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# Northern Hemisphere control of deglacial vegetation changes in the Rufiji uplands (Tanzania)

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Received: 19 August 2014 – Accepted: 11 September 2014 – Published: 30 September 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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## Abstract

In tropical Eastern Africa, vegetation distribution is largely controlled by regional hydrology which has varied over the past 20 000 years. Therefore, accurate reconstructions of past vegetation and hydrological changes are crucial to better understand climate variability in the tropical Eastern African region. Through high-resolution pollen records from a marine sediment core recovered offshore the Rufiji River, our data show significant shifts in pollen assemblages during the last deglaciation identifying, through respective changes in both upland and lowland vegetation, specific responses of plant communities to atmospheric (precipitation) and coastal (coastal dynamics/sea level changes) alterations. Specifically, an interval of maximum pollen representation of dry and open vegetation occurred during the Northern Hemisphere cold Heinrich event 1 (H1) suggesting the expansion of drier upland vegetation under arid conditions. This dry spell is followed by an interval in which forest and humid woodland expanded, indicating a hydrologic shift towards more humid conditions. Droughts during H1 and the return to humid conditions around ~ 14.8 kyr BP in the uplands are primarily attributed to latitudinal shifts of the Intertropical Convergence Zone (ITCZ) driven by high-latitude Northern Hemisphere climatic fluctuations. Additionally, our results show that the lowland vegetation, consisting of a well developed salt marshes and mangroves in a successional pattern typical for vegetation occurring in intertidal habitats, has responded mainly to local coastal dynamics related to marine inundation frequencies and soil salinity in the Rufiji Delta as well as the local moisture availability. Lowland vegetation shows a substantial expansion of mangrove trees after ~ 14.8 kyr BP suggesting also an increased moisture availability and river runoff in the coastal area. The results of this study highlight the de-coupled climatic and environmental processes to which the vegetation in the uplands and the Rufiji Delta has responded during the last deglaciation.

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# 1 Introduction

The African tropics, a region of major importance for the global hydrologic cycle, have experienced large-scale changes in climate and rainfall fluctuations over the last deglaciation and the Holocene (e.g. Street-Perrot and Perrot, 1990; Lézine et al., 1995; Gasse et al., 2000, 2008; Johnson et al., 2002; Vincens et al., 2005; Castañeda et al., 2007; Tierney et al., 2008; Schefuß et al., 2011; Stager et al., 2011; Bouimetarhan et al., 2012, 2013; Ivory et al., 2012). While millennial-scale hydroclimatic variations in Northwest Africa are commonly linked to atmospheric processes involving latitudinal migrations of the Intertropical Convergence Zone (ITCZ) associated with changes in the intensity of the northeasterly trade winds and related to North Atlantic climate anomalies (Dahl et al., 2005; Stouffer et al., 2006; Tjallingii et al., 2008; Mulitza et al., 2008; Itambi et al., 2009; Penaud et al., 2010; Bouimetarhan et al., 2012; Kageyama et al., 2013), the mechanisms responsible for southern tropical climatic changes remain a matter of debate. The Indian Ocean Dipole (IOD) has been shown to influence modern East African rainfall variability at the interannual scale (Saji et al., 1999; Saji and Yamagata, 2003), but on longer timescales, Indian Ocean sea surface temperature (SST) has been suggested to play a dominant role (Tierney et al., 2008, 2013; Tierney and deMenocal, 2013; Stager et al., 2011). The El Niño–Southern Oscillation (ENSO) has also been invoked to explain extreme rainfall reductions over modern East Africa (e.g. Nicholson, 1996; Plisnier et al., 2000; Indeje et al., 2000; Kijazi and Reason, 2005). Other studies suggest that East African rainfall variability was rather, atmospherically linked to North Atlantic climate fluctuations through a southward shift of the ITCZ (Johnson et al., 2002; Broccoli et al., 2006; Brown et al., 2007; Castañeda et al., 2007; Schefuß et al., 2011; Frierson et al., 2013; Mohtadi et al., 2014).

As the distribution of tropical African vegetation is largely controlled by regional hydrology, past climate changes are commonly associated with reorganizations of biomes (Gasse, 2008; Dupont, 2011). Therefore, understanding the response of vegetation to climate change is crucial for a meaningful assessment of possible forcing mechanisms.

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Today, most evidence of tropical Eastern African vegetation changes during the last 25 000 years derives from pollen records with the majority reconstructed from continental archives (Gasse, 2000; Vincens et al., 2005; Garcin et al., 2006, 2007; Ivory et al., 2012). These archives serve as a useful tool to reconstruct environmental changes as they highlight the vegetation response to the North Atlantic climatic perturbations and allow obtaining information about their impact on local hydrologic changes.

However, it appears that the response to abrupt climate changes varied geographically and no definitive consensus has been reached on defining which climatic pattern was causing East African vegetation changes. While terrestrial records are, in most cases, very local, marine pollen records, given they have sufficient temporal resolution to resolve millennial-scale climate oscillations, provide a regionally integrated signal of continental climate conditions through changes in vegetation cover. The aim of this study is to document, through high-resolution palynological analysis, vegetation changes in the Rufiji catchment (Southern Tanzania, SE Africa) during the last deglaciation to provide more insight into the timing of arid and humid phases and their connection to global climate forcings. We were able to discern specific responses of plant communities to coastal (marine inundations/sea level changes) and atmospheric (rainfall) alterations in the Rufiji Delta and uplands, respectively. Specifically, the lowland (coastal) vegetation is shown to be strongly affected by the intertidal conditions in the Rufiji Delta, such as river runoff and soil salinity, due to marine inundation frequencies, sea level changes, and coastal moisture. The upland vegetation reconstructions presented in this study and their comparison with continental and marine records from the region provide explicit evidence that the deglacial history of vegetation and hydroclimate in the Rufiji uplands was associated with latitudinal shifts of the ITCZ causing dry conditions during H1.

## 2 Regional setting and background

The Rufiji River, formed by the convergence of three principal tributaries, Kilombero, Luwegu and the Great Ruaha located in the high elevations (750 to 1900 m) of the East African Rift (Temple and Sundborg, 1972; Sokile et al., 2003), lies entirely within Tanzania. With a mean annual discharge of  $\sim 30 \times 10^9 \text{ m}^3$  and a catchment basin area of  $\sim 174846 \text{ km}^2$ , the Rufiji forms the second largest delta in eastern Africa after the Zambezi (Temple and Sundborg, 1972). The north-south extent of the Rufiji Delta along the eastern Tanzanian coast is  $\sim 65 \text{ km}$  and comprises largely undisturbed saline swamps, tidal marshes and woodland (Temple and Sundborg, 1972). The delta contains the largest estuarine mangrove forest in East Africa with a total area of 53 000 ha (Masalu, 2003) found along shorelines and tidal channels that are protected from high-energy wave action and periodically flooded by seawater. Typical mangrove species in the delta include *Avicenna marina*, *Ceriops tagal* and *Rhizophora mucronata* (Masalu, 2003).

The climate of Tanzania is tropical and particularly sensitive to the seasonal migration of the ITCZ. As such, the northern part experiences a bimodal rainfall regime with a long rainy season from March to May and a short rainy season from October to December (e.g. Nicholson, 1996, 2001; Indeje et al., 2000; Agricultural Research Service, 1977). In contrast, the southern regions of Tanzania ( $8\text{--}12^\circ \text{ S}$ ), that contain the major part of the Rufiji catchment and the southern uplands, experience tropical summer rainfall with a single well defined rainy season that lasts from November to April (Temple and Sundborg, 1972; Kijazi and Reason, 2005). The dry season occurs during May–October and is dominated by the southeasterly trade winds (Walter and Lieth, 1960–1967; Griffiths, 1972; Nicholson et al., 1988). This seasonality results in strong environmental gradients that have a clear influence on plant distribution.

The vegetation distribution of tropical Africa is controlled mainly by rainfall and its seasonality although temperature is also an important controlling factor at high altitudes (White, 1983; Hély et al., 2006). In Southeast Africa, the vegetation is very diverse, representing different communities ranging from Somali–Masai deciduous bush-

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land/wooded grassland to Zambezi woodland and includes closed forest, dry scrubland, alpine open grassland and semi-evergreen lowland forest (Fig. 1) (White, 1983). The Somali–Masai semi-desert grassland and shrubland are dominated by *Acacia*, *Boscia*, Asteraceae, *Artemisia*, *Euphorbia*, *Indigofera* and *Tamarindus*. The Zambezi humid woodland dominated by *Uapaca*, *Brachystegia*, and *Isoberlina*, is mainly well developed in the low to mid-altitudes. These woodlands are replaced by Afromontane communities above 1800–2000 m altitude and vary from montane forests to montane grasslands depending on rainfall. In the lowlands, flooded grasslands host an important community of Cyperaceae and *Typha*. Many species of fern and halophytes are common along rivers and streams. Halophytes grow on saline soils in intertidal areas, lagoons and depressions as well as salt-lake shores. They are frequently found in arid and semi-arid regions where rainfall is insufficient to remove salt from soils. Halophytic plant communities in SE Africa are mainly dominated by Amaranthaceae, grasses and some species of Cyperaceae (Kindt et al., 2011).

### 3 Material and methods

#### 3.1 Gravity core GeoB12624-1

We studied the high resolution marine sediment core GeoB12624-1 (8°14.05' S, 39°45.16' E), recovered off the Rufiji Delta in the Western Indian Ocean at ~655 m water depth during R/V *Meteor* cruise M75-2 (Savoye et al., 2013). The 600 cm-long core consists of dark olive-gray mud. Generally, the regional wind system is dominated by northeasterly and southeasterly trade winds, which are not favorable for transporting palynomorphs from the continent to the Indian Ocean. Therefore, since the core location is close to the coast and the mouth of the Rufiji River, we expect the pollen and spores to be mostly delivered by fluvial transport.

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## 3.2 Radiocarbon dating

The GeoB12624-1 age model is based on 7 accelerator mass spectrometry (AMS) radiocarbon ages, measured on mixed samples of planktonic foraminifera at the Poznań Radiocarbon Laboratory (Poland) and the National Ocean Sciences AMS Facility in Woods Hole (USA) (Table 1). Conventional radiocarbon ages were converted to calendar ages with CALIB 6.11 software, using  $1\sigma$  age ranges (Stuiver and Reimer, 1993) and the marine 09 calibration (Reimer et al., 2009) with a constant reservoir correction of 140 years ( $\pm 25$  yr) (Southon et al., 2002). Sediment ages between dated core depths were estimated by linear interpolation.

## 3.3 X-ray fluorescence (XRF) scanning

XRF Core Scanner II (AVAATECH Serial No. 2) data were directly collected from the surface of the archive half of core GeoB 12624-1 at the MARUM – University of Bremen (Germany) every 2 cm down core over a  $1.2\text{ cm}^2$  area with 10 mm down core slit size, generator settings of 10 kV, a current of  $350\ \mu\text{A}$ , and a sampling time of 30 s. The split core surface was covered with a  $4\ \mu\text{m}$  SPEXCerti Prep Ultralene1 foil to avoid XRF scanner contamination and desiccation of the sediment. The reported data were acquired with a Canberra X-PIPS Detector (SDD; Model SXP 5C-200-1500) with 200 eV X-ray resolution, the Canberra Digital Spectrum Analyzer DAS 1000, and an Oxford Instruments 50W XTF5011 X-Ray tube with rhodium (Rh) target material. Raw data spectra were processed by the analysis of X-ray spectra by Iterative Least square software (WIN AXIL) package from Canberra Eurisys.

The elements Fe, Al, Ba and Ca were measured, but only concentrations of Al and Ca were used for this study.

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### 3.4 Palynological analysis

In total, 54 sediment samples were prepared for palynological analysis using standard laboratory procedures (Faegri and Iversen, 1989). Sediment ( $4\text{ cm}^3$ ) was decalcified with diluted HCl (10%), and then treated with HF (40%) to remove silicates. One tablet of exotic *Lycopodium* spores ( $18583 \pm 1708$  spores/tablet) was added to the samples during the decalcification process in order to calculate palynomorph concentrations per volume of sediment and accumulation rates. After chemical treatment, samples were sieved over an  $8\text{ }\mu\text{m}$  nylon mesh screen using an ultrasonic bath (maximum  $\sim 60\text{ s}$ ) to disaggregate organic matter. An aliquot ( $40\text{--}60\text{ }\mu\text{L}$ ) was mounted on a permanent glass slide using glycerin. One to four slides per sample were counted under a Zeiss Axioskope light microscope at  $400\times$  and  $1000\times$  magnification. Pollen grains were identified following Bonnefille and Riollet (1980), the African Pollen Database (APD) (Vincens et al., 2007a) and the reference collection of the Department of Palynology and Climate Dynamics at the University of Göttingen (Germany). 32 pollen taxa were identified and listed in Table 1. Other microfossils such as fern spores and fresh water algae (*Botryococcus*, *Cosmarium*, *Pediastrum*, *Scenedesmus* and *Staurastrum*) were also counted.

## 4 Results

### 4.1 Age model and sedimentation rates

Radiocarbon dates from 7 samples ranging between 2 and 596 cm core depth are presented in Table 2. The time period represented by core GeoB12624-1 ranges from  $\sim 19.3$  to  $2.3\text{ kyr BP}$  (Fig. 2). High sedimentation rates are recorded, with maximum values of  $90\text{ cm kyr}^{-1}$  between  $\sim 11.6\text{--}10.2\text{ kyr BP}$ . Minimum values ( $18\text{ cm kyr}^{-1}$ ) are seen later during the Holocene (Fig. 2). The upper 8 samples show very low pollen

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counts and were excluded from the interpretation. Thus, this study focuses on the interval  $\sim 19$ – $10$  kyr BP.

## 4.2 Palynomorph concentrations and Al/Ca ratios

Plotting the concentrations of pollen and other palynomorphs shows significant changes of the terrestrial content in the marine sediment (Fig. 3). Pollen concentrations are relatively high throughout the studied sequence with an average of  $\sim 24 \times 10^2$  grains  $\text{cm}^{-3}$ , varying between  $\sim 5 \times 10^2$  and  $\sim 58 \times 10^2$  grains  $\text{cm}^{-3}$  (Fig. 3). High values are recorded after  $\sim 14.8$  kyr BP, while low values are recorded mainly between  $\sim 16.8$ – $14.8$  kyr BP and in the youngest part after  $\sim 10.6$  kyr BP. Parallel to the increase in pollen concentrations, the Al/Ca ratios increase after  $\sim 14.8$  kyr BP with a prominent peak between  $\sim 11.6$ – $10.6$  kyr BP (Fig. 3). Maxima in Al/Ca ratios correspond to higher sedimentation rates and high fresh water algae concentrations.

## 4.3 Pollen assemblages

The interval between  $\sim 19$ – $14.8$  kyr BP is marked by the presence of afromontane taxa, such as *Podocarpus*, *Celtis*, *Olea*, and *Artemisia*, exhibiting higher values at the beginning of the interval, but decrease around  $\sim 16.6$  kyr BP (Fig. 4). This interval is also characterized by the dominance of Poaceae pollen (up to  $\sim 30\%$ ) at the beginning. Poaceae pollen maxima are followed by a dominance of Cyperaceae ( $\sim 60\%$ ), which, in turn decline around  $\sim 16.6$  kyr BP when Amaranthaceae pollen increase rapidly up to  $\sim 16\%$  along with Asteraceae, *Boscia* and *Acacia*. Around  $14.8$  kyr BP, values of *Rhizophora* increase rapidly to their maximum of  $\sim 30\%$ . This occurs right after the Amaranthaceae pollen maxima and simultaneously with the increase in Al/Ca ratios. In parallel, *Uapaca* pollen increase remarkably reaching up to  $\sim 15\%$  of the assemblage along with other taxa from the forest and humid woodland, such as *Berlinia/Isobertina*, *Sterospermum*, *Ziziphus* and *Borreria*. Abundances of pollen of the aquatic taxon *Typha* and fern spores also increase after  $\sim 14.8$  kyr BP, while pollen percentages of

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Poaceae and taxa from dry woods and shrubs decline steadily. Afromontane taxa are still present albeit with lower values than in the older part of the record (Fig. 4).

Between ~ 12.8–11.6 kyr BP, percentages of Amaranthaceae and Poaceae increase simultaneously with Asteraceae and *Boscia* representatives of dry woods and shrubs.

The decrease in representation of Cyperaceae pollen, *Rhizophora*, *Typha*, fern spores, afromontane and taxa from the forest and humid woodland occurs during this time interval along with a slight decrease in Al/Ca ratios. Around ~ 11.6 kyr BP, the record is marked by a rapid increase in percentages for *Rhizophora*, *Typha* and fern spores followed by a dominance of Cyperaceae pollen which are in turn replaced by percentage maxima of Poaceae and Amaranthaceae by the end of the record (Fig. 4). These changes are concordant with the increase of Al/Ca ratios that peak ~ 11 kyr BP, only to decrease again at the end of the record.

## 5 Reconstruction of the vegetation: lowland (coastal) vs. upland

The terrestrial palynomorph content presented in this study shows that the most abundant pollen are from Poaceae (grasses), Cyperaceae (e.g. sedges), *Rhizophora* (mangrove tree), and Amaranthaceae (herbs including many species growing in salt marshes and on salty soils) followed by pollen of *Podocarpus* (yellow wood). The development of these plant communities interacts differently with inherent environmental variability such as soils, topography, and climate. Therefore, our site had received an integrated contribution from both the lowland and upland vegetation.

### 5.1 Lowland vegetation: expansion of the salt marshes and mangrove

The pollen record indicates a directional alternation of three pollen families, between ~ 19 to 14.8 kyr BP, in the following order: Poaceae, Cyperaceae and Amaranthaceae, followed by an increase in mangrove around ~ 14.8 kyr BP (Fig. 5, steps 1 to 4). The former pollen taxa belong to plant families that host the most common representatives

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of halophytic vegetation in tropical SE Africa (White, 1983; Kindt et al., 2011). Although they inhabit a wide range of environments, their development in this sequence in addition to the following expansion of mangrove suggests a gradational pattern typical of salt marshes occurring in intertidal habitats (between mean sea level and high water spring level) in coastal areas. Therefore, they are considered, due to their proximity to the shoreline, to be affected by marine inundation frequencies and sea level changes and thus to reflect the coastal dynamics in the Rufiji Delta (Blasco et al., 1996; Hogarth et al., 1999). The East African coast located in the Southwestern Indian Ocean lies in a “far-field” location (Woodroffe and Horton, 2005) considered to be situated at significant distances from ice sheet melting. This implies that isostatic effects from large ice sheets are considered to be minimal in this area (Punwong et al., 2012). Therefore, it is trustworthy to compare our high-resolution pollen record with general sea level reconstructions (Waelbroeck et al., 2002; Rohling et al., 2009). This comparison shows that when sea-level was  $\sim 80$ – $120$  m lower relative to today, the exposed shelf allowed the grass (Poaceae) and sedges (Cyperaceae) to expand (Fig. 5, Fig. 6e). During the subsequent sea level rise, only pioneer species from the Amaranthaceae tolerating highly saline environments with a permanent tidal influence and having high colonizing abilities could expand under these stressful conditions. The development of mangrove around  $\sim 14.8$  kyr BP might reflect either the expansion of mangrove vegetation along the Rufiji Delta or the erosion of mangrove peat during sea-level rise (Hooghiemstra et al., 1986; Dupont et al., 1989; Dupont and Agwu, 1991; Lézine et al., 1995; Lézine, 1996; Kim et al., 2005; Versteegh et al., 2004; Scourse et al., 2005). Mangroves are most common in wetter habitats and swamps where brackish water accumulates. They are known to be very sensitive to sea level fluctuations and runoff variability (Hooghiemstra and Agwu, 1986; Dupont and Agwu, 1991; Lézine et al., 1995; Lézine, 1996; Woodroffe, 1999). Their development would suggest a permanent marine influence, but also less saline coastal environments as they do not survive in hypersaline soils due to the rapid sea level increase (Woodroffe, 1999). Consequently, the expansion of mangrove vegetation along the Rufiji Delta in our record, during the





## 6 Paleoclimate and controlling mechanisms in the uplands

During H1, upland vegetation changed from afro-montane forest to dry woods and shrubs (Fig. 6b and c). Forest and humid woodland developed after  $\sim 14.8$  kyr BP and continued to expand through the time interval of the YD (Fig. 6a).

5 If we exclude the dominant pollen taxa (salt marshes and mangrove) from the total sum, dry woods and shrubs still show a substantial expansion during H1 as we can see in Fig. 6g. This, together with the sharply reduced Al/Ca ratios indicate increased aridity in the uplands during H1. The direct comparison of our record and terrestrial studies, shows that the signal of decreased precipitation coincides with lowered lake levels, 10 as demonstrated for Sacred Lake in Kenya (Street-Perrot et al., 1997), Lake Challa, Tanzania (Verschuren et al., 2009), Lake Rukwa, Tanzania (Vincens et al., 2005) and Lake Tanganyika (Burnett et al., 2011). Dry H1 conditions are also suggested by isotope records of the Tanganyika basin (Tierney et al., 2008) and Lake Malawi (Johnson et al., 2002; Brown et al., 2007; Castañeda et al., 2007). The expansion of forest and 15 humid woodland (Fig. 6h) along with higher Al/Ca ratios and sedimentation rates after H1 suggests a significant change in the hydrological regime towards enhanced rainfall and increased terrigenous discharge. We thus infer a shift towards more humid conditions. Significant increase in moisture after  $\sim 14.8$  kyr BP has been reported from vegetation records in continental archives (Vincens, 1993; Vincens et al., 2005, 2007b; 20 Ivory et al., 2012) as well as from lake records (Gasse et al., 2000; Junginger et al., 2014). In sum, upland aridity during H1 and the initiation of humid conditions around  $\sim 14.8$  kyr BP as reconstructed from our records correlate (within age model uncertainties) with changes inferred from continental archives from most of the tropical eastern and south-eastern African lakes and are in agreement with northern tropical African records (e.g. Hooghiemstra, 1988; Zhao et al., 2000; Mulitza et al., 2008; Itambi et al., 25 2009; Niedermeyer et al., 2009; Bouimetarhan et al., 2012, 2013).

For the tropical eastern African region where different processes can affect rainfall, several mechanisms have been proposed. Today, the IOD influences East African

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precipitation at the interannual timescale (Saji and Yamagata, 2003). However, recent hydrological records from the eastern equatorial Indian Ocean (Mohtadi et al., 2014) suggest similarly dry conditions during H1 and YD, ruling out a zonal IOD-like dipole structure between Indonesia and the eastern African lakes as suggested earlier by Tierney et al. (2008). Many studies have proposed ENSO as an important driver of extreme rainfall anomalies over East Africa (e.g. Nicholson, 1996; Plisnier et al., 2000; Indeje et al., 2000). However, evidence for an ENSO-biased mean climate state during H1 is generally ambiguous (Leduc et al., 2009; Prange et al., 2010). Moreover, it has recently been shown that the impact of the tropical Pacific on East African rainfall disappears on multidecadal and perhaps longer timescales (Tierney et al., 2013). Results from climate model studies suggest a north–south anti-phase relation in African precipitation in response to North Atlantic cooling (“H1 experiments”), consistent with latitudinal migrations of the ITCZ (e.g., Lewis et al., 2010; Kageyama et al., 2013). In line with this hypothesis, the dry spell recorded in our data during H1 has (within age model uncertainties) a pronounced wet counterpart in the Zambezi region (Schefuß et al., 2011). We therefore suggest that the ENSO impact over southern Tanzania and hence the major portion of the Rufiji catchment area was not the main mechanism for the H1 drought. Instead, based on recent model results we suggest that the observed H1 dry conditions in the uplands are part of a north-south dipole rainfall anomaly over East Africa and the Indian Ocean, consistent with a southward ITCZ shift in response to Northern Hemisphere cooling (Mohtadi et al., 2014). In this scenario, an anomalous Hadley cell develops over eastern Africa and the Indian Ocean which transports energy across the equator into the Northern Hemisphere (cf. Broccoli et al., 2006; Frierson et al., 2013). The anomalous Hadley cell is associated with a strong north-easterly surface wind anomaly and anomalous subsidence over northern and tropical East Africa resulting in drier conditions in the Rufiji uplands. Further south, anomalous ascent may explain wetter conditions during H1 as recorded for, e.g., the Zambezi catchment (Schefuß et al., 2011). Hadley cell reorganizations driven by Northern Hemisphere climatic fluctuations and involving shifts of the ITCZ are physically plau-

sible and are supported by several studies in the Indian Ocean realm (Johnson et al., 2002; Brown et al., 2007; Castañeda et al., 2007; Schefuß et al., 2011; Mohtadi et al., 2014).

Alternatively, Indian Ocean sea surface temperatures (SSTs) might also play a role in influencing SE African hydrology and vegetation. Cooler SSTs during millennial-scale stadials would have reduced moisture transport from the Indian Ocean implying a reduction of monsoonal precipitation. Therefore, dry conditions during cold stadials have been suggested to have been related to low Indian Ocean SSTs (Tierney et al., 2008; Stager et al., 2011). Lower SSTs in the Indian Ocean have been proposed as a potential mechanism for “catastrophic droughts” in SE Africa during H1 as they would tend to reduce the evaporative moisture content of the ITCZ (Stager et al., 2011). However, Mg/Ca reconstructed SSTs from the nearby core GeoB12615-4 (7°08.30' S, 39°50.45') in the western Indian Ocean show warming during H1 (Romahn et al., 2014), such that we rule out a dominant effect of Indian Ocean SST forcing on H1 aridity in the southern uplands of Tanzania.

The prominent decrease in precipitation that we infer for H1 is however not recorded during YD. The vegetation reconstructions in our record show an alternation between humid and dry taxa during YD (Fig. 6g and h). This pattern reflects no clear climatic trend, while most records from the African tropics suggest drier conditions during YD (Gasse, 2000; Barker et al., 2007; Mulitza et al., 2008; Tierney et al., 2008; Junginger et al., 2014). In addition, marine records from the northern Indian Ocean realm have also shown dry conditions during YD as a response to a southward shift of the ITCZ (Mohtadi et al., 2014). However, two vegetation records from adjacent locations in tropical East Africa highlight different regional responses during the YD. Lake Masoko, a small lake within the Lake Malawi watershed, recorded an expansion of tropical seasonal forest during YD reflecting humid conditions (Garcin et al., 2006, 2007). In contrast, a record from Lake Malawi shows YD to occur in two phases progressing in a dry-to-wet pattern (Ivory et al., 2012) reflecting a more southerly ITCZ associated with an increase in rainfall seasonality (Ivory et al., 2012). Those differences in environ-

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mental responses to YD are consistent with the heterogeneous vegetation observed in our record suggesting that the YD signal from this area is ambiguous which corroborate previous findings in the Indo-Pacific Warm Pool (Denniston et al., 2013; Dubois et al., 2014) where YD is also not well defined. Therefore, our data suggest that H1 had a greater influence on East African hydrologic conditions than the YD, another North Atlantic cold event that likely, due to its short duration compared to H1, did not displace the ITCZ as far south as H1 causing these ambiguous signals.

## 7 Conclusions

The marine pollen record off the Rufiji River provides new information on the deglacial vegetation history and hydrologic variability in SE Africa. The upland vs. lowland vegetation records offered a great opportunity to discern ecosystem responses to different environmental changes related to oceanic (coastal dynamics) and atmospheric (precipitation) alterations. The upland vegetation shows drier conditions during the Northern Hemisphere cold H1, with a return to more humid conditions around ~ 14.8 kyr BP inferred from the expansion of forest and humid woodland. The lowland (coastal) vegetation shows a well-established salt marsh vegetation and mangroves along the Rufiji Delta throughout the whole record with a substantial expansion of mangroves around ~ 14.8 kyr BP as a positive reaction to higher moisture availability in the coastal area.

The observed H1 aridity in the uplands is consistent with a southward displacement of the ITCZ driven by high-latitude climate changes in the Northern Hemisphere. This finding suggests that the extension and composition of plant assemblages in the upland during H1 is primarily controlled by Northern Hemisphere climatic fluctuations corroborating previous studies from SE Africa and the Indian Ocean realm that evidenced the response of the regional hydrologic system to millennial-scale North Atlantic cold spells. By contrast, our data suggest that Indian Ocean SSTs did not correlate with the observed climatic changes. Additionally, the coastal dynamics in the Rufiji Delta related to fluctuations in the sea level and available local moisture have played a major role in

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modulating the local coastal plant community by favoring/reducing the expansion of salt marsh vegetation and mangroves. Our results offer an important complement to previously published paleorecords from the region and highlight the contrasting processes to which upland and lowland vegetation have responded.

5 *Acknowledgements.* This work was funded through the Deutsche Forschungsgemeinschaft as part of the DFG-Research Center/Excellence cluster “The Ocean in the Earth System”. We thank the captain, the crew and participants of R/V *Meteor* cruise M75/2 for recovering the studied material. Jeroen Groeneveld, Kara Bogus and Martin Kölling are thanked for their valuable suggestions. We thank Mahyar Mohtadi and Monika Segl for help with radiocarbon datings.  
10 Laura Dohn and Monika Michaelis are thanked for their help with palynological processing, Oliver Mautner is thanked for his help with the foraminifera picking. This research used data acquired at the XRF Core Scanner Lab at the MARUM – Center for Marine Environmental Sciences, University of Bremen, Germany. Data have been submitted to the Publishing Network for Geoscientific & Environmental Data (PANGAEA, [www.pangaea.de](http://www.pangaea.de)).

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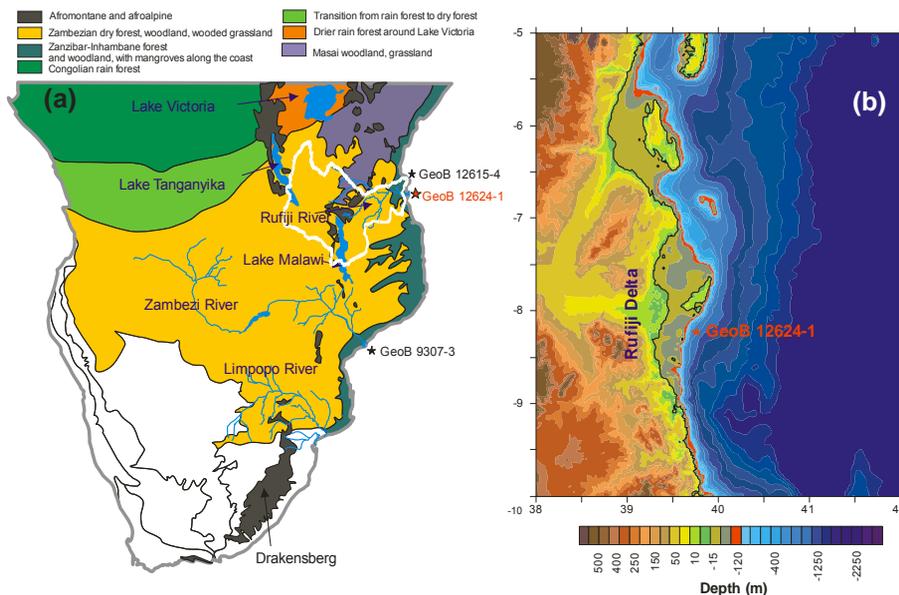
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**Table 2.** Conventional radiocarbon age and mode values of calibrated dates for marine core GeoB 12624-1. For reservoir corrections a constant  $\Delta R$  of  $140 \pm 25$  yr has been applied to all dates (Southon et al., 2002).

Core depth (cm)	Lab Code	$^{14}\text{C}$ age $\pm$ age error (yr BP)	$1\sigma$ calendar age ranges (yr BP)	Calibrated age (cal. yr BP)
2	Poz-30420	$2810 \pm 35$	2308–2419	2340 (+79/–32)
124	Poz-47931	$8680 \pm 50$	9091–9265	9178 (+87/–87)
210	OS-79104	$9540 \pm 65$	10 172–10 332	10 223 (+109/–51)
300	Poz-47932	$10 410 \pm 60$	11 184–11 312	11 212 (+100/–28)
398	Poz-47933	$11 240 \pm 60$	12 564–12 664	12 610 (+54/–46)
512	Poz-47934	$13 200 \pm 70$	14 781–15 116	15 040 (+126/–259)
596	Poz-30421	$16 630 \pm 80$	19 244–19 417	19 380 (+37/–136)

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**Figure 1.** (a) Map of Southern Africa showing the location of marine sediment core GeoB12624-1, simplified phytogeography and modern vegetation after White (1983). Indicated are: the main course of Rufiji River, Zambezi River, and Limpopo River (blue lines), major lakes in the area and the outline of the Rufiji catchment in white. Other cores discussed in the text are also illustrated: GeoB9307-3 (Schefuß et al., 2011), GeoB12615-4 (Romahn et al., 2014). (b) Bathymetric map of the study area showing the location of marine sediment core GeoB12624-1 and the Rufiji Delta.

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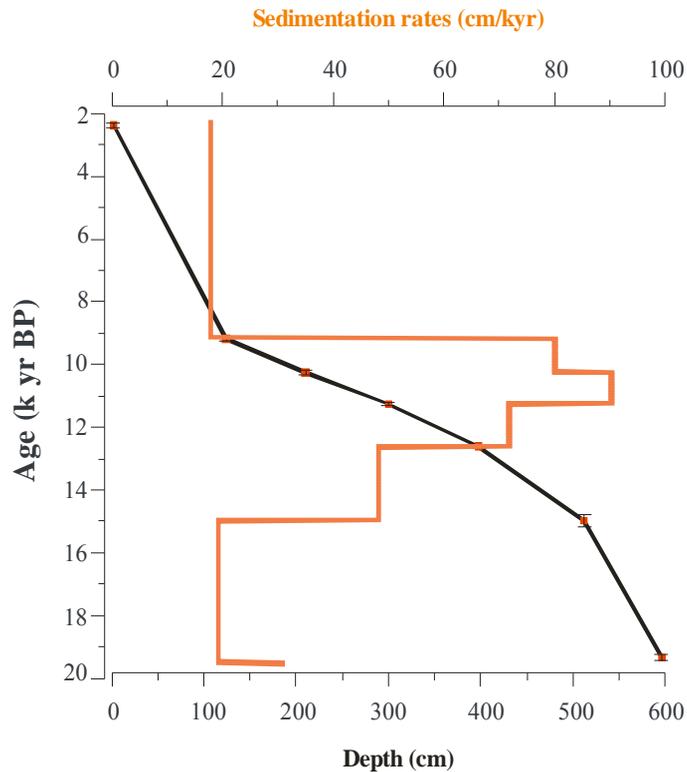
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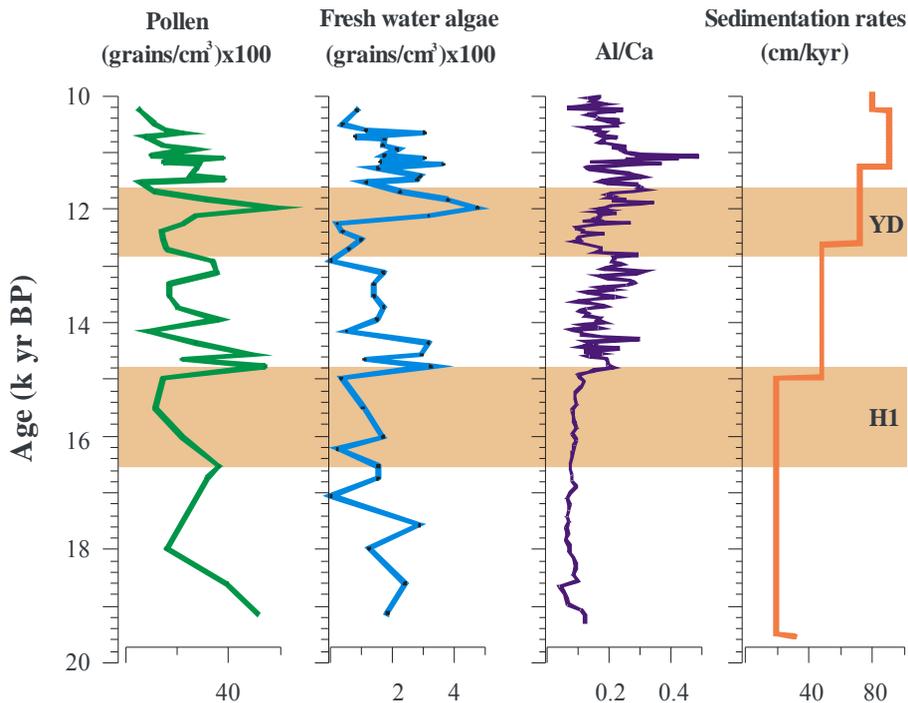
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**Figure 2.** Calibrated age-depth graph for core GeoB 12624-1 (bars indicate the  $1\sigma$  error range (yr BP)) and sedimentation rate estimates ( $\text{cm kyr}^{-1}$ ) (orange line).



**Figure 3.** Downcore variations of pollen concentrations, freshwater algae concentrations, Al/Ca ratios and sedimentation rate estimates during the interval 19–10 kyr BP. Shading indicates time intervals of Heinrich event 1 (H1) and the Younger Dryas (YD).

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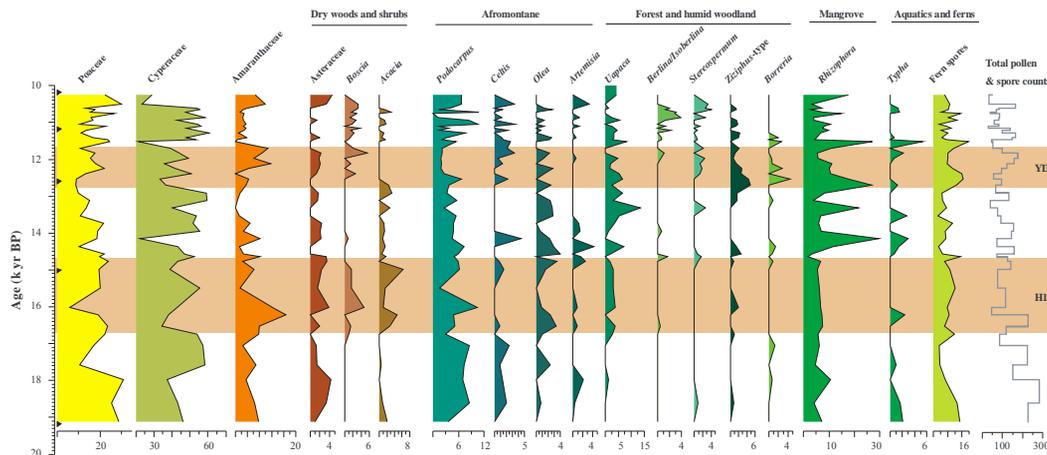
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**Figure 4.** Palynological data from marine sediment core GeoB12624-1 showing relative abundances (%) of selected pollen taxa, percentages of fern spores and the total pollen and spores counts. Note scale changes on x-axes. Shading indicates time intervals of Heinrich event 1 (H1) and the Younger Dryas (YD). Triangles indicate age control points.

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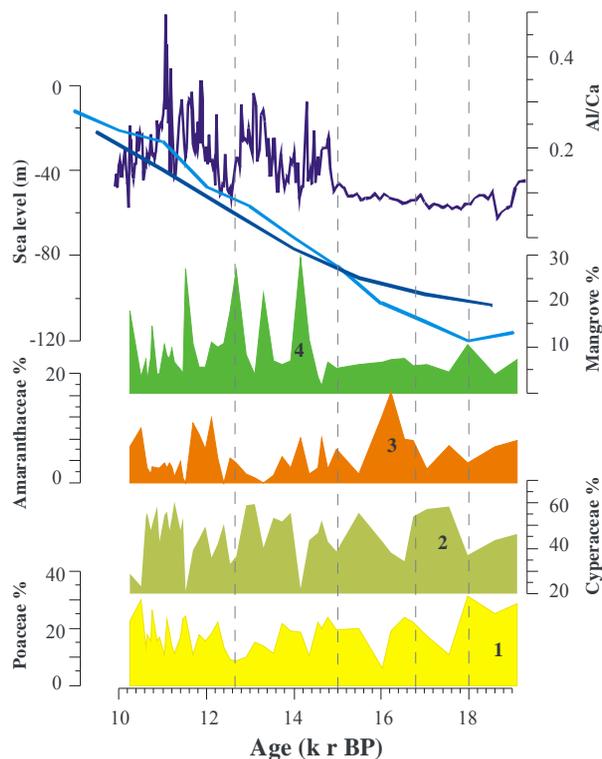
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**Figure 5.** Comparison of the pollen record from marine core GeoB12624-1 with sea level reconstructions: dark blue from Waelbroeck et al. (2002) and light blue from Rohling et al. (2009). Pollen percentages of Poaceae, Cyperaceae, Amaranthaceae indicates the succession of salt marshes (steps 1 to 3) and the mangrove forest (step 4) along the Rufiji Delta.

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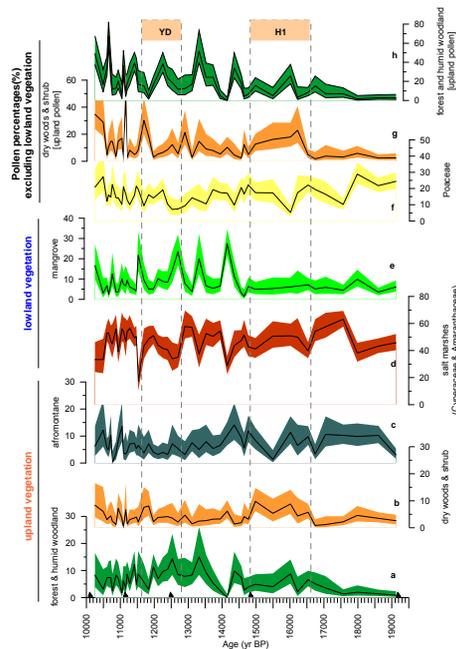
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**Figure 6.** (a) pollen percentages of forest and humid woodland, (b) pollen percentages of dry woods and shrubs, (c) afromantane taxa percentages pollen, (d) percentages of salt marshes (Cyperaceae and Amaranthaceae), (e) Mangrove-pollen percentages. Percentages of groups (a), (b), (c), (d) and (e) are based on the total sum of pollen and spores. (f) Grass-pollen percentages, (g) pollen percentages of dry woods and shrubs and (h) pollen percentages of forest and humid woodland. Percentages of groups (f–h) are based on the sum of pollen and spores excluding salt marshes (Cyperaceae and Amaranthaceae), mangrove and Typha (aquatic pollen). Shadings indicate the 95 % confidence interval. Dashed lines denote time intervals of Heinrich event 1 (H1) and the Younger Dryas (YD). Triangles indicate age control points.

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