



A 30,000 yr record of land–ocean interaction in the eastern Gulf of Guinea

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ABSTRACT

A 30,000 yr dinocyst and pollen record from the eastern equatorial Atlantic (off Cameroon) has been investigated in order to identify land–ocean linkages during the last deglacial transition. A strong correlation between the abundance of *Brigantedinium* spp. and the Ca/Fe ratio during the last glacial period suggests enhanced marine productivity in association with cool seawater temperatures and nutrient input linked to coastal upwelling and/or a proximal river mouth. Dry conditions are recorded on the adjacent continent with a significant representation of open vegetation indicators and the Afromontane taxon *Podocarpus*. After 17 cal ka BP these indicators register a sharp decline as a result of a climatic transition from the dry/cooler conditions of the last glacial period to the wetter/warmer conditions of the deglaciation. Simultaneously, dinocysts show a significant shift from dominant heterotrophs to an increasing abundance of autotrophs, reflecting warmer conditions. Significant changes are observed during the Younger Dryas, with a return to drier conditions and higher salinities. The start of the Holocene is marked by very low-salinity conditions, reflecting optimal monsoonal conditions over west equatorial Africa. The end of the African Humid Period is observed between 6 and 5 cal ka BP, followed by significant fluctuations in both terrestrial and oceanic proxies.

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Introduction

Delta and deep-sea fan sediment accumulations along the west equatorial African margin are important paleoclimate archives characterized by high sedimentation rates that integrate terrestrial and marine climate signals through proxies registering dynamics in both vegetation/landscape and in the adjacent ocean (e.g., Marret et al., 2001; Weldeab et al., 2005; Marret et al., 2008; Kim et al., 2010). For instance, dinoflagellate cyst (= dinocyst) assemblages from the tropical Atlantic have been associated with specific hydrographic contexts (Marret, 1994; Marret and Zonneveld, 2003; Marret et al., 2008) and can be used to trace the mechanisms responsible for changes in sea-surface conditions during the late Pleistocene and Holocene (Marret et al., 2008). The value of this proxy is enhanced because preservation studies of modern sediments along the west African margin indicate that transport and reworking of cysts have been found to be negligible (e.g., Zonneveld et al., 2007). The same archives have been used to reconstruct the evolution of tropical African vegetation over the last million years using terrestrial proxies such as pollen (e.g., Dupont et al., 2001, 2007; Hessler et al., 2010). Diatoms also have provided an insight

into precipitation dynamics and siliceous productivity in the eastern equatorial Atlantic over the last 40,000 yr (e.g., Crosta et al., 2012). In parallel, a quantitative elemental analysis enables the identification of the source of material delivered to deep-sea fans, characterizing periods of enhanced fluvial activity versus aridity (e.g., Adegbe et al., 2003). The integration of these different biotic and abiotic proxies from the same sediment record avoids age-related correlation problems and so permits the investigation of the temporal relationships of the coupled land–atmosphere–ocean system during climatic transitions.

The aim of this study was to investigate in detail arid–humid climatic transitions and associated changes of the last 30,000 yr in the eastern part of the Gulf of Guinea. In particular, we aimed to assess the timing of latitudinal changes in monsoon dynamics and how these relate to changes in the marine environment in order to illuminate mechanisms linking oceanic with terrestrial and atmospheric conditions. Previous studies farther south (Ogooué (Kim et al., 2010); Congo (Marret et al., 2008)) based on the same proxies (dinocysts, pollen, charred grass cuticles) have provided detailed information on the land–ocean interactions that occurred during major climatic changes of the last 30,000 yr. This study complements these earlier investigations and is based on integrated marine (dinoflagellate cysts) and terrestrial proxy (pollen and charred grass cuticles) data from a core collected in the Sanaga deep-sea fan (Fig. 1). Comparison with previously published elemental concentration data from the same core (Adegbe et al., 2003), isotopic data (Weldeab et al., 2007) and diatom assemblages (Crosta et al., 2012) enables a better understanding of

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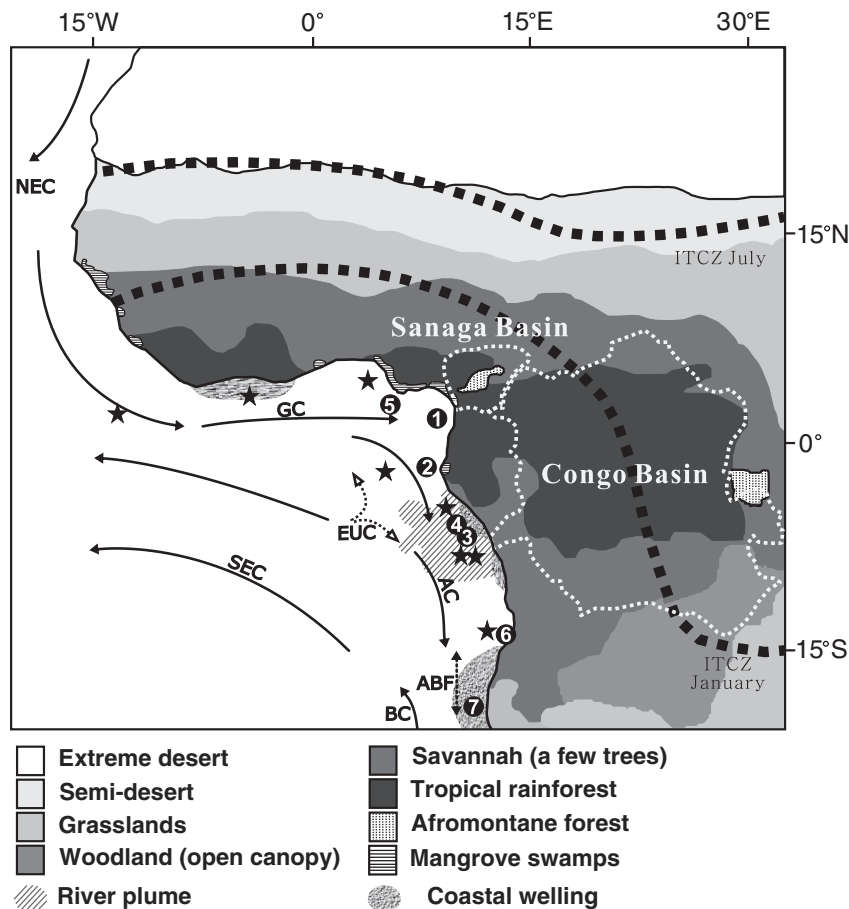


Figure 1. Map showing locations of site GeoB4905-4 (1) and other cores mentioned in the text: MD03-2707 (1, same location as GeoB4905-4) (Weldeab et al., 2007), MD03-2708 (2) (Kim et al., 2010), T89-16/GeoB1007-4 (Marret et al., 2008) (3), ODP1075 (4) (Dupont et al., 2007), KW31 (5) (Lezine and Cazet, 2005), ODP1078 (6) and GeoB1023-5 (7) (Dupont and Behling, 2006). Stars indicate the location of cores with high abundance of *Podocarpus* pollen grains (after Dupont et al., 1996, 2007). Simplified vegetation zones over Africa (see legend) and general pattern of present-day ocean currents of the adjacent Atlantic Ocean: NEC, North Equatorial Current; GC, Guinea Current; SEC, South Equatorial Current; AC, Angola Current; ABF, Angola-Benguela Front; BC, Benguela Current; EUC, Equatorial Under Current. The dotted line indicates the mean January and July positions of the Intertropical Convergence Zone. The boundaries of the Sanaga and the Congo basins are shown by dashed white lines.

the climate evolution of this region and mechanisms driving terrigenous fluxes to the ocean.

Environmental setting

The study area is located in the Bay of Biafra in the eastern part of the Gulf of Guinea (Fig. 1). Climatic regimes in western tropical Africa are related latitudinally to the N–S shifts of the Intertropical Convergence Zone (ITCZ) (Wagner and Silva, 1994; Nicholson and Grist, 2001; Vizi and Cook, 2002). Seasonal transfer of heat between ocean and land greatly influences equatorial African climates by controlling the surface airflow (e.g., Leroux, 2001). The annual average precipitation gradient controls a south-to-north zonation of vegetation zones (White, 1983; Richards, 1996). Evergreen Guineo–Congolian forests are centered around the equator, where precipitation is highest, and are limited in the south and north with first semi-deciduous forest, then grassland and savannahs in the north (White, 1983). In addition to these zonal vegetation belts, Afromontane vegetation is found at altitudes above 1600 m, and mangrove swamps along the coast.

The hydrography of the upper waters in the Bay of Biafra is largely influenced by the Guinea Current (GC) along the northern coast of the Gulf of Guinea. Forming the southern extension of the North Equatorial Current, the GC flows eastward along the coast and displaces warm, low-salinity waters. The South Equatorial Current (SEC) flows westward along the equator, separated from the GC by the northern tropical convergence along 3°N. Below the surface, and extending between 5°N

and 5°S, the Equatorial Under Current (EUC) flows to the east along the Equator driven by the trade winds transporting cold oxygen-rich water (Pickard and Emery, 1982; Peterson and Stramma, 1991; Tomczak and Godfrey, 1994).

Seasonal coastal upwelling occurs between Cap des Palmes and Cap des Trois Pointes (August–September, January), and is forced by zonal equatorial wind stress and/or remote forcing of the Gulf of Guinea, such as shallowing of the thermocline in the eastern tropical Atlantic (Verstraete, 1992). The equatorial upwelling occurs from June to September when winds are more intense, bringing cold nutrient-rich water to the surface (Bakun, 1978; Voituriez et al., 1982; Colin, 1991). Dense river networks along the Gulf of Guinea coast supply freshwater, nutrients and sediments to the ocean (Gabche and Folack, 1997). The Sanaga River, the biggest river in Cameroon and the fourth most important river (in terms of catchment size) in west central Africa (after the Congo, Niger and Ogooué), flows about 525 km southwest across the central plateau into the Bight of Biafra adjacent to the Island of Bioko. The catchment basin covers ~131,500 km² of central Cameroon with an annual discharge of 65×10^6 m³/yr (Bird et al., 1994) and an export sediment load of $\sim 5 \times 10^6$ t/yr (Bricquet, 1990). Most of the basin shows comparatively constant precipitation of ~1500 mm/yr, rising slightly to ~2000 mm/yr in the mountainous western parts of the basin and significantly to >4000 mm/yr near to the coast (Gabche and Folack, 1997). The Sanaga River rises from the savannah-covered Plateau de l'Adamaoua, flows into transitional forest–savannah, and finally through closed semi-deciduous and evergreen tropical closed forest.

The equatorial Atlantic region off Africa is characterized by relatively low salinities below 32. SSTs in this area are relatively low near the river mouths due to river-induced upwelling, but are warmer farther offshore (Eisma and van Bennekom, 1978; Pickard and Emery, 1982; Tomczak and Godfrey, 1994).

Material and methods

The 1218-cm-long gravity core GeoB4905-4 was collected close to the outflow of the Sanaga River (02° 30.0'N, 09° 23.4'E, 1328 m water depth) during the cruise M41/1 on board of the RV *Meteor* (13.2–15.3, 1998) (Fig. 1).

Age model

The chronology is based on 14 AMS (accelerator mass spectrometry) ^{14}C dates on monospecific *Globigerinoides ruber* pink and mixed planktonic foraminifers conducted at the Leibniz Laboratory AMS facility at Kiel University, Germany. The resultant ^{14}C dates were converted to calendar age using CALIB version 6.0 and the Marine09 Data Set (Reimer et al., 2009), with a reservoir correction of 400 yr (Fig. 2). Further details are presented in Adegbe et al. (2003) and Weldeab et al. (2005), and are available in PANGAEA (www.pangaea.de).

Palynological analysis

Sixty-three samples from GeoB4905-4 core sediments were analyzed for dinocysts, selected pollen taxa and charred grass cuticles. For each sample, about 5 cm³ of sediment was prepared for palynological analysis according to the procedures described in Scourse et al. (2005) and Marret et al. (2008). Concentrations were estimated using the addition of known quantities of *Lycopodium clavatum* spores by tablet. Where possible, a minimum of 100 pollen/spore grains and 100 dinocysts in all samples were counted; only two samples (at 750 and 800 cm depth) contained less than 100 cysts. Although these two samples only contain about 50 cysts, they are included in the percentage diagram for information (Fig. 3). Following the methodological approach applied to the study of core MD03-2708 off Gabon (see Kim et al., 2010), only Poaceae, Cyperaceae, mangrove taxa (*Rhizophora*)

and *Podocarpus* were identified and counted; other pollen (including spores) were counted but not identified. Pollen percentages for *Rhizophora*, Poaceae, Cyperaceae and *Podocarpus* sp. in Figure 3 were calculated based on a sum including non-identified pollen and spores, termed 'other pollen'. In parallel, charred grass cuticles were counted; these consist of dumbbells, stomata and long cells and have been used as a significant indicator of savannah fires (Morley and Richards, 1993). Dinocyst percentages were calculated based on the total dinocyst sum. *Brigantedinium* specimens were grouped together as their identification to species level was prevented by a poor visual observation of their archeopyle. Dinocyst taxonomy follows Marret and Zonneveld (2003), Fensome and Williams (2004) and Marret and Kim (2009).

Elemental analysis

Bulk sediment elemental abundances for Ca, Fe and Ti from core GeoB4905-4 were measured with an X-ray fluorescence (XRF) scanner (see Adegbe, 2001 and Adegbe et al., 2003 for details; Itambi et al., 2010).

Results

Dinocyst record

A total of 28 dinocyst taxa were identified (Fig. 3). Concentrations and fluxes were generally low (55 to 700 cysts/cm³ and 1240 to 22,125 cysts/cm²/ka, respectively). Overall, heterotrophic taxa, mainly *Brigantedinium* spp., dominate the assemblages from 31 cal ka BP to around 11.9 cal ka BP. During this period, minor but significant occurrences of open-ocean autotrophic species (*Impagidinium* species) and the neritic taxon *Tuberculodinium vancampoae* were observed. Concentrations and fluxes are relatively high compared to the entire record, until 15.6 cal ka BP. The decrease in concentrations and fluxes coincides with a significant increase of *Spiniferites delicatus* and *Spiniferites mirabilis*. From 11.9 ka onwards, autotrophic taxa become dominant, mainly *Operculodinium aguinawense* and *Spiniferites* species. *Lingulodinium machaerophorum* is also significant in the upper part of the record. Concentrations and fluxes remain less than 300 cysts/cm³ and 10,000 cysts/cm²/ka, respectively, except around 6.1 cal ka BP when both reach a maximum.

Terrestrial indicators

Percentages of the four selected terrestrial indicators (Poaceae, Cyperaceae, *Rhizophora* and *Podocarpus*) were calculated based on a total pollen and spore sum (Fig. 3) but also (with the exception of *Rhizophora*) on a sum excluding *Rhizophora* (Fig. 4), in order to better characterize their fluctuations. *Rhizophora* pollen is usually highly abundant in marine sediments from the shelves, due to the distribution of the mangrove along the coast (Van Campo and Bengo, 2004) and therefore its exclusion from the percentage calculation better differentiates the catchment signal (see Scourse et al., 2005). Cyperaceae, Poaceae and *Podocarpus* are relatively abundant from 31 ka until 15.5 cal ka BP, when *Rhizophora* starts to increase steadily. Their concentration and flux values follow the same pattern. From 15.5 cal ka BP, the pollen record is characterized by high abundance (relative and absolute) of *Rhizophora* and other pollen, with a *Rhizophora* peak between 12 and 10 ka. It is only around 6 to 5 cal ka BP that Cyperaceae and *Podocarpus* percentages rise again, followed by the Poaceae around 2.5 cal ka BP. Figure 4 shows peaks of *Podocarpus* between 4 and 2 cal ka BP. Charred grass cuticles (CGCs) are particularly abundant until around 12.5 ka and become very rare until 5 ka where their concentration and fluxes slightly increase until 2.5 ka.

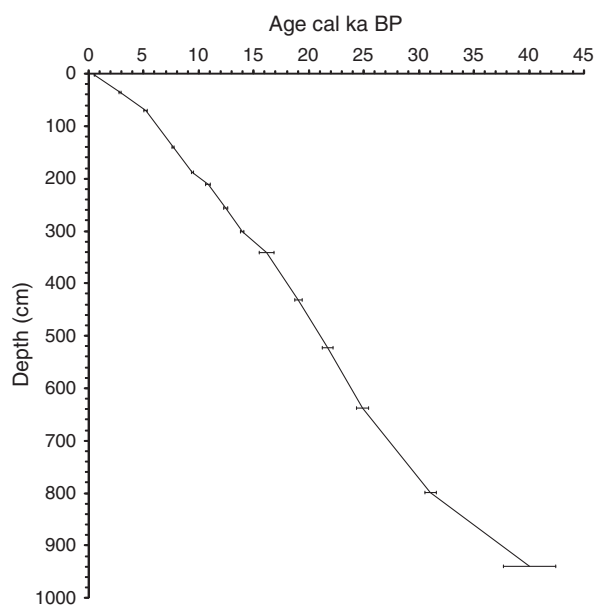


Figure 2. Age–depth diagram for core GeoB4905-4 based on 14 AMS ^{14}C dates (Adegbe et al., 2003; Weldeab et al., 2005). Radiocarbon ages were calibrated using CALIB6.0 (Marine09, Reimer et al., 2009) with a 400-year reservoir correction. Two sigma errors are plotted.

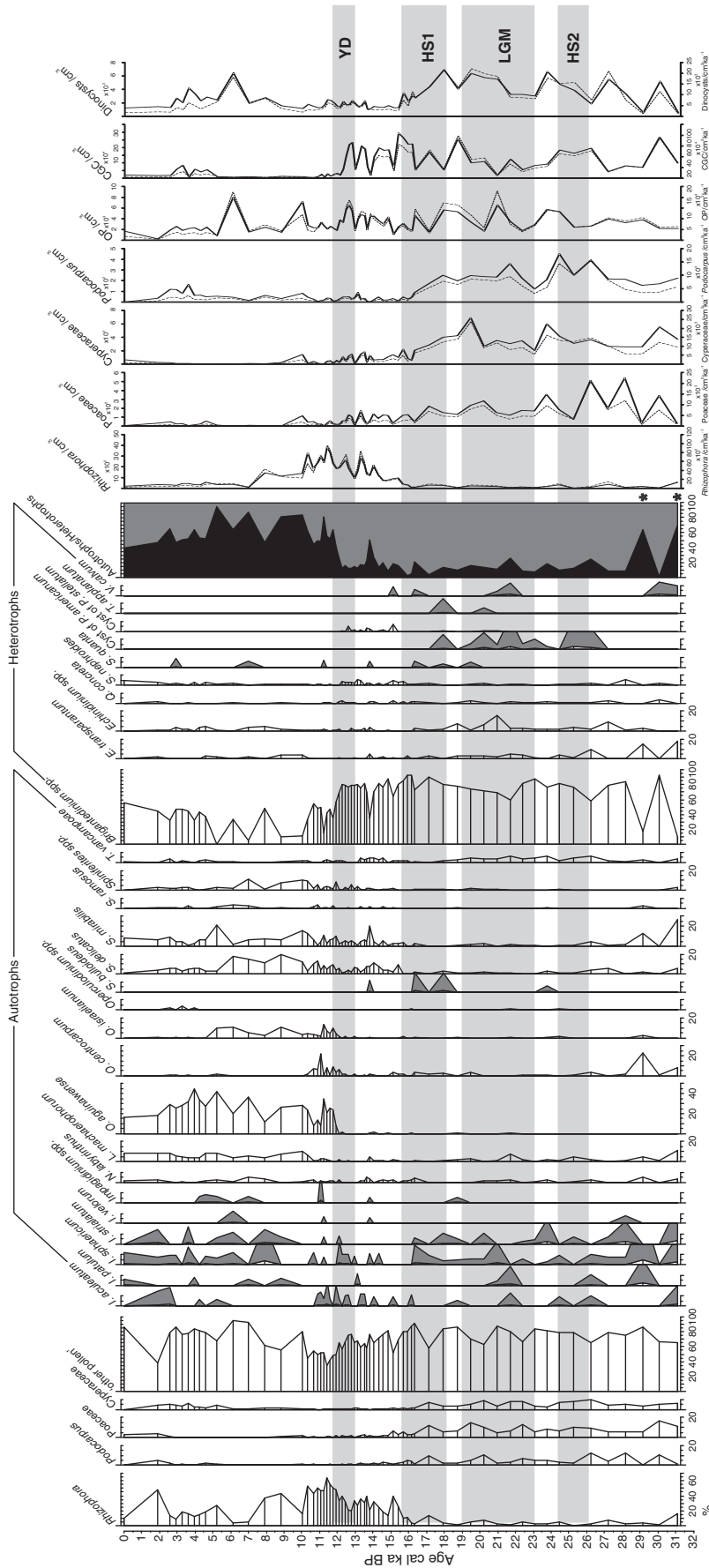


Figure 3. Diagram of percentages, concentrations (bold line) and fluxes (dashed line) for *Rhizophora* (mangrove taxon), *Podocarpus* (Afrotropical forest), *Poaceae* (open forest and savannahs), *Cyperaceae* (open swamps), non-identified other pollen (OP), dinocyst taxa, and charred grass cuticle concentrations and fluxes. Dinocyst taxa occurring in low percentages are shown at $\times 10$ exaggeration in gray. Heinrich Stadials 2 and 3, the LGM and the Younger Dryas chronozones are highlighted in gray. Samples with less than 100 cysts counted are indicated with an asterisk on the right side of the diagram.

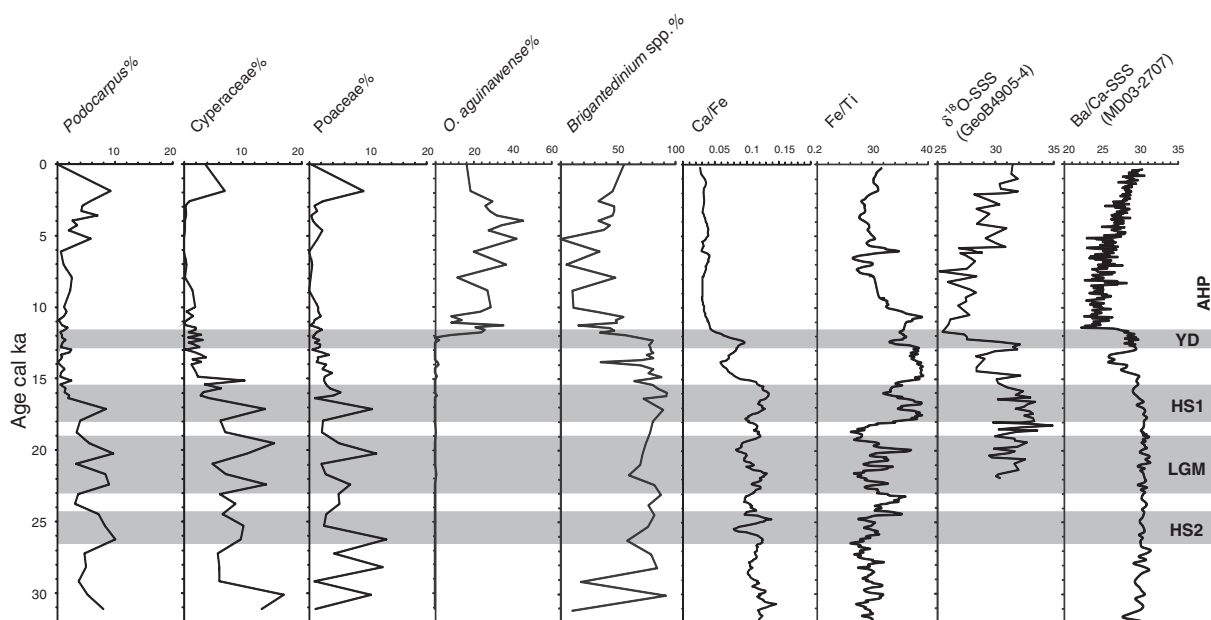


Figure 4. Comparison between relative abundance of *Podocarpus*, Cyperaceae, Poaceae pollen (calculated on a sum excluding *Rhizophora*), *O. aguinawense* and *Brigantedinium* spp. (calculated on a total dinocyst sum) with Ca/Fe and Fe/Ti ratios from core GeoB4905-4 (Adegbe et al., 2003; Itambi et al., 2010) and sea-surface salinity for core GEOB4905-4 based on $\delta^{18}\text{O}$ (Weldeab et al., 2005), and for core MD03-2707 based on Ba/Ca (Weldeab et al., 2007). Heinrich Stadials 2 and 3, the LGM and the Younger Dryas chronozone are highlighted in gray. The African Humid Period is outlined after Timm et al. (2010).

Discussion

Glacial to deglacial conditions in the eastern Gulf of Guinea and on the adjacent continent

The overall dominance of the heterotrophic taxa, *Brigantedinium* spp., suggests a context of high surface productivity that could be related to either a very active upwelling cell and/or river input. Previous studies in this region have found that preservation of this fragile taxon to be satisfactory (Zonneveld et al., 2007) and therefore changes in abundance should reflect surface productivity (e.g., Marret et al., 2008) as its modern global distribution suggests. Interestingly, similar high abundances of *Brigantedinium* were observed in last glacial maximum (LGM) records in the eastern part of the Gulf of Guinea (Dupont et al., 1998) and along the south west African coast (Shi et al., 2000; Marret et al., 2008; Kim et al., 2010, see Fig. 1). Their abundance has been related to enhanced productivity driven by coastal upwelling during the glacial. Therefore, it could be argued that a similar hydrographic context was in place off the Sanaga River mouth. However, diatom records suggest that during this time period enhanced diatom productivity was driven by either increased river input or by a river mouth closer to the core location due a lower sea level context (Crosta et al., 2012). Higher river input would have been related to increased precipitation during the glacial, as suggested by Crosta et al. (2012), but this interpretation is in contradiction with the terrestrial record which suggests drier conditions at that time, as seen by the relative high abundance of open vegetation taxa. The presence of *Impagidinium*, a fully open oceanic taxon, is indicative of sea-surface salinities above 30, a conclusion supported by the estimated SSSs from the geochemical proxies (Fig. 4), both therefore suggesting a low fluvial input. These results also support the notion that high values of Ca/Fe reflect constant biogenic sedimentation and the hypothesis of enhanced marine productivity during the last glacial period (e.g., Kallweit et al., 2012). The low values of the Fe/Ti ratio also indicate low fluvial input.

Our data, in combination with the other biological and biogeochemical proxies, confirm that productivity was enhanced; the proximity of

the river mouth due to a lower sea level may have contributed to nutrient input even in a context of low flow regime. Evidence of a drier short episode around 20 ka BP as highlighted by a decrease of diatom productivity (Crosta et al., 2012) is not observed in our record, possibly due to the lower resolution of our record or the impact being negligible on the marine and terrestrial ecosystems.

Soil availability and therefore nutrients may have been enhanced due to erosion facilitated by an open landscape. The pollen record off the Sanaga shows that savannah, swamp and Afromontane vegetation were significantly present in the Sanaga catchment region. In this respect, these data concur with other marine pollen records from farther south (e.g., Dupont and Behling, 2006) and west (Lezine and Cazet, 2005) (see Fig. 1 for site location). Charred grass cuticles are also particularly abundant during this period and may be related to higher incidence of savannah fires. The important contribution of *Podocarpus* in the pollen assemblages of our core corroborates the hypothesis of the extension of Afromontane vegetation into lower elevations due to lower temperature on the continent and the establishment of low and non-precipitating stratiform clouds due to lower SSTs in the adjacent ocean (e.g., Maley and Brenac, 1998).

The pattern of drier/cooler conditions during the LGM is in agreement with the available continental pollen records (e.g., Gasse et al., 2008) and sea-surface conditions (Weldeab et al., 2007; Waelbroeck et al., 2009). This cooling pattern in the ocean and on the continent, associated with drier conditions on the continent, supports the hypothesis of a strong latitudinal temperature and summer insolation gradient displacing the monsoon system southwards (Davis and Brewer, 2009). This contradicts the rainfall reconstruction for the equatorial zone based on *n*-alkane records by Collins et al. (2011), based on their interpretation of more C_3 vegetation during the LGM and Heinrich Stadial 1. However, it is possible that some of the C_3 vegetation may have included Afromontane taxa that are indicators of cooler and not necessarily wetter conditions. Although the proportions of C_3 and C_4 in marine sequences can help to broadly discriminate between tree/shrub (C_3) and grass/sedge (C_4) vegetation types, they do not allow the characterisation of the vegetation composition, such as rainforest

versus dry forest since both are C_3 . However, the combination of *n*-alkane with pollen assemblage data should better constrain the source of C_3 vegetation.

Our data show significant change around 15.6 cal ka BP, with the increase of two significant dinocyst species; *S. delicatus*, a species whose modern distribution in the tropics is related to stable and nutrient-rich conditions at the margins of river plumes (Dale et al., 2002; Marret and Zonneveld, 2003) and *S. mirabilis*, a thermophile taxon, both showing a strong increase compared to the preceding glacial period. In parallel, two other taxa, *Nematosphaeropsis labyrinthus* and *Selenopemphix nephroides* show a slight increase, both taxa recently associated with nutrient enrichment (e.g., Marret et al., 2004; Holzwarth et al., 2010; Rouis-Zargouni et al., 2010). In addition, a few occurrences of the low-salinity tracer *O. aguinawense* were also recorded. The marine signal therefore suggests a warming of surface waters, accompanied with lowering of salinity in relation to increased river discharge. These changes are more or less coincident with the onset of the African Humid Period (AHP) (e.g., Timm et al., 2010) and in agreement with the strong increase of diatom productivity and abundance of freshwater diatoms (Crosta et al., 2012). A significant shift in the pollen record is also observed, slightly before, with a steady increase of *Rhizophora* pollen. As similar changes are observed farther south off the Congo River mouth (Scourse et al., 2005) and the Ogooué (Kim et al., 2010), it is likely that our *Rhizophora* data also reflect expansion of mangrove habitat across the shelf and erosion of shelf sediments as sea level rose. Percentages of Poaceae, Cyperaceae and *Podocarpus* depicted in Figure 4 (calculated on a total sum that does not include *Rhizophora*) strongly decrease around 15 cal ka BP, suggesting a significant change in the adjacent vegetation, possibly with an increase in forest elements. However, without a correct identification of the specimens contained in the 'other pollen' group, it is not possible to confirm this, although marine pollen records farther south show the return of the rain and dry forests around 15 cal ka BP (Marret et al., 2001, 2008; Hessler et al., 2010, 2012; Dupont et al., 2008).

The warming trend identified from the increase of thermophile dinocyst species is consistent with the increase of insolation at the low latitudes with a weakening of the latitudinal temperature gradient, which consequently enabled the establishment of monsoonal precipitation. In parallel, the decrease of the Ca/Fe ratio slightly after 15 cal ka BP (Fig. 4) can be related to an influx of Fe as fluvial activity increased. A sharp decrease in salinity is observed later, around 12 cal ka BP, as indicated by the strong increase of *O. aguinawense* and the $\delta^{18}O$ -SSS data. Compared to the Congo fan record, where a major peak of river discharge has been reported, centered around 13.5 cal ka BP (Marret et al., 2001; Barker et al., 2004), our data do not report extreme flooding events at this time. However, the coherence between the different proxies from each site (Sanaga, Ogooué and Congo) strongly suggests that the increase in precipitation was due to a very rapid northward shift of the monsoonal system and the ITCZ.

Rapid climatic transitions: Heinrich Stadials (HS) and the Younger Dryas (YD)

This high-resolution record enables the investigation of the response of the equatorial vegetation and marine proxies at the time of well-defined abrupt climatic events in the Northern Hemisphere such as HS2 (from 26.5 to 24.3 cal ka BP), HS1 (from 18 to 15.6 cal ka BP), and the Younger Dryas chronozone (also defined as the Greenland Stadial 1 or GS-1, from 12.9 to 11.7 cal ka BP) (Lowe et al., 2001; Sanchez-Goni and Harrison, 2010). The end of HS3 (from 32.7 to 31.3 cal ka BP) is only partially recorded at the base of our record and cannot therefore be discussed in any detail. However, it is noticeable that the changes that might represent this event are observed in other marine records around 30 cal ka BP along the west African coast, including an increase of *Operculodinium centrocarpum* shortly after 30 cal ka BP, reaching a maximum around 29 cal ka BP, off the Congo

(Marret et al., 2008) and Ogooué (Kim et al., 2010), although the dinocyst counts in core Geob4905-4 of only approximately 50 cysts during this time interval may not accurately reflect the full assemblages. In the Atlantic tropical region, *O. centrocarpum* has been associated with rapidly changing and/or unstable conditions (e.g., upwelling) (Dale et al., 2002; Marret and Zonneveld, 2003). This pattern may reflect cooling associated with enhanced upwelling conditions along the west African coast.

Our dinocyst assemblages show no significant shift during HS2 and HS1 while the pollen record shows fluctuations within the open vegetation taxa (Cyperaceae and Poaceae), although the diatom data record very low productivity during HS1 associated with drier conditions (Crosta et al., 2012). An explanation for this discrepancy may be due to the resilience of the vegetation to climate fluctuations, or distance from a major ecotonal transition, during the glacial period. The apparent non-response of the dinocyst assemblages suggests that this marine group was predominantly driven by nutrient availability. However, the end of HS1 is characterized by the strong decrease of open vegetation indicators and an increase in the mangrove that may indicate a return of wetter conditions. This subdued representation in tropical Africa to these northern latitude events has been recorded previously, and supports the notion that the eastern Atlantic Ocean tropics played little role in influencing rapid climatic changes during the deglacial period. It is therefore possible that the southerly position of the ITCZ during the glacial period hindered the impact of cooling during HS or that the impact of the HS during glacial time was not strong enough to register significant change in this region.

Significant changes occurred between 12.8 and 11.25 cal ka BP in both the biological and geochemical proxy records (Fig. 4). Small peaks of open vegetation indicators, as well as high values of the heterotrophic taxon *Brigantedinium* and $\delta^{18}O$ -SSS values mark the beginning of the YD chronozone. A sharp increase in the low-salinity indicator *O. aguinawense* as well as a strong decrease of $\delta^{18}O$ -SSS and a more subdued decrease in Ca/Fe characterize the end of the YD. These suggest an episode of drier and possibly cooler conditions at the beginning of the YD, conditions also reflected in the decrease of diatom productivity (Crosta et al., 2012) and followed by a return of wetter conditions before the end of the YD. This early return of monsoonal conditions observed in our core is consistent with other findings from east and west equatorial Africa that record an abrupt northward shift of the ITCZ at the end of the YD (e.g., Talbot et al., 2007; Gasse et al., 2008). The mechanisms behind this abrupt shift may be explained by a global atmospheric reorganization in relation to a weakening in the latitudinal temperature gradient (as observed with the increase in SST) as insolation increased and polar ice sheets retreated (Davis and Brewer, 2009).

The African Humid Period and the mid- to late Holocene climatic variability

After an initial sharp decrease in the open vegetation indicators at the end of HS1, the gradual establishment of the AHP can be seen with a steady decrease of open vegetation and Afromontane indicators between 16 and 15 cal ka BP (Fig. 4); this trend is also coincident with an increase in mangrove, reflecting both an extension of the mangrove on the coast and a flooding of shelves due to sea-level rise. In the marine domain, the dinocyst record suggests an increase of SSTs. SSS proxies and diatom records (Crosta et al., 2012) also document this gradual increase of precipitation. It is from the end of the YD that salinity may have reached a minimum, suggesting a complete development of monsoonal conditions over the Sanaga catchment region. The low values for the open vegetation reach a minimum between 6 and 7 cal ka BP, suggesting an extended forest cover in the Sanaga basin similar to conditions in the Congo basin (Marret et al., 2008). The *Podocarpus* increase that is observed from 8 cal ka BP is coherent with other records that register similar expansion of the Afromontane vegetation (e.g., Assi-Kaudjhis, 2012).

Although the resolution of the record for the mid- to late Holocene section is only millennial to sub-millennial, rapid changes seem to have occurred before 5 cal ka BP, with a sudden increase of *Podocarpus* as well as an increase in SSSs. Open vegetation returns, coincident with an increase in nutrient-related dinocyst species. These changes mark the end of the AHP, around 5.5 cal ka BP, with a strong reduction in fluvial input, although the nutrient input remains high, possibly related to soil erosion as the forest cover diminished. The strong fluctuations of *Podocarpus* percentages between 5.5 and 1.8 cal ka BP have also been previously recorded farther south and west (Lezine and Cazet, 2005; Marret et al., 2006; Dupont et al., 2007; Kim et al., 2010) and over the adjacent continent, together with a reduction in the rainforest cover, expansion of dry forest and savannah, and lower lake levels (e.g., Marchant and Hooghiemstra, 2004). These significant changes in vegetation and lakes have been explained as drought events in association with a decrease in SSTs (Weldeab et al., 2005) in the equatorial Atlantic. A lowering of SSTs would have affected the land–ocean temperature gradient, weakening atmospheric convection and reducing monsoonal precipitation. The millennial fluctuations recorded between 5 and 2 cal ka BP in the relative abundance of *Podocarpus*, as well as in $\delta^{18}\text{O}$ SSS, might reflect rapid changes in monsoon dynamics. Our dinocyst record for the late Holocene also indicates a cooler ocean compared to the early Holocene, as indicated by the strong decline of thermophile species (*S. mirabilis*, *Operculodinium israelianum*). Although the last few thousand years are of low resolution in the Sanaga record, they reflect an increasing trend towards drier/cooler conditions on the continent and possibly an increase in productivity in the ocean, with cooler and more saline conditions.

Conclusions

Analysis of the dinocyst and pollen assemblages in core GeoB4905-4 has enabled an investigation of the linkages between ocean–atmospheric–land systems over the last 30,000 yr in the eastern part of the Gulf of Guinea. The data indicate a strong correlation between weak (strong) monsoonal conditions, high (low) sea-surface salinity and low (high) sea-surface temperatures. The timing of dry to humid conditions registered in the terrestrial proxies is coherent with other records from across central equatorial Africa in the context of increasing insolation. Dry conditions characterized the glacial period, including the LGM, and marine productivity was enhanced, likely due to the proximity of the river mouth and nutrient supply. The onset of the AHP is clearly registered in our record with an initial sharp decrease in open vegetation between 17 and 16 cal ka BP likely linked to a gradual increase in monsoonal activity. The period of wettest conditions, as documented by the SSS proxy and terrestrial indicators, occurred after the YD.

Millennial-scale variability is detected during the deglaciation, in particular associated with the Younger Dryas, which is more clearly represented in the marine domain than in the terrestrial record. This may indicate either resilient vegetation and monsoonal conditions suitable for the establishment of forest vegetation, or distance from a major ecotonal boundary. Other millennial-scale fluctuations (HS) originating in the Northern Hemisphere are not strongly registered in the marine record and only slightly in the pollen record. In contrast, it is likely that changes in the latitudinal temperature gradient have a strong influence in the southward/northward migration of the ITCZ, and in that respect the YD was registered clearly as it occurred during the warming phase when the ITCZ was migrating northward. Overall, our record demonstrates coeval millennial-scale variability in river-discharge, vegetation and marine proxies, highlighting the sensitivity of the tropical vegetation to moisture content and marine ecosystems to salinity, temperature and nutrient variability.

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