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## A Review of the Late Pleistocene-Holocene Climatic and Paleoecological Records in Tanzania

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### Abstract

Climate change is poorly addressed in the developing countries particularly in tropical East Africa such as Tanzania. This paper aimed to reconstruct the late Pleistocene to Holocene Tanzanian climate change using proxies from terrestrial and marine environment. Although data are limited, the inferred major events were found to have a link with global events. In late Pleistocene, during the Last Glacial Maximum (LGM), Tanzania experienced aridity as the other areas in the tropics. This was followed by the humid high precipitation period, highly pronounced between 9-6 ka. Proxies indicate that the humid period was interrupted by a brief dry Younger Dryas (YD) around 13.0-11.5 ka and a cool dry event at 8.2 ka. Other remarkable events are the cool event in the mid Holocene at 5.2 ka and the global dry event at 4.0 ka. There is a general decrease in precipitation from 5 ka to present with the aridity being pronounced between 3-2 ka and 1.2-0.5 ka. Despite of relatively low precipitation in Late Holocene, wet conditions are inferred between 1.7-1.2 ka (being interrupted by remarkable episodes of aridity) and the late periods of the 19<sup>th</sup> and 20<sup>th</sup> centuries. The 20<sup>th</sup> century which is marked by increased temperature is likely to cause changes in hydrological circle leading to the increase in heavy rainfall and drought periods. Through this study, it is revealed that works are limited and concentrated in some specific areas within the country which exhibit different climatic condition. As a result, some proxies particularly from Eastern Arc Mountains show contradicting records and, in some places, interpretation is partial due to extrapolation of the proxies which are not widely distributed within a specific climate zone.

**Keywords:** Climate change; Paleoecology; Holocene; Proxies; Pleistocene; Tanzania.

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## 1. Introduction

Climate has been changing from glacial to interglacial conditions over geological time owing to alteration of sun's energy reaching the earth surface [1–7]. Records of such changes have been preserved in various forms of proxies [8–12]. However, global documentation of the climatic variability is biased towards northern mid to high latitudes [13,14]. In the tropics, documentation is low with tropical east Africa being poorly represented. Most of the paleoclimatic records have been documented using microfossils (pollen, charcoal, phytoliths, grass cuticles, diatoms, stromatolite and Ostracode) in marine and lake sediments, swamps, peat bogs, and soils (eg. [15–37] stable isotopes ( $^{18}\text{O}$ ,  $^{13}\text{C}$  (inorganic and organic),  $^{15}\text{N}$ , and  $^2\text{H}$ ) in corals, sediments, stalagmite and ice sheet/caps [28,38–42], lake level records [43–46], seismic reflection data [29,47–49], and C/N ratio of organic matter (eg. [50]).

A review of late Quaternary climatic changes in East Africa, which covered works that utilized pollen, diatoms, microscopic charcoal, lake levels and the associated proxies ( $^{15}\text{N}$ , %N,  $^{13}\text{C}$ , HI, %TOC) was carried out by [11]. Because of poor spatial distribution and low resolution of paleoclimate works in East Africa, their work recommended the use of higher resolution palynological approach in conjunction with multi-proxies to reconcile properly the Holocene climate changes, which are influenced by both natural and anthropogenic processes.

In Tanzania, much of the paleoclimate studies have been done in some lakes (Tanganyika, Victoria, Nyasa (Malawi), Rukwa, Challa, Empakai, Massoko), Indian Ocean, Mt. Kilimanjaro and Eastern Arc Mountains (EAM) (Table 1). These works have not been integrated together to associate proxies with trends of climate parameter such as rainfall and temperature. Despite the use of multi-proxies in various areas in Tanzania, information on the distribution and consistence of the available climate records is poorly known, creating difficulties in paleoclimate reconstruction. Therefore, this review paper focused on ecological and hydrological changes in terrestrial and marine environments of Tanzania during the Late Pleistocene-Holocene period. Because of the lack of local scale paleoclimatic records in Tanzania and complex tele-connectivity between land, atmosphere and ocean, this review is partly supported by regional climatic records to strengthen our climate reconstruction. The work puts together the available Holocene climatic records as an attempt to address climate changes and its implication to national economy. This is important in development of national strategic plans for mitigating climate change impacts such as food shortage, water scarcity and floods. In future, these impacts are expected; resulting from abrupt short periods of heavy rainfall and droughts as the feedback response of the current global warming.

**Table 1:** Common proxies that have been used to infer palaeoclimate and paleoecology in Tanzania

Zone/archive	Proxies/Measured parameter	Authors
Lake Tanganyika	Stromatolites	[29, 51]
	$\delta\text{D}_{\text{wax}}$ in combination with the Branched and Isoprenoid Tetraether (BIT) index of soil bacterial	[45]
	Seismic reflection (Acoustic impedance)	[52]

	Elemental geochemistry-soluble elements and sedimentological records	[53]
	Stable isotopes of carbon and nitrogen, contents of OC and nitrogen	[50]
	Ostracode	[30, 54]
	Sedimentological data	[55]
	Diatom and Pollen	[56]
	Pollen	[53]
Lake Malawi	$\delta^{18}\text{O}_{\text{diatom}}$	[57]
	Pollen	[58, 59]
	Lignin phenols, plant leaf wax carbon isotopes, TOC	[60, 61]
	Seismic reflection (Acoustic impedance)	[62, 63]
	Diatom	[64]
	Terrestrial and aquatic biomarkers (diatom, cyanobacteria etc), $\delta^{13}\text{C}_{\text{TOC}}$	[60]
	Elemental geochemistry (Sedimentary calcite, TOC, Si:Ti, Rb:K ratios)	[65,66]
Lake Victoria	Seismic reflection (Acoustic impedance)	[47]
	Stable isotopes of carbon and nitrogen, contents of OC and nitrogen	[38]
	Pollen	[67]
Lakes Massoko, Mbaka	Diatom and cyanobacteria	[68, 69]
	Charcoal	[70]
	Pollen	[71]
	Stable isotope of Oxygen and Hydrogen	[72]
	Pollen, Magnetic susceptibility	[73]
Lake Empakai Crater	Stable isotopes of carbon and nitrogen, contents of OC and nitrogen	[74]
	Ostracode, Chironomids, Diatoms, Pollen	[75]
Lake Natron	Stromatolites	[76]
Coastal and Island caves	Stalagmite and Stalactite ( $\delta^{18}\text{O}$ , $\delta^{13}\text{C}$ )	[39]
Western Indian Ocean	Corals	[77, 78]
	Foraminifera	[79,80]

Lake Challa	$\delta^{18}\text{O}$ , $\delta^{13}\text{C}$	[28, 42]
	$\delta\text{D}_{\text{wax}}$ in combination with the Branched and Isoprenoid Tetraether (BIT) index of soil bacterial	[46]
	Seismic reflection (Acoustic impedance)	[46, 49]
	$^{14}\text{C}$ and $^{210}\text{Pb}$ -dating and $\delta^{13}\text{C}$	[81]
	Stable isotopes of carbon and nitrogen, contents of OC and nitrogen	[42]
Lakes Magat (Ngorongoro Crater)	Stable isotopes of carbon and nitrogen, contents of OC and nitrogen	[40]
Lake Duluti	Diatom and Pollen	[82]
Lake Rukwa	Diatom	[83]
	Pollen	[10]
Mt. Kilimanjaro	Oxygen and Hydrogen Isotopes in Ice cores	[28, 84]
Mt. Udzungwa	Stable isotopes of carbon and nitrogen, contents of OC and nitrogen, Spores, Macrofossil, Pollen	[41]
Mt. Uluguru	Charcoal, Pollen	[85]

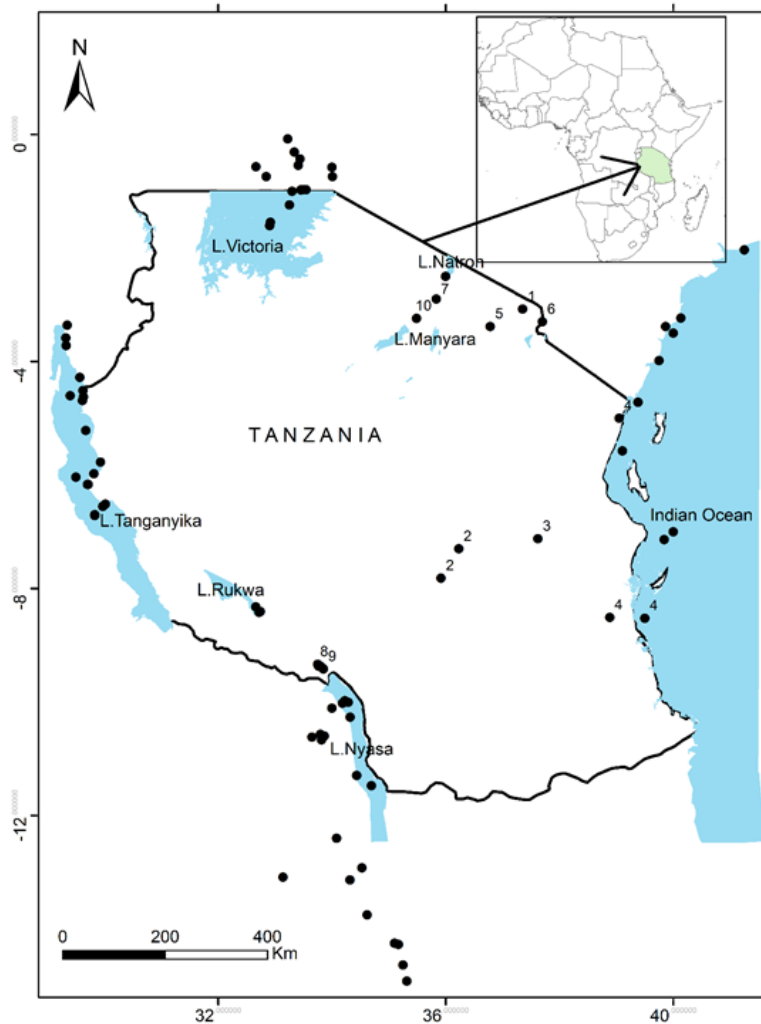
## 2. Study Approach

To reconstruct the Holocene climatic changes in terrestrial and marine environments in Tanzania, major focus has been on the areas with integrated data (multi-proxies). These are lakes, Indian Ocean and eastern arc mountains (Table 1 and Fig. 1). Lakes have been used as a major archive because most of them are sensitive to climate change. For example, lake level fluctuations, changes in water chemistry and processes have been used to reconstruct the past temperature and rainfall trends [29,30,43–45,49,52,86,87]. Lakes reviewed were crater lakes (Challa, Duluti, Ngorongoro, Empakai and Massoko), East Africa Rift Lakes (Tanganyika, Malawi, Rukwa and Natron) and Lake Victoria (Table 1 and Fig. 1).

Mountains were found to be potential areas with proxies for paleoclimate reconstruction in Tanzania through vegetation (eg. pollen, charcoal) and Ice core particularly on Mt. Kilimanjaro. Mountains reviewed are Mt. Kilimanjaro and Eastern Arc Mountains (EAM) of Tanzania comprising mainly Uluguru and Udzungwa mountains (Table 1 and Fig. 1). These are potential areas with paleo-indicator fossils such as corals, foraminifera and diatoms. Coastal areas are potential areas with caves where geological materials mainly stalagmites and stalactites are found. These materials are the best recorders of paleo-hydrological environment.

In general, review was based on the integrated proxies (Table 1). These proxies were utilized to reconstruct chronologically major events from late Pleistocene to present by integrating proxies from the same area and comparing them with other proxies in different areas. Furthermore, to infer dry and humid periods and ecological changes, proxy data were used to generate maps that showed spatial and temporal climatic variability,

general lake level fluctuations for major lakes for (1.) the Holocene period, (2.) the past two centuries, a period with increased modern lake records relative to pre-1800 period.



**Figure 1:** Distribution of the recorded proxies in Tanzania and surrounding areas. The numbers 1-3 represent proxies on Mountains Kilimanjaro, Udzungwa and Uluguru respectively. 4- Caves along the coast and Songo Songo Island whereas 5-10 represent proxies on craters and small Lakes- Duluti, Challa, Empakai, Massoko, Mbaka and Ngorongoro respectively. Major water bodies are labelled in the map.

### 3. Paleoclimatic Records and Major Events of The Late Pleistocene to Present

#### 3.1 Late Pleistocene-Early Holocene

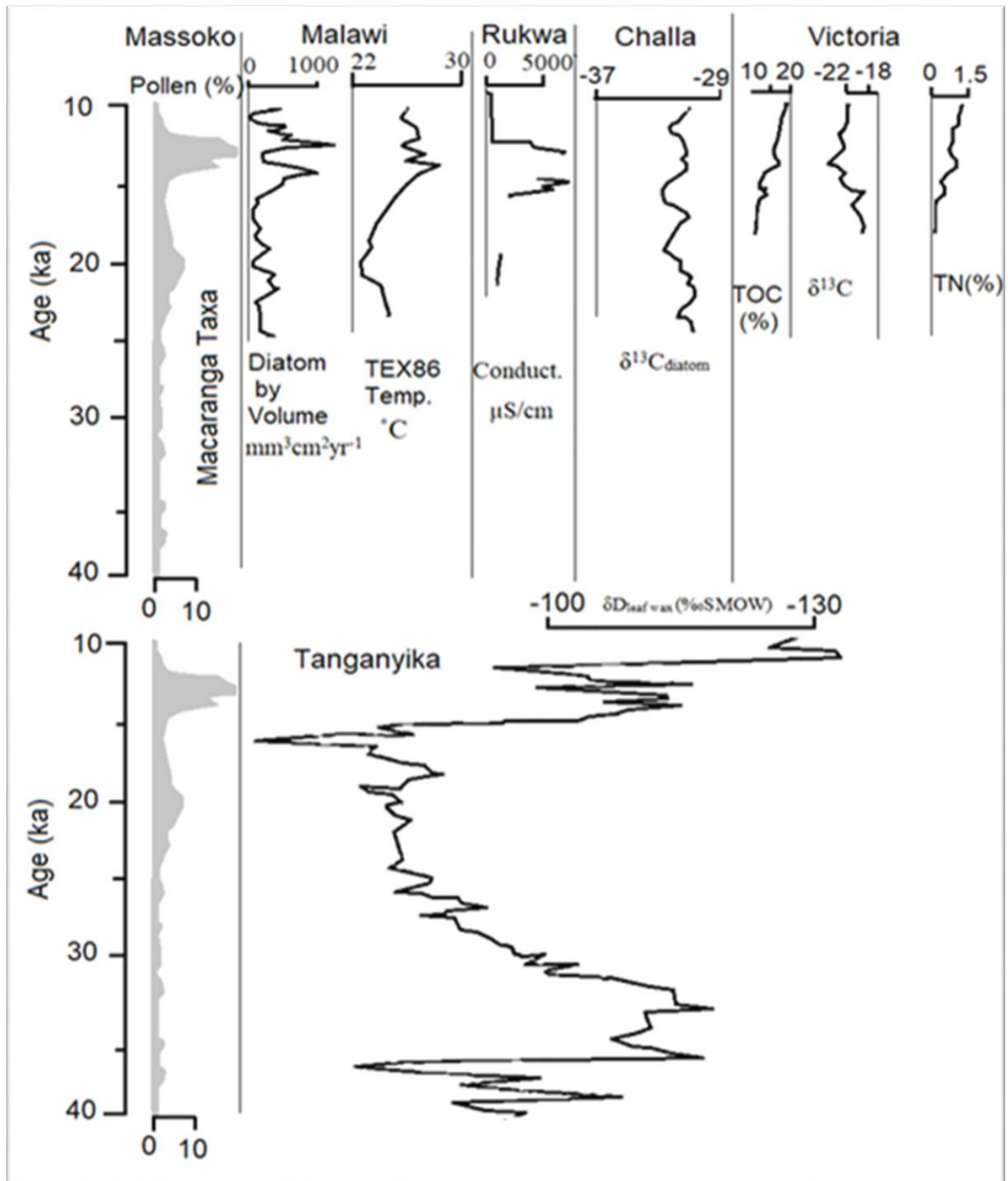
##### *Last Glacial Maximum (LGM)*

Various works using Lake sediments have carried out in all major lakes of Victoria, Tanganyika and Malawi to infer palaeoclimate changes (eg. [29,38,45,52,55,57–59,88]). These works include pollen analyses as a powerful

tool for inferring palaeo-hydrological conditions (eg. the work by [9]), stable isotope of carbon and nitrogen with C/N ratios for accounting the sources and proportion of organic matters [89] and paleolimnological studies using sediment cores for assessing ecological changes in Lake Victoria [88]. Also, diatom studies in combination with water conductivities have been useful in palaeoclimate reconstruction (eg. [90][67]). Diatoms are important in inferring palaeoclimate through  $\delta^{18}\text{O}$  in combination with other proxies. Their powerfulness is attributed to their sensitivity to water chemistry, particularly pH, salinity and nutrients [91]. These works have shown that Africa was dry during the Last Glacial Maximum (LGM) [7,28,50,53,69,92]. In this period, most of the East African lakes were characterized by low lake levels and the basins were dominated by savanna vegetation compared to wood vegetation [7,93, 94]. Aridity was severe such that Lake Victoria was completely dry [90] and Lake Massoko was completely saline [69].

In Lake Tanganyika, apart from the other proxies, diatom study has been a significant tool in paleoclimate reconstruction (eg. [42,56,57,68,69]). The Lake level has been changing in response to climate change over the entire period, it dropped more than 350 m during the LGM period [53,93]. The work by [53] in Lake Tanganyika using elemental geochemistry and textural changes in sediments suggested aridity period between 16 and 15 ka. This agrees with low diatom productivity between 17 and 10 ka of which hydrological changes are linked with changes in ITCZ [93].

In Lake Malawi, various proxies such as diatom, pollen, stable isotopes, lignin phenols and plant leaf wax carbon isotopes, elemental composition as well as sedimentological data have been used in paleoclimate reconstruction [57–64, 66]. Lacustrine records provided evidences of dry condition during LGM concomitant with other lake records in northern and southern equatorial Africa [57,64,65,95–97]. Furthermore, lake level records derived from benthic diatom assemblages, seismic reflection data and geochemical analyses of endogenic calcite showed low lake level and hence aridity during LGM [98]. For instance, drop in lake level to about 100 m was inferred using diatom records and seismic data between 23-19 ka [64]. This agrees with the works by [63] which indicated a significant drop of lake level to about 75 -100 m below the modern levels during LGM. Furthermore, according to [57], a pronounced dry period is inferred through enrichment of  $\delta^{18}\text{O}_{\text{diatom}}$  between 17.8 -14.5 ka. However, some workers have indicated less intense Glacial maximum conditions. For example, the work of [58] using pollens showed widespread montane forest in the Lake Malawi catchment basin. This is in close agreement with a study by [65,97] which revealed a general high lake level between 60 ka to present relative to the period between 145-60 ka. Dry condition during LGM is not well pronounced in Lake Massoko as evidenced by vegetation cover (eg. Macaranga Taxa, Fig. 2) and magnetic susceptibility [99]. Since the formation of the Lake, lake levels have been fluctuating depending on rainfall intensity without any pronounced dry period. This is contrary to most of the low land lakes in tropical Africa [99]. The core results integrating dating and litho-correlation indicate strong variability of sediments deposition from 45 ka (Early period of lake formation) to 11.7 ka (Last Glacial Period) [73]. However, this is not in close agreement with a study by [100] using diatom which showed that the Lake was completely saline during LGM suggesting aridity. This agrees with observations in other Lakes (Fig. 2).



**Figure 2:** Various proxies indicating dry condition during LGM in major Lakes of Tanzania with exception of Lake Massoko which showed fluctuation of wet and dry seasons as evidenced by vegetation (Macaranga taxa). Data are compiled from [83]-Lake Rukwa, [57]-Lake Malawi, [42]- Lake Challa, [99]-Lake Massoko, [38]-Lake Victoria and [7]-Lake Tanganyika.

The biodiversity in the Eastern Arc Mountains of Tanzania (plants and animals) is high to the extent of providing ecological data for paleo climate reconstruction. The forest over this area is believed to have retained moist since the last glaciations [41, 85]. In attempt to reconstruct paleoclimate of these mountains, ecological stability of the forest was tested using a combination of pollen, charcoal, spores, macrofossils and stable isotope

proxies [41, 94]. Results inferred the cool and dry conditions associated with high ecological stability in the late LGM to the start of Holocene period. High stability during this aridity period is linked to the influence of Indian Ocean in maintaining moist forest cover [41].

#### *African Humid Period*

Last Glacial Maximum (LGM) was followed by the African Humid Period (AHP) between 14-5.5 ka, being culminated in Holocene between 9 and 6 ka [27]. During AHP, the known Sahara Desert in Africa was nearly covered by vegetation mainly shrubs and grasses and various Lakes existed in the sub-tropical areas of Northern Africa. Some of the Lakes with saline water during this time such as Lake Rukwa were characterized by freshwater during the humid period due to high precipitation [83]. In Lake Rukwa, the transition from fresh to saline water is evidenced by change in diatom species composition from freshwater to saline water diatom species as well as the fluctuations of pH and conductivity inferred using diatoms [83].

Integrated proxies in Lake Empakai indicate a period of high lake level with freshwater between 14.8 to 12.3 ka being well pronounced between 14.8 -14.4 ka and 13.2 - 12.3 ka [74]. [75] indicated that the lake exhibited a general high lake level between 12.7 - 10.3 ka and thereafter a decreased precipitation which led to abrupt transition of lake water from fresh to alkaline at 9.7 ka. This is in close agreement with an abrupt climatic change at 8.7 ka inferred using stable isotope of organic carbon and nitrogen [74]. The cores were characterized by enrichment of both  $^{15}\text{N}$  and  $^{13}\text{C}$  prior to 8.7 ka and depletion of these isotopes post 8.7 ka suggesting climatic changes from wetter to dryer conditions [74].

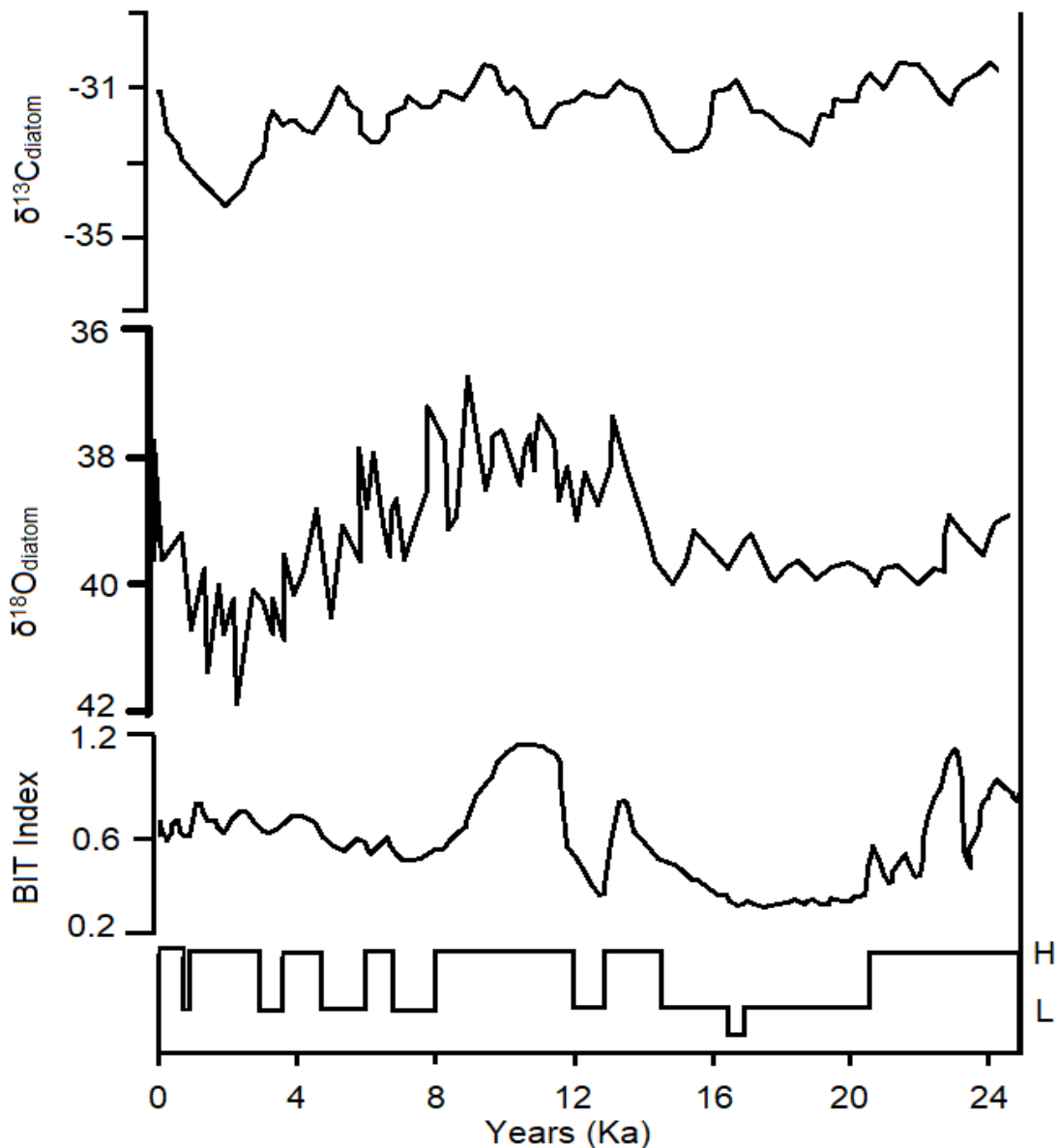
From Lake Challa, a lake that has been responding well to climate changes, the  $\delta^{18}\text{O}_{\text{diatom}}$  were relatively low (average =  $38.2\text{‰}$ ) along with high lake level and BIT index in the late Pleistocene to early Holocene (~15-9 ka) ([101]; Fig. 3) suggesting a reduced aridity with high precipitation. In Lake Tanganyika, the humid period is indicated by a significant drop of  $\delta^{13}\text{C}$  between 19-9 ka associated with changes in vegetation from  $\text{C}_4$  to  $\text{C}_3$  types and increase in C/N ratio [93]. African Humid period is also inferred using corals from the equatorial continental margin of the western Indian Ocean [80]. However, they are restricted in tropical climate and their records through skeletons enable short- term paleoclimate reconstruction generally up to few centuries [39]. Therefore, because of the above coral-limitations in reconstruction of paleoclimate, they have been used together with stalagmites and stalactites to infer Holocene ecological changes in Tanzania. Using a combination of foraminiferal Mg/Ca ratio from the tropical western Indian Ocean and  $\delta^{18}\text{O}$  from the sediment core off northern Tanzania, it was possible to infer a warm phase at (~7.8–5.6 ka) [80].

#### *Younger Dryas*

Humid period was interrupted by the cool and dry short-lived period of Young Dryas (YD) around 12 ka [7,27,28,40,46,57,73,75,99]. It was terminated abruptly, completed within tens to hundreds of years [27], [28]. Geological evidences indicate that termination of the humid period was immediately followed by change in African climate to more arid condition and decline in lake levels for major Lakes. The work of [27] off Cap Blanc, Mauritania has shown sharp increase in eolian sediments between 13.4-12.3 suggesting the YD period. In



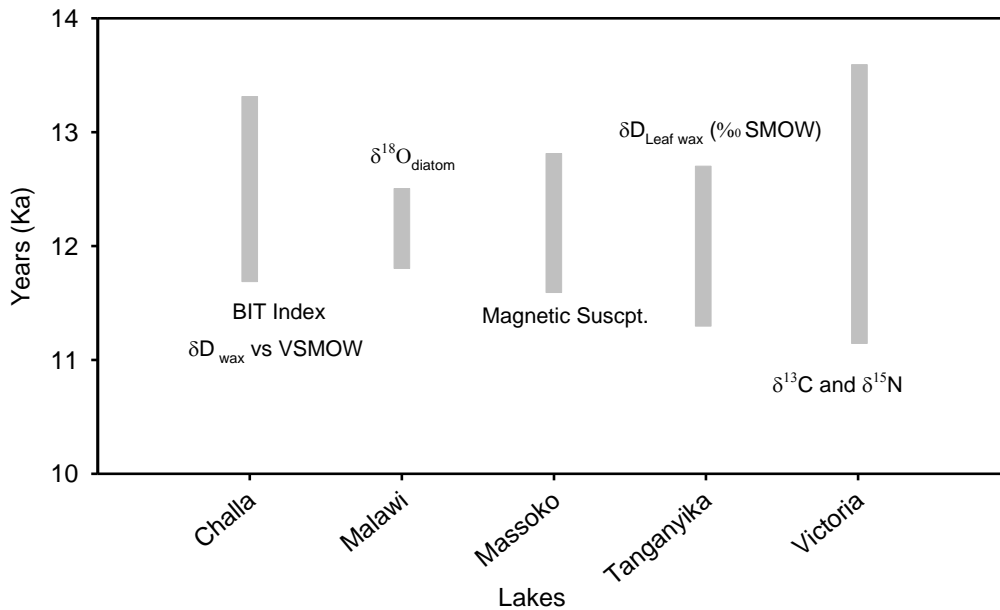
this period, most east African lakes are known to have experienced low lake levels [46].



**Figure 3:** Late Pleistocene to Holocene paleoclimate reconstruction using multi-proxies from Lake Challa. H and L are high and low lake levels reconstructed using seismic data (after [46]). Unlike drier periods, wetter periods as discussed in text are well reflected by high lake levels, high BIT index, depletion of  $\delta^{18}\text{O}_{\text{diatom}}$  and  $\delta^{13}\text{C}_{\text{diatom}}$ . Other data sources are BIT Index [46],  $\delta^{18}\text{O}_{\text{diatom}}$ , [28] and  $\delta^{13}\text{C}_{\text{diatom}}$  [42].

In Tanzania, the Younger Dryas event has been documented widely using integrated proxies particularly in Lake Tanganyika ([7] ~ 12 ka), Lake Malawi ([57], 12.5-11.8 ka), Lake Victoria ([38], ~13.5-11 ka), Lake Challa ([46], 13.3-11.7 ka), Lake Massoko [99], 12.8-11.6 ka) (Figs. 4 and 5) and other smaller lakes [28,40,57,75]. In Lake Malawi, the YD is reflected by high  $\delta^{18}\text{O}_{\text{diatom}}$  (+39.7‰) at 12.5 ka suggesting very dry condition [57]. In Lake Massoko, it is well reflected by the sharp decline in magnetic susceptibility [99]. Furthermore, branched isoprenoid tetraether (BIT) record in Lake Challa sediments together with  $\delta^{18}\text{O}_{\text{diatom}}$ ,  $\delta^{13}\text{C}_{\text{diatom}}$  and lake level, show that drought encompassing the YD in equatorial East Africa lasted from 13.3 to 11.7 ka, with most intense

aridity during 12.4 –12.8 cal. kyr BP ([45]; Fig. 3). Hydrological changes during YD period are linked to changes in earth orbital oscillations [27] leading to the changes in ITCZ [99]).



**Figure 4:** Variation of Younger Dryas period in various lakes in Tanzania as inferred using multi-proxies. The indicated proxies were the major proxies used in conjunction with other proxies as indicated in text. Data are compiled from [57]-Lake Malawi, [99]-Lake Massoko, [38]-Lake Victoria, [7]-Lake Tanganyika and [46]-Lake Challa.

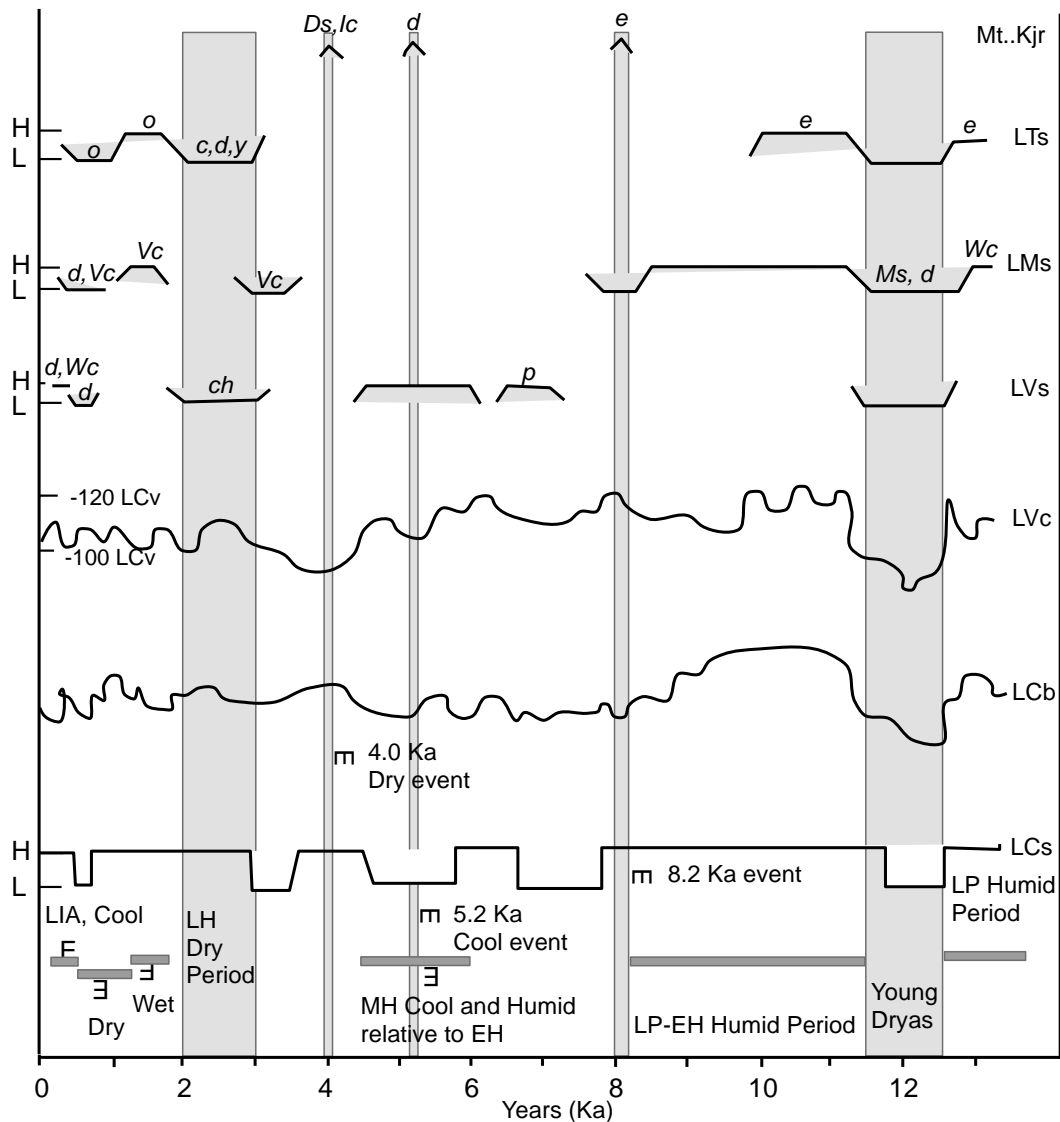
### 3.2 Early-Mid Holocene Period

#### Early Holocene Period

Towards the beginning of Early Holocene, Tanzania was characterized by high precipitation [27,46,53,74,101–104]. In this period, the lake levels for most of the eastern Africa lakes were above the present levels [28]. In Lake Tanganyika, around 10 ka, high precipitation is evidenced by increase in soluble components in lake sediments represented by Be/Al, Ni/Al, Cr/Al, Fe/Al ratios [53] and depletion of  $\delta D_{leafwax}$  relative to late Holocene values [7]. In Lake Emakat, the early Holocene high precipitation is evidenced by the increase in  $C_3$  vegetation type with depleted  $\delta^{13}C$  value averaging at -27‰ compared to -12‰ of the  $C_4$  plant types [74] whereas in Lake Massoko, it is inferred through diatom by low water conductivity between 13.1 to 8.5 ka [69]. In Lake Challa it is reflected by high Lake level supported by elevated BIT index and depletion of  $\delta D_{wax}$  vs VSMOW (Fig. 5). The high precipitation in this period is linked/related to the increase in Northern Hemisphere precession leading to strengthening of summer and winter monsoon [7].

According to the work by [75] in northern Tanzania, within the early Holocene period, there was a short period between ~10.3-9.7 ka with decreased precipitation followed by abrupt transition from fresh water to high salinity and alkalinity in Lake Empakai. This is closely in agreement with the study by [74] in the same lake which indicated abrupt climate change around 8.7 ka and the study by [101] in Lake Challa which indicated an

increase in  $\delta^{18}\text{O}_{\text{diatom}}$  around 9 ka. Furthermore, as pollen can be transported a long distance [105], decrease in precipitation in this particular period is supported by the decrease in pollen over lake Challa as noted by [101] as a result of reduced vegetation cover over Mt. Kilimanjaro.



**Figure 5:** Relative lake levels variation from late Pleistocene to Holocene reconstructed using integrated proxies with “H” as high stand and “L” as low stand (left). Gray paint indicates the major abrupt climatic event inferred using both lake levels and Ice core at Mt. Kilimanjaro. LCs, LCb, LCv are Lake Challa lake level fluctuation, BIT Index and  $\delta\text{D}_{\text{wax}}$  Vs VSMOW respectively as modified from [45]. LVs, LMs and LTs (right) are the relative lake level fluctuations for lakes Victoria, Massoko and Tanganyika respectively. Mt. Kjr is Mt. Kilimanjaro abrupt event records. The symbols in specific segments indicate the common proxies used where c:  $\delta^{13}\text{C}$  or  $^{14}\text{C}$  dates Ch: charcoal, d:  $\delta^{18}\text{O}$ , Ds: dust cover, e: elemental geochemistry, Ic: Ice cover, Ms: magnetic susceptibility, o: ostracode records, p: pollen, Vc: vegetation cover, Wc: water conductivity and y: sediment textural changes.

*The 8.2 ka event*

Despite the fact that the early Holocene was a period of high precipitation [50, 69], a short period of dry event about 8-8.2 ka has been inferred (eg. [81,92,96]). Records from many lakes in Tanzania show that at around 8 ka, the area experienced climatic reorganization in concomitant with global observations [31,53,106]. Such a record has been preserved in the Kilimanjaro ice field through high concentration of  $\text{Na}^+$  and  $\text{F}^-$  at around 8.3 ka suggesting decline in regional lake levels [84]. This is in close agreement with the relative high-water conductivity in Lake Massoko as inferred from diatoms between 8.5-7.8ka, suggesting dry condition in this period [100]. Generally, the 8.2 ka event has been recorded in both lacustrine and marine environments in Northern Hemisphere and has been referred to be a cooling event which resulted from meltwater outflow into the North Atlantic Ocean and a slowdown of North Atlantic Deep-Water formation [57, 107,108].

### *Mid Holocene*

Mid Holocene is recognised as a humid period in equatorial East Africa [46] with high precipitation reflected by high lake levels in major Lakes of Tanzania - Victoria, Tanganyika and Rukwa [9, 50]. In Lake Victoria, this is supported by the pollen data which indicate abundance of Moraceae/Urticaceae between 7.1- 6.5 ka suggesting humid condition around Lake Victoria catchments [9].

### **3.3 Mid Holocene-Present**

Available data indicate a general progressive decrease in precipitation from mid-Holocene to present in Tanzania likely to be attributed to the intensity variation of the monsoon winds. For instance, diatom records from Lake Victoria and  $\delta^{13}\text{C}$  values for the core in Lake Tanganyika indicated a general decrease in precipitation from mid-Holocene to present [50]. In Lake Tanganyika, aridity has been interpreted through a down-core decrease in  $\delta^{13}\text{C}$  which indicate changes from the dominance of  $\text{C}_4$  to  $\text{C}_3$  vegetation types [50]. In Lake Challa aridity is reflected by high  $\delta^{18}\text{O}$  values averaging at  $40.3^\circ/\text{‰}$  from 5 ka to present [101].

### *Mid Holocene 6-4.1 ka*

The period from 6-4.1 ka was wet relative to the present climatic condition and dry relative to early Holocene with pronounced cooling episodes [84]. High precipitation (high lake level stands) was inferred over Lake Victoria between 6.5 – 4.1 ka [9] and water levels were maximum in the basins such as Ziway-Shala in the main Ethiopia rift system [84]. From the Indian Ocean, off northern Tanzania, foraminiferal Mg/Ca ratio and  $\delta^{18}\text{O}$  from sediment cores inferred a cool period between ~5.6-4.2 ka with the temperature decreased to about 2 °C relative to the preceded early to mid-Holocene period [80]. From the ice core retrieved from Mt. Kilimanjaro, a cool climatic condition is reflected by depletion of  $^{18}\text{O}$  at about 6.5 ka with maximum depletion at about 5.2 [84], [109]. The 5.2 ka event agrees with Greenland Ice core where in both cores, the cooling event is reflected by the decline in lake levels,  $\text{CH}_4$  concentration as well as the vegetation cover [84]. The cooling event is also reflected in northern Africa to Arabia [84]. Thus, it is likely that the event was influenced by regional climatic forcings. In general, precipitation in this period was found to be relatively lower than the precipitations in the Early Holocene [84].

### *The 4.0 ka event*

Global climatic data particularly from Northern Africa, China and Southern America suggest another climatic event around 4-4.5 ka. This event was associated with the decrease in precipitation leading to low lake levels. On Mt. Kilimanjaro, this period is evidenced by decrease in ice cover and thick dust deposit at around 4 ka [45, 84, 109]. On this mountain, the event is shown in Fig. 5 where the dust histories and  $\delta^{18}\text{O}$  values are compared with other proxy records. The same event is recorded in the nearby crater lake (Lake Challa) where it is reflected by depletion of  $\delta\text{D}_{\text{wax}}$  [45] (Fig. 5). This was a regional event as the thick dust deposit was also recognised in other parts of the world such as the Gulf of Oman, the eastern parts of Mediterranean Sea around 4.2 ka [45].

From marine cores (eg. Core from Indus Delta and Gulf of Oman), the dry event is reflected by sharp peaks of carbonates (short period of high carbonates) [109]. In China, it is reflected by a sudden decrease in pollen concentrations around 3.95-4.45 ka [109]. In Southern America, it is evidenced by high  $\delta^{18}\text{O}$  in Amazon fan from planktonic foraminifera suggesting the decrease in river flow. Furthermore, dry condition is recognized in other lakes of Africa such as Lakes Tilo in Ethiopia, Bahr-El-Ghazal, Ziway-Shala, and Abhe in the Northeast of Africa [45]. The 4.0 ka dry event is likely to have been caused by strong changes in solar activity influencing changes in systems such as deep ocean circulation and El Niño-Southern Oscillation (ENSO) [45, 109].

### *3-2 ka event*

The 3-2 ka period is recognised as the dry period characterized by low stands for most of East Africa Lakes [52]. In Lake Tanganyika, low precipitation period is supported by stromatolitic data ( $^{14}\text{C}$  dates,  $\delta^{18}\text{O}$ ,  $\delta^{13}\text{C}$ ) coupled with elemental geochemical and sedimentological data which indicated a low lake levels about 5-10 m below the present lake level and enrichment of  $^{18}\text{O}_{\text{stromatolite}}$  around 800 BC to 400 A.D (2.8-1.6 ka) [29]. This is in close agreement with both stromatolite records which indicated maximum aridity at 2.5 ka [51] and ostracode records where a low stand period was inferred between 2.2-2 ka [30].

The 3-2 ka dry period is in close agreement with the charcoal studies in Lake Victoria which indicated the relative dry period between 3-2 ka as reported by [70]. The work by [28], specified this low stand period for Lake Victoria to be between 2.7 and 2.4 ka. In Lake Massoko catchments, there was a decline in vegetation cover around 3.45 -2.8 ka [71]. The 3-2 ka dry condition is further supported by other proxies from other areas. For instance, studies in other Lakes of Africa (eg. Lake Bosumtwi – Ghana, Lake Turkana- Kenya) suggest more dry condition around 3 ka [104] and some of the lakes such as Lake Naivasha were completely dry around this period [42].

Aridity in the 3-2 ka period was not so intensive as the aridity in the LGM. In the Eastern Arc Mountains (EAM),  $\delta^{13}\text{C}$  values suggest high proportion of  $\text{C}_3$  plant materials compared to the LGM  $\text{C}_3$  proportions [94] probably owing to increased precipitation. There is clear evidence that from 3.5 ka to present, there is an increase in human activities which are affecting ecological stability of Eastern Arc Mountains (EAM). For instance, the abundance of fungi which are associated with herbivores such as pleospora and Sordalia between 3.5 ka to present reflects the increased cattle over the area [85]. Also, the Neuspora records particularly in the past 2000 yrs indicate the increase in fire burning activities over the EAM [85].

### *2-1.7 ka*

The available records in East Africa indicate a transition from the dry to wet period. [9] reported the wet period in Turkana basin, Kenya. This is closely in agreement with a 2 ka event inferred using  $\delta^{13}\text{C}_{\text{diatom}}$  over Lake Challa where the  $\delta^{13}\text{C}_{\text{diatom}}$  values were totally depleted relative to the pre and post 2 ka values [42]. Contrary to this, records from the same lake (Lake Challa) indicate that the period from 2.0–1.7 ka is among the drought periods that match properly with other Eastern Africa droughts [46]. This is further supported by records over lake Edward and most of the east Africa Lakes where a short period from 1.8 to 1.7 ka was inferred as the aridity period [92].

### *1.7-1.2 ka*

This is recognised as a period of high precipitation in equatorial East Africa with the peak around 1.5 ka [46], [110]. In Lake Massoko, this is evidenced by expansion of vegetation cover in Lake Massoko catchment's from 1.65 to 1.2 ka [71]. This is further supported by wet condition inferred through diatom records at 1.7 ka in Lake Massoko [91].

In Lake Tanganyika, this period is marked by high stand through ostracode records [110]. In this lake, [56], through sedimentary time series, diatom and pollen records inferred this wetter period in a specific interval between 1.7 and 1.4 ka. As the peak of early summer isolation are associated with high rainfall, the high precipitation in this period (as well as the period at ~11.5ka) is explained as the outcome of maximum early summer insolation in either north or south of the tropics over these periods [46].

### *Medieval Warm Period (1.2-0.5 ka)*

A combination of proxies such as pollen, diatom and magnetic susceptibility indicate that this period was characterized by a dry climatic condition [71]. In Lake Massoko, this is supported by diatoms records which suggest dry period between 1.0-0.5 ka [91] and the decrease in vegetation cover (woodland type) from 1.1-0.6 ka [70, 71]. In Lake Tanganyika, this is supported by the low lake level between the eighth and fourteenth centuries (1.2-0.6 ka) which corresponds to the low Nile River discharge over this period [29]. This agrees with the ostracode abundance records in Lake Tanganyika which revealed low stands between 1.2-1.15 ka and 0.95-0.75 ka [110]. In Lake Victoria, diatom records suggest minima lake levels in this period, specifically between 0.82-0.76 ka, 0.68-0.66 ka and 0.64-0.62 ka [67]. In Lake Duluti, northwest of Tanzania, a dry climatic condition was inferred using pollen and diatom records between ~0.97-0.54 ka [82]. However, very short wetter periods are suggested within this period. For instance, [45] interpreted a wetter condition between 1-0.9 ka using  $\delta\text{D}_{\text{wax}}$  data from Lake Challa and [56] interpreted such condition between 1.15-0.9 ka and 0.7-0.55 ka using sedimentary time series, pollen and diatom records from Lake Tanganyika.

### *Little Ice Age (0.5 -0.15 ka)*

Little Ice Age (LIA) was cool and dry with some episodes of wet conditions [45, 67]. Aridity during the LIA was inferred between 0.5 and 0.35 ka using sedimentary time series, diatom and pollen records of Lake

Tanganyika [56]. Also, in the same lake, short brief periods of low lake levels are recognised using ostracode records around 0.42, 0.27 and 0.2 ka [30]. In Lake Duluti, a brief low lake level is inferred using pollen and diatom records between ~0.41-0.37 ka [82] while in Lake Victoria short periods of low stands which are concomitant with the short dry periods in Lake Tanganyika were inferred between 0.37-0.34 and 0.22-0.15 ka [67].

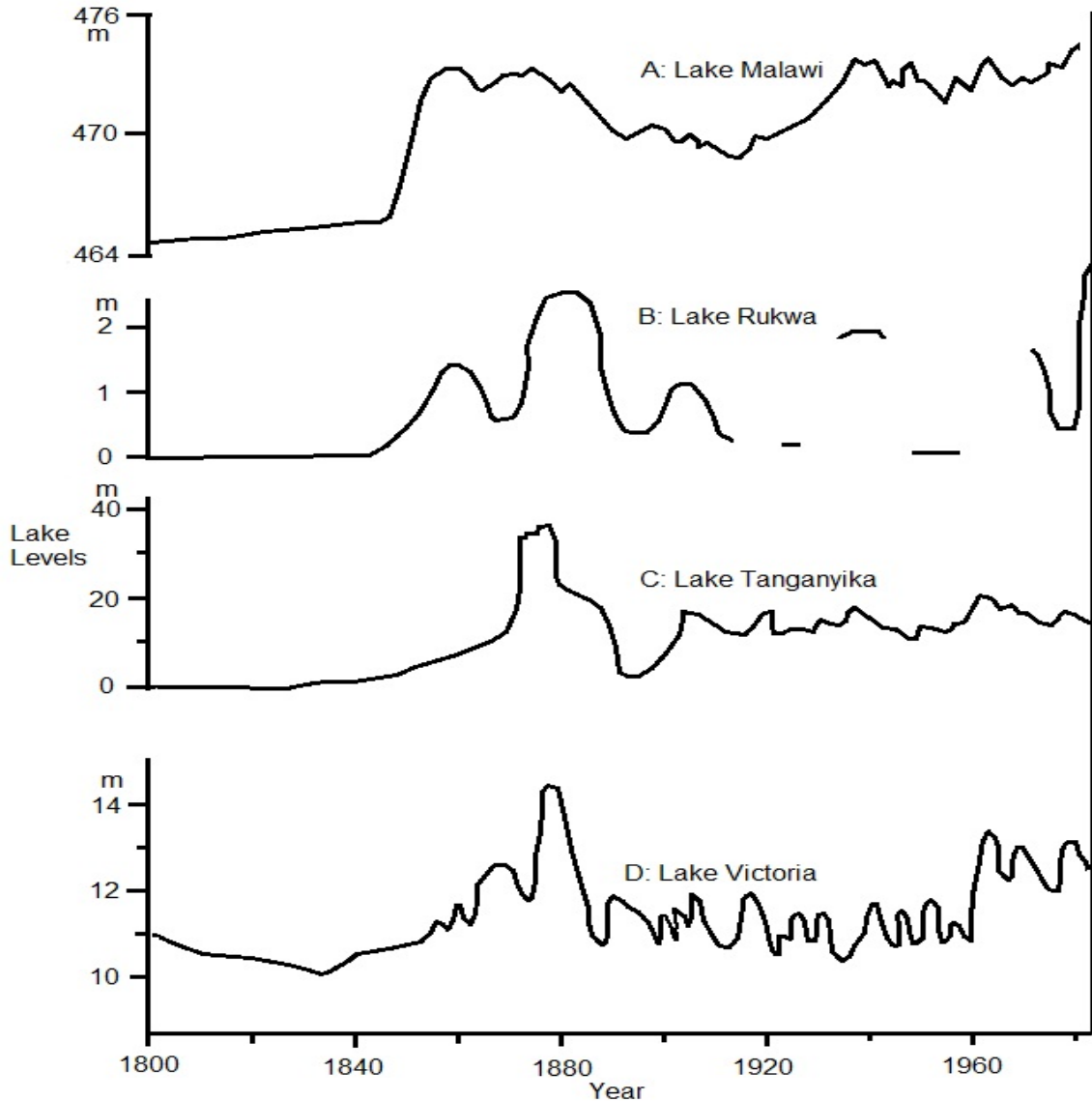
Episodes of high precipitation are evidenced by the dominance of terrigenous sediments with low biogenic silica concentration in most of the lakes [111]. In Lake Tanganyika, this is supported by the relative high lake level stands from the 14<sup>th</sup> to 19<sup>th</sup> century [29] with the remarkable high stands inferred using ostracode abundances at 0.5 and 0.13 ka [110], pollen and diatom records between 0.35-0.2 ka [56]. The Tanganyika high lake levels in the 19<sup>th</sup> century compare well with the relative increase in Nile River discharge suggesting high precipitation in the corresponding catchments [29]. In Lake Victoria, high precipitation was inferred using water conductivities and shallow water diatoms as proxies with the highest peaks around 0.5 ka and 0.3-0.25 ka [67]. In Lake Massoko, it is evidenced by the increase in sedimentation rate with high content of terrigenous sediments from 0.5 ka [70]. Generally, the available data in Tanzania indicate that there was high variability of rainfall during the LIA with early period characterized by high precipitation relative to the late period.

#### *Period from 1800-1900*

For the last two centuries, water balance models in conjunction with oral tradition records have been used to reconstruct rainfall (eg. [44, 112]). In the nineteenth century (also a part of LIA), the first half was characterized by low precipitation relative to the second half of the century and this is evidenced by low lake levels for most of the lakes in East Africa ([113]; Fig. 6). For instance, in 1830s, integration of recorded data (history of indigenous people, European explorers and settlers) around Lake Victoria in all bordering countries indicated that the drought was so intensive to the extent of forcing migration of local people [44]. The Lake began to rise slowly around 1850s (Fig. 6) in response to increased precipitation that led to expansion of vegetation cover in East Africa [44].

Around 1870s, precipitation was also low leading to low stands for most of the lakes in East Africa [46]. In this period, water level in Lake Rukwa was completely low (Fig. 6) as evidenced by Livingstone's servant who encountered salt residue at the bottom of the former lake [86]. From the mid of 1870s to 1900, most of the East Africa Lakes were characterized by high lake levels [113] suggesting increased precipitations. However, some brief periods of droughts occurred in 1880s [43, 44].

From 1870s to 1900, Catholic missionaries at Buganda measured levels of Lake Victoria frequently and therefore data are based on modern gauge measurements [44]. Such data indicated that in the late 19<sup>th</sup> century, the main precipitation peak over Lake Victoria was around 1890s [44] This peak is also reflected in all major lakes of Tanzania (Fig. 6). This is supported by [87], where records indicated the period between 1895 and 1897 as the main peak of precipitation over Lake Victoria and 1898 as the year peak in Lake Tanganyika.



**Figure 6:** Lake levels fluctuations of major lakes in Tanzania from the 1800 to 1980. Lake Victoria- it is redrawn from [44] where data source are historical data (pre-1900) and modern measurements (post 1900). For Lake Tanganyika, it is redrawn from [86] and source of data are historical and geographical information (pre-1900), early rainfall records (1902-1921) and modern records (post-1921). The scale is in meters above modern gauge height. For Lake Rukwa, it is redrawn from Nicholson, 1999 and data source are historical and geographical information (pre-1840), proxy data (1840-1960) and modern lake records (post 1970). Lake Malawi-redrawn from Nicholson, 1998b and data source are historical and geographical information (pre-1845), proxy data (1845-1896) and modern lake records (post 1896).

*Period from 1900 – Present*

The twentieth century was characterized by variable precipitation with increased temperature. From the beginning of the century to around 1920, the high precipitation was recorded through high lake levels in East Africa [113]. In Lake Victoria, the major peaks in the early 20<sup>th</sup> century were recorded between 1903-1907 and



1916-1918 through gauge measurements [87]. From 1920s to 1960s, most of the major lakes of Tanzania were at low levels characterized by minor fluctuations (Fig. 6). Remarkable low precipitation period was recorded between 1940 -1950 evidenced by low stands in most of the lakes in East Africa [113].

The 1960s precipitation was a high rainfall event in East Africa and extended across the Indian Ocean [67], [113]. In Tanzania, lake levels responded immediately after the 1960s precipitations. This is well reflected in Fig.3 particularly through Lakes Victoria and Tanganyika. In Lake Victoria, the peak was reached in 1964 [87] whereas in Lake Tanganyika it was reached in 1965 [86]. As the rains started early in 1960s, the peaks suggest that the high rainfall period persisted for not less than 5 years. Despite of having other peaks in Lake Victoria towards the end of the 20<sup>th</sup> century, particularly in 1978-79, 1990-91 and 1997-98, the 1960s precipitation is recorded as the highest peak of the century in Lake Victoria [114].

The 1997-98 high precipitation event has been documented in many locations in East Africa [78,87,113]. The East Africa lakes and streams responded to this precipitation. Stream flooding associated with major economic impacts such as infrastructure destruction occurred in all eastern Africa countries including the countries in the Horn of Africa. This event together with the 1960s event was related to changes in ENSO with the strong SST anomalies being developed in Indian Ocean causing unusual SST gradient (in reverse ways) that led to disruption of the normal wind trends.

#### **4. El Niño and La Niña**

El Niño and La Niña result from variation in temperature between the ocean and atmosphere in the east-central Equatorial Pacific. It is basically a deviation from the normal surface sea temperature. Both events; El Niño and La Niña which are the warm and cold events of ENSO respectively occur irregularly creating small to large scale impact on weather and climate. Globally, ENSO events have been known to control inter-annual climate variability in many countries [115, 116]. Holocene climate records indicate that frequency of occurrence of El Niño which is commonly associated with extreme events such as flood and drought is 2-8 yrs [116]. This agrees with WHO report [117] which indicated El Niño frequency interval of 2-7 yrs. However, each event exhibit unique characteristics in terms of duration and intensity [117]. For instance, East Africa records from 1975 indicate that El Niño was strong in 1982/83, 1997/98 and 2014/15 [118]. This frequency of occurrence of strong El Niño (recurrence interval of about 15 years) is high compared to La Niña which was strong in 1988/89 [118] in the last 42 yrs.

#### **5. Conclusions and Recommendations**

Limited terrestrial and marine proxies in Tanzania have used to reconstruct paleoclimate from the late Pleistocene to present. The major pronounced events were found to be linked with global events. The first event was the Last Glacial Maximum (LGM) in the late Pleistocene. This was the period of extensive aridity in the late Pleistocene-present records with some shallow Lakes such as Victoria being completely dry. This period was followed by the humid period with high precipitation which continued to early Holocene but being interrupted by a brief cool and dry Young Dryas (YD) period around 13-11.5 ka. The early Holocene was

generally marked by high precipitation with a brief cool and dry period at 8.2 ka. The mid Holocene between 8-4.5 ka was a cool period with high rainfall but relatively lower than early Holocene precipitations. This period was interrupted by a brief cooling event at 5.2 ka. The termination of the humid mid-Holocene period was marked by the global dry event at 4 ka.

Integrated proxies showed a general decrease in precipitation from the Late Holocene to present with the pronounced aridity between 3-2 ka and 1.2-0.5 ka. Remarkable high precipitation in the late Holocene was recorded between 1.7-1.2 ka, LIA-a cool period (~0.5-0.1 ka) and the late period of the 20<sup>th</sup> century. In the 20<sup>th</sup> century, a century with increased temperature, Tanzania and East Africa in general experienced high precipitation in the early and late periods of the century with low precipitation in the mid of the century around 1940-1960s. The 1960s and 1997/98 rainfall were recorded as the major high precipitation events in late period of the 20<sup>th</sup> century. Between these two events, there is a general decline in Lake levels and hence, low rainfall with exception of few periods between 1978-79, 1982/83 and 1990-91. The 1960s and 1998 events are related to changes in ENSO; the current increase in temperature is likely to trigger such events which exhibit unique characteristics causing large scale impact such as floods, infrastructure and settlement destruction.

This review work indicates that the available data are concentrated in specific areas and are not well distributed, do not fully represent the whole country. Because of different climatic zones in Tanzania, there is a need of more paleoclimate studies which are widely distributed based on climatic zones. Geographically, more paleoclimate studies are needed in the central parts of Tanzania, a climate zone which is very poorly represented. In general, potential areas that are not well researched include small lakes; these are very sensitive to climate changes, river basins, tropical and equatorial forests. With this study, it is still difficult to predict future long-term climatic changes in Tanzania. To achieve this, and to resolve existing conflicting records such as the records during the Little Ice Age and records from the Eastern Arc Mountains, modelling of specific climatic parameters using high resolution multi-proxies which are widely distributed are required.

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