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Climate of the Past Discussions

Interactive comment on "Masked millennial-scale climate variations in South West Africa during the last glaciation" *by* I. Hessler et al.

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First of all we want to thank Reviewer 2 for taking the time to conduct the review and comment on our manuscript.

Before we will address the general comments of Reviewer 2 we want to emphasise why our vegetation record is so important:
- only a few African vegetation records exist that cover a time-span as long as 50-10 ka BP and are sufficiently resolved to potentially record millennial-scale climate variations (Hessler et al., 2010)
- we show that there is no direct land-sea correlation during times of abrupt climate variability

- we show that the combination of our vegetation record with an Earth System Model of Intermediate Complexity results in a additional possibility to interpret the vegetation record by providing insight into the behavior of the physical parameters such as precipitation, temperature and evaporation
- most importantly we show that the HS response in southern Africa neither equals nor mirrors the northern African response to abrupt climate changes.

General comments:

A) "The muting of D-O and Heinrich signals in hydrological proxy records of equatorial Africa is not new but has been previously documented and discussed. For example, in the catchment of the Gulf of Guinea, glacial riverine runoff did not fluctuate in concert with Greenland interstadials and stadials (Weldeab et al., 2007, Science 316, 1303-1307). These authors argued that the impact of short-term northern hemisphere climate variability was dampened by glacial oceanic boundary conditions of the eastern South Atlantic." We think that this comment of Reviewer 2 is not exactly correct in this context.
Weldeab et al. (2007) show that neither Ba/Ca nor $\delta^{18}O_{sw}$ fluctuates in concert with Greenland Interstadials and stadials. They suggest that the response of the West African monsoon system to glacial Greenland Interstadials (GIS) (also known as Dansgaard-Oeschger warming events) is damped by the glacial boundary conditions. They further suggest that "the ITCZ response to glacial GIS warming was dampened by the large thermal inertia of the ocean." However, Weldeab et al. (2007) discuss neither about Heinrich Events or Heinrich Stadials nor atmospheric processes that cancel each other.
In contrast to our study there are actually several studies that claim that there is an effect of the glacial Northern Hemisphere variability in West Africa (e.g. McIntyre and Molfino, 1996; Maley and Brenac, 1998; Adegbie et al., 2003; Peck et al., 2004;

Hessler et al., 2010) or tropical Africa in general (e.g. Bonnefille and Riolett, 1988; Bonnefille and Chalié, 2000; Johnson et al., 2002; Stager et al., 2002; Brown et al., 2007; Vincens et al., 2007; Tierney et al., 2008;).

Consequently, we think it is indeed a new result that Heinrich Stadials are likely to be muted in the terrestrial African tropics by the counteracting response of precipitation and evaporation.

However, to highlight the originality and significance of our study we re-wrote the Conclusion chapter in the revised version of the manuscript.

The high-resolution vegetation record of ODP Site 1078 gives new insights into the climate and vegetation development of South West Africa between 50 and 10 ka BP. Throughout the last glacial, grassland and savannah vegetation dominates the pollen source area. This open vegetation type is possibly the result of reduced moisture availability and low atmospheric CO_2 concentrations. During the deglaciation when the monsoon strengthens and CO_2 concentrations are rising, tree taxa dominated vegetation types (tropical forest, Miombo woodland) become more widespread.

The impact of abrupt climate change on the study area differs between the oceanic and terrestrial realm. While Mg/Ca based SSTs from ODP 1078 respond to HSs (Hessler et al., 2011) the vegetation reconstructed from the same core remains unaffected. Hence, one can assume that the climate response in South West Africa is too weak to noticeably affect the vegetation composition. However, combining our vegetation record with model results (from the UVic ESCM and CCSM3) we infer that an impact of HSs on the South West African vegetation has potentially been mitigated by counteracting mechanisms. The partial cancellation of enhanced precipitation and evaporation rates may have led to a negligible change in the moisture supply. Consequently, the resulting climatic response was possibly too weak to induce changes in the vegetation composition.

The dissimilarity between our vegetation record and the SST record of ODP 1078 (Hessler et al., 2011) regarding their response to abrupt climate variations further indicates that the vegetation development in South West Africa was decoupled from

variations in the SST and no direct land-sea correlation existed in the study area during HSs.

We further assume that the low glacial atmospheric CO_2 concentration may have limited the vegetation response to HSs by favouring the development of grassland over the expansion of forest.

We particularly want to highlight that the results presented here show that the HS response in Southern Hemisphere Africa neither equals nor mirrors the northern African response to abrupt climate variations such as HSs.

B) We are aware that changes in the Agulhas Current system may have contributed to variations in the surface ocean hydrology off Angola (Hessler et al., 2011). However, the influence of the Agulhas Leakage on our study area is rather indirect via the Benguela Upwelling System (BUS) and the Angola Benguela Front (ABF). Changes in ABF and BUS could have influenced the Angolan vegetation at a local scale, namely the coastal desert vegetation, which apparently has not been the case.

In addition, the variability of the Agulhas Current over longer time periods or estimates of the Agulhas Current transport and its contribution to the AMOC are highly uncertain (Beal et al., 2011) and contradictory.

Several publications (Peeters et al., 2004; Gersonde et al., 2003, 2005) suggests that less Agulhas waters entered the South Atlantic during glacial periods due to a northward shift of the Subtropical Front compared to its present day position. In contrast, there are also studies indicating that the Southern Atlantic Frontal System was stable during the last glacial (Matsumoto et al., 2001).

Due to the general uncertainties related to the Agulhas Current, the existing contradicting results and the only minor contribution of Agulhas waters to the BUS (e.g Nelson and Hutchings, 1983), we think it would be far fetched to discuss the potential influence of the Agulhas Current on the vegetation composition in an area located between 4°-18°S. We further want to point out that we focus on large-scale processes that are able to influence the vegetation at a regional scale.

Although, for example, Stuut et al. (2002) and Stuut and Lamy (2004) argue for a northward displacement of the Southern Hemisphere Westerlies, the resulting position would still be far to south to even marginally influence our research area. They further suggest that the proposed northward shift of the Polar Front is coupled to an increase in the trade wind intensity. In our manuscript we discuss the point of a possible increase in the trade wind intensity in relation with the deglacial increase in Podocarpus pollen. However, there are several publications showing contradicting results in terms of shifts in the Polar Front (Matsumoto et al., 2001, Anderson et al., 2002). These studies also just consider glacial conditions but do not deal with the very different background conditions during Heinrich Stadials. If we assume the effect of the bipolar see-saw being equivalent to warming climates then the Westerlies are supposed to shift southward (Beal et al., 2011).
In summary, both the Agulhas Current and the Westerlies seem to have not the potential to affect the vegetation composition in Angola and the southern Congo Basin. There is also no indication for other Southern Hemisphere climatic factors that influence the vegetation composition in our study area and/or over-run the effects of North Atlantic Heinrich Stadials. Hence, including a paragraph in the discussion dealing with potential Southern Hemisphere climate and oceanographic mechanisms that may influence the vegetation in our research area would far too far-fetched.

C) There is a large body of literature recently reviewed by Hooghiemstra et al. (2006) and Dupont (2011) that show that the pollen composition in marine records reflect the prevailing vegetation on the adjacent continent well, also over longer time periods. In terms of transport, there is no indication that the pollen source area changed significantly over the studied time-span (Dupont and Wyputta, 2003).
In chapter 2.2 (Recent South West African vegetation composition) of the revised manuscript we will mention the points (1) that the pollen composition of the marine sediments reflects the vegetation on the adjacent continent (Hooghiemstra et al., 2006; Dupont, 2011), (2) that the dispersal of pollen and spores by ocean currents is minor

in this area (Dupont and Wyputta, 2003), and (3) that the pollen source area appears to be stable over the investigated time frame.
(1) *Several studies (Hooghiemstra et al., 2006; Dupont, 2011; and references therein) have shown that the distribution of pollen and spores in marine sediments reflects the vegetation composition on the adjacent continent well. Thus, analysing the past pollen composition of marine sediments provides a strong tool to reconstruct the vegetation and climate history of the continent.*

(2) and (3) *According to the trajectory model of Dupont and Wyputta (2003) the pollen source area for ODP Site 1078 are Angola and the southern Congo Basin. The prevailing wind pattern during austral spring may also cause the transport of terrestrial particles from the northern Namib Desert into the Angola Basin. Dupont and Wyputta (2003) also indicate that the pollen source area has been stable over the investigated time-frame of 50-10 ka BP and that a potential dispersal of pollen and spores by ocean currents is minor.*

D) We will address the statistics issue in the revised version of the manuscript (Chapter 3.2 Analytical Methods, Figure 2B).
The statistical precision of the pollen percentages is shown in Figure 2B. We calculated the upper and lower error for a 95% confidence interval by considering the proportion of each vegetation group within the pollen sum (Maher, 1972).

E) The Age Model is not particularly precise and the record not long enough to establish precessional variability. The record is not suitable for testing precessional forcing.

F) Changes in the oxygen content of intermediate water masses likely do not influence the preservation of pollen grains at ODP Site 1078 since this site is located at 426 m

water depth, which is too shallow to be affected by intermediate water masses. During glacial times the water depth was even shallower.
Indeed, it might be true that different sedimentation rates may influence the pollen record. According to our age model, however, sedimentation rates did not vary much during the glacial period and do not strongly affect the trends in pollen concentration. Because our age model is not very precise we refrain from publishing pollen accumulation rates. Differential preservation is not an issue for the following reasons. On the one hand the high sedimentation rates make oxygen degradation of pollen during sedimentation relatively unlikely, while on the other hand the pollen's optical appearance in the microscopic slide gave no indication of degradation or differential preservation. We will mention these points in chapter 3.2 (Analytical methods) in the revised version of the manuscript.
Potential taphonomic biases such as differential preservation of pollen and spores are considered minor for our study site since (1) the high sedimentation rates mostly prevent the palynomorphs from a degradation by oxygen and (2) the optical appearance of the pollen and spores gave no indication of degradation or differential preservation.

More specific comments:

The abstract in the revised version of the manuscript will be re-written to exclude introductory information and adjust the abstract to better reflect the content of the paper.
To address the connection between tropical African vegetation development and high-latitude climate change we present a high-resolution pollen record from ODP Site 1078 (off Angola) covering the period 50-10 ka BP. Although several tropical African vegetation and climate reconstructions indicate an impact of Heinrich Stadials (HSs) in Southern Hemisphere Africa, our vegetation record shows no response. Model simulations conducted with an Earth System Model of Intermediate Complexity including a dynamical vegetation component provide one possible explanation. Because both

precipitation and evaporation increased during HSs, and their effects nearly cancelled each other, there was a negligible change in moisture supply. Consequently, the resulting climatic response to HSs might have been too weak to noticeably affect the vegetation composition in the study area. Our results also show that the response to HSs in southern tropical Africa neither equals nor mirrors the response to abrupt climate change in northern Africa.

Chapter 3.1 (Site description and age model): In the revised version of the manuscript we will include the information which taxa of planktonic foraminifera have been dated, namely *Globigerinoides ruber*, *Globigerinoides sacculifer*, *Orbulina universa*, *Neogloboquadrina dutertrei*, and *Globorotalia menardii*. Mollusc species could only be identified for sample KIA13017 (*Nacariua wolfi*) since usually only test fragments have been available.
The chronostratigraphy used in this study was established by linear interpolation of accelerator mass spectrometry (AMS) radiocarbon dates which have been determined on planktonic foraminiferal tests and molluscs fragments (Kim et al., 2003; Rühlemann et al., 2004; Dupont et al., 2008). More specifically, planktonic foraminifera samples used for AMS dating were a mixture of Globigerinoides ruber, Globogerinoides sacculifer, Orbulina universa, Neogloboquadrina duterei, and Globorotalia menardii. The dated mollusc for age control point 10281 cal yr BP (Lab. no. KIA13017) (Kim et al., 2003; Rühlemann et al., 2004) has been precisely identified as Nacariua wolfi. Further age control points based on molluscs (Kim et al., 2003; Rühlemann et al., 2004) have been measured on unidentified fractured specimens.

Chapter 5.4.1. The level of the atmospheric CO_2 concentration plays an important role in the competitive balance of C_4 and C_3 plants and hence in their distribution. With this chapter we tried to provide another attempt to explain the vegetation development in the catchment area of ODP 1078. However, in the revised version of the manuscript we will re-write this chapter highlighting the connection to the vegetation development in Angola and the southern Congo Basin.

The level of the atmospheric CO_2 concentration plays an important role in the competitive balance of C_4 and C_3 plants and hence in their distribution.

The low glacial (190-200 ppmv; e.g. Petit et al., 1999) atmospheric CO_2 concentration could be considered as a candidate to limit the long-term development of the tropical African vegetation substantially. Both model simulations and glasshouse experiments indicate that the concentration of atmospheric CO_2 influences the global distribution of vegetation due to the different carbon dioxide fixation strategies of plants (C_3, C_4/CAM)(Ehleringer and Monson, 1993; Polley et al., 1995; 1996; Ward et al., 1999). At low CO_2 concentrations, plants using the C_3 photosynthetic pathway (most woody species) are less competitive than C4/CAM plants (mainly grasses and succulents), and the growth of arboreal taxa is reduced (Johnson et al., 1993; Street-Perrott et al., 1997). It is suggested that vegetation types representing the C_4/CAM pathway (grassland, shrubland, savannah) were more important and widespread during the glacial compared to today (Prentice et al., 2000). Model simulations conducted by Harrison and Prentice (2003) further indicate that regions which are nowadays actually or potentially covered by tropical forest were possibly occupied by more drought tolerant biomes under LGM conditions. An even larger reduction of forested areas in the tropics has been simulated if physiological effects of low atmospheric CO_2 concentrations (200 ppm) are taken into consideration (Harrison and Prentice, 2003). During the deglaciation the atmospheric CO_2 concentration rises, shifting the competitive balance in the direction of C_3 vegetation by increasing plant productivity and water use efficiency (Pearcy and Ehleringer, 1984; Chapin et al., 1990; Johnson et al., 1993; Cowling and Sykes, 1999; Ward et al., 1999).

Applying these hypotheses to our vegetation record of Angola and the southern Congo Basin we find that under full glacial conditions and low atmospheric CO_2 concentrations the South West African vegetation is dominated by grassland (Figure 2A). In contrast, with increasing CO_2 concentrations during the deglaciation vegetation

groups representing the C_3 pathway (tropical seasonal forest, Miombo woodland) become increasingly important (Figure 2A).

We therefore assume that a possible explanation for the steady Angolan vegetation composition during the last glacial and the absence of HSs in the record may be the low atmospheric CO_2 concentration. The potential increase in arboreal taxa during HSs may have been limited by the shift in the competitive balance towards C_4 vegetation which favours the development and stability of grasslands.

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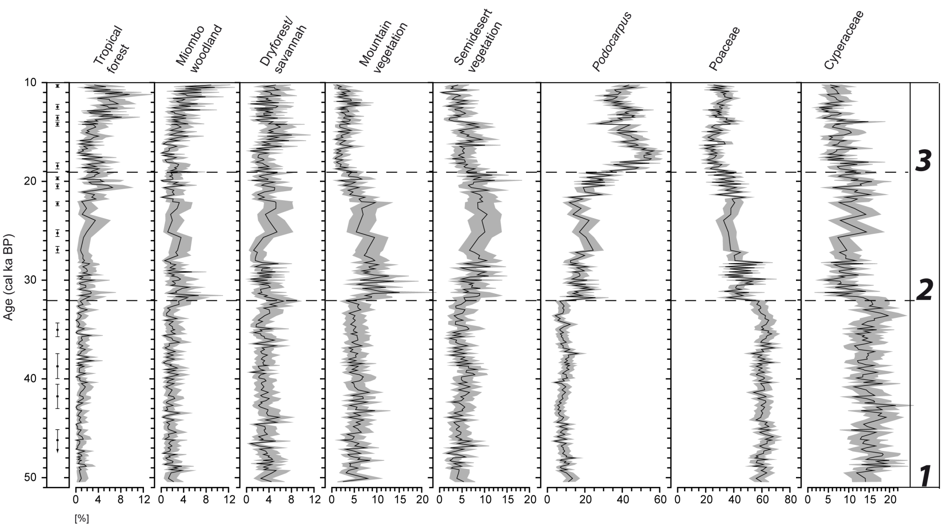

Fig. 1. Figure 2B: Statistical precession of pollen percentages of the vegetation groups. 95% Confidence Intervals considering the proportion of the vegetation groups within the pollen sum have been calculate