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Masked millennial-scale climate variations in South West Africa during the last glaciation

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Abstract

Large and abrupt shifts between extreme climatic conditions characterise the last glacial and deglacial period and are thought to be transmitted by the atmospheric and oceanic circulation. Millennial-scale climatic shifts associated with North Atlantic Heinrich Stadials (HSs) are thought to be closely related to a reduction of the Atlantic Meridional Overturning Circulation (AMOC), which lead to the accumulation of heat in the South Atlantic and a southward shift of the Intertropical Convergence Zone (ITCZ). Due to the linkage between the oceans and the atmosphere it is assumed that HSs also influence the vegetation composition in the African tropics. To address the connection between tropical African vegetation development and high-latitude climate change we present a high-resolution marine 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 HSs on the African subcontinent, our vegetation record shows no response. Model simulations conducted with an Earth System Model of Intermediate Complexity (EMIC) including a dynamical vegetation component lead to the hypothesis that the vegetation response during HSs might have been muted by mechanisms that partly cancel each other.

1 Introduction

The last glacial period including the deglaciation is characterised by abrupt climate perturbations on millennial and centennial time scales. Millennial-scale climate changes associated with Northern Hemisphere Heinrich Stadials (HSs) are thought to have a near global-footprint due to the transmission of the signal via the atmospheric and oceanic circulation (e.g. Alley et al., 1999; Hostetler et al., 1999; Broecker, 1996). While Heinrich events are defined by the occurrence of layers of ice-rafted debris in the North Atlantic (Heinrich, 1988), Heinrich Stadials are associated with the abrupt cooling of the North Atlantic region due to a reduction or possible shut-down of the Atlantic

Meridional Overturning Circulation (AMOC) (e.g. Broecker, 1994). Hence, a Heinrich Stadial contains a Heinrich event but is not equivalent to it (Barker et al., 2009).

During HSs ice core records from Greenland and Antarctica reveal a contrasting temperature response, with cold conditions in the Northern and warm conditions in the Southern Hemisphere (EPICA members, 2006). This anti-phase behaviour is suggested to result from the reduction in the strength of the AMOC that leads to a temperature decrease in the north and an accumulation of heat in the south, thus representing the concept of the thermal bipolar see-saw (Broecker, 1998; EPICA members, 2006; Barker et al., 2009).

In the tropics, a southward shift in the migration pattern of the Intertropical Convergence Zone (ITCZ) is a persistent feature related to the slow-down of the AMOC in climate models and may play an important role in the atmospheric transmission of the Northern Hemisphere signal (Mulitza et al., 2008; Lee et al., 2011). Model simulations conducted under modern climate boundary conditions indicate that a southward shift of the ITCZ causes precipitation anomalies over South America and Africa (Vellinga and Wood, 2002; Zhang and Delworth, 2005). During HSs these precipitation anomalies are reflected in tropical South American vegetation records by an opposing vegetation development north and south of the modern position of the ITCZ (Hessler et al., 2010). North of the modern position of the ITCZ the drier conditions resulted in abruptly expanding salt marsh vegetation (González et al., 2008; González and Dupont, 2009), while south of it more humid conditions led to an expansion of forests (Dupont et al., 2010). On the African continent the impact of HSs appears to be similar, with arid conditions prevailing north of the modern position of the ITCZ (e.g. Mulitza et al., 2008) and wetter conditions south of it (Dupont et al., 2008; Collins et al., 2010). In contrast to the hypothesis of a southward shift of the ITCZ during HSs (e.g. Mulitza et al., 2008; Lee et al., 2011), Collins et al. (2010) suggests that the African rainbelt rather contracts during those periods, yet leading to an increase of precipitation in southern equatorial Africa during HSs compared to the LGM.

Most existing studies that deal with abrupt climate variability in the African tropics cover HS1 (e.g. Dupont et al., 2008; Collins et al., 2010; Handiani et al., 2011), which is a period where the environmental background conditions differ substantially from the prevailing conditions during Marine Isotope Stage 3 and its HSs. In addition, the nature of the vegetation response to HSs and between the different HSs varies on a regional scale, particularly in tropical Southern Hemisphere Africa (Hessler et al., 2010). In general, atmospheric and oceanic processes controlling the tropical African climate and hence the vegetation composition on the subcontinent is highly complex and still only partly understood (Gasse et al., 2008).

In our study, we present a high-resolution marine pollen record of ODP Site 1078 (off Angola) which reveals for the first time the vegetation and climate development of Angola and the southern Congo Basin between 50 and 10 ka BP.

In order to get insight into atmospheric and oceanographic processes that affect the regional vegetation development during HSs model simulations have been performed using the UVic Earth System Climate Model (UVic ECSM) of intermediate complexity that includes active vegetation and land-surface components (Handiani et al., 2011).

The combination of proxy data and model experiments represents a unique opportunity to evaluate the importance of different forcings on vegetation and climate change in the tropics, particularly during times of abrupt climate perturbations.

Based on the results of several tropical African vegetation records (Hessler et al., 2010) we expect an increase of arboreal taxa in tropical South West Africa due to enhanced moisture availability during periods of HSs (Collins et al., 2010). We want to verify if this expectation is reflected in our vegetation record of ODP Site 1078 which reflects a catchment area that is anticipated to be most sensitive to climate change (Dupont et al., 2008) and so far has been lacking in high-quality terrestrial records.

2 Study area

2.1 Modern regional climate and oceanic conditions

The climate of the African tropics is strongly coupled to the latitudinal position of the ITCZ, the trade winds and the monsoon circulation. Due to a strong linkage between variations in atmospheric and oceanic conditions the position of the ITCZ follows an annual cycle, being in its northernmost position during austral winter and shifting to its southernmost during austral summer (Fig. 1). The shift of the ITCZ to its northernmost position (15–18° N) also indicates the beginning of the summer monsoon and hence rainy season (Sultan and Janicot, 2003). During austral summer, when a strong tropical trough is developed over central Africa (Angola Low, ~22° E–15° S), the ITCZ lies at 5–6° N in the western part of Africa and at 15–20° S in the eastern part (Gasse et al., 2008). The annual migration pattern of the ITCZ also affects the rainfall distribution in tropical regions by inducing alternating wet and dry seasons. Additionally, the eastwards penetrating West African Monsoon and the trade winds control the precipitation by bringing moisture from the Atlantic Ocean into tropical Africa (Gasse et al., 2008; Nicholson, 2000). The inland flow of moisture-laden air-masses is limited in the east by the highlands of East Africa as well as the surface position of the Congolian Air Boundary, a low pressure area and southern branch of the ITCZ (Leroux, 1983).

The system of ocean currents dominating the South East Atlantic also contributes to the complexity of our research area. The north-westward flowing Benguela Current (BC) separates at around 24°–30° S into the westward directed Benguela Ocean Current (BOC) and the northward oriented Benguela Coastal Current (BCC) (Stramma and Peterson, 1989; Shannon and Nelson, 1996; Fig. 1). The BC and the coastal upwelling of the eastern South Atlantic are driven by the southeasterly trade winds. As a result of the convergence of the BCC with the southward directed Angola Current (AC) the Angola-Benguela Frontal Zone (ABF) emerges, and separates the warm Angolan waters from the cold Benguela upwelling regime (Fig. 1). Similar to the seasonal shifts of the ITCZ, the ABF reaches its northernmost position in austral winter (20° S) and is farthest south during austral summer (16° S) (Shannon et al., 1987).

Since the climate and the near shore ocean current system strongly influence the vegetation pattern of South West Africa, changes in both are expected to be reflected in the vegetation record of ODP Site 1078.

2.2 Recent South West African vegetation composition

The close proximity of ODP Site 1078 to the African continent provides a pollen source area that covers several vegetation zones (Fig. 1). According to the trajectory model of Dupont and Wyputta (2003) the pollen source areas 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. Fluvial transport is also important since ODP Site 1078 is located off the mouth of the Balombo River, which traverses several vegetation zones.

Simplifying the South West African vegetation according to White (1983) eight vegetation types can be distinguished (Fig. 1). In the north of the pollen source area tropical forest of the Guineo-Congolian phytogeographical region prevails. To the south a transition zone between tropical forest and dry forest/savannah vegetation occurs. Wide parts of Angola are occupied by vegetation that belongs to the Zambezian Region, which is characterised by a highly diverse flora ranging from closed semi-deciduous forests in the north to broad-leaved savannah types in the south. On the relatively nutrient-poor soils of the Angolan highlands and its flanking escarpment (above ∼1000 m altitude) a distinctive type of savannah woodland, the Miombo woodland, grows and is dominated by the tree species of the genus *Brachystegia*. Afromontane forests including the conifer tree *Podocarpus* exist in only a few high mountain sites in Angola (above ∼1500 m altitude). The semi-desert and desert vegetation of the southern Angolan coastal areas belongs to the Nama-Karoo phytogeographical region and is characterised by small shrubs and succulents. The desert vegetation in coastal Angola is directly influenced by the offshore oceanic systems, particularly by the cold BCC and the related upwelling area that reduces atmospheric convection and hence minimises precipitation (Nicholson and Entekhabi, 1987). Dry deciduous forest and savannah vegetation including trees of the *Acacia* genus dominate the source area in the southeast.

3 Material and methods

3.1 Site description and age model

The sediments analysed in this study originate from ODP Site 1078 Hole C that is situated in the Bight of Angola (11°55′ S, 13°24′ E) in 426 m water depth (Fig. 1). Lithologically, the material is composed of moderately bioturbated olive-grey and dark olive-grey silty clay with varying amounts of nannofossils and foraminifera (Wefer et al., 1998).

The chronostratigraphy used in this study was established by linear interpolation of accelerator mass spectrometry (AMS) radiocarbon dates determined on planktonic foraminiferal tests and molluscs fragments (Kim et al., 2003; Rühlemann et al., 2004; Dupont et al., 2008). Fourteen radiocarbon dates are within the investigated time interval and have been calibrated using INTCAL98 (Stuiver et al., 1998), MARINE04 (Hughen et al., 2004) and Fairbanks0107 (Fairbanks et al., 2005). The radiocarbon dates were corrected with a reservoir age of 400 yr reflecting the present-day global average (Hughen et al., 2004). Although simulations for the glacial ocean indicate an increase in the surface water oceanic reservoir age of up to 600 yr (Butzin et al., 2005), an increase of 200 yr in the glacial dates of ODP Site 1078 would not significantly change the age model (Dupont et al., 2008) and the interpretation of our vegetation record. Model simulations also show that temporal fluctuations in the marine reservoir age are of minor importance in the tropical Atlantic (Hughen et al., 2004; Franke et al., 2008). All ages given here are in 1000 yr calibrated before present (ka cal BP).

3.2 Analytical methods

For pollen analysis, samples were taken every 2 to 7 cm resulting in an average temporal resolution of about 300 yr. All samples were prepared using standard palynological procedures (Faegri and Iversen, 1989), which includes the decalcification with diluted HCl (∼10 %) and the removal of silicates with HF (∼40 %). During the decalcification, two *Lycopodium clavatum* tablets were added to determine the pollen concentrations (pollen grain^{-1} cm^{-3}) (Stockmarr, 1971). To remove particles with a diameter <10 µm the samples were sieved over a 8 µm mesh using ultrasonic treatment. For identification of pollen grains, spores and other palynomorphs the samples were mounted in glycerine and microscopically examined at a magnification of 400 and 1000 times. About 300 grains of pollen and spores were counted for each sample. Only in a few samples, only 100–250 grains were counted due to a low pollen concentration in the sediments (Fig. 2). The different types of pollen, spores and palynomorphs were distinguished using the reference collection of University of Göttingen, Department of Palynology and Climate Dynamics, the African Pollen Database (http://medias.obs-mip.fr/pollen/) as well as several publications (Bonnefille and Riollet, 1980; Maley, 1970; Sowunmi, 1973, 1995; Ybert, 1979). The percentages are calculated on the basis of the pollen sum including terrestrial pollen taxa, aquatics (mainly Cyperaceae and *Typha*) and spores (mainly ferns). Identified pollen and spores have been summarized into the groups "tropical seasonal forest", "mountain vegetation", "Miombo woodland", "dry forest/savannah", and "semi-desert" following the climatic and ecological preferences of the pollen taxa related plants (see Supplement).

3.3 Models and experiments

Model experiments have been conducted using the University of Victoria Earth System Climate Model (UVic ESCM version 2.8; Weaver et al., 2001) that includes a dynamic vegetation (TRIFFID; Cox, 2001) and a land-surface component (MOSES 2; Cox et al., 1999) (Fig. 3). The UVic ESCM is an Earth System Model of Intermediate Complexity

(EMIC) that owes its efficiency to a simplified atmospheric component (Weaver et al., 2001). The TRIFFID model simulates the state of the terrestrial biosphere in terms of soil carbon, and the structure and coverage of five plant functional types (broadleaf tree, needleleaf tree, C_3 grass, C_4 grass and shrub) (Cox, 2001). The land surface scheme MOSES 2 calculates the surface-to-atmosphere fluxes of heat and water, updates the surface and subsurface variables that affect these fluxes, and calculates the vegetation-to-atmosphere fluxes of CO_2(Cox et al., 1999). The major vegetation composition has been diagnosed in terms of mega-biomes as classified by the BIOME6000 project (Harrison and Prentice, 2003) and is compared to our palaeovegetation record. A detailed description of the simulation design and boundary conditions is given in Handiani et al. (2011). Two simulations for two time periods have been accomplished, a HS1 and a Last Glacial Maximum (LGM) simulation. HS-like climate conditions have been generated by adding fresh-water to the North Atlantic under glacial boundary conditions. All presented model results show the anomalies between the HS1 and LGM simulations.

4 Results

4.1 Pollen data

The diagram presented in Fig. 2 covers the interval 50–10 cal ka BP and shows percentages of identified pollen taxa grouped according to the ecological preferences of the associated plants (see supplementary material) and the three most common pollen taxa, *Podocarpus*, Poaceae and Cyperaceae. Based on the relative abundance of pollen groups and taxa three pollen zones (PZ1, PZ2, and PZ3) are distinguished. In addition to the pollen percentages the concentrations (grains ml^{-1}) for the same pollen groups and taxa are indicated in Fig. 2, hence providing an independent measure for their representation in the sediment.

Podocarpus is excluded from the group “mountain vegetation” in both the pollen percentages and concentrations and is shown separately to avoid a bias of the record, since its high pollen production rates generally result in its over-representation. For the same reason, values of Poaceae (grass) are not included in any vegetation group and are shown separately in the diagram.

Poaceae (grass) pollen dominate PZ 1 (50–32 ka BP) by reaching percentages up to 60 %. Pollen of the vegetation groups “tropical forest” (max. 2 %), “Miombo woodland” (max. 3 %), and “mountain vegetation” (max. 8.5 %), excluding the conifer *Podocarpus* (max. 11.5 %), show low values. The concentration of Poaceae pollen is high (12 000–4000 grains ml^{-1}) during PZ 1, while that of *Podocarpus* is low (2000–400 grains ml^{-1}). Pollen taxa summarised in the mountain and semi-desert vegetation group reach their maximum concentration at the beginning of PZ 1 (mountain max. 1100 grains ml^{-1}; semi-desert max. 1000 grains ml^{-1}). Towards the end of PZ 1 the concentration values of both groups start to decline.

Spanning the period 32–19 ka BP, PZ 2 is characterised by an early decline of grass pollen from about 44 % to 32 %. Pollen percentages of sedges (Cyperaceae) which are widespread in swamps and along riversides but not restricted to it (Dupont and Agwu, 1991) decrease during the same period to values between 4–13 %. The semi-desert vegetation group including taxa from the coastal deserts and xerophytic shrubland doubles its percentages from about 5 % at the beginning of PZ 2 to about 10 % towards the end of the pollen zone at 19 ka BP. Pollen percentages of the group “mountain vegetation” increase significantly just at the beginning of PZ 2 (32–31 ka BP) from about 4 % to 10–12 %. However, following the maximum between 31–29 ka BP, pollen percentages of this group start to decline to minimum values of 2 % at about 19 ka BP.

Relatively stable pollen percentages of Afromontane *Podocarpus* (20 %) are found during PZ 2. Percentages of tropical forest reach a first maximum with 6 % between 21 and 20 ka BP and decline subsequently. However, the pollen concentration values (Fig. 2) of *Podocarpus*, semi-desert, and mountain vegetation do not increase during PZ 2. Indeed, all vegetation groups show at least a slight decrease in their pollen concentrations. *Podocarpus* concentrations are even on the lowest level (1000–200 grains ml^{-1}) during PZ 2.

A strong increase of *Podocarpus* pollen percentages is recorded directly at the onset of PZ 3(19–10 ka BP), reaching its maximum representation of 52 % at circa 17 ka BP (see also Dupont and Behling, 2006; Dupont et al., 2008). Following this maximum, pollen percentages of *Podocarpus* decrease continuously to 30 % at 10 ka BP. Similarly, relative abundances of Poaceae, mountain, semi-desert, and dry forest/savannah pollen decline continuously until they reach minimum values at 10 ka BP. Pollen percentages of both Miombo woodland and tropical forest reach a maximum value of 7 % at 10 ka BP. A similar pattern as in the pollen percentages of *Podocarpus* can be observed in its concentration, with a steep increase (from 1000 to 4000 grains ml^{-1}) at the beginning of PZ 3 (19–17 ka BP) followed by decreasing values down to 700 grains ml^{-1} at 10 ka BP. Poaceae, mountain, and semi-desert pollen concentrations continue with their downward trend which already started in PZ 2. Only the concentrations values of tropical forest (100 to 250 grains ml^{-1}) and Miombo woodland (60 to 200 grains ml^{-1}) increase slightly towards 10 ka BP.

4.2 Model results

The model simulations conducted with the UVic ECSM show the annual-mean differences between HS1-like and LGM conditions for physical parameters such as SST, precipitation, evaporation and net-freshwater flux (Fig. 3).

Under HS1 conditions the SST in the southeast Atlantic is between 0.5° and 1.5 °C higher compared to the LGM. The amount of precipitation increased during HS1 by about 0.3 mm per day compared to LGM conditions. Evaporation also shows higher values (0.25–0.5 mm day^{-1}) during HS1 over South West Africa and the southeast Atlantic. The net-freshwater flux anomaly, which is the anomaly of the difference between precipitation and evaporation, is about zero in our research area.

The difference in the simulated vegetation distribution between HS1 and LGM conditions reveals a small extension of the forest biome in South West Africa during HS1 compared to the LGM (Fig. 3e).

5 Discussion

5.1 The glacial vegetation development in South West Africa

Combining the vegetation record of ODP 1078 published by Dupont and Behling (2006) and Dupont et al. (2008) with our newly obtained pollen data for the period 50–30 ka BP, the tropical South West African vegetation history of the last glacial including the last deglaciation (50–10 ka BP) becomes more complete and distinct.

During the last glacial (50–19 ka BP) South West Africa was dominated by grassland and savannah vegetation indicating an open landscape likely due to drier conditions compared to today. The low amount of arboreal taxa in the lowlands and mountain areas during the last glacial and deglaciation (Dupont and Behling, 2006; Dupont et al., 2008) supports the assumption of a reduced moisture availability. Dry and even cooler conditions during the last glacial compared to recent times are also indicated by a vegetation record from Namibia (Shi et al., 1998). The central-east African glacial vegetation and climate history (Kashiru swamp; Bonnefille and Riolett, 1988; Bonnefille and Chalié, 2000) compares partly to the development in South West Africa. A more open vegetation cover due to a reduction in precipitation is suggested for the period between 40 ka BP to 10 ka BP (Bonnefille and Riolett, 1988; Bonnefille and Chalié, 2000). In addition, the increasing abundance of pollen taxa representing temperate plants indicate the influence of cooler climates (Bonnefille and Riolett, 1988; Bonnefille and Chalié, 2000). However, between 50 and 40 ka BP high percentages of arboreal taxa reveal wet climate conditions similar to today (Bonnefille and Riolett, 1988). At intermediate altitude, temperate montane forest started its expansion during the LGM which is indicated by the increasing occurrence of Afromontane *Podocarpus* (Dupont et al., 2008). During the deglaciation *Podocarpus* pollen became more and more abundant in the sediment representing either a closure of the vegetation cover, particularly on the plateau, or an intensification of the trade winds, since its bisaccate pollen grains are readily transported by wind. A closure of the vegetation cover is, however, doubtful due to the rather stable concentration of grasses, semi-desert and dry forest/savannah vegetation throughout the deglaciation (Fig. 2). Although no reconstructions of trade-wind intensities from this region and time frame exist, an increase in wind strength appears to be a convincing mechanisms. However, there is, within dating uncertainties, an apparent similarity of our *Podocarpus* record from the South West African highlands to the East African Lake Tanganyika TEX_{86} record which is considered to represent the lake's surface temperature (Fig. 4; Tierney et al., 2008). Although the amount of precipitation and the duration of the rainy season is thought to be the main limiting factor for the tropical vegetation development, Afromontane *Podocarpus* seems to be dominated by the southern African temperature signal which follows Northern Hemisphere insolation (Fig. 4; Tierney et al., 2008).

5.2 Abrupt climate variations in the African tropics

The impact of millennial-scale climate fluctuations such as HSs on the tropical African environment and the vegetation development has been addressed by several studies (Tierney et al., 2008; Tjallingii et al., 2008; Collins et al., 2010; Hessler et al., 2010, and references therein). In the Southern Hemisphere African tropics, vegetation changes related to HSs appear to be marked by an increase in arboreal taxa, perhaps related to an increase in the moisture availability (Hessler et al., 2010). The pollen record from the Kashiru swamp in east equatorial Africa, for instance, clearly shows the impact of HSs on the vegetation with abrupt increasing percentages of arboreal taxa likely due to wetter conditions (Bonnefille and Riolett, 1988; Bonnefille et al., 2000). However, Hessler et al. (2010) also indicate that the magnitude and manifestation of vegetation changes might differ when multiple events are registered at one site and between different sites of the Southern Hemisphere African tropics. In the East African

Rift system (Lake Masoko) the mountainous species *Olea*, which is a characteristic of warm-temperate/mixed forest and temperate-montane forest, only increased following HS4 and HS1 which indicates an increase in moisture availability in the otherwise dry glacial environment (Vincens et al., 2007). In western equatorial Africa (Barombi Mbo) vegetation changes are recorded that are associated with HS1 and HS2 (Maley and Brenac, 1998). While *Olea capensis*, a representative of warm-temperate mixed forest, reaches its highest abundance during HS2, grasses (Poaceae) show maximum values in relation to HS1 (Maley and Brenac, 1998).

Although there are several records in Southern Hemisphere Africa providing evidence for an impact of HSs, our high-resolution vegetation record obtained from ODP 1078 gives no indication for an impact of HSs in the study area. Vegetation change coinciding with HS1 does not seem to be tied to the duration of the HS1 stadial (14.6–16.3 ka BP according to Greenland Ice Core Chronology 2005; Andersen et al., 2006; Skinner, 2008; Wolff et al., 2010). However, Mg/Ca based summer sea surface temperature (SST) reconstructions of ODP 1078 reveal several warming episodes coinciding with HSs (Hessler et al., 2011). Therefore, in the following, we will discuss mechanisms or a combination of them, which might be responsible for the rather stable vegetation cover in South West Africa during the last glacial.

5.3 Are millennial-scale climate changes masked in South West Africa?

Our hypothesis that an impact of HSs on the tropical South West African vegetation may have been masked or mitigated is based on modelling experiments conducted with the UVic ESCM including a dynamic vegetation component (Fig. 3).

The simulated SST anomaly between HS1 and LGM conditions in the UVic ESCM (Fig. 3) suggest the establishment of anomalous warm conditions in the southeast Atlantic during HSs. These results are consistent with an alleged general warming of the South Atlantic surface waters during HSs due to a reduction of the AMOC (the “seesaw hypothesis”, Broecker, 1998), as well as with local SST reconstructions from the southeast Atlantic (Kim et al., 2002; Hessler et al., 2011). In association with the warming of the southeast Atlantic the UVic ESCM simulates an increase in the evaporation rates over the South West African continent (Fig. 3c). At the same time, there is an increase in the precipitation rates over largely the same area. Both effects nearly cancel each other and lead to a change in the net-freshwater flux that is about zero, except in the immediate vicinity of the Namibian upwelling region (Fig. 3d). Thus, although the hydrological cycle intensifies, there is only a small change in the net moisture supply and, consequently, only a minor extension of the forest biome in South West Africa during HS1 compared to the LGM is simulated (Fig. 3e). Thus, we hypothesise that the partial cancellation of enhanced evaporation and enhanced precipitation leads to a muted response of the vegetation in the study area, as evident from the pollen record of ODP 1078 (Fig. 2) and the model experiments (Fig. 3).

We note that simulations of the LGM and HS1 with a coupled climate model that contains comprehensive atmospheric and land model components (Merkel et al., 2010) also suggest a similar partial cancellation of changes in evaporation and precipitation over the South West African continent. Although the patterns and amplitudes slightly differ from the UVic results (not shown), they nevertheless support the findings from the UVic simulations.

5.4 Are there other mechanisms possibly dominating the glacial South West African vegetation development?

The counteracting mechanisms described above seem to play an important role in the climate and vegetation development in the South West African tropics during the last glacial. However, these are not the only crucial parameters for the vegetation development in tropical environments during the last glacial. Therefore, in the following paragraph we will briefly discuss two further parameters with the potential to limit the Southern Hemisphere African vegetation development.

5.4.1 Atmospheric CO_2 concentration

The low glacial (190–200 ppmv; e.g. Petit et al., 1999) atmospheric CO_2 concentration could also 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 C_4/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 we find that under full glacial conditions the South West African vegetation is dominated by grassland (Fig. 2) while during the deglaciation vegetation groups consisting mainly of arboreal taxa (tropical seasonal forest, Miombo woodland) become more important (Fig. 2). Hence, we speculate that a substantial fraction of the vegetation changes in Angola during the last glacial including the deglaciation as well as stability of the vegetation during HSs is due to the physiological response to variations in the CO_2 concentrations.

5.4.2 Monsoon circulation

Due to a reduced solar insolation and the presence of large ice sheets in the high latitudes of the Northern Hemisphere, the African summer monsoon circulation was weaker during the last glacial compared to today (Braconnot et al., 2000; Gasse, 2000; Janicot, 2009; Revel et al., 2010), which potentially is another important factor influencing the vegetation development in tropical Africa. The generally low glacial temperatures are associated with a reduction in the evaporation, which in combination with a reduced monsoon circulation results in less precipitation and drier conditions (Braconnot et al., 2000). Applying these facts to our pollen record, the dry glacial conditions are reflected in the high pollen percentages of grasses (Poaceae) and the corresponding low values of groups representing tree taxa (tropical seasonal forest, *Podocarpus*, Miombo woodland) (Fig. 2).

Although we suggest several approaches to explain the glacial and deglacial vegetation development in South West Africa, there are further factors and feedbacks that are still only partly understood and need further investigation (e.g. Gasse et al., 2008), such as topographic elevation, the feedback of evaporation upon ecosystems, varying thresholds, and species-dependent response to variations in the prevalent CO_2 concentration.

6 Conclusions

The presented high-resolution glacial (50–10 ka BP) vegetation record of tropical South West Africa gives insight into the climate and vegetation development from a region where high-quality terrestrial records are lacking.

Throughout the last glacial, grassland and savannah vegetation dominates the pollen source area, indicating an open vegetation type possibly as a result of reduced moisture availability and low atmospheric CO_2 concentrations. During the deglaciation when the monsoon strengthens and CO_2 concentrations are rising, biomes dominated by tree taxa (excluding Afromontane *Podocarpus*) become more widespread.

Although there are several tropical paleoclimate and paleovegetation records showing an impact of HSs in Africa south of the equator, our high-resolution vegetation record with its pollen source areas in Angola and the southern Congo Basin provides no evidence for an impact of HSs in the study area. Model simulations conducted with the UViv ECSM including a dynamical vegetation component indicate that there may be an impact of HSs in the study area, but that the vegetation response is muted because of the partial cancellation of changes in precipitation and evaporation, leading to a negligible change in moisture supply.

Furthermore, the vegetation development in the African tropics during the last glacial and deglaciation is also strongly influenced by the factors such as atmospheric CO_2 and the intensity of the African monsoon.

Supplementary material related to this article is available online at: http://www.clim-past-discuss.net/7/3511/2011/cpd-7-3511-2011-supplement.pdf.

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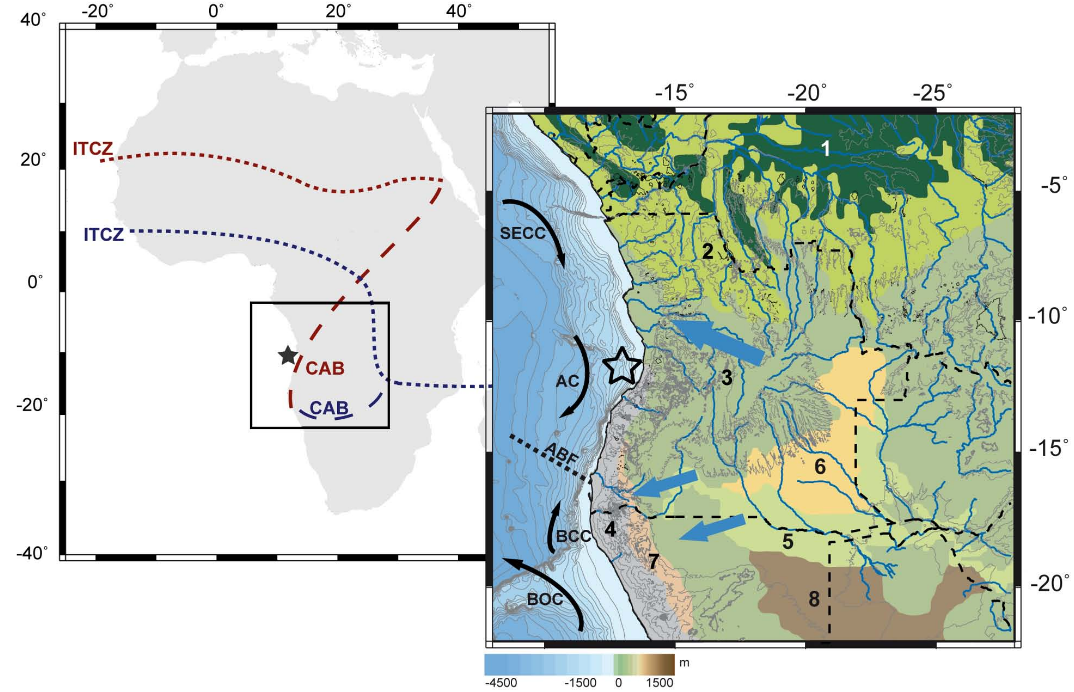

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Fig. 1. On the left the position of the Intertropical Convergence Zone (ITCZ) and Congolian Air Boundary (CAB) is indicated for austral summer (red) and austral winter (blue). The black square shows the extent of the figure on the right hand. The location of ODP Site 1078 is indicated by a star. In the right hand figure the prevailing vegetation types in the pollen source area of ODP Site 1078 simplified after White (1983) and modern southeast Atlantic bathymetry and surface water oceanography is shown. **(1)** = Tropical forest of the Guineo-Congolian phytogeographical region; **(2)** = transition between tropical forest and dry forst/savannah; **(3)** = dry forest/savannah of the Zambezian phytogeographical region, wetter Miombo woodland above 1000 m altitude, Podocarpus above 1500 m altitude; **(4)** = desert and semi-desert of the Nama-Karoo phytogeographical region; **(5)** = deciduous forest; **(6)** = grassland and Miombo woodland; **(7)** = woody shrubland; **(8)** = dry deciduous forest and savannah of the Kalahari. Blue lines indicate major rivers. Blue arrows indicate major wind transport direction of the pollen towards the core location. AC = Angola Current; ABF = Angola-Benguela Front; BCC = Benguela Coastal Current; BOC = Benguela Ocean Current; BC = Benguela Current. Star indicates location of ODP Site 1078.

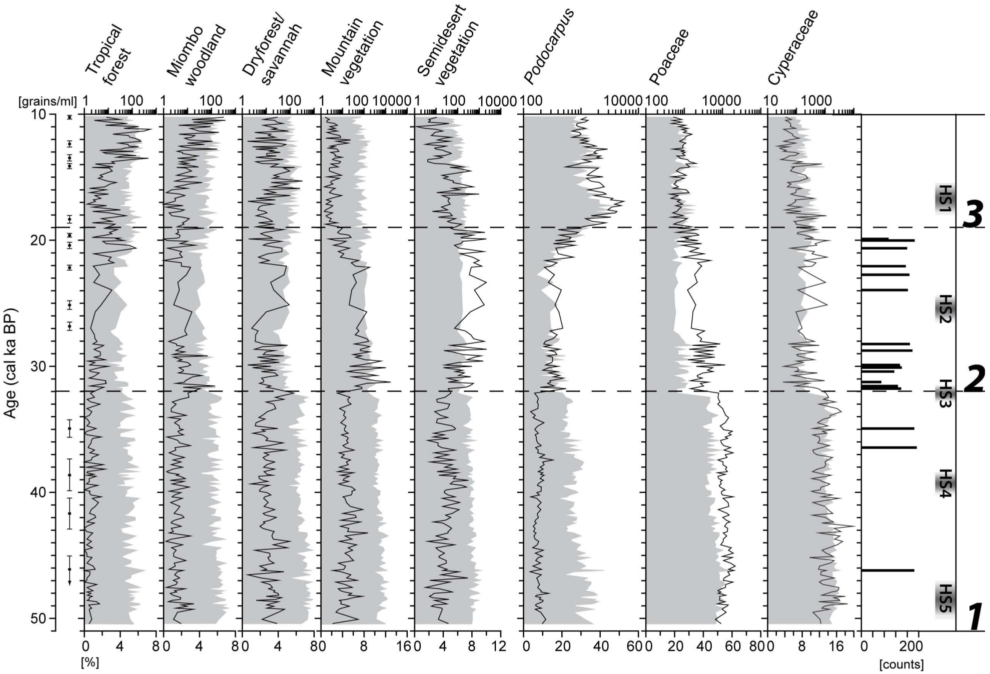

Fig. 2. Pollen percentages (black) and pollen concentrations of vegetation groups and selected pollen taxa (shaded). Concentrations are given in log10 grains ml^{-1}, note different scales. Timespans of calibrated ^{14}C age (Kim et al., 2003; Rühlemann et al., 2004; Dupont et al., 2008) are indicated next to the time axis on the left hand side. On the right hand side samples with less than 250 pollen grains counted are indicated. Ages of Heinrich Stadials (HSs) are according to Sanchez-Goni and Harrison (2010): HS1 = 15.6–18.0 ka BP, HS2 = 24.3–26.5 ka BP, HS3 = 31.3–32.7 ka BP, HS4 = 38.3–40.2 ka BP, HS5 = 47.0–50.0.

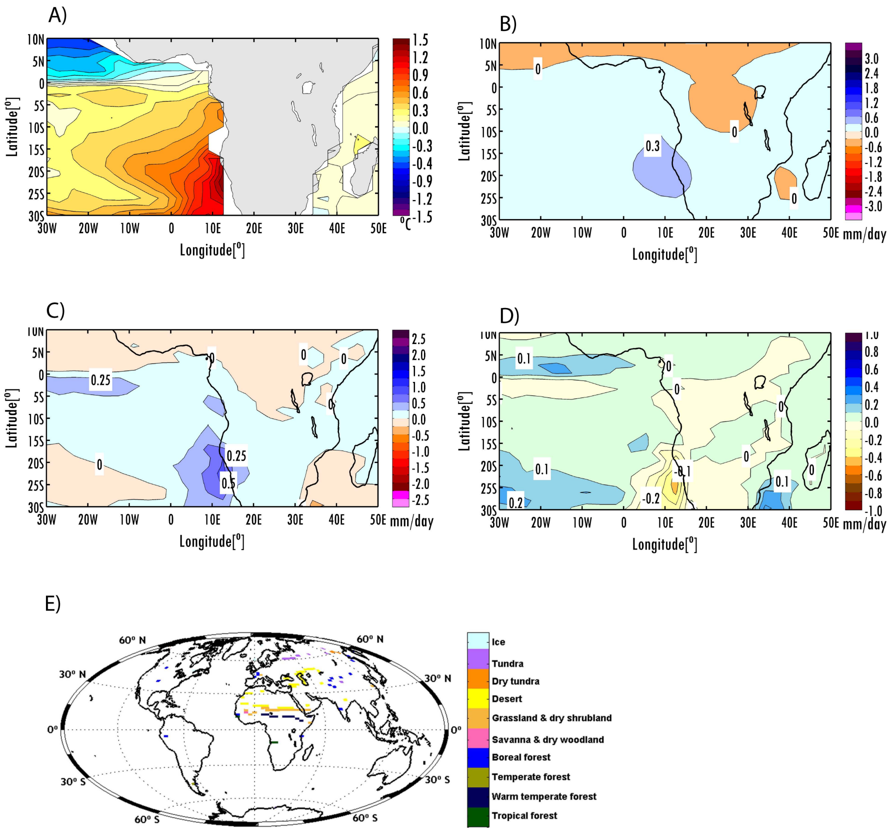

Fig. 3. Model simulations of the UVic ECSM including a dynamic vegetation component shows the anomalies between LGM and HS1 conditions. **(A)** Sea surface temperature in degree Celsius (°C), **(B)** precipitation in mm per day, **(C)** evaporation in mm per day, **(D)** net-freshwater flux (precipitation minus evaporation) in mm per day, **(E)** vegetation anomaly at HS1, based on grouping vegetation into mega-biomes according to Harrison and Prentice (2003).The HS1 biome of each grif cell is only plotted if it is different from the LGM biome.

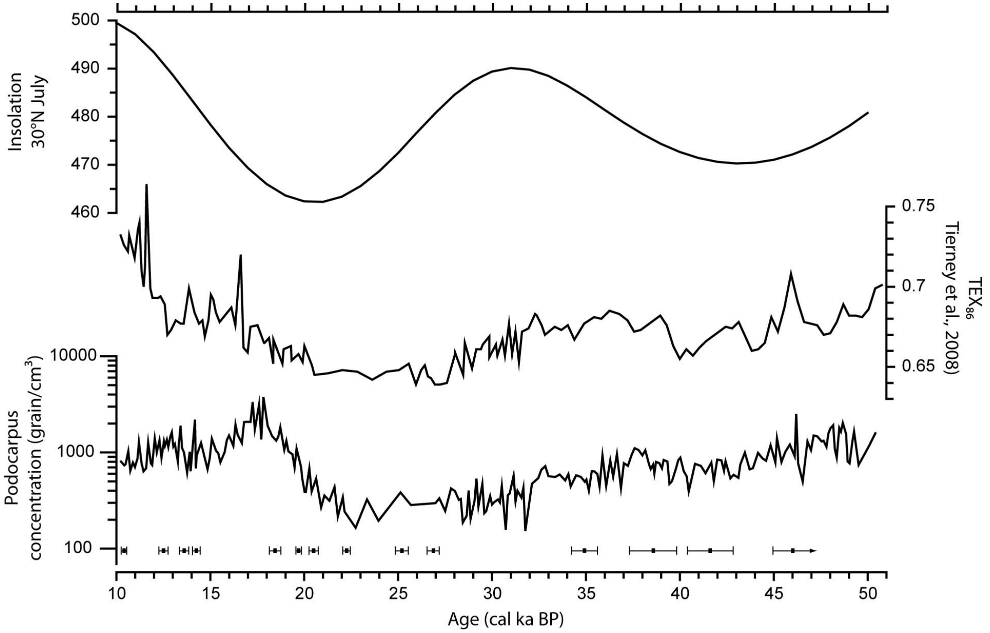

Fig. 4. Concentrations of Podocarpus (grains cm^{-3}). Concentrations are given on log10 scale. TEX$_{86}$ is considered to represent lake surface temperature of Lake Tanganyika, East African Rift system (Tierney et al., 2008). Uppermost curve gives Northern Hemisphere summer insolation at 30° N during July. Timespans of calibrated ^{14}C age (Kim et al., 2003; Rühlemann et al., 2004; Dupont et al., 2008) are indicated on top of the time axis.

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Masked millennial-scale climate variations in South West Africa

I. Hessler et al.