An overview of Holocene monsoon variability of Sri Lanka and its association with Indian subcontinent climate records

K.M. Premaratne, R. Chandrajith* and N.P. Ratnayake

Highlights

- Sri Lanka and South India are located in the core of the Asian Monsoon domain.
 - The region provides an ideal platform for paleoclimatic investigations on Indian monsoon systems.
 - This review synthesized the paleo-monsoon variability of the South Asian region during the Holocene.
 - High-resolution paleoclimate records from both Sri Lanka and the Indian subcontinent are well consistent.
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REVIEW ARTICLE

An overview of Holocene monsoon variability of Sri Lanka and its association with Indian subcontinent climate records

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Abstract: Located in the core of the Indian monsoon domain, Sri Lanka has a classic tropical monsoonal climate, thus making it an ideal platform for paleoclimatic investigations. During past decades, extensive studies have been carried out to explore the Indian Ocean monsoon variability across different time scales including in Sri Lanka. This review synthesized a comprehensive picture of the paleo-monsoon variability of Sri Lanka during the Holocene and compared it with the regional records from the Indian monsoon regime. Available paleoclimate information indicated that the early Holocene is characterized by a strong monsoon phase in Sri Lanka. This enhanced monsoon activity phase was followed by a weak monsoon phases around 8.0 kyr BP. Mid-Holocene was identified as a semi-arid to arid or a period with decreased monsoon activity. The late Holocene showed a highly variable climate with a large spatial variability across Sri Lanka. These observations are almost consistent with the climatic records of the Indian monsoon regime. Dissimilarities in the timing of onset and withdrawal of monsoons were also noted in different geographical localities in Sri Lanka that are possibly due to localized responses of the climate system. Paleoclimate records from Sri Lanka revealed that summer and winter monsoons behaved mostly in a similar way, implying similar forcing mechanisms. Despite the contrasting differences among regional records across shorter time scales, the monsoon climate of Sri Lanka during the Holocene has varied coherently with the climate of other regions of the Indian monsoon domain including the Indian subcontinent, the Bay of Bengal, Northern Andaman Sea, Eastern, and Western Arabian Sea, Northern and Southern Oman, Yemen and as far as some locations from China.

Keywords: Winter monsoon; summer monsoon; South Asia; Indian monsoon domain.

INTRODUCTION

The term ‘tropical monsoon’ is technically used to describe a major wind system that shows a profound seasonal contrast of the predominant wind regime between the summer and winter seasons. The monsoons occur in equatorial regions of South Asia, Africa, Central America, and Australia. Monsoons are considered to be a unique atmospheric circulation phenomenon in the tropics that has distinctive local, regional and global climate impacts (Wang *et al.*, 2014). It is one of the most important

climatic systems that affect the livelihood of over 60% of the world population. From among monsoon systems in the world, the Asian Monsoon System (AMS) is the strongest monsoon circulation compared to all other regional monsoons (Gadgil, 2003; Cane, 2010; Rashid *et al.*, 2011). The fluctuations of monsoons over South Asia have drastic socio-economic constraints since weak monsoon activities affect agriculture through extreme droughts while strong monsoons cause natural disasters such as floods and landslides (Ratnayake and Herath, 2005; Huang *et al.*, 2012). The seasonal reversal of monsoon circulation affects the climate of Asian landmass as well as the Indian Ocean and the South China Sea. Such variations cause cool and dry winters, rainy summers, variations in sea surface temperature, and ocean salinity patterns. In addition, seasonal changes in the monsoon wind regime could lead to variation in the upwelling process in oceans (Morrison *et al.*, 1998; Jayaram and Kumar, 2018; Patel *et al.*, 2019).

In Sri Lankan and South India, monsoon rainfalls serve as an important factor for agricultural activities. Thus, lifestyles of people in the region have developed on the variabilities in monsoonal features. For instance, the timing of the monsoon burst and termination, amount of precipitation, rainfall intensities have immense socio-economic impacts on communities that are engaged in agriculture. Even the earliest human civilization in the Indian subcontinent was shifted following the spatio-temporal variation of the South Asian Monsoon (SAM) (Kathayat *et al.*, 2017).

During the last few decades, monsoons have sparked the interest of the climate research community (Wang *et al.*, 2014). Since then extensive scientific investigations have been carried out to explore the unique atmospheric circulation phenomenon. Among them, the Indian monsoon is one of the most explored weather phenomena of the Asian subcontinent (Achuthan *et al.*, 2014), since the Asian monsoon has known to be stronger during warm interglacial or interstadial climate and weaker during cooler glacial or stadial periods (Tiwari *et al.*, 2010).

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Sri Lanka, a small island in the Indian Ocean, located 800 km north of the equator, is largely affected by the monsoon climates. Located in the core of the Indian monsoon domain, the climate of Sri Lanka is described as tropical monsoonal that has a distinct rainfall rhythm throughout the year. Thus the rain-fed agro-economy in Sri Lanka is highly vulnerable to seasonal changes in the monsoon climate. Seasonal crop calendars are also prepared following the timing of the monsoon rainfall. Early-onset or late withdrawal of monsoons causes devastating impacts such as floods and landslides or droughts. Therefore, a long-term observation of the variability of the monsoon system is extremely important to predict future scenarios and to reduce the impacts of extreme events.

Several paleoclimatic investigations have been carried out in Sri Lanka to explore monsoon variability across different time scales. These studies can be used to enhance our understanding of monsoon predictability, improve the accuracy of predictions, and refine the projection's climate modeling. Therefore, this review aims to synthesize a comprehensive picture of the paleo-monsoon variability in Sri Lanka during the Holocene. The information gathered is compared with regional records, particularly with the records from the Indian subcontinent.

INDIAN MONSOON REGIME

The Indian monsoon is a dynamic and widely explored feature of the tropical atmospheric circulation system. The Asian Monsoon System (AMS) consists of two subsystems, the South Asian Monsoon (SAM) which is also known as the Indian Monsoon, and the East Asian Monsoon (EAM). The SAM is geographically occupied mostly over the Indian subcontinent and the Indian Ocean while EAM covers the East Asian regions of China, the Korean peninsula, and Japan (Huang *et al.*, 2012). The AMS brings remarkable imprints on the global climate, hydrological cycles, and energy flow through the ecosystems, thus having significant socio-economic consequences (Gadgil, 2003; Rashid *et al.*, 2007; Cane, 2010; Achyuthan *et al.*, 2014). Indian monsoon often originates over the equatorial Indian Ocean and spread northward over land and eastward over the tropical ocean (Figure 1).

As explained by the modern air mass theory, the monsoons are caused by the seasonal movement of the Inter-tropical Convergence Zone (ITCZ) over the equatorial region (Schneider *et al.*, 2014). During the northern hemisphere summer, ITCZ shifts northward and causes southwest (summer) monsoons. When it is shifted towards the south, northeast (winter) monsoon occurs. The ITCZ migrates between latitudes of 20° N and 8° S depending on the boreal summer and winter, promoting the rainfall over the south Asian region (Schneider *et al.*, 2014). The Indian Summer Monsoon (ISM), or south-west monsoon is a major component of the Asian monsoon system which has significant impacts on a hydrological cycle during summer months (Wang, 2002; Gadgil, 2003; Cane, 2010; Rashid *et al.*, 2011; Ota *et al.*, 2017). During the northern hemispheric summer, pressure differences over warm

Tibetan Plateau and cooler Indian Ocean generate south-westerly winds which could result in high rainfalls over southern and south-west Asia (Webster *et al.*, 1998; Wang *et al.*, 2001; Rashid *et al.*, 2007). The intensity of south-west monsoon links with strengths of the low pressure over the Tibetan Plateau and high pressure over the southern Indian Ocean, the effect of Somali Jet (Findlater Jet) and Somali current (Findlater current), Indian Ocean branch of Walker Cell (Walker circulation) and effect of the Indian Ocean Dipole (Trott *et al.*, 2017; Wang *et al.*, 2018).

During September, air pressure over northern India increases because of the rapid cooling of the northern Indian subcontinent, following the retreating Sun into the southern hemisphere. However, air over the adjacent Indian ocean does not cool that fast and holds the heat, resulting in a low-pressure zone. Due to this pressure gradient, cold air masses move from Himalayan and Indo-Gangetic Plain headed towards the Indian Ocean through the Deccan plateau. This is referred to as the northeast monsoon or retreating monsoon (Gupta *et al.*, 2006; Clift and Plumb, 2008; Singhvi *et al.*, 2010; Rajmanickam *et al.*, 2017). The formation of the northeast monsoon is affected by the strengthening of high-pressure cells over Tibetan and Siberian plateaus during the northern hemisphere winter. During this period, the ITCZ shifts towards the south of India, with westward migration and subsequent weakening of the high-pressure cell in the southern Indian Ocean. In shorter time scales, monsoon intensity fluctuates with the sea surface temperature, notably in the tropical Indian Ocean, and with the extension of Eurasian snow cover (Philander *et al.*, 1996; Webster *et al.*, 1998; Robock *et al.*, 2003; Rashid *et al.*, 2011).

MONSOON CLIMATE OF SRI LANKA

The rainfall regime of Sri Lanka is characterized by two monsoon periods known as the southwest monsoon (May to September) and the northeast monsoon (December to February). However, the annual average rainfall varies considerably across the country; with much higher rainfalls are on the central highlands and the western slopes of the central highlands receives an annual average rainfall exceeding 5000 mm (Figure 2). In contrast, the eastern and northern parts of the island receive only about 1300 mm average annual rainfall. During its northward movement, ITCZ crosses Sri Lanka and activates the summer monsoon. As a result, the southwestern part of the island receives steady rain (Suppiah, 1997). The orographic effect of the island causes heavy rainfalls on the western slopes (Figure 3). During the southwest monsoon period, cyclonic wind circulations in the mid-troposphere cause spells of heavy rain from June to August (Suppiah and Yoshino, 1984; Suppiah, 1996). Further, the troughs of low pressure which may spread out of Sri Lanka from the northern Bay of Bengal cause stormy weather and heavy rain. With the southward movement of ITCZ, the summer monsoon season ends in September. The northeast monsoon (winter monsoon) arrives in Sri Lanka in December when ITCZ migrates southwards. In December, spells of heavy rain occur in the eastern lowlands as with passing waves of

Figure 1: Movement of the Inter-Tropical Convergence Zone (ITCZ) in July (summer) and January (winter). Red arrows indicate the movement of air masses over the Indian subcontinent and the Indian Ocean (after Robinson and Henderson-Sellers, 1999; Yan, 2005).

Figure 2: Physiographical feature, climatic zones, and locations of paleoclimate records available in Sri Lanka (1- Potana cave site near Sigiriya; 2- Gawaratenna Plateau (Adam's Peak); 3- Horton Plains; 4- Panama; 5- Okanda; 6- Kirinda; 7- Bolgoda Lake; 8- Colombo; 9- Negombo) (modified after Chandrajith, 2020).

Figure 3: Annual average precipitation (in mm) over tropical Sri Lanka (source: Department of Meteorology, Sri Lanka).

small amplitude in the easterly wind stream and cyclonic wind circulations. Nearly 50% of the annual rainfall from the northeast monsoon is received by the eastern half of the country whereas the northwestern and southeastern regions receive relatively lower precipitation (Figure 3). The orography of the island also causes steady rain on the eastern slopes of the highlands. During the inter-monsoon periods of March-April and October-November, tropical cyclones and thunderstorms have also influenced the climate of Sri Lanka (Suppiah and Yoshino, 1984).

Despite the small size of the country, Sri Lanka has a remarkable spatio-temporal rainfall variation with differences in a hydrological and agro-ecological environment that are controlled by the monsoon pattern and the topography (Jayasena *et al.*, 2008; Chandrajith, 2020). Subsequently, the island is divided into two main climatic zones known as dry zone and wet zone however, an intermediate zone occurs in between main climatic zones (Domrös, 1979). Two third of the island, particularly north, northeast, and south-east terrains belongs to the dry zone regime (Figure 3). Due to its position in the core of the Indian monsoon domain, the rain-fed agro-economy in the island is highly vulnerable to the influence of both summer and winter monsoons. Early-onset or late withdrawal of monsoons causes devastating impacts such as floods and landslides or droughts and even spreading of some vector bone diseases (Zubair, 2002; Ratnayake and Herath, 2005; Briët *et al.*, 2008; Sirisena and Noordeen, 2014).

PALEOCLIMATE RECORDS FROM SRI LANKA

The great chronicle of Sri Lanka, the *Mahāvamsa* provides the first documentary evidence on a palaeoclimatic event that occurred in Sri Lanka. The *Mahāvamsa* refers to an extreme drought period that lasted around 700 BP on the island (Geiger and Boad, 1964). However, systematic paleo-environment and paleoclimate studies have been initiated in Sri Lanka in the '90s. Deraniyagala, (1992) reconstructed the late Quarternary paleo-environment of Sri Lanka and identified wet pluvials that were in phase with glacial stages while dry interpluvials were associated with inter-glacial stages. Besides, paleo-proxy records were investigated in different sites in Sri Lanka to reconstruct the Holocene climatic history. From among these studies, a palynological study of sediments from Potana cave in Sigiriya (Premathilake and Caratini, 1994) and Horton Plains (Premathilake, 2003; Premathilake and Risberg, 2003; Routh *et al.*, 2014), geochemical and sedimentological investigations of sediment cores from the southeastern coastal plain (Ranasinghe *et al.*, 2013a, 2013b), southern coastal area (Ranasinghe *et al.*, 2013a) and western coastal region (Gayantha *et al.*, 2017; Ratnayake *et al.*, 2017; Gayantha *et al.*, 2019a,b; Gayantha *et al.*, 2020) used to elucidate paleo-climate conditions prevailed in Sri Lanka (Figure 2). Table 1 summarizes the paleo-climatic records available in Sri Lanka and the proxies used for these investigations.

PALEO-MONSOON VARIABILITY OF SRI LANKA DURING HOLOCENE

The early Holocene period of Sri Lanka was characterized by a strong monsoon phase as depicted by several studies (Premathilake and Risberg, 2003; Premathilake, 2006). Based on the pollen and spore records, information obtained from total organic carbon (TOC), total nitrogen (TN), $\delta^{13}\text{C}$ and siliceous microfossils found in peat sequences from the Horton Plains indicated a per humid event that occurred from 10.2 to 9.9 kyr BP with a hyper-humid event around 8.7 kyr BP. Increased pollen abundance with higher TOC content and lower TN were observed during these events (Premathilake and Risberg, 2003). During a strong monsoon phase, the flourishing of vegetation could result in increased pollen and spore production. In addition, wet periods also favor high primary productivity that is reflected in increased TOC contents. Changes in the presence of dominant pollen types indicate vegetation changes due to shifts in warm/wet and dry/arid climate conditions (Misra and Bhattacharyya, 2014; Veena *et al.*, 2014; Srivastava *et al.*, 2017). Similarly, wet or dry monsoon climate can be identified based on the dominance of each taxon of siliceous microfossil types within a specific period (Premathilake, 2006; Misra and Bhattacharyya, 2014; Veena *et al.*, 2014). Based on upwelling and terrestrial proxies, enhanced southwest monsoon activity during the early Holocene (10.0-8.0 kyr BP) was also detected in a marine record from the western continental shelf off Colombo (Ranasinghe *et al.*, 2017). After the 12.5 kyr BP Younger Dryas cold event, wet and warm conditions were gradually increased and depicts an early Holocene summer monsoon strengthening as evident in LOI, TOC, TN, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, major and trace element ratios, and diffuse color reflectance proxies in sediment records from Gawaratenna Plateau (Ranasinghe *et al.*, 2017). However, monsoon strength has weakened at around 8.2 kyr BP, showing a teleconnection with North Atlantic cold episodes.

In most paleoclimate records, the mid-Holocene of Sri Lanka was noted as a semi-arid to arid phase or a period of weakened monsoon activity (Figure 4). From 8.7 to 3.6 kyr BP, a semi-arid climate was characterized as indicated by decreasing pollen abundance (Premathilake and Risberg, 2003). However, around 5.7 kyr BP, a slightly wetter climate was observed in the dry zone area where rainfall mainly receives from the northeast monsoon (Premathilake and Caratini, 1994). The Horton Plains, which receive excessively high rainfall at present, remained semi-arid during the mid-Holocene. Premathilake (2006) further revealed that the monsoon precipitation over the Horton Plains commenced to decrease from around 8.7 kyr BP and continued until 3.6 kyr BP. Therefore, this period can be considered as a semi-arid phase or a weakened phase of southwest monsoon with an extreme arid period in between 5.4 to 3.6 kyr BP (Premathilake, 2006). This was also supported by the marine sediment records from the western continental shelf where decreased flux of terrestrial Ti and Fe_2O_3 were noted particularly during 8.2 to 2.0 kyr BP. A sedimentary record from the western continental shelf revealed a low terrestrial influx from 4.0

Table 1: Paleoclimate records from Sri Lanka.

Location	Archive	Proxies used	Monsoon	Allometric relationships used for determination below ground biomass (BGB)
Potana cave site, Sigiriya	Soil	Pollens	north-east	Premathilake and Caratini (1994)
Horton Plains	Peat sequence	Pollen and spores, siliceous microfossils (phytoliths, diatoms, chrysophyte stomatocysts), TOC, TN, $\delta^{13}\text{C}$, C/N ratio	south-west	Premathilake and Risberg (2003)
Horton Plains	Mire sediments	Pollen and spores, siliceous microfossils (phytoliths, diatoms, chrysophyte stomatocysts), TOC, TN, $\delta^{13}\text{C}$, C/N ratio, Magnetic Susceptibility	south-west	Premathilake (2003) Routh <i>et al.</i> (2014)
Horton Plains	Peat sequence	Pollen and spores, phytoliths, TOC, TN, $\delta^{13}\text{C}$, C/N ratio, Magnetic Susceptibility	south-west	Premathilake, (2006)
Southeastern coast	Lagoon sediments	Grain size, Magnetic Susceptibility, visible diffuse spectral reflectance, chemical composition, Rb/Sr ratio	north-east	Ranasinghe <i>et al.</i> (2013a)
Continental shelf, off Negombo	Marine sediments	Color reflectance of sediments, chemical composition Ti, Fe_2O_3 , $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of <i>G. ruber</i> , benthic and planktonic form abundance	south-west	Ranasinghe <i>et al.</i> (2017)
Continental shelf, off Colombo	Marine sediments	Grain size, chemical composition, Color reflectance,	south-west	Ranasinghe <i>et al.</i> (2017)
Bolgoda lake	Lake sediments	Grain size, major and trace elements, TOC, TN, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, Mass Accumulation Rates	south-west	Gayantha <i>et al.</i> (2017); Gayantha <i>et al.</i> (2019); Gayantha <i>et al.</i> (2020); Ratnayake <i>et al.</i> (2017)
Gawaratenna Plateau, Adam's Peak	Terrestrial Sediments	LOI, TOC, TN, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, element ratio, diffuse color reflectance	south-west	Ranasinghe <i>et al.</i> (2017)

Figure 4: Summary of paleoclimate phases recorded in Sri Lanka (i) Premathilake and Risberg (2003); (ii) Premathilake (2003); (iii) Premathilake (2006); (iv) Ranasinghe *et al.*, (2017); (v) Ranasinghe *et al.*, (2016); (vi) Gayantha *et al.*, (2017); (vii) Ranasinghe *et al.*, (2013b).

kyr BP to 2.0 kyr BP, indicating a decreased intensity of southwest monsoon precipitation. However, the monsoon winds were stronger during this period as depicted by upwelling proxies (Ranasinghe *et al.*, 2016).

Mid-Holocene aridity was also detected in north-east monsoon records from the southeastern region in Sri Lanka. Geochemical proxies of lagoon sediments from the south-eastern coast indicated an arid phase from 7.3 to 6.75 kyr BP and a semi-arid interval extending from 6.25 to 4.60 kyr BP (Ranasinghe *et al.*, 2013b). However, a short wet interval during mid-Holocene was observed during 6.50-6.25 kyr BP (Ranasinghe *et al.*, 2013a), and a slightly more humid climate was noted around 5.7 kyr BP in the Potana Cave site (Premathilake and Caratini, 1994). Late Holocene (4.2 to 0.0 kyr BP) is characterized by fluctuating weak and enhanced monsoon conditions (Premathilake and Risberg, 2003; Premathilake, 2006; Ranasinghe *et al.*, 2013a,b; Gayantha *et al.*, 2017). The winter monsoon-dominated southeastern part of the island experienced an arid climate during 4.0-3.0 kyr BP but a wet climate during the 3.0-1.5 kyr BP period (Ranasinghe *et al.*, 2013a). However, strengthened summer monsoon activity was observed during 3.6 to 2.0 kyr BP, but decreased around 2.2 kyr BP as indicated from archives from central highlands (Premathilake and Risberg, 2003). Multi-proxy paleo-climate data obtained by sedimentary archives from the Bolgoda Lake on the west coast showed an intensification of south-west monsoon from 2.9 to 1.3 kyr BP (Gayantha *et al.*, 2017). Signs of fading monsoons were also detected during the period of 2.4-2.0 kyr BP (Gayantha *et al.*, 2019b) and 2.0 kyr BP to present (Premathilake and Risberg, 2003) in the south-west monsoon. A sediment core from the central highland also indicated a dry period from 4.0 to 1.0 kyr BP (Ranasinghe *et al.*, 2017). Depicting the highly dynamic nature of the late Holocene summer monsoon, the periods extending from 1.78 to 1.29 kyr BP and 1.0 kyr BP to present were recorded as active monsoon phases (Ambillapitiya *et al.*, 2017; Gayantha *et al.*, 2017). Premathilake and Risberg (2003) also suggested an increasing trend in summer monsoon towards the late Holocene. Despite the wax and wane behavior of monsoon strength was recorded during the late Holocene period, an overall weakening of the southwest monsoon throughout the late Holocene was evident from lake sediments from the west coast (Gayantha *et al.*, 2017; Ratnayake *et al.*, 2017).

RELATIONSHIP WITH REGIONAL RECORDS

Considering the regional coherence of the Indian monsoon domain, paleoclimate records of the Indian subcontinent, Bay of Bengal, Andaman Sea, Arabian Sea, and continental records around the Arabian Peninsular, provide useful insight into the highly dynamic nature of the Holocene monsoon climate (Figure 5). Although only a few studies have been carried out in Sri Lanka, extensive investigations on the Holocene climatic variation were carried out in India and surrounding regions for the last few decades using different physical, geochemical and biological proxies. In particular, marine sediments from the Bay of Bengal, and

cave stalagmites showed marked changes in biological, chemical, and physical proxies corresponding to active and weak monsoon phases as documented in Sri Lanka.

Early Holocene

Progressive strengthening of the Indian summer monsoon was observed from ~11.0 to 9.4 kyr BP in northwest India, based on lake sediment records from Kottla Dahar (Dixit *et al.*, 2014). Enhanced monsoon activity phases were also identified from 10.0 to 7.0 kyr BP (Nair *et al.*, 2010) and from 10.7 to 8.6 kyr BP (Sandeep *et al.*, 2017) in lake records of Shantisagara lake in southern India. Comparable paleoclimate records were also noted in the eastern Arabian Sea (Sarkar *et al.*, 1990), Oman and Yemen (Fleitmann *et al.*, 2003; Fleitmann *et al.*, 2007), and Andaman Sea (Rashid *et al.*, 2011) and supported the monsoon intensification observed in Sri Lanka during the early Holocene. A rapid northward displacement of the mean position of summer ITCZ and Indian summer monsoon rain belt during early Holocene were reflected by the rapid decrease of $\delta^{18}\text{O}$ in a cave stalagmite from Oman and Yemen (Fleitmann *et al.*, 2007), while a wetter and humid climate was observed in a marine record from Andaman sea (Rashid *et al.*, 2011). Strengthening of monsoon from 11.0 to 7.0 kyr BP was observed in sediments from the Ganges-Brahmaputra river delta on the east coast of India (Goodbred Jr. and Kuehl, 2000). These records are consistent with the observed strong monsoon activity recorded in Sri Lanka during the early Holocene. Paleoclimate archives from south India and surrounding regions showed the single-step development of the Indian monsoon during the early Holocene (Figure 6).

Despite the observed single-step monsoon strengthening, an apparent two-step progression of Indian summer monsoon during early Holocene was noted in some paleoclimate records (Overpeck *et al.*, 1996; Thamban *et al.*, 2007; He *et al.*, 2018). Abrupt strengthening of the Indian monsoon was observed from 13.0 to 12.5 kyr BP and from 10.0 to 9.5 kyr BP, implying that monsoon progression did not follow astronomical forcing at the dawn of Holocene (Overpeck *et al.*, 1996). Thamban *et al.* (2007) also identified abrupt strengthening of monsoon, one at 9.5 kyr BP and the other at 9.1 kyr BP, based on marine records from the eastern Arabian Sea. Similar events were also recorded in the Central Tibetan Plateau around 11.7 kyr BP and 10.0 kyr BP inferred by decreased $\delta^{18}\text{O}$ in Ostracods and a significant increase of sedimentary Ti concentration (He *et al.*, 2018). During the second event, which extended from 10.0 to 7.0 kyr BP, leaf-wax hydrogen isotope composition ($\delta\text{D}_{\text{wax}}$) values decreased progressively and reached the minimum indicating enhanced precipitation.

Significant weakening of the Indian summer monsoon was recorded from 11.1 to 10.7 kyr BP as identified in the Shantisagara lake record (Sandeep *et al.*, 2017) while a dry phase with the decreasing trend in winter monsoon precipitation was detected during 10.0-4.83 kyr BP based on the sedimentary record from Palar River basin,

Figure 5: Map showing paleoclimate records available in the Indian and Indian Ocean region that cited in the text- (1) Kottla Dahar, Haryana; (2) Plaeo-lake Riwasa, India; (3) Kedarnath, Himalayas; (4) Benital Lake, Himalayas; (5) Nir' Pa Co Lake, Tibet; (6) Ganges-Brahmaputra River Delta; (7) Bay of Bengal; (8) Landfall Island, Andaman Sea; (9) Ayeyarwady continental shelf, Andaman Sea; (10) Andaman Sea; (11) Kukkall Lake, South India; (12) Asthamudi-Sathamkotta Lake, Kerala; (13) South Kerala sedimentary basin; (14) Kanjani region and Chettura estuary, Kerala; (15) Pookude Lake, Kerala; (16) Nilgiri Hills; (17) Palar River Basin, South India; (18) Eastern Arabian Sea; (19) Shantisagara Lake, South India; (20) the Arabian Sea; (21) Off the coast of Oman; (22) Continental margin of Oman; (23) Dimarshim Cave, Socotra; (24) Defore Cave, Southern Oman; (25) Qunf Cave, Southern Oman; (26) Hoti Cave, Northern Oman.

Figure 6: Summary of climatic events recorded in India and Indian Ocean regions; (a) Nair *et al.* (2010); (b) Kumaran *et al.* (2008); (c) Misra and Bhattacharyya (2014); (d) Rajagopalan *et al.* (1997); (e) Veena *et al.* (2014); (f) Lone *et al.* (2018); (g) Sandeep *et al.* (2017); (h) Sarkar *et al.* (2000); (i) Thamban *et al.* (2007); (j) Gupta *et al.* (2003); (k) Fleitmann *et al.* (2007); (l) Fleitmann *et al.* (2003); (m) Goodbred Jr. and Kuehl (2000); (n) Achyuthan *et al.* (2014); (o) Rashid *et al.* (2011); (p) Dixit *et al.* (2014); (q) Bhushan *et al.* (2018); (r) Srivastava *et al.* (2017); (s) He *et al.* (2018).

South India (Resmi and Achyuthan, 2018). Apart from that, significantly weak monsoon phases from 10.8 to 10.2 kyr BP, 9.8 to 8.8 kyr BP, and 8.4 to 8.0 kyr BP were also recorded in marine sediments from the Arabian Sea. These events have coincided with 10.3, 9.4, and 8.2 Bond events, respectively (Gupta *et al.*, 2005). However, only the 8.2 Bond events were recorded in Sri Lanka. This cold episode was recorded as a period of low terrestrial influx which depicts a weakening of rainfall. An abrupt weakening of the Indian summer monsoon which was reported during the 8.3 to 7.9 kyr BP period, is coincided with the 8.2 kyr BP cold event as evident by abrupt desiccation marked by Nir' Pa Co lake record in southeastern Tibet (Dixit *et al.*, 2014).

Mid Holocene

Semi-arid climate and increased arid conditions were recorded in the central highlands of Sri Lanka from 8.7-3.6 kyr BP and 8.0 to 3.6 kyr BP (Figure 4). This observation is consistent with the records from Kukkal and Shantisagara lakes (Rajmanickam *et al.*, 2017; Sandeep *et al.*, 2017). A gradual decrease in monsoon precipitation was also initiated in ~8.0 kyr BP as evident from cave stalagmite records from southern Oman (Fleitmann *et al.*, 2003). Sediments from the Arabian sea and Riwasa lake in northwest India also recorded a similar event (Thamban *et al.*, 2007; Dixit *et al.*, 2014). A cave stalagmite record from Oman and Yemen showed decreasing monsoon precipitation in the mid-Holocene due to the southward migration of ITCZ (Fleitmann *et al.*, 2007). These events are also evident in mid-Holocene paleoclimate records from both Sri Lanka and the Indian subcontinent. This was followed by weak to moderate precipitation conditions mainly from 5.0 to 4.2 kyr BP (Fleitmann *et al.*, 2007). However, the eastern Arabian sea recorded a more arid episode from 6.0 to 3.5 kyr BP and a significantly weak monsoon period from 6.0 to 5.5 kyr BP (Sarkar *et al.*, 2000; Thamban *et al.*, 2007). Although the mid-Holocene is identified as a weak monsoon phase in most paleoclimate records in Sri Lanka, deviations to this generalized figure can be observed in some records. Such events include a short wet climate recorded during 6.50-6.25 kyr BP (Ranasinghe *et al.*, 2013a) and a slightly more humid climate around 5.7 kyr BP (Premathilake and Caratini, 1994). The reported short wet period during 6.5-6.25 kyr BP in the winter monsoon is consistent with the warmer and wetter conditions that appeared during 6.5-5.4 kyr BP (Srivastava *et al.*, 2017).

Late Holocene

During the late Holocene period, intense monsoon activity phases were recorded in many parts of Sri Lanka as revealed by different paleoclimate proxies. Similar climate conditions were also observed in paleoclimate records from the Indian subcontinent and surrounding regions. Rapid intensification of the summer monsoon with wet and strong climate phases was observed between 3.2-1.8 kyr BP in sediment recodes from Kukkal Lake, South India (Rajmanickam *et al.*, 2017). A strengthening of monsoon activity from ~3.6 to 1.5 kyr BP, recorded in Sri Lanka is

comparable to the records from both the eastern Arabian Sea and northern Andaman Sea (Achyuthan *et al.*, 2014; Sarkar *et al.*, 2000). However, the above observations are not consistent with some terrestrial records that showed the onset of aridity occurred ~4.0 kyr BP (Sarkar *et al.*, 2000). The dissimilarities in the timing of onset and retreating monsoons are obvious in both summer and winter monsoons in different geographical localities in Sri Lanka implying the localized response of the climate system to a unique tropical atmospheric circulation phenomenon.

A palynological study coupled with magnetic susceptibility and stratigraphy of subsurface sediment from the South Kerala sedimentary basin (Kumaran *et al.*, 2008) revealed that south-west monsoon became gradually reduced after ~5.0 kyr BP or 4.0 kyr BP thereby, having a late Holocene dry climate. A significant weakening of the Indian summer monsoon after ~5.0 kyr BP was noted in the Andaman Sea and southern India (Rashid *et al.*, 2011; Sandeep *et al.*, 2017). The declining trend of Indian summer monsoon precipitation was identified from cave stalagmite obtained from northeast India during the same period (Berkelhammer *et al.*, 2012). In addition, abrupt weakening of south-west monsoon was observed in lake sediment record from Haryana, India around 4.1 kyr BP following 4.2 kyr BP Bond event (Dixit *et al.*, 2014). The weak monsoon phases recorded in Sri Lanka during the late Holocene to the present are consistent with the weak monsoon phase recorded in the South Asian region including recodes from the Arabian Sea.

Climate variations were important during the late Holocene period since expansion of human settlements was expanded during this period. An extremely strong south-west monsoon phase was recorded in hydrological conditions observed during 1.8-1.0 kyr BP in higher central Himalayas (Bhushan *et al.*, 2018) and increased winter monsoon precipitation was recorded from 1.88 to 1.44 kyr BP in South India (Resmi and Achyuthan, 2018). In contrast, a weakening of the southwest monsoon was recorded in central Sri Lanka from ca. 2.0 kyr BP to present (Premathilake and Risberg, 2003). This observation is supported by a weak monsoon phase recorded in continental margin sediments off Oman, during 1.9-1.4 kyr BP (Gupta *et al.*, 2003). Furthermore, a prolonged and gradual intensification of the Indian summer monsoon was observed from 0.4 kyr BP to present in the northern Andaman Sea record (Ota *et al.*, 2017). Despite the two discrete, short humid events with significantly high rainfall around 0.6 kyr BP and around 0.15 kyr BP in the southwest monsoon record (Premathilake and Risberg, 2003). Veena *et al.* (2014) also noted uninterrupted phases of enhanced monsoon activity during the periods of 1.4-0.76 kyr BP and 0.42-0.14 kyr BP in the Pookude Lake record. A colder phase with suppressed monsoon activities from 0.60-0.25 kyr BP (Srivastava *et al.*, 2017), decreased winter monsoon precipitation from ca. 1.44 kyr BP to present (Resmi and Achyuthan, 2018) and wetter to drier transition around ~0.68 kyr BP which was continued till 0.34 kyr BP as identified in Kedarnath peat records, from

Central Himalayas, river sediments of Palar River basin, South India and in a Cave Stalagmite record from Southern Oman, respectively (Fleitmann *et al.*, 2004).

SUMMARY

Palaeoclimatic information available in Sri Lanka suggested that the early Holocene was characterized by a strong monsoon phase. This enhanced monsoon activity phase was followed by a weak monsoon period around 8.0 kyr BP. In most paleoclimate records, the mid-Holocene was identified as a semi-arid to arid phase or a period of decreased monsoon activity. Late Holocene is a highly variable climate and in millennial and centennial time scale. There is a large spatial variability that existed in paleo-monsoon records from Sri Lanka during the late Holocene. The monsoon variability inferred from paleoclimate records in Sri Lanka is almost consistent with regional records from the Indian monsoon regime. Dissimilarities in the timing of onset and withdrawal of monsoons were obvious among different geographical localities in Sri Lanka for both summer and winter monsoons suggesting localized response of the climate system to these unique atmospheric circulation phenomena. The Indian summer monsoon showed a pronounced phase difference across the country. For example, the southwest monsoon affected the western part of the country experienced a strong monsoon phase while the central Highlands having a weak monsoon phase during the same time interval. Both phases are supported with regional paleo-monsoon records to a large extent. Paleoclimate records from Sri Lanka revealed that summer and winter monsoons behaved mostly in a similar way, implying similar forcing mechanisms. Despite the contrasting differences among regional records across shorter time scales, the paleo-monsoon climate of Sri Lanka during the Holocene has been varied coherently with other of the Indian monsoon domain including the Indian subcontinent, Bay of Bengal, Northern Andaman Sea, Eastern and Western Arabian Sea, Northern and Southern Oman, Yemen and as far as some locations in China where Indian Summer Monsoon has a greater impact than East Asian Summer Monsoon. Based on the monsoonal response at around 8.2 kyr BP, it could be concluded that Sri Lanka showed a teleconnection with the North Atlantic cooling events during Holocene.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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