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RESEARCH ARTICLE

Chronological framework of Asian Southwest Monsoon events and variations over the past 24,000 years in Sri Lanka and regional correlations

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Abstract: An accelerator mass spectrometry (AMS- ^{14}C) dated multi-proxy upper montane rainforest record from the Horton Plains, Central Sri Lanka reveals a ~ 24,000 year history of millennial-scale monsoon climate variability since the last glacial maximum (LGM). The vegetation history indicates that post-LGM earliest tropical warming and monsoon initiation preceded the Northern Hemisphere ice-sheet melting by over 3000 years before the Bolling interval, with a significant increase in the precipitation at Termination 1A (event-B in the Horton Plains). This suggests a major early strengthening of the monsoon. Starting ca. 17,600 years before present (yr BP), the rainforest diversity increases in-step with four progressively increasing humid events (A-D) and interrupted by two relatively semi-arid/weak episodes of which the second (Termination 1B) ending ca. 10,400 yr BP may reflect a delayed Younger Dryas event. The optimum rainforest diversification coincides with the Holocene monsoon precipitation maximum ca. 9,200 − 8,800 yr BP (event-D). A disruption to these millennial cycles coincided with a gradual monsoon downturn, precipitation and rainforest decline and aridity between ca. 8,100 − 3,400 yr BP. The conditions became more humid again for rainforest expansions between ca. 3,400 − 1,500 yr BP (event-E). Broadly synchronous millennial-scale climatic records of the Horton Plains, Arabian Sea, Oman, Yemen and India, equatorial West and East Africa, and the North Atlantic regions indicate two-way teleconnections between the tropical Asian Monsoon fluctuations and high latitude events. The above changes reflect vast spatial rearrangements in atmospheric circulation patterns, probably caused by forcing associated with coupled ocean-atmosphere-vegetation feedbacks. There is a remarkably close correlation of the different proxies that has tracked the Southwest Monsoon variations across the region since the LGM.

Keywords: Holocene aridity, Palaeomonsoons, millennial cycles, rainforest diversity, regional chronology, Sri Lanka.

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INTRODUCTION

Litho-, bio- and chrono-stratigraphic studies have been carried out for studying the environmental history during the past c. 24,000 years in the upper monsoon rainforest (UMRF) region of the Horton Plains, Central Sri Lanka (Premathilake, 2006, 2012; Premathilake & Risberg, 2003). The objective of this study is to construct a ^{14}C age-model of the Horton Plains peat sequence (Table 1), identify the climate oscillations and compare these chronologically with the proxy records of the Southwest Monsoon (SWM) of other regional locations

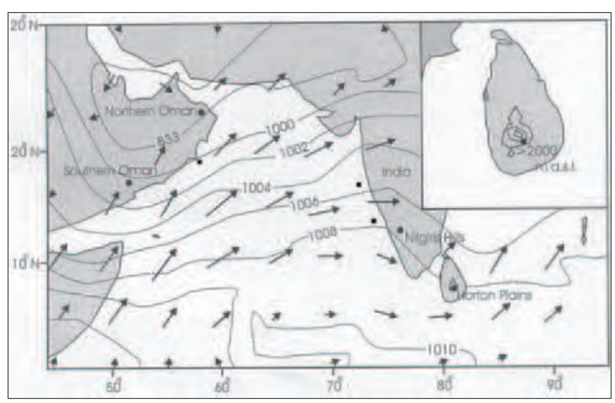

Figure 1: Location of Horton Plains, Sri Lanka and regional monsoon wind-flow regime. The isobaric lines depicted are for summer monsoon airflow today. Other regional study sites are also indicated (filled circles for terrestrial records and filled squares for marine records).

in the monsoonal domain of southern Asia represented in Figure 1. Abrupt, millenial scale climate oscillations are indicated for a part of the Horton Plains monsoonal record (ca. 24,000 to ca. 8,100 yr BP) as shown in Table 1.

Table 1: ^{14}C Age model (AMS) of the Horton Plains peat sequence

AMS sample depth(cm)	AMS ^{14}C Age (^{14}C yr BP)	Error (1-ô)	Events	Calibrated age* (cal. yr BP)	Interpolated age (cal. yr BP)
			F, G (PH)		650; 150
80	1,025	± 70		1,060 – 790	
125	3,235	± 60		3,560 – 3,380	
160	2,675	± 60		2,850 – 2,745	
230	3,120	± 70		3,450 – 3,210	
250	3,060	± 50	**E** – (HH)	3,350 – 3,210	3,400 – 1,500
	Mid-Holocene Aridity			5,500 – 3,600	
290	5,080	± 65		5,910 – 5,740	
305	7,935	± 80	**D** - (HH)	8,990 – 8640	9,200 – 8,800
	Early Holocene Climatic Optimum				
350	8,805	± 70		10,150 – 9,990	
			C - (PH)		10,400 – 9,900
420	9,125	± 80		10,400 – 10,210	
460	9,195	± 75		10,480 – 10,240	
	Cool Dry Phase			12,000 – 10,200	
			B - (H) Monsoon onset		13,700 – 12,800
487	12,970	± 115		16,000 – 15,200	
499	12,950	± 100		15,950 – 15,150	
			A - (SH)		17,650 – 16,000
540	15,045	± 140	**G/PG**	18,350 – 17,650	18,500 – 17,600
580	18,410	± 185	Semi-Arid	22,300 – 21,450	< 24,000

SH: semi-humid < H: humid < PH: per-humid < HH: hyper-humid

G/PG : glacial/postglacial transition

Note: inverted date in the upper part of sequence probably due to contamination. The upper part of alternate cores was analyzed to rectify this and clarify true relationships in Figure 2.

* Stuiver *et al.*, (1998)

The geological signature of abrupt climate oscillations is well established in marine, continental and ice-core records of the late Quaternary (Bradley, 1999). They are also known from tropical Pacific and Atlantic regions and equatorial East Africa (Street-Perrot & Perrot, 1990; Bond *et al*., 1997; Hughen *et al*., 1997; Visser *et al*., 2003). A comprehensive review on this is given by Chiang (2009). The Indian Ocean SWM also underwent millennial to century scale abrupt changes during the late Quaternary in the Arabian Sea (Sirocko *et al*., 1993, Overpeck *et al*., 1996). Further, near synchronicity between high latitude climate changes and sub-tropical Asian monsoon fluctuations has also been demonstrated (Sirocko *et al*., 1996; Haug *et al*., 2001; Neff *et al*. 2001, Wang *et al*., 2001; Fleitmann *et al*., 2003; Gupta *et al*., 2003; Sinha *et al*., 2007; Zhang *et al*., 2008). These studies show the distinctive impact of the Atlantic Ocean thermohaline circulations on the Indian Ocean monsoonal regime. Intervals of weak and strong summer monsoons correlate with cold and warm periods, respectively in the higher latitudes. Our study highlights and extends this palaeomonsoonal synchronicity to the Asian tropics as well, giving added insight into the mechanism of global climate changes.

Horton Plains palaeomonsoonal record

Sri Lanka is ideally situated for investigations on the impact of atmospheric/oceanic events on the equatorial climate regime. The highlands act as a physiographic barrier to trap moisture laden monsoon winds and are a natural climatological observatory in the Indian Ocean. The Horton Plains (6^0 47' to 6^0 55'N latitude), an ecologically threatened upper montane rainforest (UMRF) system is located at 2100 − 2600 m asl. This ecosystem contains a total of 50 known arboreal species of which,

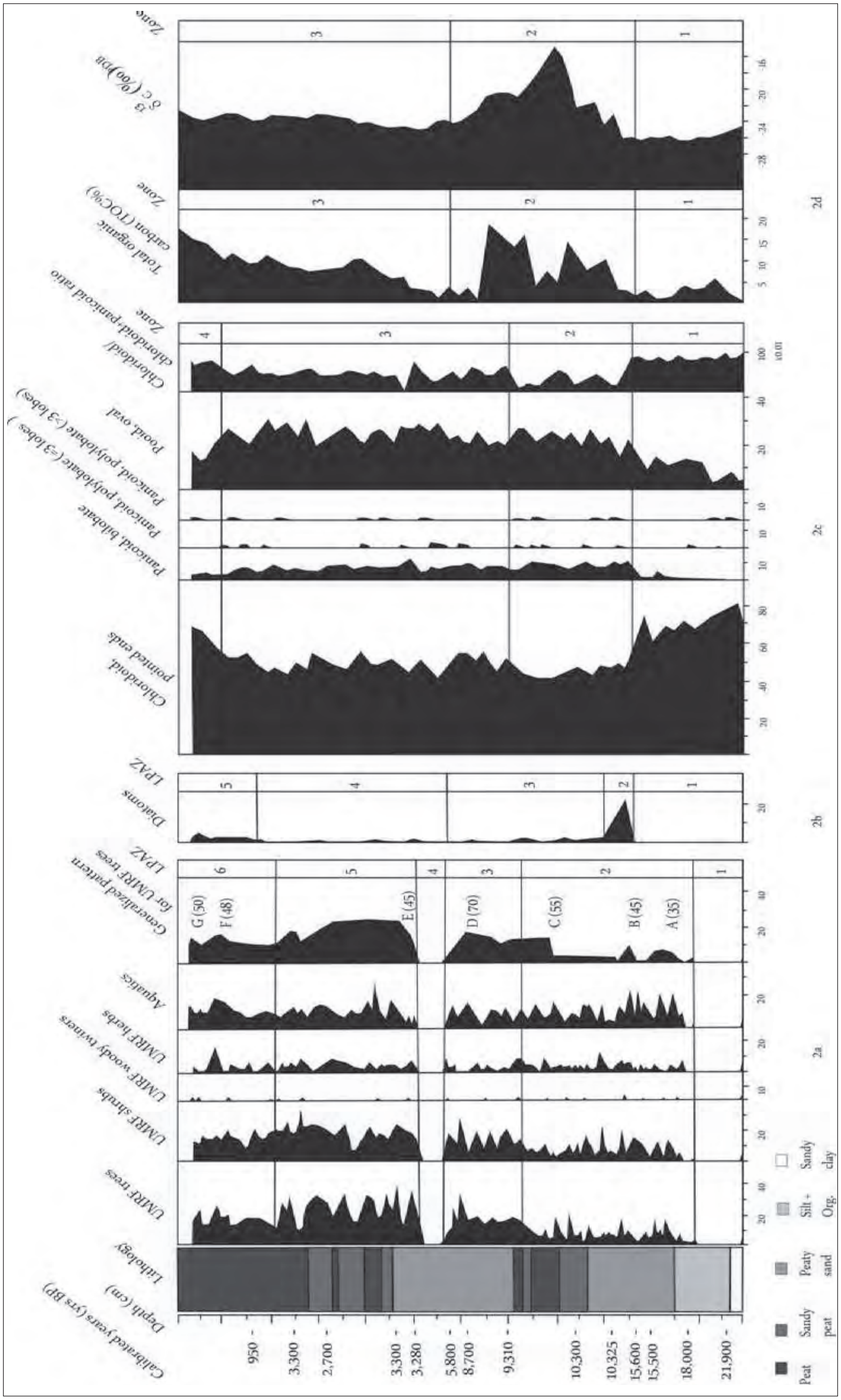

Figure 2: Percent distribution of UMRF pollen/spores (2a); diatoms (2b); phytoliths (2c); total organic carbon (TOC %) and δ^{13}C ‰ (2d); in the Horton Plains AMS-dated peat sequence

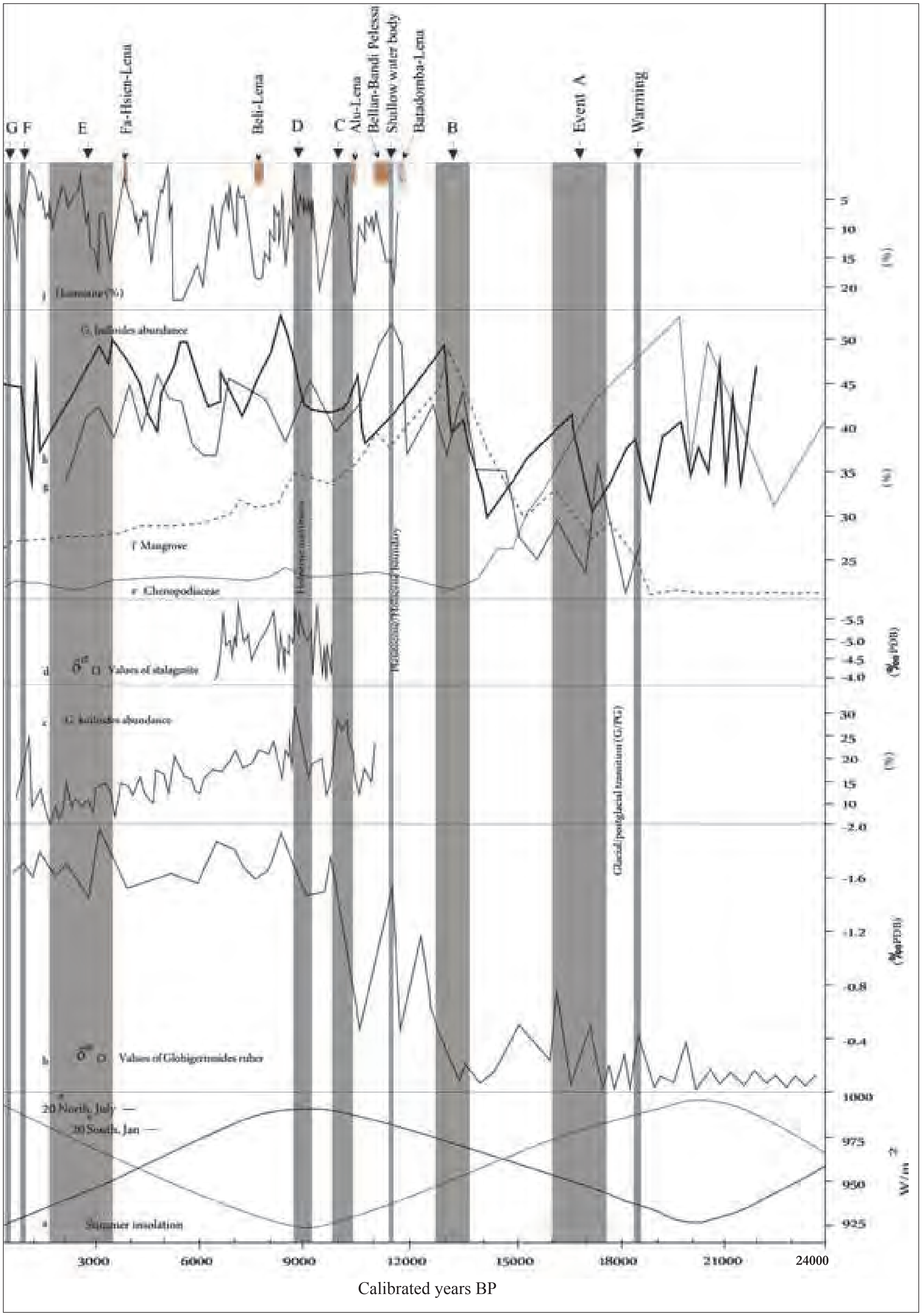

Figure 3: Palaeo-hydroclimatic reconstruction. Correlation between Horton Plains monsoon events (dark vertical bars A-G) and other regional proxy records (see appendix 1 for details). The brown bars indicate the apparent termination of human occupations in several cave locations in Sri Lanka, which occurred during monsoon downturns.

over 50 per cent are endemic to Sri Lanka (Werner & Balasubramanian, 1992). The rainfall averages 2150 mm yr^{-1}, most of which occurs during the SWM (May to August). The site, one of the southernmost in the northern hemisphere, records one of the three main branches of summer airflow from the ocean to land (Figure 1).

This study presents a 24,000-year monsoon proxy record from a peat sequence in the climatically sensitive Horton Plains. Pollen, spores, diatoms, phytoliths, total organic carbon (TOC) and $\delta^{13}C$ variations were utilized to track the development of the SWM precipitation dependent UMRF in the region (Figure 2). The above proxies resolve clear and abrupt signals of millennial-scale tropical monsoon variability and climate change in the region since the LGM. Unlike marine proxies, which primarily register changes in wind strength and upwelling events and may or may not reflect changes in moisture on the continents, the number of UMRF taxa and terrestrial proxies ($\delta^{13}C$ and total organic carbon) may be a direct indicator of the amount of monsoon precipitation.

METHODS AND MATERIALS

A master core of 6 m (compiled of 36 cores) was taken from mire sediments for detailed litho- and biostratigraphic investigations (Premathilake & Risberg, 2003). Pollen, spores and phytoliths were extracted and identified from these cores and the relative contribution of UMRF taxa to the botanical assemblage was quantified. The generalized stratigraphic pattern of UMRF vegetation proxies and the changing numbers of arboreal taxa in the Horton Plains signify progressive diversification or decline of the rainforest with increasing/decreasing monsoon strength/precipitation through time. The moisture regime is described as hyper-humid – perhumid – humid – semi-humid; based on a relative precipitation range when compared to the present-day rainfall values. The Holocene climatic optimum with 70 arboreal species implies significantly much higher rainfall compared to today's values (by an unknown factor). Enhanced aridity is shown by an increase in the ratio of chloridoid/chloridoid + panicoid phytolith morphotypes.

A chronological framework was established by 22 ^{14}C dates using bulk peat material and analyzed at the Angstrom Laboratory of the University of Uppsala, Sweden. Age intervals of zones and events (A-G) are deduced from linear interpolations of lines adapted to AMS dates. All ^{14}C dates in Figure 2, 3 and Table 1 were recalculated in calendar years, cal. yr BP (after Stuiver *et al.*, 1998).

RESULTS & DISCUSSION

A chronological reconstruction of monsoon activity in the Horton Plains over the past 24,000 years is presented based on radiocarbon dated proxies of vegetation cover (mainly the abundance of UMRF species and also a number of other botanical and geochemical proxies such as total organic carbon, carbon isotopes etc.). The data are summarized in Figure 2 and Table 1. From this evidence the climate record is resolved into a succession of seven stages of strong monsoonal activity and three intervening phases of monsoonal downturns (Figure 3).

ca. 24,000 – ca. 18,350 yr BP

The distribution of UMRF pollen/spores, diatoms and phytoliths in the sampled sequence indicates a semi-arid climate during this period. The sparse flora is characterized mainly by grassland, dry shrub-forest and xerophytic species, with a total lack of UMRF elements. This suggests a very weak SWM with low precipitation during the LGM.

ca. 18,350 – ca. 17,650 yr BP

An increase in humidity is indicated by an abrupt development of UMRF elements from ca. 18,350 yr BP (LPAZ 1/2 boundary) onwards, suggesting either climate warming and/or strengthening of the monsoon. This initial expansion of the UMRF species probably indicates the transition from glacial to post-glacial (G/PG) conditions.

ca. 17,650 – 16,000 yr BP (A) to ca. 13,700 – 12,800 yr BP(B) to ca. 10,400 – 9,900 yr BP (C)

The regional vegetation was dominated first by grasslands, followed by weakly developed UMRF taxa until ca. 14,000 yr BP. The three events marked A, B, C (Table 1 and Figures 2 & 3) signify progressive diversification of the UMRF (increasing from ~ 35 to 50 arboreal species) following stepwise strengthening of the monsoon between ca. 17,650 − 9,900 yr BP, being characterized by semi-humid, humid and per-humid conditions respectively, as inferred from the detailed pollen spectra. Significantly, evidence of cereal-type plants (i.e. *Oryza* spp.) appeared during Event-B when UMRF flora now dominated the vegetation.

Monsoon downturns: ca. 16,000 − 13,700 yr BP (between Events A and B) and ca. 12,800 − 10,400 yr BP (between Events B and C)

The above three wet Events A, B and C were interrupted by two relatively 'semi-arid/weak' monsoonal phases (UMRF species decrease significantly), ending ca. 13,700 and 10,400 yr BP, respectively. The first change in pollen stratigraphy around ca. 14,000 yr BP (between humid Events A and B, Figure 2) correlates chronologically with the Older Dryas-Allerod transition. The second between ca. 12,800 and 10,400 yr BP (of uncertain duration) appears to correlate with the Younger Dryas event in high latitudes. In the Horton Plains it is a rather mild signal, as the UMRF species only reduced by about half from the previous wet phase with a moderate aridity index, while very little pollen of cereal-type plants occurred. Between ca. 12,200 − 10,900 yr BP, the proxies indicate a relatively dry climate, but aquatics and planktonic diatoms (e.g. *Aulacoseira laevissima*) suggest the presence of a waterbody around ca. 11,500 yr BP, which apparently desiccated within a short time (Figures 2 & 3). This abrupt change could indicate the local late Pleistocene/Holocene transition. The data are inadequately resolved for the two weak monsoon phases. Nevertheless, both downturns are on millennial scales.

ca. 9,200 − 8,800 yr BP (D)

Per-humid Event-C is followed by a hyper-humid Event-D ca. 9,200 − 8,800 yr BP (Holocene monsoon precipitation peak and first rainforest culmination – 70 UMRF taxa). The period from ca. 8,800 − 8,100 yr BP is poorly resolved in the record.

ca. 8,100 − 3,400 yr BP: major downturn of the monsoon and the mid-late Holocene aridity

Starting ca. 8,100 yr BP, a rapid reduction of the rainforest flora is indicated heralding the mid-Holocene climate aridity (Figure 2). Pollen of cereal-type plants disappear by ca. 6,000 yr BP. UMRF elements disappear completely between ca. 5,400 and 3,400 yr BP, to be replaced almost entirely by Poaceae. The numbers of grass pollen are much diminished, ruptured or bent and in a poor state of preservation. The total organic carbon shows very low values. Simultaneously, the phytolith aridity index increases. The increase of microscopic charcoal particles could indicate forest fires. A very weak monsoon and a drastic decrease in precipitation (probably a palynological hiatus) are indicated. The entire period from ca. 8,100 − 3,400 yr BP is characterized by *a lack of millennial scale events*. This is undoubtedly the major change in the Holocene. This long arid phase is now the subject of a separate study and indicates an almost near complete monsoonal downturn with little or no evidence of any significant precipitation. Pollen analyses of peats from three widely separated locations in the southwestern lowlands show that the mid-late Holocene climatic deterioration is also indicated by the lack of lowland rainforest elements (*R. Premathilake*, *unpublished data*). This suggests that the mid-Holocene aridity probably affected the whole country.

ca. 3,400 yr BP onwards

Following the above critical aridity phase, rainforest expansion now commenced once again and fluctuated with the waxing and waning of monsoonal intensity/ precipitation. A rapid expansion and diversification of the rainforest is represented by humid Event-E, between ca. 3,400 − 1,500 yr BP (LPAZ-5). Following a weaker monsoon after ca. 1,500 yr BP (Figure 3), two short wet phases (Events-F, G) ca. 650 and 150 years ago are indicated (Figure 3). However, this was a time of intense human activity throughout southern Sri Lanka, so these ecological signals could also reflect human use of the forested landscape. Around 50 arboreal species are present today in the Horton Plains.

Human settlements and monsoon downturns

Investigations in Beli-Lena rock shelter in Kitulgala, southwestern Sri Lanka suggest that early hunter-gatherer cave dwellers who foraged in the surrounding forest from ca. 31,000 yr BP suddenly disappeared around ca. 7,880 yr BP (Kourampas *et al.*, 2009) – during the mid-Holocene monsoon downturn. Similarly, traces of cave dwellers in Batadomba Lena, near Kuruwita, southwestern Sri Lanka starting around 37,000 yr BP abruptly disappeared ca. 11,700 yr BP (Perera *et al.*, 2011) – again during the monsoon downturn ca. 13,900 − 10,200 yr BP. At the Fa-Hsien Lena (Kalutara District) ca. 38,500 − 3,900 yr BP, Alu Lena ca. 10,350 yr BP (one date only and not an occupation range) and Bellan-Bandi Palassa ca. 12,250 − 11,000 yr BP (Premathilake, 2012), termination of all human occupations appears to have coincided with low precipitation and weak monsoon phases (Figure 3). These were most likely lowland forest refugia. However, in view of the complex taphonomy of these sites, more accurate data on terminal occupation chronologies from many sites will be required. In many of these cave sites the upper part of the stratigraphy has been truncated or jumbled by guano collection, shrine building etc. Consequently, this apparent correlation between climate and human occupation should be treated with caution.

Correlation with regional proxy records

Below, we compare the regional monsoon events of the Horton Plains with those of the Northwestern Indian Ocean (Arabian Sea) and Southwestern India, both long-term records of palaeoclimate (Figure 3). The first increase in humidity in the Horton Plains ca. 18,300 yr BP is ~ 1000 years earlier than the initial onset of climate change in the Arabian Sea ca. 17,200 yr BP (Event-1; Sirocko *et al*., 1993) and near synchronous with the Nilgiri Hills, South India (Sukumar *et al*., 1993). Event-A (ca. 17,600 − 16,000 yr BP) at Horton Plains correlates well with Events 1 − 3 (ca. 17,200 − 15,900 yr BP) in the Arabian Sea. The Horton Plains Event B is synchronous with the intensification of the monsoon inferred from upwelling indices (in the Arabian Sea) ca. 13,100 yr BP (Naidu & Malmgren, 1996) and the mangrove culmination record (and *Chenopodiaceae* minimum) from South India (Van Campo, 1986). Horton Plains Events-C ca. 10,000 yr BP and –D ca. 9,000 yr BP, which coincided with orbitally induced maximum summer insolation and albedo at these latitudes are bracketed with humid events ca. 10,000 yr BP and 8,600 yr BP respectively in the Arabian Sea, upwelling Event-5 (ca. 9,850 yr BP) and the lowest dolomite dust input intervals into the Arabian Sea ca. 9,800 and ca. 8,600 yr BP respectively (Figure 3). Horton Plains Events-C and D correlate well with Event-5 in the Arabian Sea, representing the peak of the early Holocene monsoon intensification in the region. In the Arabian Sea, the monsoon weakened significantly between ca. 10,800 − 10,400 yr BP (Figure 3).

The abrupt change at ca. 8,100 yr BP at Horton Plains coincides with the Event-6 dolomite peak (dust input) into the Arabian Sea (Figure 3) and is followed by almost 4,500 years of progressive monsoon weakening leading to seasonality, aridity and vegetation decline. The peak of the monsoon downturn was between ca. 5,500 yr BP to ca. 3,400 yr BP (Figures 2 & 3). Monsoon reactivation after the mid-late Holocene aridity (Horton Plains Event-E) correlates well with the regional record (Figure 3). The Horton Plains Event-F centered ~ 650 years ago could be the local correlative of the European Medieval Warm Period (MWP). This and Event-G about 200 years ago – a possible local correlative of the Little Ice Age (LIA) in Europe are both robust signals (Figure 3), with a good correlation with the Arabian Sea (Sirocko *et al*., 1993) and Nilgiri Hills records in South India (Sukumar *et al*., 1993).

The terrestrial records of both the Arabian Peninsula including Yemen and the Nilgiri Hills indicate that the peak intensification of the Holocene Asian monsoon was around ~ 10,000 years ago, whereas the peak of Holocene aridity was ~ 5,000 years ago (Lezine *et al*., 2011). The Holocene precipitation maximum (event-D) appears to have occurred a little later in Sri Lanka. It is, therefore, evident that the Horton Plains record of monsoonal changes contains climate events near equivalent to those resolved elsewhere in the tropics and the sub-tropics. Some of these correlations can be further improved with only slight adjustments to the age model (Table 1). On millennial scales it would be rare to expect perfect synchronicity of terrestrial events over this vast monsoon region.

The short present day instrumental records (150 years at best) underestimate the magnitude of past monsoon rainfall variability in Sri Lanka. Longer periods of monsoon failure have occurred in the past and will no doubt also occur in the future (Figure 3). A terrestrial palaeomonsoonal record of wet/dry cycles going back to ~ 10 million years in Oman has also been reported (Rodgers & Gunatilaka, 2002). This record shows that monsoon cyclicity is a long-term phenomenon, and that cyclicity operates at different periodicities (orbital/sub-orbital etc.). Since over 3 billion people inhabit the monsoonal regions of Asia today, understanding the long-term monsoonal cyclicity has serious future implications for water resources, agriculture, land-use and human health. We wish to emphasize that the periods of monsoon weakening generally lasted longer than the periods of monsoon intensification during the past 24,000 years (Figure 3). This climate record from Sri Lanka will also throw some light into the pre-history of South Asia and the long term ecology of tropical ecosystems.

Comparison with regional and hemispheric chronologies of the late Quaternary climate change

The evidence presented here indicates that post-LGM humidity in the Horton Plains began to increase more than 3000 years before the beginning of Bolling warming in high latitudes or that temperature/precipitation changes in the tropics long preceded ice melting in high latitudes. The Indian Ocean monsoon-winds increased in step with deglaciation (Sirocko *et al*., 1993). Tropical warming in the Horton Plains also preceded by 2000 − 3000 years the $\delta^{18}O$ change that signals warming of the tropical western Pacific (Visser *et al.*, 2003; Partin *et al*., 2007).

The post-LGM record of rainforest expansion, diversification, fluctuation and decline (Figure 2) essentially reflects the amount of monsoon precipitation and variability. The very early phases of rainforest growth may actually represent increased humidity related to Bolling warming. When did the monsoon exactly begin? Perhaps the magnitude of floral change at

Horton Plains Event-B (ca. 13,200 yr BP) when UMRF elements dominated the vegetation for the first time, and the first appearance of pollen from cereal-type plants (i.e. *Avena* sp. and *Hordeum* sp.) is a reflection of actual monsoon onset. Clearly, Event-B is a landmark in local deglacial history. Terminations 1A and 1B are followed by increasingly humid regional Events B, C and D respectively. It is postulated here that the prevailing monsoon actually 'switched-on' at Termination 1A. From ca. 18,000 yr BP the abrupt changes in monsoon precipitation appear to have been initially controlled by glacial boundary conditions and to have overlapped with insolation forcing during the early Holocene (millennial cycles); thereafter, precipitation decreases in response to reduced summer solar insolation with disruption of the millennial cycles until ~ 3,400 yr BP (Figure 3).

The gradual long-term mid-late Holocene monsoon downturn (ca. 8,100 − 3,400 yr BP) when the intertropical convergence zone (ITCZ) seems to have gradually reduced its influence in the region by moving further south of Sri Lanka, could be a (hitherto underestimated) critical period in the continental tropics. Supporting evidence for this assertion is provided by the weakening upwelling record in the Arabian Sea and from tropical South America (Figure 3; proxies b and c). The precipitation also decreased, resulting in increased climate seasonality and aridity in the equatorial regions of East Africa between ca. 7,800 − 2,700 yr BP (Bonefille & Chalie, 2000; Stager *et al*., 2003). Also, the Northern Oman speleothems stopped depositing calcite after ca. 6,200 yr BP (Figure 3: proxy-d). The ITCZ had moved south of sub-tropical Kuwait/Saudi Arabia (30^0 N latitude) by ca. 6,600 yr BP (Gunatilaka, 2011). A similar arid phase is also known from the peats of the UMRF Nilgiri Hills region (ca. 6,000 − 3.200 yr BP), while the lakes in Northwestern India gradually dessicated (Enzel *et al*., 1999). However, in Southern Oman, the speleothems continued to deposit calcite from ca. 10,300 − 2,700 yr BP, but from ~ 8,000 yr BP, the precipitation decreased gradually in response to summer insolation changes (Neff *et al*., 2001; Fleitmann *et al*., 2003).

In the Horton Plains, rapid UMRF expansion indicates precipitation increase ca. 3,400 yr BP (Event-E). Interestingly, the earliest records of rice cultivation in Sri Lanka are dated ca. 2,900 yr BP (during monsoon Event-E). The Medieval Warm Period and the Little Ice Age signals in the Horton Plains data imply that tropical responses were generated even by smaller oscillations of the Northern latitudes (correlative signals are also recorded in the Nilgiri Hills, South India (Figure 3). These records inform much about the dynamics of the ITCZ in the tropics. Even in the Horton Plains, rainforest diversity, which has increased since ca. 3,400 yr BP to 50 species today, never recovered fully to the levels of the Holocene optimum wetness ca. 9,000 yr BP (Event-D-70 species). The monsoons appear not to have recovered in the Arabian Peninsula sites.

Disruptions of the insolation - driven early - mid Holocene climate trends starting ca. 8,100 and 5,400 yr BP also coincided with meltwater and ice-rafting events in the North Atlantic (Bond *et al*., 1997), the abrupt 8.2 ka BP cooling spike in ice-cores (Alley *et al*., 1997) and glacial advances in the Himalayas, Nepal and Tibet (Yonebayashi & Minaki, 1997), but the effects of these events on the monsoon are not clear. A major European vegetation response to the abrupt ca. 8.1 − 8.2 ka event is now well documented (Tinner & Lotter, 2001). This mid-Holocene event appears to be of hemispheric importance.

CONCLUSION

The Horton Plains records an important branch of the summer monsoon air flow across the Southern Asian region over the past 24,000 years. From the palaeoecological data presented here we resolve the climate of Sri Lanka into a succession of seven monsoonal stages and three intervening monsoonal downturns of varying duration and intensity, which are then correlated with a number of long-term records from the wider tropics and the northern hemisphere. These correlations provide a basis to discuss the timing of tropical climate changes (mainly monsoonal activity – one of the main drivers of precipitation in the region) from the LGM to the near-present. The evidence and conclusions presented in this study are consistent with the prevailing general 'tropical climate hypothesis' comprehensively reviewed by Chiang (2009).

The evidence indicates that there is near synchronicity of Indian Ocean SWM events and their variations on millennial scales across the region. This regional calibration is what is attempted in this study. Hemisphere wide post-LGM millennial scale climate events are also recorded in Sri Lanka until the beginning of the insolation driven mid-late Holocene monsoon downturn (ca. 8100 yr BP − 3,500 yr BP). Also, strong teleconnections seem to exist between tropical Asian monsoon fluctuations and high latitude temperature changes since the major terminations. It is possible that these teleconnections are 'two-way street' representations and the tropical regions also play a crucial role in driving global climate changes. The linkage between high latitude climates and the Asian monsoon is a major aspect of the global climate. The dynamics of a coupled ocean-atmosphere-vegetation monsoon system and its feedbacks need to be better understood to explain these climate changes.

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Appendix 1.

The proxies are as follows: a. variations in summer insolation at 20^0 N and 20^0 S latitudes (Berger, 1978); b. $\delta^{18}O$ (‰), upwelling records of *Globigerinoides ruber* formaminifera proxy from the Arabian Sea (Naidu & Malmgren, 1996); c. high resolution upwelling indices abundance of *G. bulloides* proxy, Arabian Sea (Naidu & Malmgren, 1996; Gupta *et al*., 2003); d. $\delta^{18}O$ speleothem record from Southern Oman (Neff *et al*., 2011; Fleitmann *et al*., 2003); e-f. *Chaenopodiaceae* pollen (aridity indicator proxy) and mangrove pollen records from the Southwestern Indian Ocean (Van Campo, 1986); g-h. long-term upwelling record (abundances of *G. bulloide)s* in the Arabian Sea (Overpeck *et al*, 1996); j. North Atlantic Ocean haematite record indicating warming/ cooling events at high latitudes (Bond *et al*., 1997).

The timing of Events A, B, C corresponds to relative increase in upwelling indices and decrease in $\delta^{18}O$ values. The short lasting wet event ca. 11,500 yr BP (a shallow local water body) coincides with high values of upwelling indices (b, g). This is the inferred Pleistocene/ Holocene boundary. The monsoonal peak (Event-D), which occurred during maximum insolation corresponds with decreased $\delta^{18}O$ values, ocean upwelling records and haematite percentages. Events E, F and G coincide with changes in upwelling records in the Arabian Sea and North Atlantic climatic conditions quite well (j). Event-B is an important phase in the local deglacial record and correlates well with other regional and North Atlantic proxies quite well.