Journal of Geological Society of Sri Lanka Vol. 16 (2014), 159-170
Professor P.G. Cooray Memorial Volume

LATE QUATERNARY – HOLOCENE PALEOENVIRONMENTAL RECONSTRUCTION AND HYDRODYNAMICS BASED ON SOME LAKES AND MARINE SEDIMENTS OF INDIA: A REVIEW

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ABSTRACT

No rigorous and quantitative paleoclimate data for the Late Quaternary to Holocene period are available; prediction of future climate is difficult using climate models such as REGCM and GCM. This is also because continuous sediment records revealing paleo-southwest monsoonal (SWM) shifts since the Late Quaternary period are few. Here, we present a review of the work carried out on the lakes and marine sediments using various proxies for inferring Late Quaternary-Holocene SWM variations. Stable isotope data on foraminifera separated from the marine sediments indicate a wetter MIS3 followed by a dry and arid conditions during the Last Glacial Maximum (LGM). The data indicate that during the Early Holocene, the SWM was intense and the climate was wet and humid. Significant fluctuations in the intensity of the SWM occurred since the middle to late Holocene, causing overall dry conditions since then. Several civilizations collapsed due to the weakening of the monsoon as well as winter rains causing drought around 4.2 ka. In an overall dry conditions since 4.2 ka intermittent wet phases caused expansion of the lake margins. However a period of intense dry conditions prevailed around 3.2 ka also.

Keywords: *Lakes, Marine sediments, Late Quaternary –Holocene, Southwest monsoon (SWM), Dry and wet phases*

INTRODUCTION

Paleoclimate data are important for climate modeling programs such as global climate modeling (GCM) and regional climate modeling (REGCM) to predict future environment conditions. Varied environmental conditions leave 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 are potential proxies which offer important information on long-term climate variability of the Holocene period and beyond. Recent studies estimate that the total surface area of the lakes is at about 4,200,000 km^2, which is only about 2.8% of the planet's land surface area (or less than 1% of the Earth's total surface area). The Indian subcontinent is one of the largest monsoon dominated regions of the Earth and the climate is controlled primarily by the southwestern monsoon (SWM). Lakes are major sinks not only for sediment deposition in a closed system, but also are major sinks for carbon, carbon sequestration and also signatures for reconstructing paleoenvironments.

In the Indian subcontinent paleoenvironmental reconstruction based on proxies such as pollen and spores, diatoms, foraminifer, speleothems, stalactite, stalagmites, phytoliths and sediments have helped in reconstructing Late Quaternary-Holocene paleomonsoon records. They are based on lacustrine deposits of the Himalayas (Bhattacharyya, 1989), western Rajasthan and Gujarat (Kusumgar et al., 1992; Prasad et al., 1997; Chauhan et al., 2000; Enzel et al., 1999; Sinha et al., 2006; Achyuthan et al., 2007a,b), tree rings and speleothems (Tiwari et al., 2009; Yadava and Ramesh, 2005), marine sediment cores (Rangarajan and Sant, 2000), mangrove and peat (Kumaran et al., 2005; Farooqui et al., 2010), Ganga plain (Srivastava et al., 2010) and the Nilgiris (Sukumar et al., 1993). A summary of the proxy paleoclimate records indicates three distinct paleoclimate events since 20 ka, i). from 19 to 13.5 ka the climate was arid and warm; ii). from 13.5 ka to 10 ka it was dry and warm and iii). warm since 3.4 ka to the present. However, low values of $\delta^{18}O$ and increased growth rates in speleothems reveal that the southwest monsoon became stronger around 3 ka (Veena et al., 2014). Magny (2004) opined that the unstable Holocene-Late Quaternary climate was punctuated by fifteen phases of higher and lower lake levels and solar activity played a major role in these oscillations.

Several studies have shown that the periods of high sedimentation rates and higher lacustrine primary productivity have not preserved the evidence of these short-term processes that affect organic matter delivery and burial in sediments. Moreover, continuous high resolution records indicating that paleomonsoonal shifts of the SWM since the Late Quaternary period are sparse, few and far between. Hence, in this paper, we present a review on Late Quaternary–Holocene paleoenvironments and paleo SWM shifts based on several proxy records using lake sediments (Figure 1).

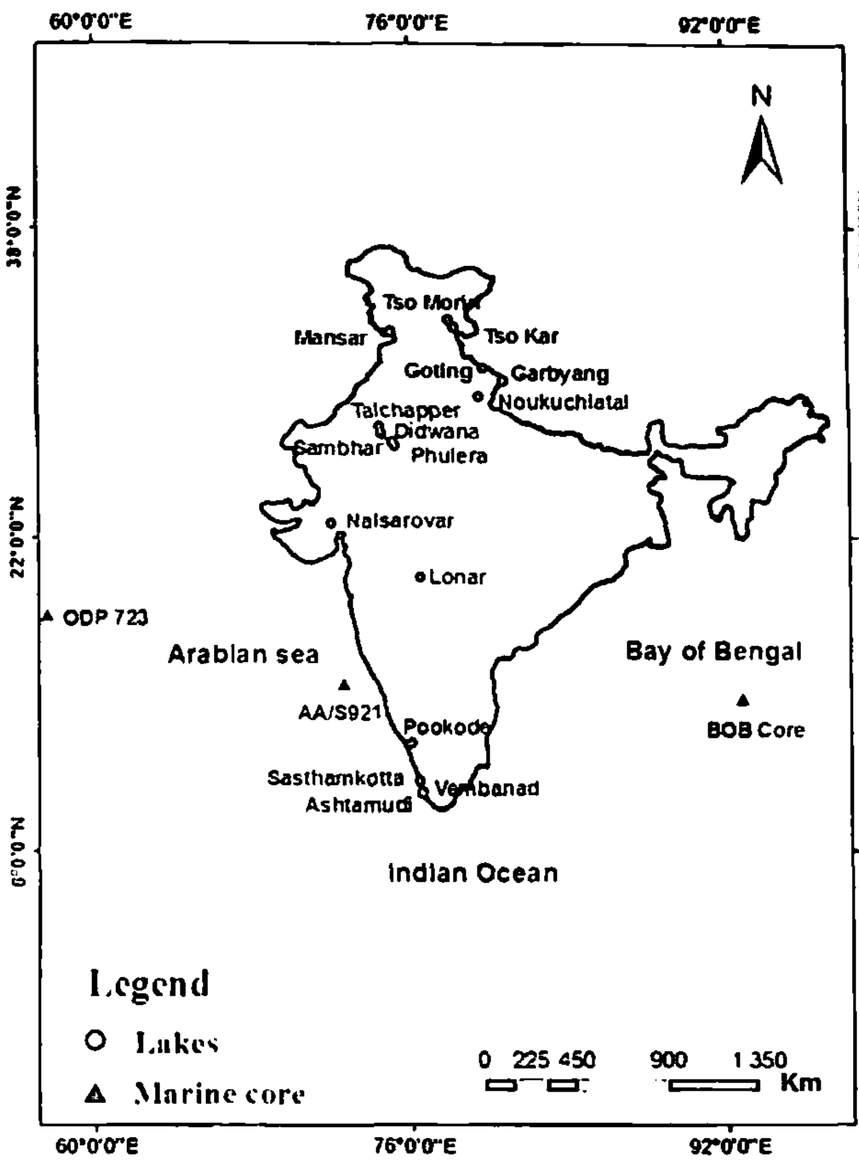

Fig. 1 Location map showing some important lakes and marine sediment cores that were used for paleoclimatic studies.

THE HIMALAYAN LAKES

Fresh water lakes situated in the Himalayan region are structurally controlled closed basins. Lake deposits have provided a continuous paleoclimate record since the Last Glacial Maximum (LGM); 20±3 ka to 18±3 ka to the beginning of the Holocene. Magnetic susceptibility and geochemical data of the Goting Lake sediments indicate a moderate to strong monsoon around 25 ka, 23.5 ka-22.5 ka, 17 ka, 16.5 ka and after 14.5-13 ka, whereas around 22 ka the early LGM climate was mainly arid (Juyal et al., 2009). First evidence of cooling during the younger Dryas was provided by mineral magnetic susceptibility data and elemental concentrations that reveal a high around 13±2 ka to 11±1 ka. The biochemical data of the Mansar Lake sediments, Lesser Himalaya, indicate a hot and wet climate regime during the early Holocene and a dry and cold one during the late Holocene period (Das et al., 2010). Mineral magnetic studies on proglacial deposits of the Goting and Garbiyang basins situated in the higher Central Himalaya have preserved the evidence of the region that responded to ice sheet dynamics of the northern latitudes and the high melt water discharge. Deposition of outwash gravels occurred at the beginning of the Holocene period (Basavaiah et al., 2004). Kotlia et al., (1997) investigated the lacustral succession of the Bhimtal-Naukuchiatal basin, south-central Kumaun Himalaya adopting the methods of palynology, paleontology as well as ^{13}C measurements and found various climatic variations.

Pithoragarh paleolake, in the eastern Kumaun Lesser Himalaya, represents an ideal location for paleo climate studies. Part of the lake sequence was previously studied for palynology and magnetostratigraphy (Kotlia and Phartiyal, 1999; Kotlia et al., 2000) and clay mineralogy (Phartiyal, 2000). Radiocarbon analysis suggests that the lake existed since 35 ka to 10 ka. Tso Kar lake sediments of Himalaya dated from 15.2 ka to 14 ka reflect dry and cold conditions and the pollen studies indicate strengthening of the summer monsoon after 14 ka (Demske et al., 2009). The Chenopodiaceous-dominated vegetation represents weak monsoon conditions that occurred around 12.2–11.8 ka during the Younger Dryas. Interstadial monsoon was high between 10.9 ka to 9.2 ka. Extreme humidity between 11 and 9.6 ka existed around the Tso Moriri Lake (Leipe, 2013). Palynological analysis of the lake sediments in the Dokriani Valley, Garhwal Himalaya, reveals that between 12.5 ka and 10.7 ka the vegetation was sparse due to cool and dry climate, attributable to the Younger Dryas event (Bhattacharya et al., 2011).

Tso Kar Lake and Startsabuk Tso Lake margins shrank to the present level from a single water body since the Holocene period. Permafrost occurred between 20-10 ka and subsequent to 5 ka. Since 8–5 ka high lake level existed, and the high lake level reveals the absence of permafrost (Wunnemann et al., 2008). The lakes in the Sat Tal complex (Beon Tal, Suuha Tal and Garud Tal), are characterized by high soil-derived components (xfd 6-10%) and this is due to low sedimentation rate (< 2 mm/yr) and thus indicating little erosion in the catchment area (Kusumgar et al., 1989).

NORTH WESTERN AND WESTERN INDIA

The Thar Desert hosts numerous closed basin playas (salt lakes) supporting a centripetal drainage pattern and the absence of a distinct outflow. Pollen data from lakes in Rajasthan, India, (Singh et al., 1990) signify that the late Holocene period was more arid as compared to the mid-Holocene period. This is supported by archeological evidences (Rajaram, 1999; Radhakrishnan, 1999; Lambrick, 1967; Raikes, 1964; Dales, 1966), suggesting local aridity in the Kutch - Rajasthan - Indus Plain region that compelled the population to migrate to the Indus valley. Many important paleoclimatic events occurred in the mid-Holocene period that is significant in terms of the decline of the great Indus Valley Civilizations such as the Harappan civilization (Dixit et al., 2014a,b). It is now well established and that the IV major civilizations collapsed around 4.2 ka. The period around 4.2-4.0 ka experienced severe drought for nearly 200 years and was a regional significance. Coevally, the Akkadian empire that stretched from the present day Turkey and N. Syria to southern Mesopotamia and the Arabian-Persian Gulf of today declined around 4.1 ka (Weiss et al., 1993). The Akkadian empire collapsed within 100 years (Weiss et al., 1993). Deep sea sediment core collected from the Gulf of Oman (Cullen et al., 2000) shows the occurrence of calcite and dolomite minerals from 4.25 ka that lasts for nearly 300 years. These minerals are wind blown as dust from the dry, windswept regions of the Mesopotamia. Cullen et al., (2000) suggest that the intense wind blowing activity is due to the abrupt drying of the Tigris and Euphrates flood plains. It is very likely that the increase in the windblown silt and the collapse of the Akkadian empire happened at the same time. Mineralogy and stable isotope data on stalactite from the cave deposits of Israel (Bar-Matthews et al., 2003) show nearly 30% reduction in the precipitation between 4.2 and 4 ka. Interdisciplinary paleo-climate studies from central Sri Lanka indicate a gradual monsoon decline and reduction in the expansion of the rain forests and arid environment between 8.1-3.4 ka (Premathilake and Gunatilaka, 2013). Further, signatures for a dry spell that lasted several hundreds of years is also inferred from the cave deposits in Italy, marine sediments from the Red Sea and Arabian Sea, and an ice core from Mount Kilimanjaro in Africa (Thompson et al., 2002; Staubwasser et al., 2003; Arz et al., 2006; Drysdale et al., 2006). However, the causes for the sudden drought around 4.2 ka is still unresolved, One of the plausible cause may be the anomalous cooling event of the North Atlantic around 4.2 ka. The modern instrumental record shows that when the north Atlantic sea surface temperatures are anomalously cool; droughts in Mesopotamia occur. Both, archaeological records (from well excavated sites) and paleoclimate evidences point towards climate change playing an important role in the decline of the civilizations that was prevalent around ~ 4.2 ka.

In the Thar desert India, this important archaeological event took about 200 years for the eventual collapse of the Harappan civilization. The Harappan was a large urban civilization on the subcontinent with planned cities and heavily depended on the Indus river for water and agriculture. The reasons for the drought is well established as the Southwest monsoon as well as the winter rains weakened over an extended period of time. During this period ~ 4.2 ka, it is postulated that the ITCZ migrated well to the south of the present latitudes. Important civilizations such as the Akkadian, Sumerian, Mesopotamian and the Harappan that were located in the subtropical latitudes received less or no rain for a very long period of time. The monsoonal collapse lead to a train of events resulting in wars, famine, disease, etc., thus pushing the civilizations over the edge. Many civilizations across the world also collapsed at various times due to climate shifts (e.g. Maya, Inca, Angkor).

Detailed sedimentology of the Didwana Lake reveal that the water level distinctly fluctuated widely between 13 ka and 6 ka; however the lake water level dropped drastically around 4 ka (Wasson et al., 1984). Achyuthan and Reddi (1993) and Achyuthan et al., (2007a) discussed the evolutionary history of the Talchappar salt lake, Rajasthan, using geomorphic and sedimentological analyses and inferred an early Quaternary evolution of the salt lake and suggested that the development of the lake basin was influenced by neotectonic activity. Detailed study on Talchappar and Parihara salt lake basins indicates hydrologic oscillations since ~14 ka (Achyuthan et al., 2007a). Geochemical and mineralogical analyses of the lacustrine sediments, supported by radiocarbon dates indicate the existence of an ephemeral lake earlier than ~13 ka as sediments deposited in a lacustrine environment, implying sustained runoff in the catchments (Achyuthan et al., 2007a,b).

Sambhar Salt Lake is one of the largest playa in the eastern margin of the Thar Desert. The lake sediments host a wide variety of evaporite deposits. The lake sediment core reveals paleoclimatic-paleohydrological information for a period > 30 ka (Sinha et al., 2004). Variation in precipitation as short rainfall events occurred between 6.6–4 ka, higher rainfall during 4–2.3 ka, and low rainfall event during 2.3–1.1 ka while the sediments from Phulera lake point towards the area receiving less rainfall during < 2.3 ka to >1.4 ka. After 14 ka both the playas reflect less saline conditions due to the SWM fluctuations over the Indian subcontinent (Roy et al., 2009).

Lonar Lake in Maharashtra, which is formed by the impact of a meteorite, is the only impact crater in a basaltic terrain in the world. Being the third largest saline lake in the world, it has geological importance. Extended dry periods occurred prior to 11.4 ka resulting in shallow lake levels around 3 ka and these signatures were demarcated by high detritus input and aquatic productivity (Prasad et al., 2014). Studies from Nal Sarovar and Iskyrpalli provide information related to prominent drought and reduced monsoon during 4-3 ka (Basavaiah et al., 2004).

LAKE SEDIMENTS FROM SOUTHERN INDIA

The palynological study of the organic matter (OM) rich deposits from Chaganachery, Kerala, reveals that the rainfall in the Indian Peninsula was less during the Pleistocene glacial and interglacial cycles (Garn et al., 2003). Expansion of mangrove vegetation during 7.2 to 3.5 ka suggests warm and humid climate and intense monsoon. Reductions in the areal extent of the mangrove swamps reflect decrease in the intensity of the southwest monsoon (Misra and Bhattacharyya, 2014). Van Campo (1986) opined that the decline of mangrove vegetation after 6 ka around Cochin and the higher representation of mangrove pollen in the subsurface sediments of the flood plains point towards a relatively humid climate during the early to mid Holocene times. Coastal wetland systems in SW India around 8.92 ka is represented by a sub-fossil wood/peat or carbonaceous clays (Padmalal et al., 2011). A detailed palynological analysis of sediments from Ashtamudi--Sasthamkotta backwater lake systems of Kerala revealed a marine transgression at ~ 6 ka (Nair et al., 2010) and that a vigorous monsoon occurred between 10 to 7 ka. Pollen data obtained from the subsurface sediments of South Kerala sedimentary basin point towards high rainfall during early Holocene and dry climate during the late Holocene (Kumaran et al., 2008). Pollen analysis of Vembanad lake peat revealed the existence of mangrove vegetation and evergreen forest, suggesting a humid climate and higher intensity of SWM during that period (Padmalal et al., 2014). Presence of desiccated clays beneath the peat deposits suggest arid and dry climate prior to the humid climate during the past 40 ka (Narayana et al., 2002). A transgression (8 to 6 ka) and a regression (5 to 3 ka) occurred along the Kerala coast during the Holocene (Rajendran et al., 1989). The present Vembanad Lake and low-lying lands marked the eastern limits (Malik and Suchindan, 1984). The occurrence of a peat sequence in the sediments in the low-lying area around Vembanad Lake and radiocarbon dating studies indicate that their formation was from the submerged coastal forests, especially of mangrove vegetation (Rajendran et al., 1989).

A detailed study carried out by Veena et al., (2014) in Pookode lake, Kerala, analyzing sediment texture, radiocarbon dating, phytolith, diatoms, spores and pollen revealed a change in lake hydrology as well as shallowing of the lake. 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 presence of a warm and dry period that prevailed during 6.2 to 0.420 ka and were interrupted by the wet phases between ~ 3.9 to 1.9, 1.4 to 0.760, 0.420 to 0.140 ka due to strengthening of SWM, rise of water level, and the expansion of the Pookode lake margin.

A COMPARISON WITH MARINE AND TERRESTRIAL RECORDS

In the Asian region paleoclimate records based on lake sediments indicate that both southwest summer and northeast winter rains were stronger in the early Holocene period (10–7 ka) than today, resulting in a wetter and cooler climate over the Asian continent. But Holocene Megathermal was a much warmer phase in areas that received the East Asian monsoon (Shi, 1993; An et al., 2000; Sun et al., 1999; Wang et al., 2005; Sun and Li, 2011). Warming started around 8 ka and the Holocene Megathermal Maximum occurred between 7.2 and 6 ka. The subsequent period after 3 ka, the climates were cold and dry (Shi et al., 1993; Sun and Li, 2011). These studies were based on a wide variety of proxy techniques, including pollen and diatom analyses (Prell and Kutzbach, 1987; Van Campo et al., 1986), oxygen isotope analysis of marine sediments (Sirocko et al., 1993), and Arabian Sea upwelling intensities (Prell and Van Campo, 1986; Overpeck et al., 1996). However, detailed and continuous Late Quaternary paleoenvironmental shift related to SWM variability in the Asian region is lacking (Figure 2).

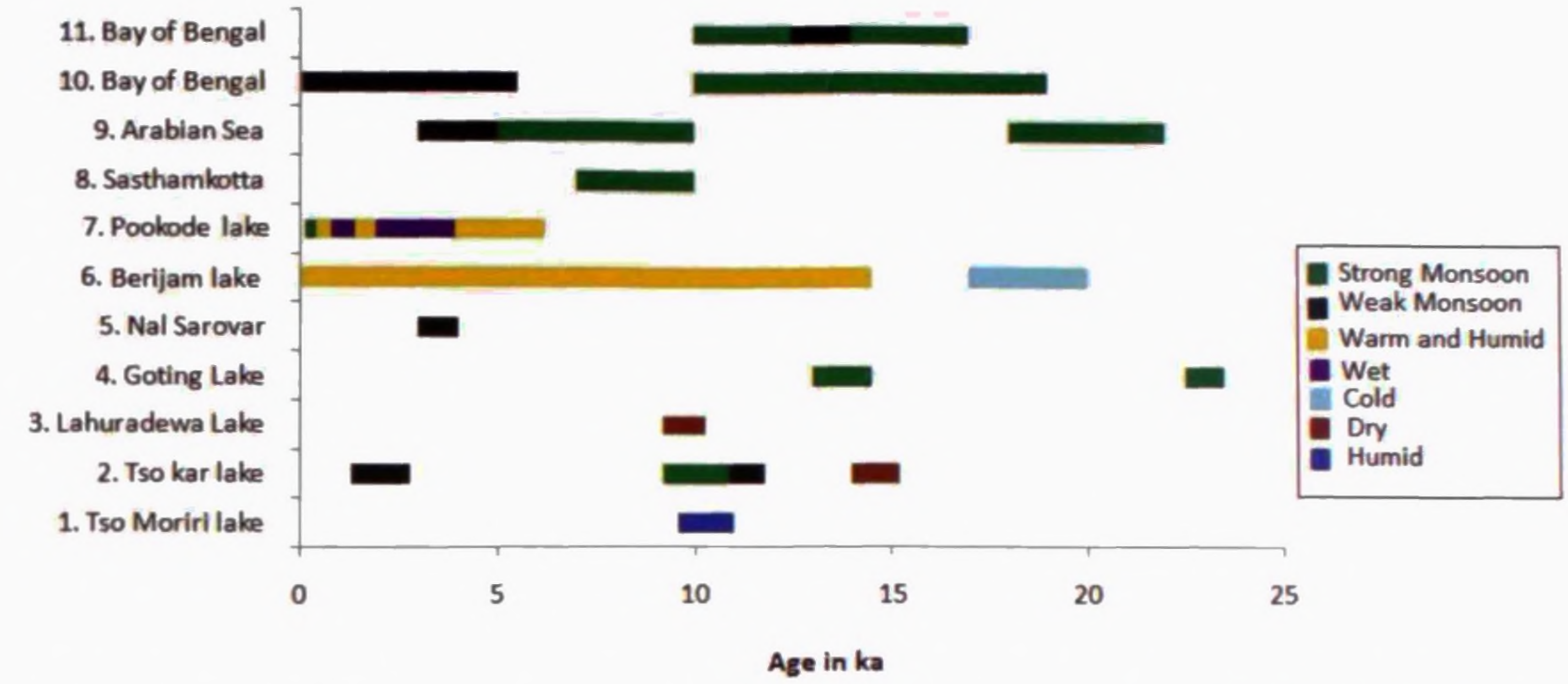

Fig. 2 Comparison of Southwest monsoonal shifts using various proxies from the lake sediments.

Naidu and Malmgren (1996) analyzed the sediment cores from the western Arabian Sea and concluded that SW monsoon was relatively stronger during 22–18 ka than 18–13.8 ka with a major intensification at 13 ka and a maximum between 10 and 5 ka, after which it declined with the weakest phase at around 3.5 ka. The Eastern Arabian Sea (EAS) sea surface temperature (SST), ^{18}O of sea water and salinity data indicate that Mg/Ca derived SST record varied by $4^{O}C$ implying that the marine isotope stage 4 (MIS4) was warmer than MIS3, Last Glacial Maximum (LGM) ~20 ka was $4^{O}C$ cooler than the present, and there was a $2^{O}C$ increase within the Holocene period. Govil and Naidu (2010) found that the transition from MIS4 to MIS3 reflects a decrease in the evaporation, precipitation budget in the Eastern Arabian Sea, perhaps due to the strengthening of southwest monsoon because of higher precipitation during MIS3 and MIS1 and lower during MIS2 and MIS4. Further, Govil and Naidu (2011) observed that the during the LGM the temperatures were ~$3.2^{O}C$ cooler than the

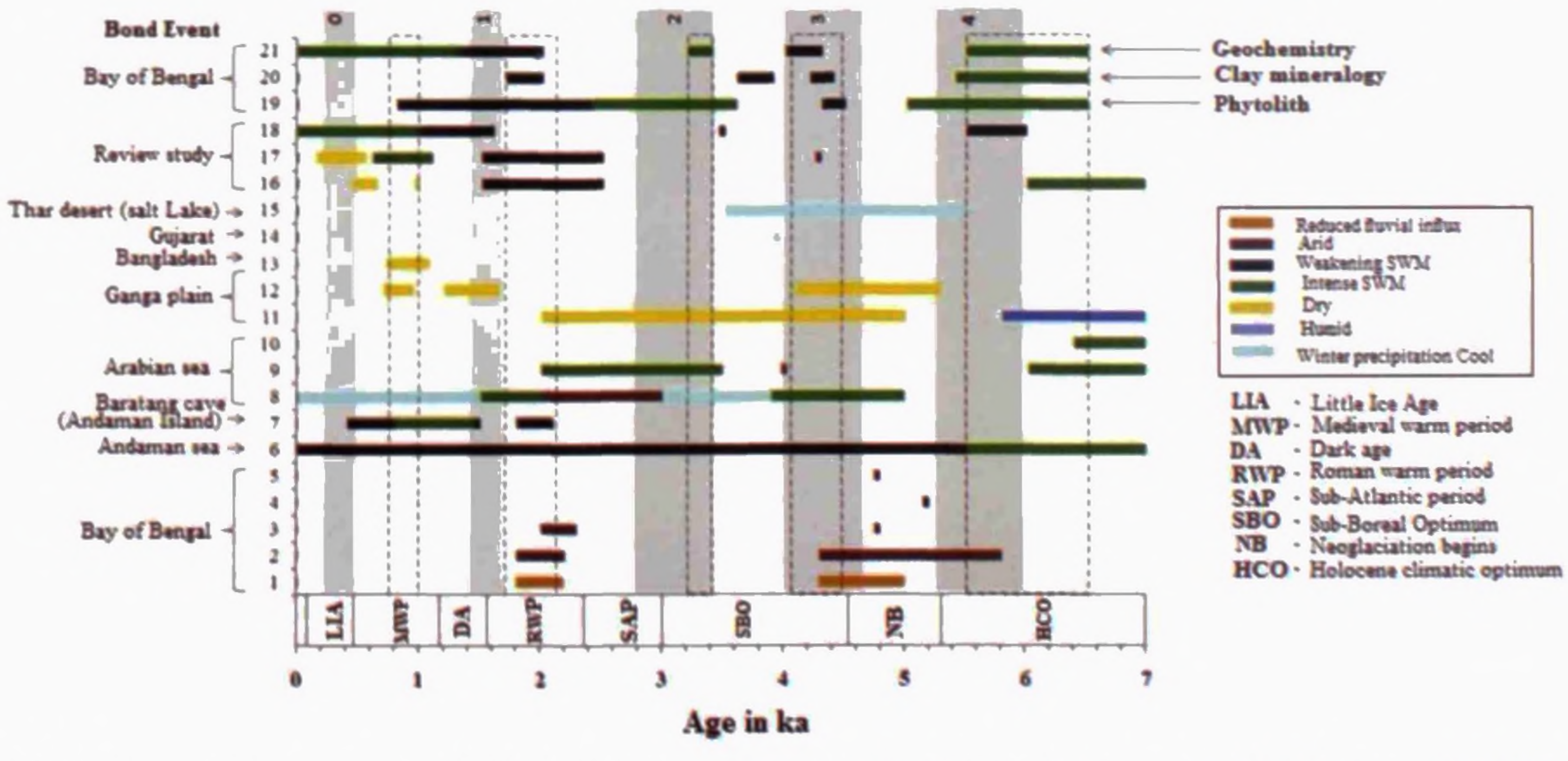

Fig. 3 A comparison of monsoonal shifts of the present study with global climate events, Bond events (shaded) and other paleoclimate records, reviews from Arabian sea , Bay of Bengal, Andaman sea and Indian Sub-continent. [Reference. 1) Chauhan et al., (2004), 2) Chauhan and Vogelsang (2006), 3) Chauhan and Sunethi (2001), 4) Mathien and Bassinot (2008), 5) Chauhan et al., (2000), Rashid et al., (2007), 7) Laskar et al., (2013), 8) LuÈckge et al., (2001), 9) Sarkar et al., (2000), 10) Thamban et al., (2002), 11) Sharma et al., (2006), 12) Saxena et al., (2013), 13) Masud Alam et al., (2009), 14) Singh et al., (2007), 15) Enzel et al., (1999), 16) Patnaik et al., (2012), 17) Kupusamy and Ghosh (2012), 18) Thamban et al., (2007) and 19) 20) 21) after the marine sediment core data studied by Nagasundaram (2014)].

present, and a ~3.5°C rise is documented from 17 to 10 ka in the Bay of Bengal and this was highly influenced by the river runoff and rainfall during the southwest monsoon with the sea surface temperature (SST). Both SST and ^{18}O exhibit greater amplitude fluctuation during MIS2; this was due to the variability of NE monsoon rainfall and associated river discharge into the Bay of Bengal in association with strong seasonal temperature contrast. One set of strengthening phase of SW monsoon was started during Bolling/Allerod as evidenced by the $^{18}O_{sw}$ values ~14.7‰, (Govil and Naidu, 2011). This is consistent with the rainfall maximum in northern India from 15 to 13 ka as documented in the speleothem ^{18}O recorded from Timta Cave (Sinha et al., 2010) $^{18}O_{sw}$ have consistently lower values during the Holocene, which suggest that the freshening of the Bay of Bengal due to heavy precipitation and river discharge were caused by the strong SW monsoon (Govil and Naidu, 2011).

The increased total organic carbon (TOC) values during 14-12.5 ka indicate weaker summer monsoon and weak oxygen minimum zone (OMZ). Further, several studies using tree-ring based climatic records, monsoon record from speleothems, monsoon and associated oceanographic effects of marine proxy studies have shown that the southwest monsoon was maximum during the inter glacial period and was less in glacial period where as northeast monsoon showed opposite behavior. During glacial time snow cover increased over the Tibetan plateau and central Asia, this caused a reduction in land, ocean temperatures during the summer and increase during winter that ultimately made the SW monsoon weak and strengthened the winter monsoon. NE monsoon strengthened during the early glacial/late glacial period (19–17 ka; Tiwari et al., 2009).

Studies of the sediment cores collected from the Arabian Sea and Bay of Bengal indicate that SW monsoon shows an increase from 10 ka to 20 ka and declined after 5.5 ka. Existence of arid climate and weak phases of the monsoon is supposed to be the reason for declining plant growth in Western Ghats. It also affected the rate of discharge of rivers too in Western Ghats. The river valley of peninsular India preserves a great wealth of paleoclimate and archeological data, spanning the last 100 years. The ^{18}O data of the Ganga plain show periodic changes in rainfall amounts between 100 ka and 18 ka with three peaks of the higher monsoon at about 100 ka, 40 ka and 25 ka compared with marine, and the other terrestrial records (Agarwal et al., 2012).

The vegetation for the time period 84 to 18 ka based on ^{13}C values of soil carbonate indicates the relative abundance of C3 and C4 vegetation that were mainly driven by variations in monsoonal rainfall (Agarwal et al., 2012). Similar observations were made using pedogenic carbonates from the eastern margin of the Thar desert (Achyuthan et al., 2007b).

A COMPARISON WITH OTHER STUDIES

Information obtained till date show stronger SW monsoon since about 1.5 ka and the temperature indicators are less clear, except around the Medieval Warm Period (MWP) and Little Ica Age (LIA) (Figure 3). Peat deposits studies from Sanjiang Plain, China revealed a dry and warm climate, environment from 1.9 to 1.0 ka, a warm and humid phase from 1 to 0.5 ka, and a cool and dry climate since 0.5 ka (Yu-me and Pei-fen, 2001). The co-eval warming of Oman was observed from the wind-induced up welling index fossil Globigerinoides bulloides during 0.6 to 1.2 ka (Gupta et al., 2003). Chauhan et al., (2006) reported that the LIA has a large temporal and spatial variability across the globe where it showed a mild cooling event in the northern hemisphere (Crowley and Lowery, 2000). Hence it is summarized that a significant variation in several phases of SWM has occurred during the long phases of dry conditions since the middle to late Holocene.

High resolution paleoclimte data and present day meteorological records when applied to various climate models such as GCM 1, 2, 3, and REGCM 1, 2, 3 versions of climate models provide a powerful tool to predict the future climate with greater degree of accuracy. However, the simulation of the monsoon circulation has posed a tough challenge to global climate modeling efforts such as GCM and REGCM's, and the rigorous paleoclimatic evidences of monsoon intensity changes that can be used in improving the formulation of monsoon related aspects in the climate models. This can be also done by improving the quality and quantifying the high resolution data generation from the terrestrial and marine sediments.

ACKNOWLEDGEMENTS

The authors dedicate this manuscript to Prof. P.G. Cooray. Keerthi B Nair thanks Anna University, Chennai, for the Anna Centenary Research Fellowship that helped to carry out this work. Babeesh C. is grateful to the UGC, New Delhi, for the JRF UGC BSR fellowship. The authors thank the HOD, Department of Geology, Anna University, Chennai, for extending the necessary facilities to carry out this work.

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