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A multi-proxy reconstruction of the late Holocene climate evolution in Lake Bolgoda, Sri Lanka

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ABSTRACT

Palaeoclimate investigations in Sri Lanka have been rarely attempted despite being located directly in the path of the Inter Tropical Convergence Zone. In this study, a 4.1-m undisturbed sediment core was retrieved from the Bolgoda Lake situated in the western coast of Sri Lanka, and influenced by the strong southwest monsoons. Mollusc shells in the core were dated, and the age-depth model indicated a depositional history extending from 2941 cal yr BP to the present. Grain size, major and trace elements, total organic C and N content and stable C and N isotopes were analysed in freeze-dried sediments to reconstruct the palaeoclimate changes. The multi-proxy records in the core revealed four distinct zones that show distinct variations in physical and chemical conditions in the lake associated with climate change. *Zone 1* (2941 to 2390 cal yr BP; 385-252 cm) indicated the climate to be warm and humid with intense precipitation. The resulting high lake level helped in organic matter preservation in bottom sediments. *Zone 2* (2390 to 1782 cal yr BP; 252-140 cm) indicated an unstable dry period associated with weak precipitation. Consequently, low lake level and intense degradation of organic matter occurred in this zone. *Zone 3* (1782 to 1299 cal yr BP; 140-60 cm) indicated a

resurgence of intense monsoon along with warm and humid conditions. *Zone 4* (1299 cal yr BP to present; 60-0 cm) indicated dry conditions with less intense monsoon, low lake level and extensive degradation of organic matter. Vascular plants were the predominant organic matter source into the lake during the late Holocene. In contrast, algal input was significant between 2390 cal yr BP and 2153 cal yr BP. The palaeoclimate evidences in this study showed an overall weakening trend of SW monsoon during the late Holocene, and this was consistent with changes happening in other locations as in southern and western India.

Keywords: Monsoon; Organic matter; Metals; Isotopes; Palaeoclimate;

1. Introduction

High-resolution multi-proxy records from lake sediments provide excellent archives for reconstructing palaeoclimate and palaeoenvironmental changes in the catchment (Hausmann et al., 2011; Smol and Cumming, 2000). This is beneficial for developing climate change models that enables us to understand the variabilities in climate such as precipitation, increasing global temperature and impact of greenhouse gas emissions (Solomon, 2007). The Indian summer monsoon plays a critical role in the global climate, hydrological, and energy cycles. The monsoons are caused by movement of the Inter Tropical Convergence Zone (ITCZ) over the equatorial region (Ghosh et al., 1978). Although the monsoon system is driven by geographical features of the sub-continent, and associated atmospheric and oceanic circulation patterns, its intensity can change due to various local factors (Schott and McCreary, 2001). Even small-scale variability in rainfall across the Indian sub-continent, where the southwest monsoon accounts for 80% of the precipitation, has severe impacts on socio-economic conditions in the region (Krishna Kumar et al., 2004). This strong influence on monsoons has significantly varied over time, and in turn, it has affected the landscape and vegetation cover

during periods of intense droughts and floods. For example, during the late 1960s, El Niño related monsoon failure for three consecutive years resulted in nearly 1.5 million deaths in India from devastating famines (CRED, 2005).

Lying directly in the path of the ITCZ, Sri Lanka is strongly impacted by the SW (summer) and NE (winter) monsoons, which play a key role in controlling the majority of hydrological and agro-ecological differences in this island nation (Jayasena et al., 2008). In particular, the central mountains act as an orographic barrier resulting in summer monsoon towards the southwestern part of the country, whereas the retreating winter monsoon brings rainfall to the northeastern part of the country (Fig. 1; Ranasinghe et al., 2013). However, regional variability in the monsoon system not only strongly affects the landscape and vegetation pattern in Sri Lanka but also plays a major role in the global climate system.

Premathilake and Risberg (2003) reconstructed the late Quaternary climate history of the central highlands in Sri Lanka, and suggested strengthening of the SW monsoons during the late Holocene (3600-2000 cal yr BP). Multi-proxy palaeoclimate records from the mid-to late Holocene in the southeastern coastal region of Sri Lanka revealed a strong similarity with the Indian summer and winter monsoons, possibly due to similar forcing mechanisms (Ranasinghe et al., 2013). The contrasting differences during the late Holocene (< 4000 yr BP) monsoon intensity in Sri Lanka (Premathilake and Risberg, 2003), North India (Phadtare, 2000; Ponton et al., 2012; Roy et al., 2006), Andaman Sea (Rashid et al., 2007), and Arabian Sea (Fleitmann et al., 2004) are examples of regional differences in monsoon strength and its impacts. These investigations from different locations indicate a strong variability in monsoon intensity over millennial (Thompson et al., 2000), centennial (Anderson et al., 2002; Gupta et al., 2003) and decadal time scales (Jung et al., 2002). However, key drawbacks in the marine records are the uncertainties in ^{14}C ages due to marine reservoir effect, bioturbation, and the noisy character of different proxies. Likewise, most of the terrestrial records suffer from low

temporal resolution during the late Holocene and uncertainties in ^{14}C ages due to the use of bulk sediments.

The main objectives of this study are to reconstruct a high-resolution Holocene palaeoclimate record, and investigate the associated palaeoenvironmental and palaeolimnological changes in Bolgoda Lake located in southwestern Sri Lanka (Fig. 1). Bolgoda Lake is a promising site that lies directly in the path of the SW monsoons. The paleoclimate interpretations in this study are based on calibrated ^{14}C ages, sediment characteristics and different bulk geochemical proxies such as total organic carbon (TOC), total nitrogen (TN), $\text{C}_{\text{org}}/\text{N}_{\text{total}}$ ratio, stable C and N isotopes and geogenic elemental ratios. We correlated our results with other palaeoclimate records from Sri Lanka and India to trace the local versus regional changes in SW monsoon and its impacts. This is one of the first studies on multi-proxy late Holocene climate reconstructions in a lake from Sri Lanka, and the information provides a better understanding about monsoon variability in the core monsoon zone in southeast Asia.

1.2 Study area

Bolgoda Lake is a semi-closed brackish water body located on the west coast of Sri Lanka ($6^{\circ}40'56''$ - $6^{\circ}48'47''$ N, $79^{\circ}53'55''$ - $79^{\circ}58'25''$ E; Fig. 1). The lake connects with the Indian Ocean through a narrow estuary. Bolgoda Lake consists of two interconnected water bodies named as the North lake and South lake that are connected by a narrow channel. The North lake is relatively large and fed by two perennial streams. The lake is shallow and the maximum depth is about 2-3 m (Ratnayake et al., 2017). The total catchment area of the Bolgoda Lake is ca. 374 km² consisting of a flat terrain with rice paddy fields that is underlain by high-grade metamorphic rocks such as charnockitic gneiss, undifferentiated charnockitic biotite gneiss and undifferentiated Proterozoic gneiss (GSMB, 1996). These rocks

are overlain by sandy and lateritic gravel. Marshes and seasonally flooded grasslands with isolated medium sized trees can be found near the lake. The lake and its watershed are mainly fed by the southwest monsoons active from May through September. The area has tropical humid conditions, and the annual rainfall is ~2550 mm and the mean annual temperature is around 27 °C (Ranwella, 1995). Aquatic vegetation such as *Potamogeton indicus*, *Aponogenton* sp., *Limnophila* sp., *Nymphoids* sp. and *Nyphaea* sp. can be identified in the lake. In addition, the lake is surrounded by a mixture of marsh vegetation (e.g., *Utricularia* sp., *Bacopa* sp.), mangrove associates and littoral jungle consisting of *Anona* sp., *Melastoma* sp., *Wormia* sp., and *Osbeckia* sp. (Ranwella, 1995). The catchment around Lake Bolgoda supports a large population, and paddy, coconut and rubber plantations are common.

2. Materials and Methods

An undisturbed 4.1 m long sediment core was retrieved from the Bolgoda Lake in 2013 using a mechanical piston corer from a floating platform. The sampling point was located in the North Bolgoda Lake ca. 300 m from the shore (06°45'32" N, 79°55'09" E). The sediment core was sliced into half centimetre intervals and sealed in plastic Ziploc bags. The sub-samples were freeze-dried for various analyses. The lithological characteristics in the cores were recorded along with grain-size variation, and presence of shells and charcoal in the layers.

2.1 Radiocarbon dating

Six mollusc shells were sampled from the sediment core for ¹⁴C-radiocarbon dating. In addition, two plant macrofossils (a charcoal fragment and twigs) were also selected. ¹⁴C dating was carried out on an Accelerated Mass Spectrometer at the Poznań Radiocarbon Laboratory, Poland. The sediments were chemically pre-treated as described by Brock et al. (2010) with the exception of using 0.25 M HCl instead of 1 M HCl. The samples were combusted with

CuO and Ag wool at 900 °C for 10 h and the CO₂ was reduced to pure graphite in a vacuum line as described by Czerwik and Goslar (2001). Coal or IAEA C1 Carrara Marble and international modern Oxalic Acid II standards were subjected to the same pre-treatment and combustion procedure. The age-depth model for the sediment core was developed using the Bacon modelling software (Blaauw and Christen, 2011), which uses Bayesian statistics to reconstruct the sediment chronology. Bacon divides the core into many thin vertical sections and through millions of Markov Chain Monte Carlo (MCMC) iterations estimates the accumulation rate for each of these sections. Combined with an estimated starting date for the first section, the accumulation rates form the age-depth model (Blaauw and Christen, 2011). In the age-depth model for Bolgoda Lake (Fig. 2), accumulation rates were constrained by gamma distribution with mean of 5 yr/cm. The ¹⁴C dates in shells were calibrated using the Marine13 curve (Reimer et al., 2013). The plant macro fossils dates were calibrated using the Northern Hemisphere terrestrial calibration curve (IntCal13; Reimer et al., 2013) using OxCal version 4.2. In addition, reservoir correction was applied to ¹⁴C dates in the shells to minimize misleading interpretations about age.

2.2 Grain-size analysis

Forty-one sub-samples containing ca. 4-6 g of freeze-dried sediment from each layer were used for the grain-size analysis. The analysis was carried out according to the protocol by Kilmer and Alexander (1949). We used 0.05 % sodium hexametaphosphate for separating the grains. The sample was wet-sieved and sediment grains >63 µm were separated. The sieved extract consisting of silt and clay particles were homogenised using a Sonic Vibra-Cell VC 750, ultrasonic stirrer, and analysed for grain size in a Sedigraph Micromeritics III Particle Size Analyser. The results were expressed as weight percentages of sand, silt and clay.

2.3 Metal extraction

Sixty-two sub-samples from the sediment core were selected for metal analysis. Approximately 0.5 g of sediment was directly weighed into Teflon vessels, and 10 ml of suprapure 7-M HNO₃ (65 %) acid was added. Microwave assisted digestion was performed using the Milestone Ethos-1 Microwave Digester. The extracts were analysed using a Perkin Elmer Nexion 300 ICP-MS for Al, Fe, K, Mg, Mn, Na and Ti.

One reagent blank was added with each set of batch extractions to assess contamination problems. Three duplicate samples were analysed to measure the reproducibility of our results. Standards from the Norwegian Geochemical Council (Jet Rock-1 and Svalbard Rock-1) and a peat standard (NIMT/UOE/FM/001) were analysed with the samples to assess the accuracy and precision. The percentage error is < 20% for the majority of major elements in all 3 standards. Analytical precision was within 3% except for Al (~10%).

2.4 Analyses of stable isotopes, total organic carbon and nitrogen

The freeze-dried samples (total 62) were analysed for C_{organic} %, N_{total} % and stable C and N isotopes. Approximately 500 mg of freeze-dried sample was de-carbonated following the rinse and wash method described in Brodie et al. (2011). The pre-treated samples were analysed using a Carlo Erba NA 1500 Series-2 Elemental Analyser attached to a Thermo Finnigan Delta Plus XP isotope ratio mass spectrometer (IRMS). The analyses were carried out at the laboratory of Stable Isotope Geosciences Facility (SIGF), Texas A&M University, USA. The nitrogen isotope composition was expressed relative to atmospheric N₂, whereas the C isotope composition was reported relative to the Vienna Pee Dee Belemnite (V-PDB) standard. One to three internal laboratory standards similar to the sample matrix were utilized as internal checks for the accuracy of our results. The Norwegian Jet Rock-1 standard showed percentage error 18.2 % and -11.53 % for TOC and $\delta^{13}\text{C}$, respectively.

3. Results

3.1 Chronology

In contrast to ^{14}C dates of mollusc shells, the two ^{14}C dates derived from charcoal and plant twigs were significantly old and indicated nearly the same age (~ 7800 cal yr BP) despite the stratigraphic gap (depth interval) of 100 cm between these two samples (Table 1). These shell ages were in chronostratigraphic order (Fig. 2), and ^{14}C ages were between 3128 to 1059 cal yr BP (Table 1).

3.2 Lithology

From the bottom to nearly 385 cm, the core consisted of coarse to medium sand with light grey colour. Visually detectable charcoal particles were observed in the upper part of this section. From 385 cm to the top, the core consisted of sandy-silty clay with brownish colour. Four sub-zones with abundant shells were observed in this zone that extended from 390-355 cm, 255-235 cm, 204-197 cm, and 60-10 cm. In addition, few large shells were found scattered throughout the whole sediment core. These shells were identified as *Terebralia palustris*, *Cerithidea cingulate* (gastropods) and *Gafrarium* sp. (bivalve) that occur in estuarine and mangrove habitats.

3.3 Grain-size and metal ratios

The core consisted of high sand content (average 53 %). The average silt and clay contents were lower ~29 % and 18 %, respectively. The core bottom extending from 410-385 cm showed extremely high sand content and abrupt metal ratios with high values. Sediments extending from 385 cm to 252 cm indicated high sand content (average 60 %). Elemental ratios of Ti/Al, K/Al and Mg/Al showed high values in this section. However, Mn/Al and Fe/Al ratios indicated low values. The sand and silt content from 252 cm to 140 cm showed a core upward

decreasing trend. In the upper section of the core, the clay content increased marginally. The ratios of Ti/Al, K/Al and Mg/Al were generally low in this section, whereas Mn/Al and Fe/Al ratios were high except the depths between 195 cm and 172 cm that showed an opposite trend. This was more obvious for Mg/Al and Mn/Al ratios in the core. From 140-60 cm the sand content showed an increasing trend upward; Ti/Al, K/Al and Mg/Al indicated higher values with a slightly increasing trend upwards. Decrease in Mn/Al was observed in this section, but variation in Fe/Al was not as evident. The lowest average clay content (6 %) occurred in this section. From 60 cm to the core top, the sand content showed a clear decreasing trend upward, whereas the clay content showed an increasing trend. The highest clay content (average 38 %) and the lowest sand and silt contents (46 % and 16 %, respectively) occurred in this zone. Ti/Al, K/Al and Mg/Al ratios showed low values with an upward decreasing trend, whereas Mn/Al and Fe/Al ratios showed the opposite trend (Fig. 4).

3.4 C_{org}/N_{total} ratio, $\delta^{13}C$ and $\delta^{15}N$ trends

Atomic C_{org}/N_{total} ratio showed constant values between 21 and 25 from 385-252 cm except the intervals between 309 cm and 302 cm indicating C/N ratio of ~16. The $\delta^{13}C$ values ranged around -27‰ ; some less negative values were observed at depths of 302 cm, 309 cm and 327 cm, respectively (Fig. 4). From 252-202 cm the C/N ratio ranged between 18 and 14 with a slightly decreasing core upward trend. The $\delta^{13}C$ values also increased in this section and ranged $\sim -26\text{‰}$. The C/N ratio increased and varied between 25 and 47, whereas $\delta^{13}C$ values decreased ($\sim -27\text{‰}$) from 202 cm to 140 cm. From 140 cm to the top of core, the C_{org}/N_{total} signal showed a gradual upward decreasing trend from 47 to 20, whereas the $\delta^{13}C$ values decreased and ranged between -27‰ and -28‰ . An upward increasing trend of $\delta^{13}C$ values was visible between 60 cm and the top, ranging between -28‰ to -26‰ (Fig. 4). The $\delta^{15}N$ values showed a consistent trend throughout the core and varied between 2‰ and 4‰ . However, from the bottom to 385 cm the $\delta^{15}N$ values were high (Fig. 4).

3.5 TOC and TN Mass Accumulation Rates (MAR)

Mass Accumulation Rates (MAR) for TOC and TN in the Bologoda sediments were calculated as:

$$\text{MAR} = \text{weight fraction (X)} \times \text{dry bulk density } (\rho) \times \text{linear sedimentation rate (LSR)}.$$

TOC and TN MARs showed approximately similar trends throughout the sediment core. Between 385 cm and 252 cm the TOC and TN MAR values were relatively high and fluctuated between $21.3\text{--}4.2 \text{ gm}^{-2}\text{y}^{-1}$ and $0.89\text{--}0.12 \text{ gm}^{-2}\text{y}^{-1}$, respectively. From 252 cm to 140 cm in the core, TOC MAR showed generally low values with an average value of $6.34 \text{ gm}^{-2}\text{y}^{-1}$ in the section. From 252 cm to 202 cm there was a decreasing trend for TOC and TN MAR. Then TOC and TN MAR stabilize in low values above this section (202–140 cm). The TOC MAR indicated high values between 140 cm and 60 cm; both TOC and TN MARs showed a slight increasing trend upwards. From 60 cm to the top of the core, TOC and TN MAR showed low values (Fig. 4). The high positive correlation (Pearson's $r = 0.79$) identified between TOC and TN MARs indicate that loss of N with time is not significant in these lake sediments.

4. Discussion

4.1 Palaeoclimate and palaeoenvironmental proxies

Grain-size distribution is a primary indicator of energy driven processes in lacustrine sequences (Sly, 1978). Intense rainfall and erosion can transport higher amount of coarse fraction (sand and silt) from the surrounding watershed, and subsequently discharge into the lake (Peng et al., 2005). With decrease in rainfall, the fine sediment fraction with high clay content becomes dominant in the sediment layers. However, other factors such as stream and catchment morphological changes, variation in vegetation around the lake and human activities can affect grain-size variation in lake sediments.

Geogenic elements such as Al, K, Mg, Ti, Fe and Mn in sediment sequences are important geochemical proxies indicating the chemical weathering intensity and erosional processes in the catchment that can be related to lake level changes (Sun et al., 2010; Veena et al., 2014a). Usually the concentration of these elements are plotted as Al normalized values in order to evaluate their behaviour relative to Al because of its general insolubility under both oxic and anoxic conditions, and availability as a ubiquitous terrestrial element (Brown et al., 2000; Sun et al., 2010). Hence, strong positive correlation between K/Al, Mg/Al and Ti/Al ratios implies enhanced chemical weathering in the catchment. It is likely that precipitation and temperature fluctuations have a direct influence, and warm and humid conditions can significantly increase chemical weathering in the catchment (Sun et al., 2010).

Total organic carbon (TOC) and total nitrogen (TN) in lake sediments are important proxies that can be used to track biomass production and organic matter preservation in sediments (Meyers, 2003; Talbot et al., 2006). Addition of clastic particles can dilute TOC, whereas dissolution of carbonate minerals can increase TOC levels (Dean, 1999). In addition, TOC can vary according to grain size because fine-grain sediments have typically high TOC content (Thompson and Eglinton, 1978). Therefore, use of TOC and TN MARs are preferred over TOC and TN weight percentages to trace information about organic matter sources, delivery routes, depositional processes and preservation (Meyers and Teranes, 2001).

The bulk organic proxies such as C/N ratio, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ isotopic values in sediments are also useful proxies to identify organic matter sources, palaeoenvironmental conditions, lake productivity and preservation. A significant difference in C/N ratio can be identified between organic matter derived from algal and terrestrial vascular plants. Algae poor in cellulose content, but rich in protein result in atomic C/N values from 4-10. In contrast, vascular land plants, which contain higher amount of cellulose, have atomic C/N values >20 . Thus, C/N values of 12-18 suggest a mixture of algal and vascular plants (Fig. 3; Meyers and Ishiwatari,

1993; Talbot and Lærdal, 2000). However, diagenetic alteration of organic matter can result in modifications of C/N ratios in sediments (Gälman et al., 2008). In particular, selective degradation of carbon-rich components in vascular plants and nitrogen-rich proteins in algae/phytoplankton happens during early sedimentation. After initial degradation, the C/N ratio however stabilizes, and undergoes little diagenetic alteration (Meyers and Ishiwatari, 1999; Routh et al., 2004). Hence, C/N can be used to assess diagenetic alteration and microbial denitrification after burial. However, interpretation of C/N ratio can be problematic in sediments with very low organic matter content ($C < 0.3\%$), because the inorganic N fraction may be significant in such sediments (Meyers and Teranes, 2001), and analysing the low organic C content is an analytical challenge itself.

The $\delta^{13}\text{C}$ value of sedimentary organic matter is an indicator of palaeoproductivity rates and availability of nutrients in surface waters (Meyers, 2003). Algae prefer using ^{12}C during photosynthesis. Consequently, increasing the algal population in the water column removes ^{12}C from the dissolved inorganic carbon (DIC) pool. As a result, the $^{13}\text{C}/^{12}\text{C}$ ratio increases in the DIC pool and subsequently produced algal-rich organic matter utilizing the DIC. Therefore, increased productivity within the lake coincides with less negative $\delta^{13}\text{C}$ values (Brenner et al., 1999).

Source changes in the catchment and lake can be tracked using the $\delta^{13}\text{C}$ values and C/N ratio. Organic matter derived from algae and C_3 terrestrial plants have $\delta^{13}\text{C}$ values between -25‰ and -30‰ . However C_4 land plants that are characteristic of arid conditions show $\delta^{13}\text{C}$ values between -10‰ and -15‰ (Meyers, 2003). However, these interpretations about end-member sources and their characteristic $\delta^{13}\text{C}$ values can be altered when algae start using the dissolved HCO_3^- (1‰) pool instead of dissolved CO_2 (-7‰) for their photosynthesis due to limitation of dissolved CO_2 in aqueous phase. This kind of situation occurs during periods of high primary productivity in the water column (Keeley and Sandquist, 1992), and when the

HCO_3^- to CO_2 ratio is high due to alkaline conditions (Hassan et al., 1997). As a result, ^{13}C values in algal derived organic matter can show higher (less negative) values that are in the range of C_4 plants. Diagenetic alteration of sedimentary organic matter can also alter the bulk $\delta^{13}\text{C}$ values. Organic matter content in sediment diminishes due to microbial degradation. However, their impact on altering the bulk $\delta^{13}\text{C}$ values in organic matter is minimal, and they have less effect on interpreting palaeoenvironmental conditions (Meyers and Lallier-Vergès, 1999).

The $\delta^{15}\text{N}$ values in lake sediment are also helpful to track source changes and palaeoproductivity rates. $\delta^{15}\text{N}$ value in dissolved inorganic nitrogen (DIN) ranges between 7 ‰ and 10 ‰, whereas for atmospheric N_2 it is 0 ‰. Hence, phytoplankton that use DIN have $\delta^{15}\text{N}$ values around 8 ‰ and land plants that use atmospheric N_2 fixed by soil N fixers, have values from ca. 0 to 2 ‰. In addition, $\delta^{15}\text{N}$ isotope values are useful for understanding productivity shifts and N budget in lake systems (Talbot and Lærdal, 2000).

4.2 Age-depth model in Lake Bolgoda

Two radiocarbon dates derived from charcoal and plants twigs are excluded from the age-depth model due to their significant offset from the shell derived ^{14}C dates, and poor chronostratigraphic order (Table 1). The relatively older ages in these samples (> 7000 cal yr BP) suggest they were probably reworked before being transported into the lake. In contrast, the ^{14}C ages of shells range between 1059 cal yr BP and 3128 cal yr BP, and belong to the late Holocene (Table 1). The mollusc species dated in this study are commonly found in mangrove and estuarine habitats, and they are native to this area. This gives confidence in the ^{14}C dates in mollusc shells from the Bolgoda Lake sediments. In addition, the catchment has hardly any calcareous rock formations of significance to contribute old carbon (HCO_3^-) to the lake. Hence, the possibility of hardwater reservoir effect is minimized. However, due to its close proximity

to the sea, the marine reservoir effect cannot be neglected in Bolgoda Lake, and this should be taken into consideration. The local reservoir age around Bolgoda Lake was determined from the online Marine Reservoir Database, at Queen's University, Belfast, UK. The weighted mean of local reservoir age (ΔR) for the area around Bolgoda Lake was 133 ± 65 years. This value was applied for reservoir correction when constructing the age-depth model. While extrapolating the age-depth model due to lack of reliable ^{14}C ages between 60 cm and up to the top of the core, we assume the top (0 cm depth) to represent the present age in Bolgoda Lake. The increase in clay content from 60 cm to the core top implies a slow accumulation rate during this period, and supports this assumption.

4.3 Inference from geochemical proxies

During periods of more warm and wet conditions that prevailed earlier (see below), minerogenic elements are added rapidly, and contribute to the elevated elemental ratios of K/Al, Mg/Al and Ti/Al in the Bolgoda Lake sediments. This interpretation is consistent with conclusions drawn from elemental ratios in other sedimentary and lacustrine basins (Chen et al., 2013; Sun et al., 2010). Notably, Fe/Al and Mn/Al ratios show strong positive correlation in the Bolgoda sediments (Table 2). Fe and Mn are sensitive to benthic redox conditions (Davison, 1993; Haberyan and Hecky, 1987). During periods of shallow lake water level, the bottom sediments remain well-oxygenated, and hence Mn/Al and Fe/Al show high values (Sun et al., 2010). However, Mn/Al and Fe/Al show a negative correlation with other elemental ratios such as K/Al, Mg/Al and Ti/Al. The contrasting low values of K/Al, Mg/Al and Ti/Al with corresponding high values of Mn/Al and Fe/Al ratios imply a period of dry and weak monsoon in the sediment core.

The Bolgoda sediments have an average of ~3 % organic carbon, and therefore inference based on elemental concentrations, C/N ratio and stable isotope composition can be

used to reconstruct the palaeoenvironmental conditions with confidence. The dominant organic matter source in these sediments is from vascular plants in the catchments based on the elemental C/N ratio and stable C isotope values. However, there is input of algal derived organic matter in the sediment layers.

The depth intervals of 252-140 cm (2390-1782 cal yr BP) and 60-0 cm (1299-0 cal yr BP) in Bolgoda Lake are characterized by increased values of $\delta^{13}\text{C}$ implying high productivity in the lake. These sections however indicate a decline TOC MARs. These results suggest that high productivity in the lake was most likely coupled with periods of increased organic matter degradation possibly due to the low lake levels during these periods.

4.4 Palaeoclimate reconstruction

Extremely high values of minerogenic elements, sand content and extremely low values of bulk organic parameters such as C/N, TOC and TN from the bottom to 385 cm (Fig. 4) characterize the core bottom. It is likely, this zone has developed from weathering of bedrock, and is hereafter, excluded from further palaeoenvironmental interpretation. We have divided the Lake Bolgoda core into four main zones based on the results of different physical and geochemical proxies. These proxies have been related to variable climatic conditions that persisted in this region, and possibly other places to provide a better understanding about the regional climate change scenario in southeast Asia during the late Holocene.

4.4.1 Zone 1 (2941 to 2390 cal yr BP; 385-252 cm)

The high sand and silt content together with the elevated values of minerogenic elemental ratios (K/Al, Mg/Al and Ti/Al) indicate strong weathering and erosion in the catchment. It is likely intense rainfall with warm and humid conditions existed during this period. This is supported by the relatively low levels of Mn/Al and Fe/Al ratios as inferred from the elevated lake level due to high precipitation. Atomic C/N ratio, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values

suggest that contribution from allochthonous material (i.e. vascular land plants) is dominant, whereas input from lake derived phytoplankton blooms is limited during this period. The high average TOC and TN MARs in Zone 1 indicate relatively good preservation of organic matter due to anoxic conditions that prevailed because of high lake level (Fig. 4).

4.4.2 Zone 2 (2390 to 1782 cal yr BP; 252-140 cm)

The upwards decreasing trend of sand and silt content and relatively low levels of minerogenic elemental ratios (K/Al, Mg/Al and Ti/Al) indicate relatively low weathering and erosion implying a trending decline of rainfall intensity, and subsequent dry conditions. This is supported by shallow lake level as implied by the relatively high levels of Mn/Al and Fe/Al ratios. The period between 2390 cal yr BP and 2153 cal yr BP (252-202 cm) is however characterized by inputs from both algae and land plants and increase of primary productivity as inferred from the atomic C/N values (from 12-18), relatively high values of $\delta^{13}\text{C}$ and a clear increase of TN MAR (Meyers and Ishiwatari, 1993). In addition, the enhanced values of TN MAR over TOC MAR confirm predominant input of N-rich algal derived organic matter to the lake sediments. Immediately after this period (between 2153 and 1782 cal yr BP), land plants become more dominant in the lake sediments as suggested by C/N values that are >20 (Fig. 4). The low average value of TOC MAR suggests enhanced organic matter degradation. It is likely that the low lake level facilitated microbial degradation of sedimentary organic matter because of well-oxygenated bottom water condition. The minerogenic elemental ratios (K/Al, Mg/Al, and Ti/Al) and redox sensitive elemental ratios (Mn/Al and Fe/Al) indicate opposite trends in this zone for a short period extending from 2112-1974 cal yr BP (195-172 cm). The elemental ratios in this section suggest rapid increase of rainfall. Based on these proxies, we interpret zone 2 as an unstable period. While the overall trend was that of dry and weakening SW monsoon it was punctuated by a brief period of more intensive rainfall.

4.4.3 Zone 3 (1782 to 1299 cal yr BP; 140-60 cm)

This zone shows somewhat similar trends as zone 1, but probably of a lower magnitude. The upward increasing trend of high sand and silt content coincides with the increased values of minerogenic elemental ratios (K/Al, Mg/Al and Ti/Al). These trends suggest enhanced weathering and erosion with gradual strengthening of rainfall. Hence, relatively warm and humid climate can be expected during this period. While Mn/Al show low values, change in Fe/Al ratio is not so clear. An increase in lake level to some extent can be expected during this period, but it may not be as high as in zone 1. The C/N ratio, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values suggest that land plants are the predominant organic matter source into the lake during this period (Fig. 4). The TOC MAR shows relatively high values during this period indicating relatively good preservation due to bottom water anoxic or sub-oxic conditions.

4.4.4 Zone 4 (1299 cal yr BP to present; 60 cm-top)

The sharp upward trend and an overall increase in clay content suggest slow accumulation and a generally quiescent period in zone 4. We suggest a morphological change occurred in the lake towards the beginning of this period (~1300 cal yr BP) that influenced sediment accumulation. The decreasing trends of minerogenic elemental ratios (K/Al, Mg/Al and Ti/Al) suggest relatively low rates of weathering in the catchment. This zone is characterized by overall weakening of rainfall and persistent dry conditions trending to present day settings. This is supported by the high levels of Mn/Al and Fe/Al ratios implying high oxygen in bottom water because of low lake level. Input of land plants is the predominant source of sedimentary organic matter in the sediments as inferred based on the C/N values >20, low $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$. The upward decreasing trends of C/N and $\delta^{13}\text{C}$ values suggest preferential degradation of organic matter due to microbial activity (Fig. 4), which is expected in the upper sections in the core. The prevalence of oxic condition has direct influence on organic matter

degradation (Choudhary et al., 2009; Routh et al., 2004). The preferential removal of carbohydrates and proteins that are enriched in ^{13}C leads to decline in $\delta^{13}\text{C}$ values. In contrast, preferential removal of N in organic matter can lead to increase in C/N ratio due to microbial degradation. This phenomenon is more noticeable immediately after deposition towards the top of the core. Consistent with this, TOC and TN MARs show very low values indicating enhanced degradation of organic matter. Organic matter degradation is more significant in this zone due to increased exposure at the sediment-water interface and slow accumulation rate during this period.

4.5 Correlation with other regional studies

Most studies conducted in southeast Asia focus on climate history beyond the late Holocene. Because the Bolgoda sediment core extends to ca. 3000 cal yr BP, we consider only the late Holocene terrestrial climate records from studies carried out in Sri Lanka and India that are directly influenced by the SW monsoon (see Table 3, supplementary data).

According to most of the previous studies conducted to date, an overall weakening trend of SW monsoons together with dry/less-humid condition can be identified during the late Holocene. This is evident in many sedimentary climate archives such as the Horton Plains (Premathilake and Risberg, 2003), Vellayani Lake (Veena et al., 2014b), Nitaya Lake (Quamar and Chauhan, 2012), Lonar Lake (Prasad et al., 2014), Nal Sarovar lake (Prasad et al., 1997), Pokharan lake (Roy et al., 2009) and the Din Gad peat deposit (Phadtare, 2000). Thus, climate proxy records presented in our study agree with the overall weakening trend in SW monsoons since the late Holocene (Fig. 5). Consistent with this, a recently published study from Bolgoda Lake suggests sea level regression and termination of direct marine influence into the lake ca. 2500 cal yr BP followed by a gradual decrease of monsoon (Ratnayake et al., 2017).

Our records reveal a period of relatively strong SW monsoon extending from ca. 3000 to 1300 cal yr BP. However, an unstable weakening of SW monsoon extending from ~ 2400 to 1800 cal yr BP, interrupted this period. This period of weak monsoon may closely correlate with the Roman Warm Period (RWP; ca. 2500-1600 BP; Wang et al., 2012) and efforts have been taken to correlate this trend with other regional palaeoclimate records from southern India (e.g. Rajmanickam et al., 2016).

The first wet phase between ~3000 and 2400 cal yr BP recorded in the Bolgoda Lake coincides with other regional studies including the Horton Plains (Premathilake and Risberg, 2003) and various Indian lakes such as the Pookude Lake (Veena et al., 2014a), Kukkal Lake (Rajmanickam et al., 2016), Lonar Lake (Prasad et al., 2014) and Pokharan Lake (Roy et al., 2009; Fig. 5). However, the upper boundary of this phase is uncertain and it is reported to occur between 2000 and 1500 cal yr BP. One possibility of this uncertainty is the low temporal resolution in the different late Holocene climate archives. Moreover, the variability in these paleoclimate records increases as we move away from the core monsoon zone (Veena et al., 2014a, b). The dry and weak SW monsoon from ~1300 cal yr BP to present suggested in this study matches closely with conditions of less humidity and weak monsoon indicated in the Nitaya Lake in southwestern India (Quamar and Chauhan, 2012). However, other lacustrine records such as the Lonar Lake, Vellayani Lake and Nal Sarovar suggest this dry and weak monsoon phase to extend from 2500 to 2000 cal yr BP (Prasad et al., 2014, 1997; Veena et al., 2014b; Fig. 5). Sinha et al (2007) reported frequent dry/weak monsoon intervals coinciding with historical reports of devastating famines that occurred during 1350-450 cal yr BP. These high-resolution speleothem records also indicated the short Medieval Warm Period (MWP) and Little Ice Age (LIA) coinciding with abrupt changes in monsoon intensity. The authors have invoked a pronounced relationship between solar insolation and the SW Indian monsoon variabilities in these high-resolution stalagmite records (Sinha et al., 2007). Due to the low

temporal resolution of our proxies in the Bolgoda core from ca. 1300 cal yr BP to present, the MWP and LIA events are however not clearly evident. It is likely that other more sensitive geochemical proxies as biomarkers and high-resolution ^{14}C ages in sediment cores can resolve these changes in Indian monsoon intensity and its impacts on the landscape. However, lack of suitable limestone caves and demand for high sample requirements for analysing biomarkers and pollens in detail will be a continuing challenge for paleoclimate studies from this region.

5. Conclusions

Our study reveals a robust climate record and environmental history preserved in the Lake Bolgoda sediments based on the multi-proxy physical and geochemical data. The late Holocene sediment core revealed a depositional history extending from ~3000 cal yr BP to the present. The different proxies suggest that climate was wet/humid with intense SW monsoon precipitation that extends from ~3000 to 1300 cal yr BP. This resulted in enhanced chemical weathering and erosion in the catchment. The lake level was high during this period and degradation of sedimentary organic matter is less due to low bottom water oxygen level. This wet phase was interrupted by an unstable dry and weak SW monsoon extending from ~2400-1800 cal yr BP. This resulted in intense organic matter degradation and low lake level. The period extending from ~1300 cal yr BP to present represents a dry period with less intense SW monsoon. Low lake level and enhanced organic matter degradation in sediments characterize this period. Terrestrial vascular plants are the predominant organic matter source in the lake. However, enhanced algal input occurs during 2390 to 2153 cal yr BP, and this is consistent with the increase in productivity in Lake Bolgoda during this short period. Finally, the data indicate an overall weakening trend in SW monsoon precipitation in the region since 3000 cal yr BP. The overall paleoclimate trends in Lake Bolgoda are mostly consistent with other Holocene climate records from Sri Lanka and India, and differences in the interpretation arise

from issues associated with the chronology and the sensitivity of the proxies used to interpret these changes.

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Table Captions:

Table 1. The ^{14}C results for different sample material from Bolgoda Lake, Sri Lanka

Table 2. Correlation coefficient for geogenic elements in Bolgoda Lake sediments, Sri Lanka

Tables

Table 1. The ^{14}C results for different sample material from Bolgoda Lake, Sri Lanka

Sample ID	Depth (cm)	Material dated	^{14}C Age BP	cal yr BP (95 %)
Poz-74795	60	Shell	1805 ± 30	1360-1059
Poz-77250	143	Shell	2330 ± 40	1978-1596
Poz-74797	202	Shell	2840 ± 30	2678-2262
Poz-74798	247	Shell	2910 ± 30	2698-2335
Poz-77251	390	Shell	3200 ± 35	3035-2708
Poz-74796	394	Shell	3275 ± 35	3128-2755
Poz-68381	297	Plant twigs	6995 ± 35	7933-7736
Poz-68382	387	Charcoal	7030 ± 40	7954-7763

Table 2. Correlation coefficient for geogenic elements in Bolgoda Lake sediments, Sri Lanka

		K/Al	Mg/Al	Ti/Al	Fe/Al	Mn/Al
K/Al	Pearson Correlation	1	0.71**	0.85**	-0.23	-0.16
	Sig. (2-tailed)		0.00	0.00	0.07	0.20
	N	61	61	61	61	61
Mg/Al	Pearson Correlation	0.71**	1	0.69**	0.37	0.11
	Sig. (2-tailed)	0.00		0.00	0.00	0.40
	N	61	62	61	62	62
Ti/Al	Pearson Correlation	0.85**	0.69**	1	-0.01	0.01
	Sig. (2-tailed)	0.00	0.00		0.92	0.94
	N	61	61	61	61	61
Fe/Al	Pearson Correlation	-0.23	0.37	-0.01	1	0.69**
	Sig. (2-tailed)	0.07	0.00	0.92		0.00
	N	61	62	61	62	62
Mn/Al	Pearson Correlation	-0.16	0.11	0.01	0.69**	1
	Sig. (2-tailed)	0.21	0.40	0.94	0.00	
	N	61	62	61	62	62

Figure Captions:

Fig. 1. Bolgoda Lake in southwestern Sri Lanka indicating the SW and NE monsoon pathways, and sampling location in the lake. Elevation of the central highlands in Sri Lanka acts as an orographic barrier and influences the rainfall pattern (inset).

Fig. 2. The Bacon age depth model applied to the Bolgoda Lake (Sri Lanka) shells using AMS ^{14}C dates. The ^{14}C dates were calibrated using the Marine13 curve (Reimer et al., 2013) and corrected for reservoir effect.

Fig. 3. Intermediate values (in the box) indicating a mixed input of algae and terrestrial organic matter in Bolgoda Lake, Sri Lanka. Majority of values indicate dominance of allothonous organic matter input.

Fig. 4. A multi-proxy record of inferred climate change in Bolgoda Lake (Sri Lanka) based on variations of: (1) grain-size, (2) minerogenic elemental ratios (K/Al, Mg/Al, Ti/Al), (3) Fe/Al and Mn/Al ratios, (4) $\text{C}_{\text{org}}/\text{N}_{\text{total}}$ ratio, (5) Carbon and nitrogen stable isotope ratios, (6) Total Organic Carbon and Total Nitrogen mass accumulation rates (MAR).

Fig. 5. Comparison of regional late Holocene climate records with Bolgoda Lake (Sri Lanka).

Figures:

Fig. 1

Fig. 2.

Fig. 3

Fig. 4

Fig. 5

Supplementary Document

Table 03. Late Holocene climate records in Sri Lanka and India

Location/ Site	Proxies	Late Holocene Climate	Reference
Horton Plains, Central Highland, Sri Lanka. (peat)	Pollen, spores, siliceous microfossils, bulk chemical parameters	Humid and strong SW monsoon from 3600-2000 cal yr BP. Weak SW monsoon from 2000-0 cal yr BP. Short humid events around 600 and 150 cal yr BP.	(Premathilake and Risberg, 2003)
South-eastern coastal lagoons, Sri Lanka	Grain size, magnetic susceptibility, chemical parameters	Arid periods from 4000-3000 cal yr BP, 1100-< 500 cal yr BP. Wet interval from 3000 -1500 cal yr BP.	(Ranasinghe et al., 2013)
Pookude Lake, South India.	Sediment texture, pollen, spores, phytoliths, diatoms	Wet and strong SW monsoon from ~3.9-1.9 ka, 1.4-0.76 ka, 0.42-0.14 ka.	(Veena et al., 2014a)
Kukkal Lake, South India	Sediment texture, bulk organic and inorganic proxies, pollen.	Wet and strong SWM between 3200-1800 cal yr BP.	(Rajmanickam et al., 2016)
Vellayani Lake, South India	Sediment texture, inorganic geochemical proxies, pollens	Weak SWM between 2300-0 cal yr BP. Overall dry condition from 3000 cal yr BP to present	(Veena et al., 2014b)
Nitaya Lake, Southwestern India	Lithology, pollen	Less humid weak monsoon between 4657-2807 cal yr BP and 1125 cal yr BP- present. 2807-1125 cal yr BP strengthening of SWM.	(Quamar and Chauhan, 2012)
Lonar Lake, Central India	Organic and inorganic geochemical proxies, pollen	Weakening monsoon rainfall and drier condition from ~2000-600 cal yr BP. Wet/strong monsoon between 3000-2000 cal yr BP.	(Prasad et al., 2014)

Location/ Site	Proxies	Late Holocene Climate	Reference
Nal Sarovar lake, Western India.	Bulk geochemical parameters	Wet climate from 4.8-3.0 ka. Trending aridity between 3 and 2 ka. Arid conditions (similar to present) from 2 ka-present.	(Prasad et al., 1997)
Pokharan Lake, Northwest India	Minerology, geochemical parameters	Higher rainfall during 4-2.3 ka. Low rainfall during 2.3-1.1 ka.	(Roy et al., 2009)
Din Gad peat, Indian Himalayas	Pollen	Gradual but unstable SW monsoon strength during 3500-1500 cal yr BP. Weak SW monsoon from 1500-800 cal yr BP.	(Phadtare, 2000)