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Editor Prof. Dr. Martin Claussen
Climate of the Past

Ihr Zeichen: Ihre Nachricht vom: Unser Zeichen: Datum: 03.03.13

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Dear Prof. Martin Claussen,

Thank you for encouraging us to submit a revised version of our manuscript entitled "*Northern hemisphere control of deglacial vegetation changes in the Rufiji uplands (Tanzania)*". We are grateful to both reviewers for their constructive comments and insightful suggestions. Hereby we respond point by point to all the comments.

Response to Reviewer Sarah Ivory

General Comments:
Although the main findings of this study of great interest, I find that there are a few problems that should be addressed throughout the paper. In particular, I thought the most novel findings in this paper are the implications for coastal processes and ecosystems, rather than the broader regional paleoclimate synthesis. I don't think the paleoclimatic implications should be removed; however, I suggest a few changes to focus more strongly on these important and rare ecological insights.

-With the help of the specific suggestions of the reviewer, we have changed the text to lay more emphasis on the coastal vegetation development. Paragraph 5 is now entirely dedicated to the deglacial ecological implications.

Specific Comments:
Abstract, Line 12, This sentence is a little confusing. I think the link the author is trying to make is a teleconnection between "arid" conditions in East Africa and cool northern hemisphere temperatures. This might be rephrased to show that. Also the term "dry spell" seems very colloquial, might change that to "arid period". This change should be made also for other instances of "dry spell" and "cold spell"in the paper.

-We have rephrased this paragraph in the revised manuscript as such it shows the link between arid East Africa and northern hemisphere cold Heinrich event 1.
We have replaced "dry spell" by "arid period" here and throughout the entire manuscript.
Page 3933

Line 17, the author mentions that we don’t really have a sense of what is influencing rainfall variability, then says that Indian Ocean SSTs are dominant on long time scales. I would back off a little on that, because it seems like the author is setting up a strawman or already making a conclusion on the most important mechanism in a very complex system. Another thing is that here the author compares the mechanisms controlling millennial scale variability in North Africa with those on all time scales in East Africa. Maybe just cite the mechanisms we think may influence rainfall in East Africa on millennial time scales here for consistency

-In this paragraph we are only citing the mechanisms that have been evoked to influence rainfall variability on both short and log-term scales. We did not attempt to make any conclusions or giving advantage to one mechanism on the other because we know that east Africa is definitely a very complex system and mechanisms are always a matter of debate. We agree with the reviewer that it is confusing to put short and long time scales mechanisms in this way and to compare millennial scale variability in North Africa with all time scales in east Africa. We have therefore, rephrased this paragraph in the revised manuscript as such we compare first the millennial timescale mechanisms, Indian Ocean SSTs and the latitudinal shift of the ITCZ and then, the interannual timescale mechanisms IOD and ENSO.

Page 3934 Line 9,

The author says that there is no consensus about which definitive climatic pattern is related to vegetation change, but around Line 15, only one mechanism is mentioned (ie North Atlantic climatic perturbations).

-This sentence is a reminder of what we have mentioned earlier about the several mechanisms that have been proposed to explain climate and vegetation change. We agree with the reviewer that the paragraph is awkwardly written. We have rephrased it in the revised version.

I feel like the author is trying to find a reason to convince people that marine records have some advantages over terrestrial records, which I completely agree with, but I wonder if this is the best way to do it. I don’t see how one extra record, just because its marine, has the power to resolve all of the complexity about East African climate.

-We are definitely not trying to underestimate terrestrial pollen records. We are stating in the previous paragraph the importance of terrestrial pollen records in reconstructing environmental changes in the area. To avoid any misunderstanding, we rephrased the text as such the marine pollen records, provided they have sufficient temporal resolution, can complement the existing records with giving a more regionally integrated signal.

The author talks in the abstract about being able to observe coastal processes and also mangrove changes. This to me seems like the real advantage of this record, that virtually no one has looked at coastal vegetation changes in the region. East African coastal vegetation is a major biodiversity hotspot (Myers, 2000), plus mangroves are very important ecosystem that have not been intensively studied, so I think you could focus your justification for the project more in ecological terms than in climatic terms. This is just a suggestion, but I think focusing on the ecological implications rather than the climatic ones would highlight the real reasons this paper is cool and interesting!

-We agree with the reviewer about the importance of ecological implications. We have rephrased the paragraph as such it emphasizes more the advantage of looking at coastal vegetation changes in this region so far, overlooked. We also have dedicated paragraph 5 entirely to these new ecological implications for the coastal processes in tropical southeastern Africa. However, the climatic implications are also important for the understanding of this highly climatically complex area and the results obtained in this study have complemented the existing body of evidence that shows a strong link between Northern Hemisphere climatic fluctuations and tropical southeast African climate and further the north-south rainfall dipole between subtropical southern Africa and equatorial eastern Africa.

Also it may be of use to do a little comparison with other mangrove systems that have been looked at in paleo-studies. Anne-Marie Lezine has looked at Holocene age mangroves in Oman and there are a few other records from that region. They are more recent in age, but talk about some of the eustatic and local processes involved in expansion and collapse of these systems

-We have extensively compared our records with Punwong work on the Holocene mangrove in the Tanzanian coast (Rufiji Delta and Zanzibar coast). To meet the reviewer's suggestion we included additional comparisons with other records (Lézine's work in Oman) and extended the discussion part in paragraph 5 accordingly.

Page 3938 line 15, How were the pollen abundances calculated (ie. Including or excluding aquatics and Cyperaceae and mangrove taxa)? I just noticed that the author does state the mangrove is excluded later in the article. This might be relevant to mention in the methods.

-Pollen abundances are expressed as percentages of total pollen including herbs, shrubs, trees and aquatics.

-In Fig. 8, in order to get more insights into the upland environmental signal, salt marshes and mangrove that dominate the vegetation record, with pollen percentages accounting for up to 80% of the total assemblage and overprinting the signal of other taxa, have been excluded from the total pollen sum to get a clearer picture.

-We added a paragraph in material and methods in the revised version to make it clearer to the reader.

Page 3937 end of page, what is the interpretation of Al/Ca and why was this selected? Some interpretation of this proxy is needed.

-As mentioned in the text, we have measured the following elements Fe, Al, Ba, and Ca.

Fe and Al are related to siliciclastic sediment components and vary directly with the terrigenous fraction of the sediment. Ca mainly reflects the biogenic carbonate content. Ba is mainly used as indicator of productivity.

-Elemental ratios such as Fe/Ca and Al/Ca are frequently used as proxy of the ratio between terrigenous and marine materials.

Since Fe is a redox-sensitive element (unstable during the early diagenesis), we have chosen the Al and thus the Al/Ca ratio as a robust record of the terrigenous input, which in our study area is associated to river runoff as the wind system is dominated by northeasterly and southeasterly trade winds, which are not favorable for transporting terrigenous material from the continent to the Indian Ocean.

-We added a paragraph for a brief interpretation of the selected proxy as requested by the reviewer.

Page 3936 Line 17 –what is the temporal resolution?

-What we meant here by high resolution is that the core has high sedimentation rates. The average sedimentation rate is 52cm/kyr which results in an average temporal resolution of ~19 years/cm. We have removed it from the revised version as it is quite confusing.

Page 3939 Line10–If most pollen is delivered via fluvial transport, how do variations in transport potentially influence your record? It seems like your high pollen concentrations occur mostly when you have higher sedimentation rates? Is that the case? A sentence about this might be good to include.

-Pollen grains are transported from the continent to the ocean, i.e. eastward via fluvial transport. Indeed, as the reviewer stated, when we have more fluvial activity, we receive more sediments and thus more pollen in our site. We have included a sentence stating the simultaneous increase of pollen concentrations, Al/Ca ratios and sedimentation rates at the end of the paragraph.

Page 3939 Line 15 –Most of this Results text should be in past tense when talking about events that happened in the past.
-We have changed the tense to the past in the revised manuscript.

Page 3941 line 14, Is there a sense of how much 80-120m sea level change would affect the proximity of the core site to the coast?
-Regarding the period considered in the study (HE1 / Termination 1), 80-120m lower sea-level than today (e.g. Siddal et al., 2003, 2010; Lambeck and Chappell, 2001) would get the core location much closer to the shoreline which would make it very sensitive to record the repercussions of sea level change on the stability of the Rufiji Delta deposits. We have included the bathymetric map of the area in figure 1 exactly for the purpose to visualize this. We have added an extra sentence for clarification in the revised version of the manuscript.

Page 3942 Line 24, reference for "Afromontane forest mainly developed in mountains favored by cold and humid conditions." Is this based on knowledge of the environmental tolerance for these plants or correlation to a paleoclimatic record?
-It is based on knowledge of the environmental tolerance of this plant community (White, 1983, Kindt et al., 2011). We have added the references in the revised version.

Page 3947 line 13 The author mentioned earlier in the paper that some of the vegetation changes (lowering of afromontane vegetation) may also be linked to temperature, not just precipitation
-This comment is a little confusing, we are not sure if we understand what the reviewer means in this context. Afromontane vegetation that expands in mountains favored by cold and humid conditions was well developed before H1, indicating a lowering of this vegetation due to cooler conditions in lower altitudes. However, in this paragraph (L13), we are specifically talking about H1, the arid interval where afromontane forest declined steadily.

Table 1. The author lists Artemisia as a common Somali-Masai taxon in the description of the modern vegetation, but in this table you have it listed as Afromontane. Since your record integrates lowland and highland, it may be the case that it is difficult to say whether Artemisia here represents arid lowland vegetation or is part of the montane assemblages.

-We thank the reviewer for spotting this. Artemisia is actually assigned to the Somali-Masai grassland and shrubland. It has not been included in the Afromonatne group in anytime in the manuscript except as a mistake in Table 1. We would like to mention that Artemisia occur in very low relative abundances with an average percentages of 0.5% and thus not influencing considerably the interpretation of lowland and highland vegetation. We have rectified the assignment in Table 1 and we have corrected it in figure 4 (now figure 5).

Figure 6. I found this figure confusing, because you include forest and dry woodland percentages twice (calculated in two different ways). Perhaps, it might be better to simplify this by only including these groups once using the percentage calculation without aquatics and mangrove.

-We agree with the reviewer that Figure 6 (now figure 7) might be confusing for the reader. We therefore, decided to separate it in two different figures in the revised version of the manuscript.
Fig. 7 showing the pollen group abundances calculated as percentages of total pollen including saltmarshes.
Fig. 8 showing relative abundances of the pollen group percentages excluding saltmarshes.

Technical Corrections: Abstract, Line 18 "consisting of well-developed salt..."
-We have rectified it in the revised version.
Page 3933 Line 2 "Climate and rainfall fluctuations" Do you mean temperature and rainfall fluctuations?
-We mean here changes in hydroclimate and rainfall fluctuations. We have rectified it in the revised version.
Page 3934 Line 6, remove "allow obtaining information about"
-We have removed from the text
Page 3941 line 18 "southwestern"
-You mean L8: we have rectified it to southwestern
Page 3942 line 2, "is likely the result of changes in local hydrologic conditions through..."
-We have rectified it in the revised version.
Page 3942 line 10 "Rhizophora pollen maximum" since its singular
-We have rectified it in the revised version.
Page 3942, line 27, "Therefore, the high abundances of the afromontane forest in the marine pollen record corroborates..."
-We have rectified it in the revised version.
Page 3943 line 18 "dry woodlands and shrublands". Same change should be made for the rest of paper, figures and figure captions
-We have rectified it throughout the whole revised version.

We thank the reviewer for her constructive remarks and helpful suggestions.

Response to Reviewer 2

General Comments

The findings of this study are of broader interest since pollen records from East Africa are rare but extremely important to understand the response of the ecosystems to climate variability in this climatically highly complex region. The most advantage of the study in my eyes is the reconstruction of the response of the coastal vegetation to the sea level rise during the deglaciation period.
-We have put more emphasis on the development of the coastal vegetation in the Introduction as also suggested by reviewer 1. We have also dedicated paragraph 5 entirely to the new ecological implications for the coastal processes and ecosystems in tropical southeastern Africa. For more details see our answers to the specific comments below.
Despite this interesting topic, the manuscript hast some difficult parts that need some modifications. In particular, the paleoclimatic implications within the manuscript are yet not convincing. In particular, climatic systems today and for the studied time period are not well explained or incomplete and it feels that the authors discuss the different possibilities not objectively enough. I suggest for the manuscript to adjust the parts about the palaeoclimate implications.

-We have modified the manuscript to clarify the paleoclimatic implications especially the paragraph 6 that is now completely re-written to meet the reviewer suggestions. Please see our answers to the specific comments below.

Please find also specific and technical comments in the attached document.

Specific Comments

1. Page 3932 - Line 14 to 17: The shift of the ITCZ as the explanation of past vegetation changes in the study area is not convincing explained in the discussion. I suggest to adjust this sentence here as suggested further below. Also, the authors write that there was a return of humid conditions after the H1 implying that tropical East Africa was wet before the H1 as well, which was not.

-It is very obvious from reading the current literature dealing with paleoclimatic, modern (historic), and possible future changes that different mechanisms/processes have been proposed to have an effect on precipitation and vegetation changes in East Africa. The reviewer is probably aware of the different (and sometimes confusing) impacts of ITCZ, ENSO, Indian Ocean Dipole (IOD), sea surface temperatures (SST) and wind in the equatorial (tropical) Indian Ocean on East African rainfall. Moreover, the Walker circulation over the Indian Ocean also plays a key role in the interaction between the ocean and the atmosphere.

-We, therefore, incorporated in section 6, a paragraph explaining a physically plausible mechanism of an ITCZ shift and why it explains our observations. All the proposed mechanisms seem to be closely linked with each other and in all cases they are linked with precipitation changes due to the seasonal movement of the ITCZ over Tanzania driven by the SE- and NE-monsoon off East Africa resulting on ITCZ playing a key role in vegetation changes in our study area.

The return to humid conditions here is relative to the droughts of H1. As it implied wetter conditions before H1, we replaced the term “return” to “shift” as suggested by the reviewer.

2. Page 3933 - Line 13:

I would add here “eastern” or “south-eastern” instead of just saying “southern” since this study is about (South-) East Africa and the authors also refer later in the article just to eastern Africa or tropical Africa. I suggest to stick with one word explaining your study region - either tropical East Africa or tropical Southeast Africa

-We have rectified it in the revised version of the manuscript.

3. Page 3933 - Line 0 - 24:

The introduction into the state-of-the-art about paleo-climatic knowledge of the region is very confusing. The authors jump from Northwest Africa to the southern tropics and then to East Africa and also between modern short-term and millennial scale influences. I suggest to structure the introduction better for consistency with explaining how the climate in tropical East Africa is believed to have been during the last 20,000 years, what are the existing views about forcing mechanisms for long-term humidity changes in East and Southeast Africa, and those responsible for millennial and centennial scale climate variability (and maybe inter-annual) in that region and what are the current debates. The study area is a very interesting and a highly debated region as it seems to be located in a climatic transition zone as proxy sites and modelling studies have shown over the past 15 years.

-We agree with the reviewer that this paragraph is a bit confusing. To put short and long time scales mechanisms in this way and to compare millennial scale variability in North Africa with all time scales in east Africa is not the best way to introduce the paleoclimatic knowledge. As also requested by the first reviewer, we have rephrased the paragraph for more consistency. See our response to reviewer 1comments: Page 3933, L17.

4. Page 3933 - Line 18 - 20:
The word ‘reduction’ should be better changed into ‘variability’ since ENSO (El Nino and La Nina) influences different regions of East Africa differently (e.g., Nicholson, 1996; Segele et al., 2009; Wolff et al., 2011).
-We have rectified it in the revised manuscript.

5. Page 3934 - Line 4 - 9:
These 3 sentences are confusing. While the authors explain in the first sentences that existing pollen records from East Africa do correlate with climatic perturbations in the North-Atlantic, they mention in the third sentence, that abrupt changes are not clear to what they react as they vary geographically.
-We meant here that the response of southeast African ecosystems to climate fluctuations vary geographically and not the abrupt changes that vary. We have rectified the text to avoid this confusion.
Which time are the authors in the first sentences are talking about and also which locality are they referring to? And what do they mean with the sentence about abrupt changes? Do they mean millennial scale or centennial scale climate variability in tropical East Africa? Maybe just use instead of ‘abrupt’ here again the term of short-term climatic fluctuations (millennial or centennial scale).
-We are referring here to the last deglaciation and to tropical southeast Africa. The sentence has been re-written for more clarification. We have removed “abrupt” from the text and replaced “climate change” with “climate fluctuations” as also requested by the first reviewer.
The authors claim also that there is no clue about what climatic pattern influences millennial to centennial-scale climate variability in East Africa. There are various publications about the last 30,000 years in East Africa suggesting most likely scenarios (e.g., Gasse, 2000; Barker et al., 2004; Gasse et al., 2008; Foerster et al., 2012; Costa et al., 2014; Junginger et al., 2014). Or do the authors mean only the tropical southeast African region?
-Please see our response to your comment 1: Page 3932 - Line 14 to 17 and our response above to the same remark by reviewer 1: Page 3934 Line 9.
Yes, we mean tropical southeast African region. We have added it in the revised version to avoid any misunderstanding.

6. Page 3934 - Line 16 - 25:
I wonder whether these sentences are necessary to remain here as these occur in the abstract and also in the conclusion. In my opinion, the introduction should introduce the reader into the topic and a short information about how this new study will contribute to the current debates. Results and interpretation may not be placed here?
-We have re-written this part of the introduction as also suggested by reviewer 1.

7. Page 3935 - Line 4 - 5 / Figure 1:
A notification that this chapter is explaining figure 1 is missing here. Also, the catchment of the Rufiji river is explained to lie entirely in Tanzania, and this is what I found in the literature, too, but in figure 1A, the outline of the catchment extends far beyond the Tanzanian boarders and makes no sense at all as the tributaries of the Rufiji river end also in Tanzania. I assume that this is just a drawing or export problem while producing the figure?
-We have actually mentioned Figure1 in this chapter (Page 3936 L2). In order to avoid confusion, we now mention it at the very beginning.

The Rufiji catchment error has probably occurred during export of the figure.

8. Page 3935 - Line 24:
What do the authors mean with “environmental gradients”?
-We mean precipitation gradients which are gradual changes of rainfall through time (or space) that affect plant distribution. We have replaced environmental by precipitation to be more precise.

9. Page 3936 - Line 17:
What temporal resolution is meant with high resolution?
-Same remark as the first reviewer. What we meant here by high resolution is that the core has high sedimentation rates. The average sedimentation rate is 52cm/kyr which results in an average temporal resolution of ~19 years/cm. We have removed it from the revised version of the manuscript as it can be quite confusing.

10. Page 3936 - Line 20 - 24:
That is convincing!

11. Page 3937 - Line 22 - 23:
Would it be possible to add a short explanation why only Al and Ca were chosen for the study and what the Al/Ca ratio is standing for?
-We have added a short explanation as also requested by reviewer 1. Please see our response above to reviewer 1 and the added paragraph in the chapter of Material and Methods (paragraph 3.3. XRF scanning).

12. Page 3939 - Line 1 - 2:
Is there an explanation why the authors think the pollen concentration is too low in the upper parts of the record, which have been excluded from the study?
-We assume that the lower pollen content of the upper samples covering the time from 10 to 2kyr BP is related to the very low sedimentation rates during this period. We can also speculate, based on the observation of different cores retrieved during our cruise, that geomorphologically speaking, the Rufiji delta may have moved its main discharge channel to a more northern location at the beginning of the Holocene . Therefore, the terrigenous input has decreased in our site but more sediments have been deposited during the Holocene in Northern locations (e.g., core GeoB16215 by Romahn et al., in revision for Marine Micropaleontology).

13. Page 3939 - Line 8 - 12:
I see only comparatively high values in the pollen concentrations around 19.2, 14.8 and shortly after as well as around 12 ka BP. Couldn't it be that the sudden increase in pollen concentrations at 14.8 and 12 ka BP may be related to the onset of the African Humid Period after the LGM drought period with higher rainfall causing enhanced erosion of sediment containing pollen from the catchment during the initial runoff?
-Erosion of sediment containing palynological material due to higher rainfall around 14.8 and 12 kyr BP could be a possibility but then the record would have to reflect an arid signal with a completely different pollen signature. However, based on the palynological reconstruction of this study, the establishment of complex and well developed plant communities in the uplands (humid woody plants) as well as the lowlands (mangrove) around 14.8kyr BP clearly indicates enhanced precipitation in the area allowing the environment to become more favorable for such a vegetation development.

The pollen concentration in the rest of the time fluctuates between 40 and 15 grains/cm3 over the entire studied period. Fluctuations seem to increase toward younger times but this might be due to the higher sampling resolution in the upper parts of the record?
-Indeed the younger part of the record is investigated in a higher resolution that is why we see more fluctuations.
I also do not see a very good correlation of high freshwater algae content and Al/Ca maxima
-The only time where freshwater algae concentrations do not follow the Al/Ca ratios and Sedimentation rates is between 19.2 and 16.8 kyr BP, an interval with a very low sampling resolution and which has not been the focus of our interpretation.

14. Page 3940 - 3941:
The chapter about the dynamics of the lowland vegetation is convincing explained. I am wondering whether the authors have an idea why or if there is a slight decline in the mangrove communities shown in the record after 11.5 ka BP?
-There is a decrease of mangrove pollen percentages after 11.6 kyr BP as shown in Figure 4 (now Figure 5) and as mentioned in paragraph 4.3. Following our logic, it is clear that the decline of the mangrove community is related to decreased terrigenous input indicated by low Al/Ca ratios and thus, low freshwater input which would be affected by the sediment routing to the north following the delta evolution at the beginning of the Holocene (please see our response to the first reviewer comment Page 3939 Line10 and to your comment 12). The mangrove development depends on the balance between the amount of sediment loads, perennial freshwater availability and sea-level rise. When sediments transported from the continent decrease along with river runoff, the intrusion of sea water occurs landward and this won't be favorable for complex plant communities to develop on the shelf and mangroves to survive. Other studies from the Rufiji Delta and Zanzibar would attribute the late Holocene decline of mangrove to anthropogenic activities as shown by increase in charcoal content (Punwong et al., 2013a, b, c see reference in the manuscript) but in our manuscript we are not able to speculate on human activities.

15. Page 3943: Line 3:
I do not see a gradual decline in the afromontane taxa between 16.6 - 14.8 ka. I rather see a collapse of the taxa at 16.8 and 15.4 ka BP with a simultaneous increase in dry wood and shrubs and a kind of gradual decline after 14.8 ka.
-We do not agree with the reviewer, here. We rather see a general decline of the afromontane taxa, which still occur regularly after 15.4 ka. We removed a "gradual" so that the description is more neutral.

16. Page 3944: Line 8:
The mentioned lowered lake levels in the cited literature were not also lowered during the H1, those have been low before as well, compared to the time after 14.8 ka. I think this is an important fact that has not been mentioned at all in this manuscript. It always feels like tropical East Africa has been wet before the H1 as well, which was not according to various publications.
-We agree with the reviewer that lake levels in the cited literature were also low before H1. But we are comparing here only the H1 time interval. We did not attempt to interpret the time interval before H1 as the sampling resolution is quite low, Furthermore, throughout the entire manuscript, we have not mentioned wet tropical southeast Africa before H1 (See paragraphs 4.3 and 6).

17. Page 3944: Line 23:

Instead of saying just 'changes' I suggest to clarify that an "increase in humidity" is meant here.
- We do not mean increase in humidity here. The meaning of this sentence is that the aridity observed during H1 and the increase in humidity after 14.8 kyrs BP correlate with climatic patterns inferred from continental records. We have rephrased this paragraph for clarification.

18. Page 3944: Line 24:
All the cited publications present data sets from NW Africa. It would be better to indicate that more clearly than just writing northern Africa.
-We have rectified it in the revised version.

19. Page 3945: Line 16 - 18:
This sentence interrupts the discussion about the north-south anti-phase relation in African precipitation. Since you already started the discussion about ENSO on longer times scales before (see your discussion in line 7-10), you could add this sentence right after this statement and follow then with the discussion about the H1 experiments etc.
-We have rephrased this paragraph as suggested.

20. Page 3945: Line 20- Page 3946 Line 3:
It was difficult to understand the mechanisms that the authors summarise here. I have the feeling some important informations are missing or are too little explained. For example: Line 28-3: I agree that shifts of atmospheric systems are physically possible and have been shown by various studies. My knowledge of atmospheric processes is restricted and I am happy to be corrected, but the shift of the ITCZ more to the south of East Africa does not explain to me, why it is dry in the Rufiji area during this time. The region of subsidence and ascendence and thus the location of the ITCZ over East Africa is dependent on the local insolation maximum which in turn is dependent on the month of the year. The ITCZ migrates over the year between its northern and southern limits (~10°N-10°S) and crosses in my opinion always the equator and thus producing the regular rainy seasons (e.g., Nicholson, 1996). A shift of the ITCZ further to the south might be of major interest for sites that usually are not reached by it? I am happy to be corrected when I am totally wrong, but dry periods in the study region should thus be caused by reduced rainfall amounts during the rainy seasons. Maybe the authors just forgot the word 'mean' annual position of the ITCZ, as it is used in the climate models such as by Mohtadi et al. (2014)? The mechanism behind, such as moisture export, SST changes, weakening of the monsoon strengths etc. as Mohtadi et al. (2014) also concluded should be noted here as well, as this is a whole coupled system and not just referring to a shift of the ITCZ further south.
- We agree with the reviewer that the paragraph was awkwardly written. In the new version, we rephrased the text to explain clearly the involvement of the ITCZ annual mean position shifts. In addition, we added a new figure 2 showing the modern rainfall seasonality, where the modern seasonality of East African rainfall indicates that a southward shift of the ITCZ-related rainbelt (by a few degrees) would lead to significantly drier conditions associated with stronger surface northeasterlies in the Rufiji catchment, only during the austral summer season (DJF). Furthermore, our hypothesis is in line with the north-south anti-phase relationship of rainfall between subtropical southern Africa and equatorial eastern Africa as suggested by model studies which can only be physically consistent with the ITCZ latitudinal shift. Please see the new version of paragraph 6 in the revised manuscript.
Yes, we mean the "annual mean position" of the ITCZ. We have rectified it in the revised version.

21. Page 3946 Line 16 - 3947 Line 4 - 17 - YD Discussion: I am wondering whether the higher

sampling resolution during the YD time interval might be responsible that larger fluctuations are observed compared to the H1 interval?
-As we mentioned in the manuscript, YD has been already defined as an ambiguous time interval in the Indo-Pacific Warm pool (Denniston et al., 2013; Dubois et al., 2014) probably due to its short duration compared to H1. Therefore, we do not think that the sampling resolution would affect strongly the YD signal.

22. In general, I am wondering why there is a detailed discussion about Hadley Cell displacements for drought periods in the study region with focus on the NH influences, but there is no explanation, why East Africa became wet although the NH was still cold and dry. A few sentences about this important transition might provide the base to strengthen the discussion.
-We have completely rephrased this paragraph with further explanations to make it clear.

23. Conclusion chapter
If the authors agree with the comments above, the conclusion should be changed accordingly. In particular between line 19-26, where they state that only due to a shift of the ITCZ southward, millennial scale droughts in the Rufiji catchment were caused. This alone is not plausible to me.
- We are positive that the changes and revisions made in section 6 supported by further explanations and extended discussion in the revised version of the manuscript have made the impact of the ITCZ on rainfall and Rufiji upland vegetation clearer.

24. Figure 1
The catchment of the Rufiji River seems to be wrong in this figure. It is explained as a basin that lies entirely in Tanzania. But the shape of the catchment extends far beyond the Tanzanian boundaries. It makes also no sense that it extends as far west and south beyond Lake Tanganyika and Malawi as it is shown in this figure. I assume that this is just a drawing or export problem while producing the figure?
-Yes, we will make sure that it appears properly in the final figure.
Additionally, it would be nice for the reader to see at least the southernmost position of the present ITCZ (and maybe also for H1), Condo Air Boundary and wind directions for the rainy season in the study region.
-We have added the ITCZ southernmost position in Figure 1 but we do not understand why we should add the Congo Air Boundary as this is definitely out of the scoop of this paper. Wind directions are indeed important to illustrate the atmospheric circulation over southern Africa but putting them in Fig. 1 will only result in overly crowded figure. Instead, we have added now a new figure 2 showing the modern atmospheric circulation with wind directions and rainfall distribution.

25. Figure 5
What are the dashed lines are for? They do not mark the YD and H1, as they did in the other pictures. A sentence in the figure caption would be good.
-Dashed lines denote the four steps of the directional alternation of the 4 families (Poaceae, Cyperaceae, Amaranthaceae and mangrove). A sentence is added in the figure caption.

26. Figure 6
This figure is a bit confusing because only forest and humid woodland and dry woods and shrubs are chosen to be excluded from the dominant pollen taxa. While the authors discuss the pollen communities in figure 6a-6e in chapter 5, the discussion in chapter 6 is about figure 6f-6h. I do not see a big advantage in displaying just the selection of the green and orange curves.

-In order to get a better picture on how the upland vegetation changed during the last deglaciation, salt marshes taxa have been excluded in figure 6f, 6g, 6h (now 8a, 8b, 8c) because they overprint the pollen assemblage. For this reason, it is very important to display the figure with green (forest and humid woodland) and orange (dry woods and shrubs) curves and look carefully at both of them if we want to understand precipitation changes in the catchment area of the Rufiji river (unaffected by the local changes in the river delta and the downslope transport to the core site).
Now the figure has been split into two figures to avoid confusion. See our response to the first reviewer.

Technical Comments
27. Page 3939 - Line 7:
The notification about figure 3 is not necessary here, because it occurs already in the previous sentence.
-We have deleted the notification.

28. Additional figure suggestion: A figure showing a compilation of cited proxy data sites for the studied time period would be helpful to better follow the discussion about the paleoclimatic implications.
- We agree with the reviewer that such a figure will help follow the discussion but the aim of our paper is not to review climate and vegetation dynamics in different site in southeast Africa. It is more about examining the responses of lowland vegetation and highland vegetation during the last deglaciation and the influence of coastal and atmospheric processes on their composition and distribution. We would not attempt to do a synthesis of the tropical southeast African vegetation dynamics during the last deglaciation as this will be beyond the scope of this paper and would increase the number of figures to 9 which is not really necessary.

We thank the reviewer for his/her constructive remarks.

We are positive that the changes and revisions made in the revised version of our manuscript have improved it dramatically and hope that by addressing these issues you will find our paper now to be engaging and suitable for publication in Climate of the Past. For your guidance, we have submitted the new revised version as a supplement. All changes are marked in yellow.

Sincerely,
Ilham Bouimetarhan

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

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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 southeastern African region. We present high-resolution pollen records from a marine sediment core recovered offshore the Rufiji River. Our data document 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, arid conditions reflected by 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 to be synchronous with cold northern hemisphere conditions. This arid period is followed by an interval in which forest and humid woodlands expanded, indicating a hydrologic shift towards more humid conditions. Droughts during H1 and the shift to humid conditions around 14.8 kyr BP in the uplands are consistent with 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 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 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.

1. Introduction

The African tropics, a region of major importance for the global hydrologic cycle, have experienced large-scale changes in hydroclimate and rainfall over the last deglaciation and the Holocene (e.g. Street-Perrot and Perrot, 1990; Lézine et al., 1995; Gasse , 2000; Gasse et al.,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., 2009, 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) 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 tropical southeastern African climate fluctuations remain a matter of debate. Whereas Indian Ocean sea surface temperatures (SST) have been suggested to influence East African rainfall variability on longer timescales (Tierney et al., 2008, 2013; Tierney and deMenocal, 2013; Stager et al., 2011), other studies suggest that East African rainfall variations were 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; Chiang and Friedman, 2012; Mohtadi et al., 2014).

On interannual timescales, the Indian Ocean Dipole (IOD) has been shown to influence modern East African rainfall variability (Saji et al., 1999; Saji and Yamagata, 2003). The El Niño-Southern Oscillation (ENSO) has also been invoked to explain extreme rainfall variability over modern East Africa (e.g. Nicholson, 1996; Plisnier et al., 2000; Indeje et al., 2000; Kijazi & Reason, 2005). As the distribution of tropical African vegetation is largely controlled by regional hydrology, past climate changes are commonly associated with reorganizations of biomes (Gasse et al., 2008; Dupont, 2011). Therefore, understanding the response of vegetation to climate change is crucial for a meaningful assessment of possible forcing mechanisms. 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 have provided explicit evidences of environmental and vegetation changes. However, it appears that the response of southeast African tropical ecosystems to climatic fluctuations during the last deglaciation varied geographically and no definitive consensus has been reached on defining which climatic pattern was causing tropical southeast African vegetation changes. While terrestrial records register, in most cases, a local signal of continental climate conditions through changes in vegetation cover, marine pollen records might, given they have sufficient temporal resolution to resolve millennial-scale climate oscillations, provide a signal integrating a much larger region. Complementary to terrestrial paleorecords from the region, we present new palynological evidence from a marine core offshore the Rufiji River that provides detailed vegetation reconstructions in the Rufiji catchment (Southern Tanzania, SE Africa) during the last deglaciation and more insights into the timing of arid and humid phases in a regional context and their connection to global climate. Furthermore, except for few studies that investigated Holocene mangrove ecosystems in the Tanzanian coast (Punwong et al., 2013 a, b , c), this is the first study from the marine realm that emphasizes the ecological implications of intertidal tropical ecosystems in this area, which are known to be very sensitive to environmental changes at the sea-continent interface. We present detailed information on the development of intertidal plant communities, through a high resolution reconstruction of sensitive salt marsh and mangrove communities during the last deglaciation. We link them to the intertidal conditions in the Rufiji Delta, such as river runoff and soil salinity, which are influenced by marine inundation frequencies, sea level changes, and coastal moisture. The present study allows to discern, specific responses of plant communities to oceanic (marine inundations/sea level changes) alterations in the Rufiji Delta and to atmospheric (rainfall) changes in the uplands underlying the local and regional mechanisms which control the observed patterns of tropical southeast African vegetation.

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 (Fig. 1). With a mean annual discharge of ~ 30 x 10^9 m^3 and a catchment basin area of ~ 174,846 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 ~65 km and comprises largely undisturbed saline swamps, tidal marshes and woodlands (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, 2000; Indeje et al., 2000). In contrast, the southern regions of Tanzania (8-12°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 (Fig. 2) (Walter and Lieth, 1960-1967; Griffiths, 1972; Nicholson et al., 1988).

This seasonality results in strong precipitation 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 bushland/wooded grassland to Zambezian woodlands 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 shrublands are dominated by *Acacia*, *Boscia*, Asteraceae, *Artemisia*, *Euphorbia*, *Indigofera* and *Tamarindus*. The Zambezian 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 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 Rufuji River, we expect the pollen and spores to be mostly delivered by fluvial transport.

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). Conventional radiocarbon ages were converted to calendar ages with CALIB 6.11 software, using 1σ age ranges (Stuiver and Reimer, 1993) and the marine 09 calibration (Reimer et al., 2009) with a constant reservoir correction of 140 years (±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 collected from the surface of the archive half of core GeoB12624-1 at the MARUM - University of Bremen (Germany) every 2 cm down core over a 1.2 cm^2 area with 10 mm down core slit size, generator settings of 10 kV, a current of 350 µA, and a sampling time of 30 seconds. The split core surface was covered with a 4 µm 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 200eV 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. Ca mainly reflects the marine biogenic carbonate content whereas Al is related to siliciclastic sedimentary components and varies directly with the terrigenous fraction of the sediment (e.g. Govin et al., 2014). The Al/Ca ratio therefore serves as an indicator of the ratio between terrigenous and marine material. High Al/Ca ratios correspond to increased terrigenous input.

3.4. Palynological analysis

In total, 54 sediment samples were prepared for palynological analysis using standard laboratory procedures (Faegri and Iversen, 1989). Sediment (4 cm^3) was decalcified with diluted HCl (10%), and then treated with HF (40%) to remove silicates. One tablet of exotic *Lycopodium* spores (18,583±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 µm nylon mesh screen using an ultrasonic bath (maximum 60 seconds) to disaggregate organic matter. An aliquot (40-60 µl) was mounted on a permanent glass slide using glycerin. One to four slides per sample were counted under a Zeiss Axioskope light microscope at 400x and 1000x 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. Pollen relative abundances are expressed as percentages of total pollen including herbs, shrubs, trees and aquatics throughout the whole manuscript. However, in order to solely identify the signal of taxa from the upland vegetation, pollen of Cyperaceae, Amaranthaceae mangrove and *Typha* have been excluded from the total pollen sum in Fig. 8.

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

~19.3 to 2.3 kyr BP (Fig. 3). High sedimentation rates are recorded, with maximum values of 90 cm/kyr between ~11.6-10.2 kyr BP. Minimum values (18 cm/kyr) are seen later during the Holocene (Fig. 3). The upper 8 samples show very low pollen counts and were excluded from the interpretation. Thus, this study focuses on the interval ~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. 4). Pollen concentrations are relatively high throughout the studied sequence with an average of ~24 x 10^2 grains cm^{-3}, varying between ~5 x 10^2 and ~58 x 10^2 grains cm^{-3}. High values are recorded after ~14.8 kyr BP, while low values are recorded mainly between ~16.8-14.8 kyr BP and in the youngest part after ~10.6 kyr BP. Parallel to the increase in pollen concentrations, the Al/Ca ratios increase after ~14.8 kyr BP with a prominent peak between ~11.6-10.6 kyr BP (Fig. 4). Maxima in Al/Ca ratios and pollen concentrations are coeval with higher sedimentation rates and high fresh water algae concentrations.

4.3. Pollen assemblages

The interval between ~19-14.8 kyr BP was marked by the presence of afromontane taxa, such as *Podocarpus*, *Celtis*, *Olea*, and *Artemisia*, exhibiting higher values at the beginning of the interval, but decreased around ~16.6 kyr BP (Fig. 5). This interval was also characterized by the dominance of Poaceae pollen (up to ~30%) at the beginning. Poaceae pollen maxima were followed by a dominance of Cyperaceae (~60%), which, in turn declined around 16.6 kyr BP when Amaranthaceae pollen increased rapidly up to ~16% along with Asteraceae, *Boscia* and *Acacia*. Around 14.8 kyr BP, values of *Rhizophora* increased rapidly to their maximum of ~30%. This occurred right after the Amaranthaceae pollen maxima and simultaneously with the increase in Al/Ca ratios. In parallel, *Uapaca* pollen increased remarkably reaching up to ~15% of the assemblage along with other taxa from the forest and humid woodlands, such as *Berlinia*/*Isoberlina*, *Sterospermum*, *Ziziphus* and *Borreria*. Abundances of pollen of the aquatic taxon *Typha* and fern spores also increased after ~14.8 kyr BP, while pollen percentages of Poaceae and taxa from dry woods and schrubs declined steadily. Afromontane taxa were still present albeit with lower values than in the older part of the record (Fig. 5).

Between ~12.8-11.6 kyr BP, percentages of Amaranthaceae and Poaceae increased simultaneously with Astercaeae 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 woodlands occurred during this time interval along with a slight decrease in Al/Ca ratios. Around 11.6 kyr BP, the record was marked by a rapid increase in percentages for *Rhizophora*, *Typha* and fern spores followed by a dominance of Cyperaceae pollen which were in turn replaced by percentage maxima of Poaceae and Amaranthaceae by the end of the record (Fig. 5). These changes were concordant with the increase of Al/Ca ratios that peak ~11 kyr BP, only to decrease again at the end of the record.

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 received an integrated contribution from both the lowland and upland vegetation.

5. Expansion of the salt marshes and mangrove: deglacial ecological implications for lowland vegetation and coastal processes

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. 6, steps 1 to 4). The former pollen taxa belong to plant families that host the most common representatives 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 around 14.8 kyr BP 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., 2013a). Therefore, it is justified 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 ~80-120 m lower relative to today, the exposed shelf allowed the grass (Poaceae) and sedges (Cyperaceae) to expand (Fig. 6, Fig 7e). The coastline was also substantially closer to the core site when sea level was low (Fig. 1). 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 at ~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 and Agwu 1986; Dupont and Agwu, 1991; Lézine at al., 1995; Lézine, 1996; Dupont, 1999; Kim et al., 2005; 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 period of global sea-level rise (Waelbroeck et al., 2002; Rohling et al., 2009) (Fig. 6), is likely the result of changes in local hydrologic conditions through an increased river runoff promoted by higher moisture availability in the coast after ~14.8 kyr BP. By this means, higher freshwater input and increased sedimentation rates may dominate over local sea-level rise, suppressing the intrusion of sea water and allowing complex plant communities to develop on the delta and mangroves to expand landward in response to increased rainfall over the Rufiji Delta. Our results corroborate previous findings in the Rufiji Delta and the coast of Zanzibar where dynamics of Holocene mangrove systems were related to past sea level changes and local moisture availability (Punwong et al., 2013a, b, and c). Furthermore, the development of Suwayh mangrove near the littoral of the Indian Ocean in Oman clearly records the influence of enhanced tropical summer precipitation (Lézine et al., 2010). Increasing both freshwater supply and sediment load would also fit the development of aquatic taxa such as *Typha*, which is represented parallel to the *Rhizophora* pollen maximum reflecting wetter coastal conditions and continuous input of freshwater. Therefore, the erosion of mangrove peat during sea-level rise is less likely because this would imply reduced freshwater flow to the coast and dry climatic conditions.

Taken together, the succession of salt marshes and mangrove reflects the response of coastal plant communities to changes in intertidal environments (soil development and salinity gradient) and coastal dynamics in the Rufiji Delta influenced by sea-level changes as suggested by González and Dupont (2009). These results add to the scarce knowledge on the East African coastal vegetation, a major biodiversity hotspot in the area (Myers, 2000), and provide an independent evidence on the close relationship between sea level changes and coastal community dynamics. In this context, our new palynological record has great ecological implications as it deals with sensitive ecosystems that are poorly documented on longer timescales.

6. Paleoclimate and controlling mechanisms in the uplands during H1

The total pollen assemblage is dominated by afromontane forest taxa in the earliest part of the record until ~16.6 kyr BP (Fig. 7c). Afromontane forest mainly developed in mountains favoured by cold and humid conditions (White, 1983, Kindt et al., 2011). Their presence in the pollen record would thus be expected if the afromontane forest had spread to lower altitudes than currently found and its pollen did not need to be transported over long distances. Therefore, the high pollen abundances of the afromontane forest in the marine pollen record corroborates previous pollen records that suggest the development of afromontane taxa at a lower elevation (Vincens et al., 2007b, Ivory et al., 2012) due to freezing conditions at higher altitudes, cooler conditions at lower altitudes, and lower $p\mathrm{CO}_2$ (Street-Perott, et al., 1997; Wu et al., 2007). During the decline of the afromontane taxa, the pollen representatives of dry wood and shrub vegetation increase significantly between ~16.6-14.8 kyr BP (Fig. 7b). This transition suggests a change towards drier conditions compared to the previous period and coincides with the timing of the North Atlantic H1 (Hemming, 2004; Stanford et al., 2011 (H1 *sensu stricto*)). Around 14.8 kyr BP, the vegetation cover became denser. The decline of elements from dry woods and shrubs and the drastic decrease in afromontane forest was followed by an increase in pollen from forest and humid woodlands (Fig. 7a). A similar vegetation trend has been recorded in several pollen records from Lakes Malawi, Tanganyika, Rukwa and Masoko, indicating the retreat of the afromontane vegetation to higher altitudes due to progressive warming after H1 and the expansion of moist forest due to enhanced rainfall (Vincens, 1993; Vincens et al., 2005; 2007b; Ivory et al., 2012).

Between ~12.8-11.6 kyr BP, the presence of elements from both the forest and humid woodland vegetation and from dry woods and shrubs (Figs. 7a, b) suggests that vegetation was more heterogeneous. In contrast to other records from most of the African tropics (Gasse, 2000; Barker et al., 2007; Mulitza et al., 2008; Tierney et al., 2008; Junginger et al., 2014) where indicators of aridity have been observed during this time interval coincident with the YD (YD, 12.8 – 11.5 kyr BP) (Alley, 2000; Muscheler et al., 2008), our records do not show a clear climatic trend.

Around 11.6 kyr BP, sharply rising Al/Ca ratios and high sedimentation rates along with the presence of pollen from forest and humid woodlands would indicate increased precipitation. However, the decline of nearly all the pollen taxa percentages, Al/Ca ratios and sedimentation rates at the end of the record, around 10.6 kyr BP, reflects either a return to drier conditions or the end of active terrestrial input.

In sum, our data show that during H1 upland vegetation changed from afromontane forest to dry woods and shrubs (Fig. 7b and c). Forest and humid woodlands developed after ~14.8 kyr BP and continued to expand through the YD (Fig. 7a).

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. 8b. This, together with the sharply reduced Al/Ca ratios indicate increased aridity in the uplands during H1. The direct comparison of our record with terrestrial studies, shows that the signal of decreased precipitation coincides with lowered lake levels of Sacred 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 humid woodlands (Fig. 8c) 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 ~ 14.8 kyr BP has been reported from vegetation records in continental archives (Vincens, 1993; Vincens et al., 2005; 2007b; Ivory et al., 2012) as well as from lake records (Gasse, 2000; Junginger et al., 2014). Taken together, upland aridity during H1 and the increased humidity around 14.8 kyr BP as reconstructed from our records correlate (within age model uncertainties) with changes inferred from continental archives that show a similar pattern in most of the tropical eastern and south-eastern African lakes and are in agreement with northwest tropical African records (e.g. Hooghiemstra, 1988; Zhao et al., 2000; Mulitza et al., 2008; Itambi et al., 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 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 that was 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 El Niño- or La Niña-biased mean climate state during H1 is 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). We therefore suggest that an ENSO-like impact over southern Tanzania and hence the major portion of the Rufiji catchment area was not the main mechanism for the H1 drought. Results from climate model studies suggest a north-south anti-phase relation in African annual precipitation in response to North Atlantic cooling, consistent with latitudinal migrations of the ITCZ's annual mean position (e.g., Lewis et al., 2010; Kageyama et al., 2013). In line with this hypothesis, the arid phase recorded in our data during H1 has (within age model uncertainties) a pronounced wet counterpart in the Zambezi region (Schefuß et al., 2011; Otto-Bliesner et al., 2014). Therefore, we suggest the observed H1 dry conditions in the uplands to be part of a north-south dipole rainfall anomaly over East Africa and the Indian Ocean corroborating the see-saw hypothesis supported by further climate model studies (Claussen et al., 2003) and which is consistent with a southward shift of the ITCZ annual mean position in response to Northern Hemisphere cooling (Mohtadi et al., 2014). The ITCZ shift is part of a reorganization of the annual mean Hadley circulation driven by Northern Hemisphere climatic fluctuations (Broccoli et al., 2006; Kang et al., 2009; Chiang and Friedman, 2012; Frierson et al., 2013) and is 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). We suggest that the reorganization of the Hadley circulation and the associated southward ITCZ shift resulted in anomalous descent of air over the Rufiji region in the annual mean (and hence less rainfall), and anomalous ascent (and hence more rainfall) to the south. The modern seasonality of East African rainfall (Fig. 2) indicates that a southward shift of the ITCZ-related rainbelt (by a few degrees) would lead to significantly drier conditions associated with stronger surface northeasterlies in the Rufiji region, only during the austral summer season (DJF).

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 relate 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 extreme 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.

7. Environmental changes during the YD

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 (Figs. 8b and 8c). 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 environmental responses to the YD are consistent with the heterogeneous vegetation observed in our record suggesting that the YD signal from this area is ambiguous which corroborates previous findings in the Indo-Pacific Warm Pool (Denniston et al., 2013; Dubois et al., 2014) where the YD is not well defined either. 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 shorter duration and weaker Northern Hemisphere cooling compared to H1, did not displace the annual mean ITCZ as far south as H1, thus causing these ambiguous signals. In addition, it has recently been suggested that gradually increasing greenhouse-gas forcing through the last glacial termination resulted in increasingly wetter conditions in tropical Africa (Otto-Bliesner et al., 2014), leading to generally higher precipitation in the Rufiji region during the later stages of the deglaciation compared to H1.

8. 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 versus lowland vegetation records allow 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 shift to more humid conditions around 14.8 kyr BP inferred from the expansion of forest and humid woodlands. 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 after ~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 annual mean 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 periods. 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 modulating the local coastal plant community by favoring/reducing the expansion of salt marsh vegetation and mangroves. Our new palynological record has a great ecological significance, as much as it deals with intertidal ecosystems that have not been intensively studied. It offers an important complement to previously published paleorecords from the region and highlights the contrasting processes to which upland and lowland vegetation have responded.

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Table 1: List of identified pollen taxa in marine core GeoB12624-1. Taxa are grouped according to their phytogeographical assignment.

Pollen type	Family
Poaceae	
Cyperaceae	
Amaranthaceae (includes Chenopodiaceae)	
Dry woodlands and shrubs	
Acacia	Fabaceae-Mimosoideae
Mimosa-type	Fabaceae-Mimosoideae
Boscia	Capparaceae
Asteroideae species	Asteraceae
Combretaceae	Combretaceae
Indigofera-type	Fabaceae-Faboideae
Caryophyllaceae	Caryophyllaceae
Plantago	Plantaginaceae
Tamarindus-type	Fabaceae
Artemisia	Asteraceae
Afromontane	
Podocarpus	Podocarpaceae
Olea	Oleaceae
Celtis	Cannabaceae
Forest and humid woodlands	
Uapaca	Phyllanthaceae
Psydrax type *subcordatum*	Rubiaceae

Berlinia/Isoberlina	Fabaceae
Stereospermum-type	Bignoniaceae
Ziziphus-type	Rhamnaceae
Vernonia	Asteraceae
Alchornea	Euphorbiaceae
Cassia-type	Fabaceae
Cleome	Capparaceae
Borreria (=Spermacoce)	Rubiaceae
Pterocarpus-type	Fabaceae-Faboideae
Piliostigma	Fabacaeae
Rhus-type	Anacardiaceae
Mangrove trees	
Rhizophora	Rhizophoraceae
Bog vegetation and swamp plants	
Typha	Typhaceae
Other elements	
Euphorbia	Euphorbiaceae

Table 2: Conventional radiocarbon age and mode values of calibrated dates for marine core GeoB12624-1. For reservoir corrections a constant ΔR of 140 ± 25 yrs has been applied to all dates (Southon et al., 2002).

Core depth (cm)	Lab Code	^{14}C age ± age error (yr BP)	1 σ calendar age ranges (yr BP)	Calibrated age (cal. yr BP)
2	Poz-30420	2810 ± 35	2308 - 2419	2340 (+79/-32)
124	Poz-47931	8680 ± 50	9091 - 9265	9178 (+87/-87)
210	OS-79104	9540 ± 65	10172 - 10332	10223 (+109/-51)
300	Poz-47932	10410 ± 60	11184 - 11312	11212 (+100/-28)
398	Poz-47933	11240 ± 60	12564 - 12664	12610 (+54/-46)
512	Poz-47934	13200 ± 70	14781 - 15116	15040 (+126/-259)
596	Poz-30421	16630 ± 80	19244 - 19417	19380 (+37/-136)

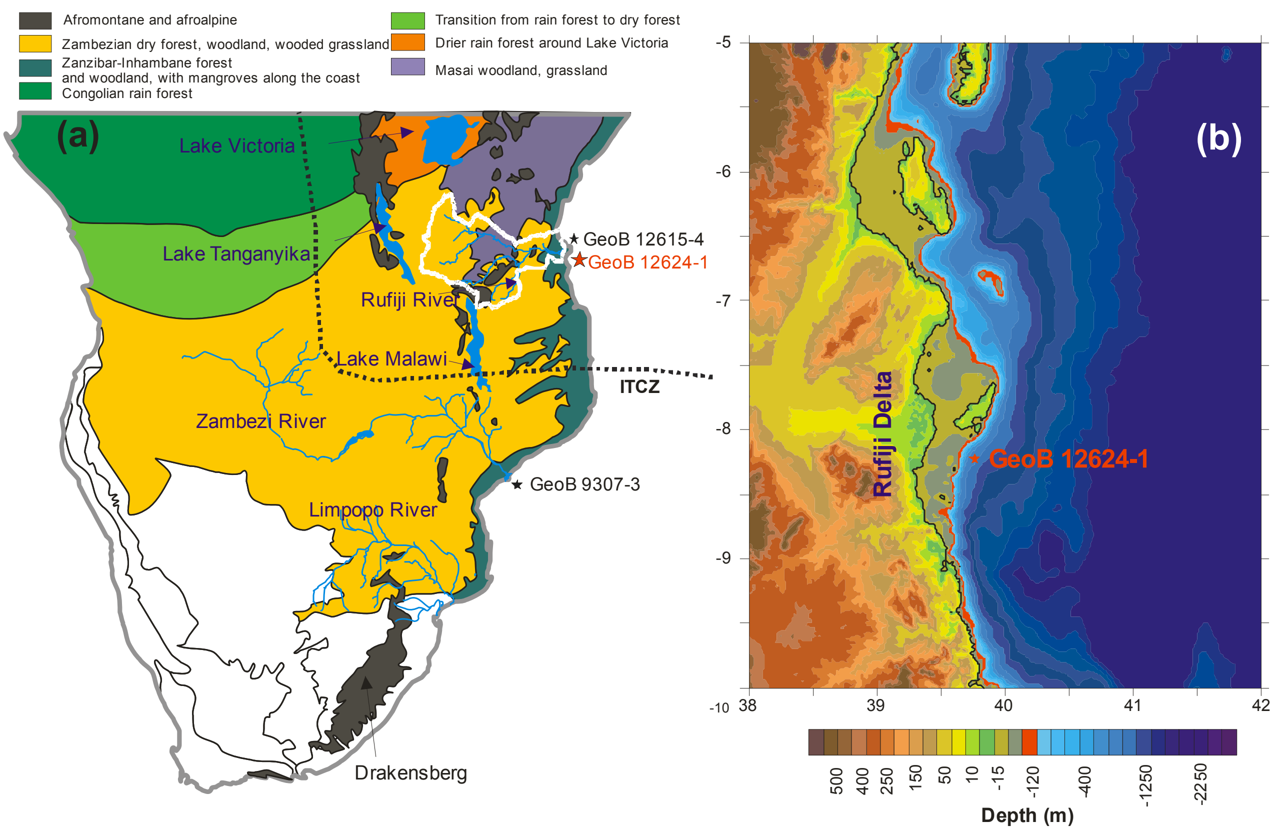

Figure 1. (a): Map of Southern Africa showing the location of marine sediment core GeoB12624-1, simplified phytogeography and modern vegetation after White (1983) and approximate position of the ITCZ during austral summer (December, January, February). Indicated are: the main course of Rufiji River, 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.

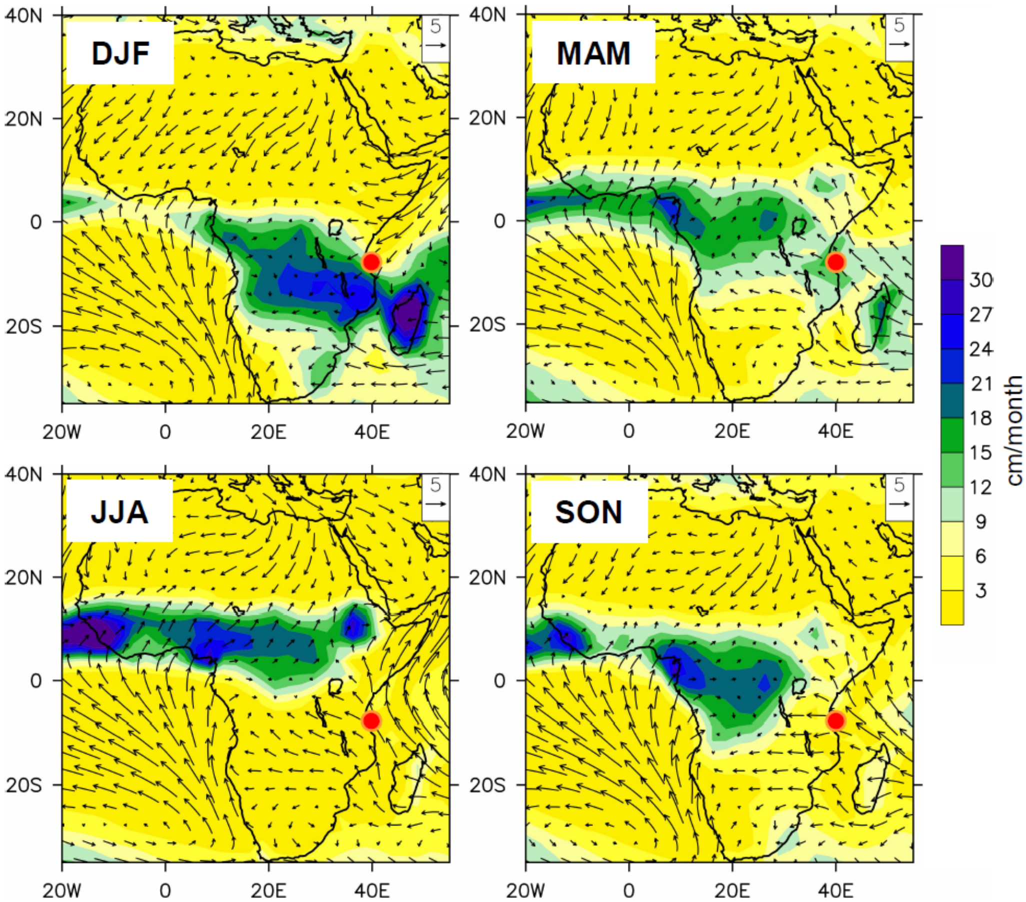

Figure 2. Modern atmospheric circulations over Africa: surface winds (m/s) (Kalnay et al., 1996) and precipitation (cm/mouth) (Adler et al., 2003) are illustrated during austral summer (DJF: December, January, february), autumn (MAM: March, April, May), winter (JJA: June, July, August) and spring (SON: Septrember, October, November). The red dot denotes the location of marine sediment core GeoB12624-1.

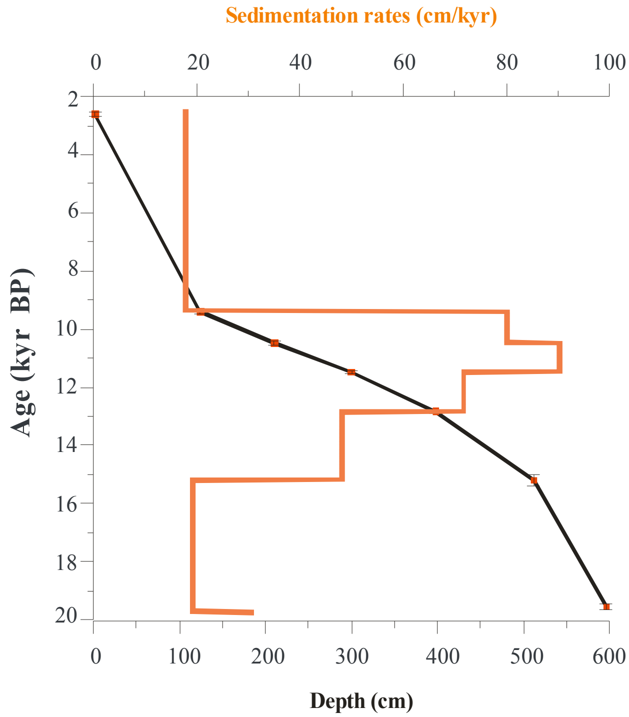

Figure 3. Calibrated age-depth relation for core GeoB12624-1 (bars indicate the 1σ error range (yr BP)) and sedimentation rates (cm/kyr) (orange line).

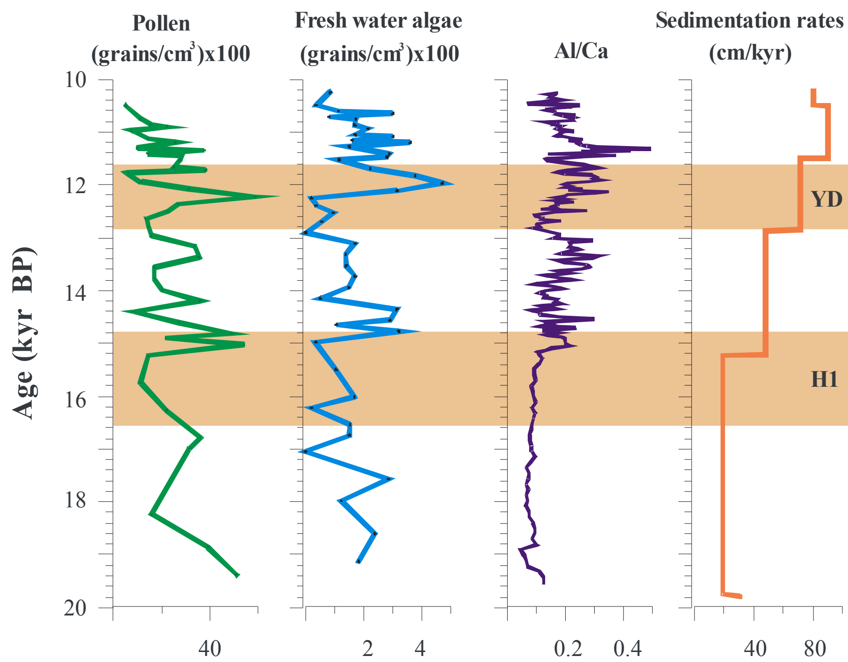

Figure 4. Downcore variations of pollen concentrations, freshwater algae concentrations, Al/Ca ratios and sedimentation rate estimates during the interval 19-10 kyr BP. Shading indicates time intervals of Heinrich event 1 (H1) and the Younger Dryas (YD).

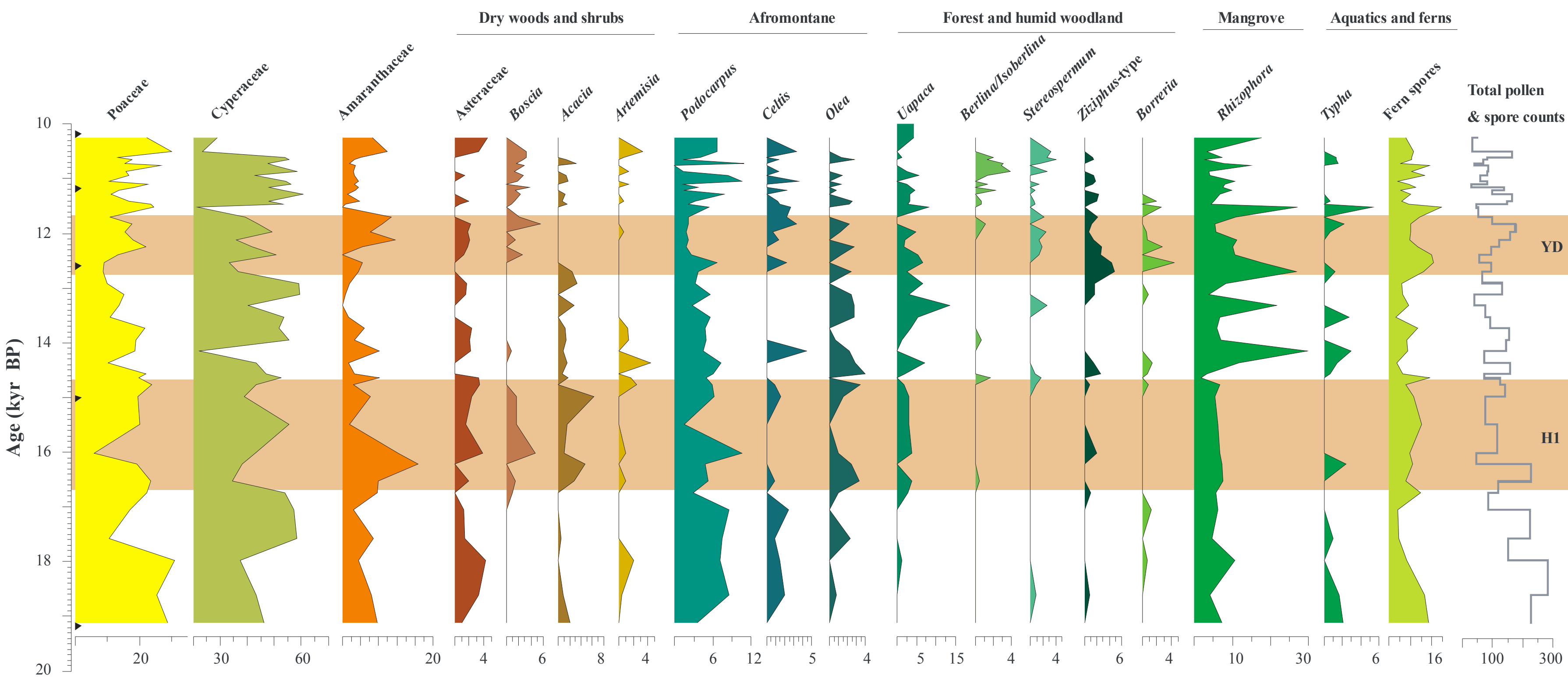

Figure 5. Palynological data from marine sediment core GeoB12624-1 showing relative abundances (%) of selected pollen taxa, percentages of fern spores and the total pollen and spores counts. Note scale changes on *x*-axes. Shading indicates time intervals of Heinrich event 1 (H1) and the Younger Dryas (YD). Triangles indicate age control points.

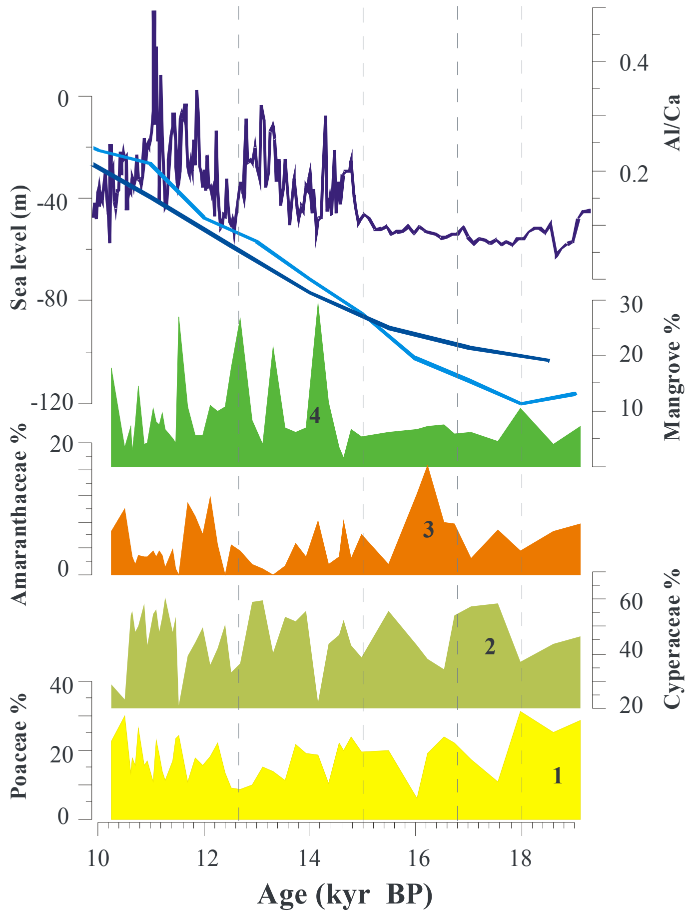

Figure 6. Comparison of the pollen record from marine core GeoB12624-1 with sea-level reconstructions: dark blue from Waelbroeck et al. (2002) and light blue from Rohling et al. (2009). Pollen percentages of Poaceae, Cyperaceae, Amaranthaceae indicates the succession of salt marshes (steps 1 to 3) and the mangrove forest (step 4) along the Rufiji Delta. Dashed lines denote the four steps of the directional alternation of those families.

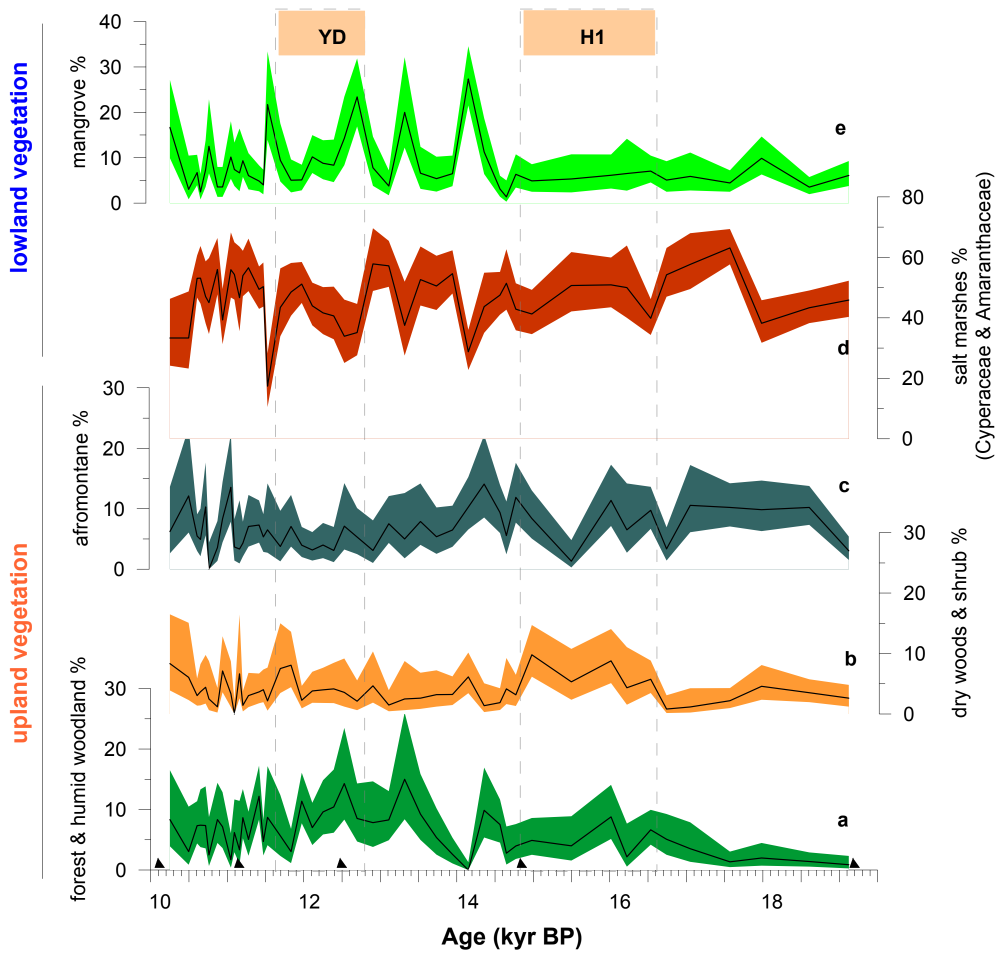

Figure 7. Palynological data showing relative abundances of major pollen groups based on the total sum of pollen and spores. (a): pollen percentages of forest and humid woodlands, (b): pollen percentages of dry woods and shrubs, (c): afromontane taxa percentages pollen, (d): percentages of salt marshes (Cyperceae and Amaranthaceae), (e): Mangrove-pollen percentages. 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.

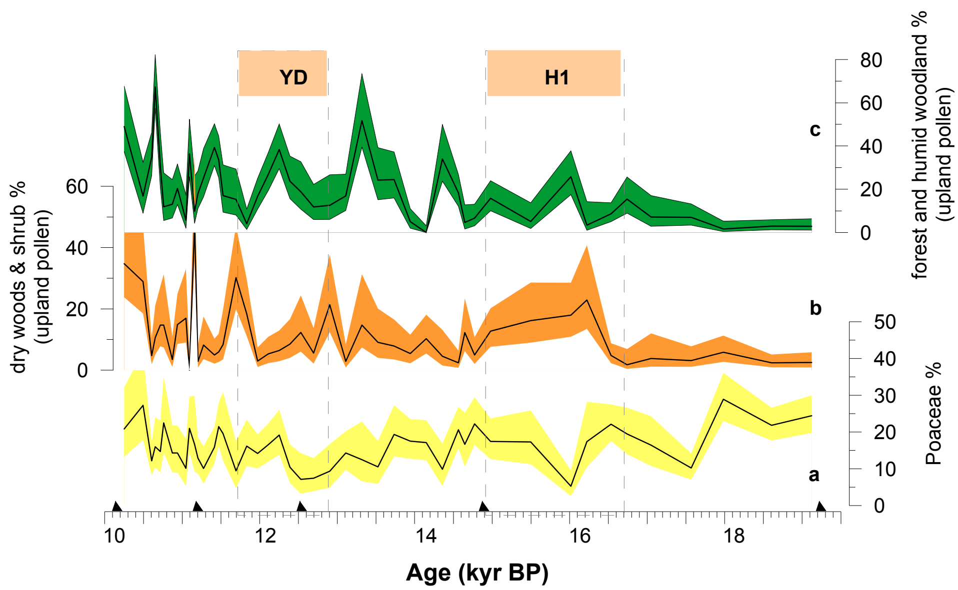

Figure 8. Palynological data showing relative abundances of (a): Grass-pollen percentages, (b): pollen percentages of dry woods and shrubs and (c): pollen percentages of forest and humid woodlands based on the sum of pollen and spores excluding Cyperaceae, Amaranthaceae, mangrove and Typha (aquatic pollen). 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.