\delta^{18}O$ increases abruptly from 0.1 to 4.4‰ reflecting drier condition (Figure 2).

Northwest India

Wadhwana Lake: Prasad et al. (2014) used palynology, phytoliths, grain size, clay mineralogy, carbon isotopes and mineral magnetism to study the past climate and monsoon variability from Wadhwana Lake (Figure 1). The proxies result from 1.03 m sediment core from Wadhwana lake**,** Gujarat, which depicts the five paleoclimatic phases. A 1.03 m sediment core was recovered from Wadhwana Lake and its sediment profile shows five paleoclimatic phases. The phase (i) (~7.5-5.56 ka) shows high lake level suggesting moist climatic conditions, followed by reduced monsoon precipitation during phase (ii) (5.56 to ~4.25 ka) (Figure 2). The phase (iii) (4 to 3.2 ka) shows a short strengthening of monsoon climate followed by dry climatic condition during phase (iv) (~3.2 to ~2.7 ka) and somewhat similar to present day climate for phase (v) (~2.7-1.3 ka BP) (Figure 2).

Pariyaj Lake: Raj et al. (2015) reconstructed the paleoclimate, paleoenvironment and tectonic history of last 11 ka from Pariyaj Lake (Figure 1); and suggested five phases (Figure 2). The phase (i) (~11 ka BP) displays high lake level under humid climate. This was followed by shrinkage in lake area during phase (ii) (~9 to 8 ka). Phase (iii) (~7.6 ka) shows moderate yield of pollen and phytolith, suggesting wet phase. Thereafter followed by phase (iv) (~5.9 to 4.7 ka BP) showing very low pollen and phytolith reflects fluctuation in monsoon and dry spells respectively. Finally, phase (v) (~4.7 to 3.5 BP) displays a rich diversity of flora.

Nal Sarovar: Prasad et al. (1997) used $\delta^{13}C$ and C/N to reconstruct past 6.6 ka climate variability in five different phases in Nal Sarovar Lake (Figures 1 and 2). During phase (v) (6.6 ka to 6 ka), $\delta^{13}C$ (-15‰) and C/N ratio 20 indicates C4 type terrestrial plants. The beginning of this phase have drier climate followed by wetter climate (ca. 6.2 ka). In phase (iv) (6-4.8 ka), the C/N ratio was 40 and 3% enrichment in $\delta^{13}C$ increased the contribution of terrestrial plant and C4 vegetation. The climate of this period is dominantly dry with short wet spells. The phase (iii) (4.8 -3 ka), the C/N ratio suggests terrestrial and aquatic contribution, along with very low organic matter suggested by $\delta^{13}C$ value around 3 ka. The increased aquatic contribution and decreased $\delta^{13}C$ value show high lake level suggesting the period is wet. The overall climate of phase (iv) (3-2 ka) is wetter than present, but trend of aridity had begun by 3 ka. In phase (v) (2 ka-present), the C/N ratio shows terrestrial and aquatic contribution of organic matter at ~1.9 ka, 1.3 ka-1 ka and ~0.4 ka and the climate of this period is wet as present.

Sambhar Lake: Sinha et al. (2006) displayed the climatic alteration of last 30 ka from Sambhar Lake (Figure 1). They used mineralogical and geochemical data to show the paleolimnological and paleohyrological condition of the Sambhar lake. The sediment core is characterized by five major and two minor facies. Two arid phase signal was preserved during Last Glacial Maxima (LGM) and 7.5 to 6.8 ka (Figure 2).

Didwana Lake: Singh et al. (1990) revealed the history of summer and winter precipitation from Didwana Lake (Figure 1). Between 20 ka and 13 ka B.P., the region was covered with steppe vegetation and lake water was hypersaline reflecting weaker monsoon and winter precipitation (Figure 2). The lake level was high from ca.13 ka, followed by freshwater between 9 ka and 6 ka B.P (Figure 2).

Riwasa Lake: Dixit et al. (2015) analyzed $\delta^{18}O$ values in ostracods in Riwasa Lake (Figure 1), which shows that there is seasonal variability in lake temperature and hydrology. They have also observed decrease in $\delta^{18}O$ values in ostracods from 9.6 to 8.3 ka suggesting the strengthening of Indian Summer Monsoon (Figure 2). Pang et al. (2004) calculated the local meteoric water line (LMWL) of Delhi, which is $\delta D = 7.15\ 9 * \delta^{18}O + 2.60$, whereas slope of the Riwasa groundwater is 5.5 which reflects evaporation of rainfall and evaporation from soils (Bhattacharya et al., 1985; Darling et al., 2006).

Lunkaransar Lake: Swain et al. (1983) used pollen as proxy to estimate paleorainfall pattern near the Lunkaransar Lake region (Figure 1). The phase between 10.5 and 3.5 ka; estimated precipitation was 500 mm or above from the modern scenario. Bryson et al. (1980) reconstructed the monsoon history of same

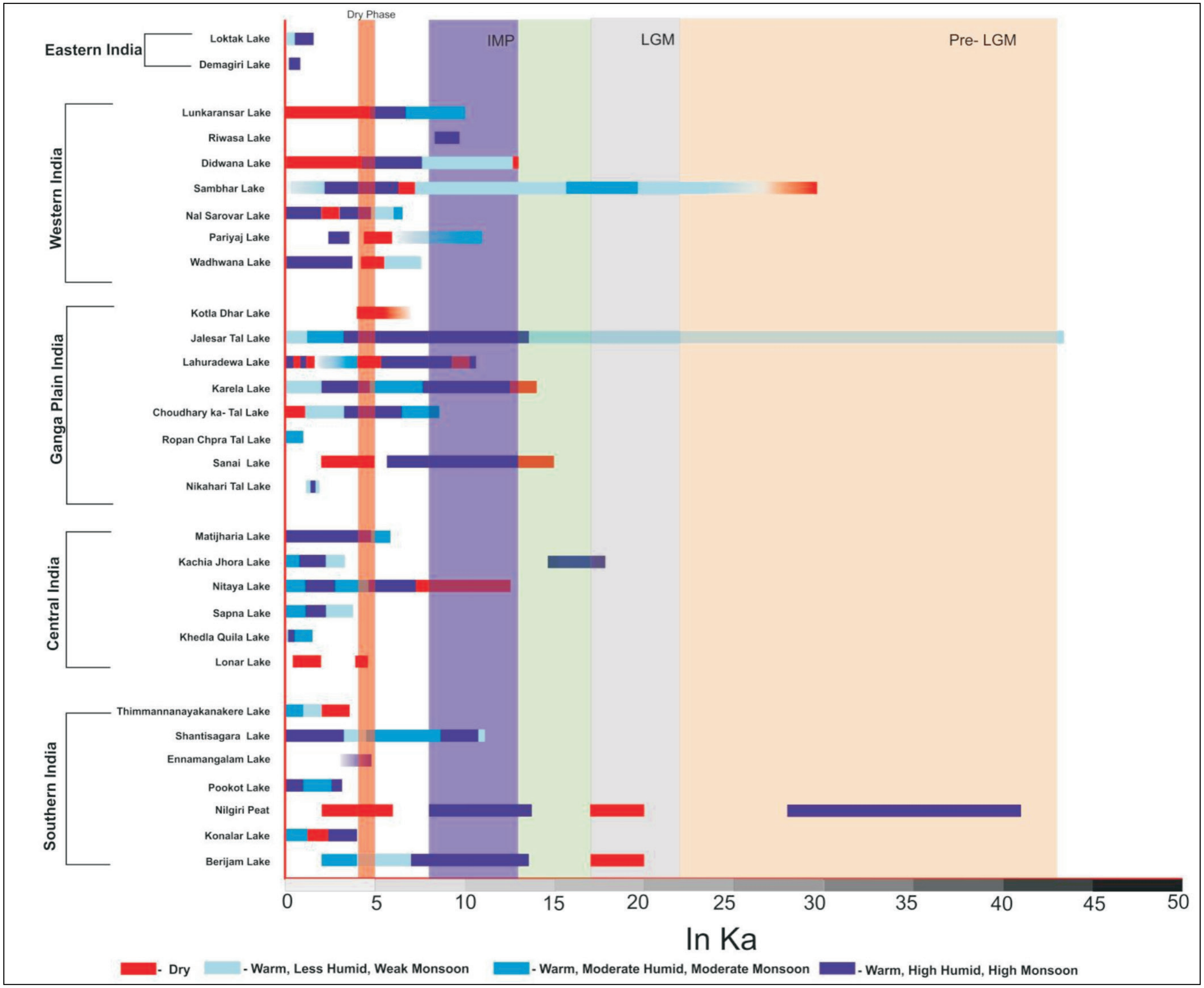

Figure 2: The dry and wet phases in the selected lakes. For location and references of the lakes please refer to Table 1. The longitudinal axis shows the age interval for the lakes, in ka.

lake by using pollen profiles and their result reflects weak monsoon during latest glacial time. Singh et al. (1971) analyzed pollen profile and they interpreted 5-3.5 ka was the wettest in past 10.0 ka (Figure 2). Enzel et al. (1999) presented the Holocene chronology of the Lunkaransar Lake using radiocarbon dating and geochemical analyses of lake deposits. Presently, lake bed is dry and water table is available 2.4 m below ground level and shows the saline nature of water. Lake profile has been fractioned into four zones following the characteristics of lacustrine deposits. The zone (iv) (4.8 to 0 ka) contains mud, silt, sand and laminar structure stating that the basin was dry during the said period (Figure 2). The absence of gypsum and presence of silt are characterizing relatively maximum lake level during period of 6.3 to 4.8 ka in Zone (iii) (Figure 2). Zone (ii) (8.3 to 6.3 ka) shows fluctuating shallow lake. The lake was not completely desiccated at any time before 4.8 ka (Figure 2).

Northeast India

Loktak Lake: Nautiyal and Chauhan (2009) have given insight into the paleovegatation pattern and climatic variability from Loktak Lake (Figure 1). The low C/N ratio, abundance of fern, fungal, algal as well as aquatics implies that humid climate prevailed in this area during 1.65 ka to 0.6 ka (Figure 2).

Demagiri Lake: Mandaokar et al. (2008) study shows fungal diversity, number and organic-rich lake profile from Demagiri Lake (Figure 1); and suggests last 0.85 ka regions enjoyed humid climates. During 0.85-0.4 ka, soil was enriched with organic matter and fungal diversity was high showing humid climate with high rainfall (Figure 2).

Discussion

We reviewed and compared high resolution paleoarchive in the different geographical regions of India to interpret the monsoon variability during the late Quaternary (Figure 1) (Table 1). The inferences of the present review have been divided into four important time periods representing a regional significance i.e. pre Last Glacial Maxima (43 ka-22 ka), Last Glacial Maxima (22 ka-17 ka), post Last Glacial Maxima (17 ka-13 ka) and Intensified Monsoon Phase (IMP) (13-8 ka).

During pre-Last Glacial Maxima (Pre-LGM), lacustrine archive from Peninsular India shows a strong monsoon activity (Figure 2). While Ganga Plain was going through weakening and dry of monsoon (Figure 2), Western India showed onset of dry spell and followed by weakening monsoon (Figure 2). During the Last Glacial Maxima (LGM), the lacustrine data reveal high variability in monsoon activity through India (Figure 2) except peninsular India, where a strong arid phase was observed in the Berijam Lake and Niligiri Peat (Figure 2). An initial phase of a strong monsoon phase was observed in Central India. Jalesar Tal Lake from Ganga Plain India reflects weak monsoon phase, while Sambhar Lake from Western India shows weak to moderate monsoon.

The paleomonsoon condition around ~15,000 ka was weaker than the present condition in southeastern Asia (Prell and Kutzbach, 1987). In post LGM period (17 ka-13 ka), the Peninsular India show strengthening of monsoon in later phase of this period. Similarly, in the Central India, strong monsoon was recorded in the Kachiajhaora Lake. Although, in the Ganga Plain, dry phases were recorded in Sanai and Karela Lake respectively. Similarly, the Jalesar Tal Lake show a long phase of weak monsoon. Also, the Sambhar Lake for Western India shows weakening of monsoon i.e. from moderate to low monsoon phase.

During Intensified Monsoon Phase (IMP) (13 ka-8 ka), a monsoon phase was recorded in all the paleoarchive of the Peninsular India (Bera et al., 1996; Rajagopalan et al., 1997; Sandeep et al., 2015). Nilgiri peats reflect the dominance of C3 vegetation at 9 kyr which suggests the moist phase (Rajagopalan et al., 1997). Similarly, Sandeep et al. (2015) show high magnetic parameter value and carbonate content were low supporting the view of previous author. Lacustrine archive from Nitalaya Lake in Central India shows a complete opposite response, a strong dry spell. On the contrary, most lakes from the Ganga Plain also suggest strong monsoon phase. Although, in the Western India all lakes show wet period, there is spatial variability in monsoon strength. Riwasa Lake in Haryana shows strong monsoon phase, whereas Pariyaj and Lukaransar Lakes show moderate monsoon phase. However, Didwana and Sambhar Lake show weak monsoon.

A strongest dry period in the study was recorded during 5-4 ka, in which nine paleorecords reveal dry phases and most of the remaining lakes showing weak monsoon (Anoop et al., 2013; Dixit et al., 2014; Enzel et al., 1999; Prasad et al., 2014; Raj et al., 2014; Rajagopalan et al., 1997; Saxena et al., 2013; Sharma et al., 2006; Singh et al., 1990). Staubwasser et al. (2003) used $\delta^{18}O$ and suggests that lakes of western India were dry at ~4.7 ka. The majority of the lacustrine studies reflect that periods of aridity occurred during the interval from ~5 to 4 ka (Prasad et al., 2014; Raj et al., 2015; Singh et al., 1990; Swain et al., 1983) which is concurrent with the collapse of the Harappa civilization.

During 2 ka to present, in peninsular India, proxy based paleoclimatic interpretation reflects high to moderate paleomonsoon. The wet period is in Peninsular India supported by study of Yadav et al. (1999) in Aklagavi Cave, Karnataka, by showing highly depleted value of $\delta^{18}O$ value i.e. high rainfall around 1666 AD. Similarly, in central India, all lakes except Lonar Lake, show high to moderate monsoon phase. In Ganga Plain, Choudhary ka Tal and Lahurdewa lake show period of aridity between 2 ka to present. Didwana and Lunkaransar Lakes from western India show strong arid phase. Laskar et al. (2013) reveal the climatic and vegetational history from Western India using climate proxy ($\delta^{18}O$ and $\delta^{13}C$). Two comparatively drier events at ~2.1 ka and ~1.3 ka are observed from the compiled dataset, consistent with widespread proxy paleoclimatic records and are attributed to a weaker southwest monsoon rain.

In general, compatibility of the monsoon variability with major climatic events confirms that geographical location of the region has a strong control over monsoon strength. Further due to limited well studied lacustrine archive in the monsoon dominated regions in study area, our review also suffers lack in temporal data in many regions. Also, comparison of multi proxies data in lacustrine archive at different locations, can give disparities in interpretation. This may be due to chronological error in the radiocarbon dating or proxies are not regionally tested.

Conclusions

Our study represents the high resolution lakes based climate and monsoon variability records over the past ~50 centuries in India. To get a broader picture we have reviewed lacustrine archives from selected 30 lakes in different geographical regions. The most significant conclusions drawn from our compilation of high resolution multiproxy records from paleoarchives are:

1. A significant high monsoon period was observed during 13 ka to 8 ka reflecting to Holocene monsoon maxima with some exception, which is signaled in majority of our paleorecords.
2. The multi-proxies reveal a significant change in precipitation (strong dry period) during ~5-4 ka that are concurrent to the offset of Harappa civilization.
3. These records demonstrate that the globally known climate event 'Younger Dryas' (12.9 to 11.5 ka) is not well preserved in the majority of lakes.

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