Clim. Past Discuss., 7, 305–345, 2011
www.clim-past-discuss.net/7/305/2011/
doi:10.5194/cpd-7-305-2011

Climate
of the Past
Discussions

# Past environmental and climatic changes during the last 7200 cal yrs BP in Adamawa Plateau (Northern-Cameroun) based on fossil diatoms and sedimentary $^{13}$C isotopic records from Lake Mbalang

**V. F. Nguetsop**[1,2], **I. Bentaleb**[2], **C. Favier**[2], **C. Martin**[2], **S. Servant-Vildary**[3], and **M. Servant**[3]

[1]University of Dschang, Department of Plant Biology, P.O. Box, 67 Dschang, Cameroon
[2]Institut des Sciences de l'Evolution (UMR CNRS 5554), Université Montpellier II – pl. E. Bataillon, case courrier 061, 34095 Montpellier cedex 05, France
[3]IRD Bondy, 32, Avenue Henri Varagnat, 93143 Bondy, France

Received: 3 December 2010 – Accepted: 27 December 2010 – Published: 21 January 2011

Correspondence to: V. F. Nguetsop (vfnguetsop@yahoo.fr)

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

## Abstract

Past limnological conditions of Lake Mbalang (7°19′ N, 13°44′ E, alt: 1130 m) and vegetation type were reconstructed from diatoms and sedimentary stable carbon isotope records ($\delta^{13}$C) since 7200 cal yrs BP. The data showed that before 3600 yrs cal BP the water column was preferentially cold and stable except around 5000–5300 cal yrs BP where diatom evidenced mixed upper water layer, $\delta^{13}$C data suggest more forested vegetation in the landscape. These stable conditions can be explained by a strong monsoonal flux and correlatively northern position of the ITCZ that entailed high/low rainfall well distributed over the year to allow the development mountainous forest taxa. The decreasing trend of the monsoonal flux towards mid-Holocene was however affected by several centennial to millennial time scale abrupt weakening at 6700, 5800–6000, 5000–5300, 4500 and 3600 cal yrs BP although their impact on vegetation is not visible probably because rainfall distribution was favourable to forest maintenance or extension. After 3600 cal yrs BP, water column became very mixed as a result of more intense NE trade winds (Harmattan) that led at ~3000 cal yrs BP to the instalment of savana in the vegetation landscape. At that time, rainfall was probably reduced following the southwards shift of the ITCZ and the distribution of yearly rainfall was no more favourable to forest development. Thus a strong seasonality with a well marked dry season was established, conditions that maintained the savana vegetation till today. Diatom data suggest the lake did not dried during the last 7200 cal yrs BP, however, a low lake level observed at 2400–2100 cal yrs BP is contemporaneous to a climatic event evidenced in several areas of tropical Africa and could correspond to the southernmost position of the ITCZ. Other low lake levels are observed at 1800 and 1400 cal yrs BP, after which lake rose to its present level.

## 1 Introduction

Climatic changes during the Holocene in Western Africa have been mostly studied in the forest subequatorial and Sahelian/arid regions. The two regions are submitted to the monsoonal atmospheric flux from the tropical Atlantic that reaches its northern maximum extension during the northern summer (July–August) in present days. It is present over the year in the northern subequatorial regions except during a 3-month dry season centered in January. At these latitudes, this monsoonal flux is characterised by a deep atmospheric convection; however, a relative stability of the atmosphere at low levels, at the base of the monsoonal flux is observed in July–August when the Intertropical Convergence Zone (ITCZ) is farthest North. Convective rainfalls are almost suppressed during this period of the year at the northern border of the Guinean Gulf.

During the Holocene, the monsoonal flux penetrated less or more deeply inside the Saharan region entailing an alternation of wet and dry phases (e.g. Servant and Servant-Vildary, 1980; Gasse, 2000), superimposed on a general trend of monsoonal weakening flux in response to decreasing summer insolation of the Northern Hemisphere (Kutzbach and Street-Perrot, 1985). Modifications in the intensity of the monsoon were also suggested by changes of precipitation *minus* evaporation balance at subequatorial latitudes (Talbot and Delibrias, 1980; Nguetsop et al., 2004).

Concordant data from low and high altitudes in Western Cameroon (Maley and Brenac, 1998; Reynaud-Farrera et al., 1996; Nguetsop et al., 1998; Stager and Afang-Sutter, 1999; Vincens et al., 1999; Ngomanda et al., 2007, 2009b; Kossoni et al., 2009) suggest that climatic changes were also controlled by modifications in the vertical structure of the atmosphere (Nguetsop et al., 2004). The present stable air layer situated at the base of the monsoonal flux in July–August could have extended on the western Cameroon lowlands and mid altitude areas during the greatest part of the year entailing the almost suppression of convective rains before 3000 yrs BP. After that date, the influence of the stable air layer has been strongly reduced and convective rainfall reappeared. If this is true, one can expect different climate evolutions between lowlands

south of the Adamawa plateau, mid altitude regions as Adamawa (1000–1100 m), and western Cameroon highlands (> 2000 m).

Available paleoclimatic records of the last 3000 years in the tropical zones of Africa; close to the Atlantic coast of Gabon, West-Cameroon and South-Congo (Ngomanda et al., 2009a; Nguetsop et al., 2004; Vincens et al., 1999) suggest significant modifications in abundance and/or seasonal distribution of rainfall in response to north south shift of the Intertropical Convergence zone (ITCZ). Thus, climatic changes affected in the past water resources that impacted on human populations and vegetation landscape of central and north tropical Africa. Paleoenvironmental studies showed that the rain forest belt was reduced and persisted only in refuge zones during the Last Glacial maximum (e.g. Maley, 1987). Between ~ 2500–2000 yrs BP, the rain forest was strongly disturbed or was replaced by savannas depending on the sensibility to climate change of each site in central Atlantic Africa (Vincens et al., 1999). The present day “hot spots” of biodiversity (Tchouto et al., 2006) and the spatial heterogeneity of the rain forest are probably inherited from past climate changes. The question is how the Adamawa plateau located between the dry zones in the North and wet areas in the south responded to this major climatic change.

The objective of this paper is to reconstruct the past 7200 cal yrs BP climate of the Adamaoua area based on diatoms analysis and sedimentary carbon stable isotopic record ($\delta^{13}$C) of a core retrieved in Lake Mbalang. Specifically, past limnological conditions will be accessed through the analysis of diatom ecological groups; variations in trade winds (Harmattan and monsoon) intensity will be reconstructed from allochtonous diatom taxa, or species that characterises stable water table. The vegetation type (C3 versus C4 plant balance) and/or lake will be reconstructed through the evolution of sedimentary $\delta^{13}$C compared to published palynological data (Vincens et al., 2010).

## 2 The site

### 2.1 Location and general characteristics of the studied lake

Lake Mbalang (7°19′ N, 13°44′ E, alt: 1130 m) lies on the Adamawa plateau that belongs to the Cameroonian volcanic line (Fig. 1). This high topographic unit (850–1200 m) extends between 6° and 8° latitude north and between 11°30′ to 15°45′ longitude east. The plateau is limited in the North by the relatively lowlands of the Benue plain (800–300 m) and in the South by sub-Cameroonian plateau (800–500 m). Crystalline and foliated metamorphic rocks composed the substratum of this unit that is largely covered today by ancient volcanic basaltic flows differently altered from one region to another (Humbel, 1967). According to Gèze (1943), in the Adamawa as in the whole volcanic line of Cameroon, three volcanic series can be encountered: the lower black series (upper Cretaceous to upper Eocene), the medium white series (end of Neogene) and the upper black series (Quaternary). These series are composed respectively by basalts and andesites conserved as yellowish clays, trachyte and phonolithe lavas, and basaltic volcanic deposits. Volcanic and ferralitic material in form of dome and outcrops is encountered at the vicinity of the lake. Soils are mostly ferralitic, rich in aluminium and iron oxides with frequent neoformation of halloysite and kaolinite. Other clay mineral present include gibbsite and siderite.

The lake, with a surface area of 50 ha, is a volcanic maar described as an asymmetric bowl with steep slopes. The water maximum depth is about 52 m. The euphotic zone is 3.45 m deep according to Kling (1987). Lake Mbalang moderately stable; however a relatively cool epilimnion is subjected to period of surface warming in a time of low wind stress (Kling, 1987). Water columns are then affected by yearly modifications of mixing depth that could be attributed primarily to higher temperatures as well as intensity of storms or maximum wind speed. The lakes is fed only by rainfall and runoff from the catchments, water losses occur through evaporation; however a surface outlet is present at the southern part of the lake but functions only during very high lake levels over the year. The $^{210}$Pb profiles along the first 80 cm of the sediment in the lake

showed that the sedimentation is regular, hence fossil sediments of the lake can be presumably suitable for paleoenvironment studies (Pourchet et al., 1987).

### 2.2 Vegetation

The Adamawa region is occupied by tree or shrub savannas characterized by *Daniellia oliveri* (*Caesalpiniaceae*) and *Lophira lanceolata* (*Ochnaceae*); these savannas are strongly altered in some areas due to their permanent use as grazing ground. Highest altitudes areas are occupied by soudano-guinean vegetation dominated by *Hymenodyction floribundum* (Letouzey, 1968, 1985). The edges of the lake are more forested with taxa as *Croton macrostachyus, Sterculia tragacantha, Polyscias fulva, Rauvolfia vomitoria, Pittosporum mannii, Ficus capensis*, etc. Typical savanna trees encountered were *Annona senegalensis, Allophilus africanus, Cussonia barteri, Piliostigma thonningi, Terminalia glaucescens* and *Harungana madagascariensis*.

### 2.3 Climate

The region is submitted to the influence of the altitudinal tropical climate that shows two distinct seasons: the dry season that last from November to March and the rainy season from April to October with rainfall maxima in July–September. The mean annual rainfall is 1500 mm; mean annual temperature varies from 23 to 26 °C (Suchel, 1988). In a classic picture, seasonal changes are explained by the displacement during the year of the intertropical convergence zone (ITCZ) in direction of the most heated hemisphere. During the dry season (boreal winter), the ITCZ is located south of the Adamawa plateau, the zone is then under the influence of the dry north-eastern trade winds (Harmattan). It moves northwards during the rainy season (boreal summer), the zone is then submitted to the influence of humid south-western air masses (monsoon flux) that bring precipitation. However, the African Easterly waves may strongly modulate the spatial organisation of rainfall over West Africa (Nicholson, 2009).

## 3 Material and methods

### 3.1 Description of the core

The core was collected in March 1998 at the centre part of the lake (44 m deep) with a Mackereth air-compressed corer by Ecofit program team. The lithology of the 6 m long core showed globally a dark clayey organic mud with clearer/darker laminas at certain levels. Coarser sandy laminas are observed at the base of the core (540 and 570 cm). Preliminary observations of thin-sections showed that biogenic particles composed of spongiae spicules and diatoms are present throughout the core (Fig. 2). Phytoliths and spicules were observed and counted during diatom counting under light microscope, but not identified to generic or specific level. Minerals such as siderite, quartz, feldspars and augite can also be observed in form of layers or scattered in the sediment (Ngos et al., 2008).

Spicules are more abundant at the base of the core (587–225 cm), the ratio spicules/diatoms counted is relatively high ($> 20 \times 10^{-2}$). The most important peaks appeared at 535 cm ($3664 \times 10^{-2}$), at 557 cm ($363 \times 10^{-2}$), at 508 cm ($649 \times 10^{2}$) and between 391 and 379 cm ($403–500 \times 10^{-2}$). At the upper part of the core, the ratio was generally low ($< 10 \times 10^{-2}$), the only relatively high values are observed at 182 cm ($89 \times 10^{-2}$) and 67 cm ($35 \times 10^{-2}$). The ratio phytoliths/diatom followed broadly the same pattern of variation as spicules/diatoms but values are lower, peaks are evidenced at 557 cm ($1208 \times 10^{-2}$), 535 cm ($2545 \times 10^{-2}$) and at 508 cm ($1607 \times 10^{-2}$). Relatively low ratios are observed between 587–585 cm ($17–31 \times 10^{-2}$), at 544 cm ($141 \times 10^{-2}$) and at 526 cm ($290 \times 10^{-2}$). A decreasing trend is observed towards the top of the core, the ratio reaches values close to $2 \times 10^{-2}$ between 39–26 cm (Fig. 2).

### 3.2 Radiocarbon dates

The chronological control is based on nine AMS radiocarbon dates performed on total organic matter (Table 1). Four of the nine dates (indicated by stars) were already published and discussed in previous articles (Ngos et al., 2008; Vincens et al., 2010). The other five radiocarbon dates were processed at the Laboratoire de Mesure du Carbone 14 (Salclay, France) with the ARTEMIS AMS facility. The calibration of $^{14}$C yr BP into cal yr BP was performed using the radiocarbon calibration program Calib Rev 6.0 (Stuiver and Reimer, 1993). Eight of the nine dates showed a good internal consistency as function of depth while one performed at 102 cm appeared younger than expected (1760 ± 30 yrs BP). Its may indicate an increase of sedimentation rate as it is observed in Lake Assom (Ngos et al., 2003) and possibly in lake Tizong in the southern part of Adamawa between 1300 and 2800 yrs BP. The lithology of the core did not show any particular unit that could indicate the changes of sedimentation, nevertheless the ratio quartz and plagioclase over kaolonite and gibbsite revealed an elevation of coarse elements in the core at 125 cm (Ngos et al., 2008) but the time resolution is not good enough to confirm the change. Here we consider the date younger as a result of allochtonous or reworked organic material and consequently the date was excluded in constructing the age model. The remaining eight dates allowed a construction of a polynomial depth-age model (Fig. 3) in order to calculate by extrapolation the estimated age of each studied sample. This age model was also applied to recent period (between 535 and the present) because $^{210}$Pb analyses are not yet available for accurate calculation of sedimentation rate for that period of time.

### 3.3 Diatom analyses

Diatom slides were prepared from ~ 0.5 g of dry sediment by gently heating in 30% hydrogen peroxide (Battarbee, 1986) followed by several washings with distilled water. Few drops (0.2 ml) of the resulting residue suspended in distilled water were evaporated onto a coverslips, which was subsequently mounted on a glass slide with

Naphrax$^{TM}$. At least 600 diatom valves were counted per sample or approximately 200–300 valves when the diatom concentrations were too low. Counts were done at magnification 1000× with oil immersion objective ($na = 1.32$) using an Olympus BHT light microscope equipped with Nomarski optics. Diatom preservation was good throughout the core.

Identification and taxonomy of diatoms were based principally on Krammer and Lange-Bertalot (1986–1991), Gasse (1980, 1986), Germain (1981), Schoeman (1973), Simonsen (1987).

Ecological interpretations are essentially based on the modern data of Lake Ossa area (Nguetsop, 1997; Nguetsop et al., 2010) coupled with previously documented taxa preferences in other regions of Africa (Gasse et al., 1995; Servant-Vildary, 1978), for most including taxa counts and water-chemistry characteristics at sampling sites.

### 3.4 Stable carbon isotope analyses

For measurement of carbon stable-isotope content and C/N ratios, 90 samples were taken along the core at intervals varying between two and 16 cm with an average interval sampling of six cm. Samples were dried at 50 °C for 48 h. We did no proceed to decarbonation due to high organic matter content in the lake. About 1 cm$^3$ subsamples were grounded using a mortar pilar and sieved through a 60 µm mesh. About 0.5 mg sediment powder is weighed and introduced in tin capsules prior to elemental and isotope analysis. Elemental C and N contents (%) and carbon isotope values of sediment were measured by dry combustion on a Euro Vector 3000 Elemental Analyzer coupled with a Micromass Optima Isotope Ratio Mass Spectrometer at ISEM laboratory (Montpellier). The C isotope results are expressed in delta ($\delta$) notation where: $\delta(‰) = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 1000$ where $R_{\text{sample}}$ and $R_{\text{standard}}$ refer to the $^{13}C/^{12}C$ ratios of sample and standard, respectively. $\delta^{13}C$ values are reported in parts per thousand (‰) relative to the Vienna Pee Dee Belemnite (VPDB) standard. Precision

for isotope measurements of chemical standards (Nist-8541 graphite and alanine international standards) within sample runs were better than 0.2‰.

## 4 Results and interpretations

A total of 98 species and varieties of diatoms were identified in the 48 studied samples of the core M4. Figure 4 shows the evolution of the most represented species (≥ 5% in at least one sample). The ecological preferences of diatoms allowed the individualization of 2 major phases (with 6 sub-phases) in the paleohydrological evolution of the lake. Planktonic diatoms were present throughout the core indicating that Lake Mbalang has never dried. This assumption is reinforced by the fact that benthic, epiphytic and aerophilic diatoms remained consistently low along the core (Fig. 5). C:N and $\delta^{13}C$ are negatively correlated along the core. This covariation is not a sign of post depositional changes of the original isotopic characteristics of the primary organic matter but we will show thanks to this multi-proxy study that the concomitant increase of the $\delta^{13}C$ and Poaceae pollen evolution (Vincens et al., 2010) together with a decrease of the C:N ratios (14 to 10) can be interpreted in terms of paleolimnological and paleovegetation variations forced by climatic changes.

### 4.1 Phase I: Between 587 and 320 cm

The diatom flora of the lake was dominated by the oligotrophic, acidophilous tychoplanktonic diatoms represented essentially by *Aulacoseira distans* var. *humilis* and *A. distans* var. *africana*. These taxa were reported in several tropical swamps and swampy lakes from East Africa as Lake Kioga (Uganda) and in the swamps of Bangweulu (Zambia). In Lake Kioga (altitude 1036 m) they can represent up to 75% of the plankton samples (Gasse, 1986). From the study of the modern diatom and associated water characteristics of Saharan/Sahelian zones, Gasse (1987) concluded that these species thrives better in cold stratified water conditions. In acidic relatively deep lakes Horn and Big Moose (7.9 and 22 m deep), they represent only 0.83 and 0.68% of the diatom flora respectively. High percentages (40–80%) of these taxa are encountered in the modern data set of Adamawa in bottom mud of lake borders occupied by aquatic vegetation. In swampy locations, dominated by sedges and Poaceae, their abundance was relatively high (28%) (Kom, 2010). We thus inferred that these species are characteristics of relatively cold and stable, stratified water table that can be occupied by aquatic vegetation or not.

*From 587 cm to 470 cm (subphase Ia)*: Tychoplanktonic abundances were very high (44–91%) suggesting generally acidic, oligotrophic and cold stratified water table. The relative abundance of benthic *Stauroneis phoenicenteron* at 557 cm (31%), 526, 508, 498 cm (7–14%) may suggest a more stable and clearer water column or a sharp lowering of water depth. However planktonic diatoms represented mainly by *A. muzzanensis* are also present but exhibits relatively low abundance, their highest abundance in this sub-phase is observed between 587 and 574 (16–22%). *A. muzzanensis* is considered as a eutrophic (Hustedt, 1927–1966; Cholnoky, 1968), planktonic taxa (Shoeman, 1973), encountered in the plankton of lakes and great rivers (Hustedt, 1930; Krammer and Lange-Bertalot, 1991) but it can also occurs in some lakes in shallow turbid waters. Their presence can thus be interpreted in this sub-phase as a result of relatively high water depth and episodic mixing of water table during episodes of wind stress or high temperatures, conditions that occur in the area during the dry season. $\delta^{13}$C values are low (−32 to −25‰) are consistent with a C3-dominated terrestrial flora. Some very low $\delta^{13}$C values (−32‰) may also be due to the presence of plant material influenced by the isotopic effects of a dense, closed canopy forest that developed at that time. However, phytoplankton with a $\mathrm{CO_2}$-based metabolism can also be suggested for the depleted $\delta^{13}$C especially for some observed $\delta^{13}$C peaks that are coincident to the increase of eutrophic pH-indifferent taxa (Fig. 5b and c) covarying with positive $\delta^{13}$C excursions that might reflect the presence or the vicinity of the aquatic vegetation. Though epiphytic diatom abundances (*Amphora ovalis*, *Cocconeis placentula* and varieties and *Gomphonema gracile*) remained consistently low, the hypothesis is nevertheless supported by high values total organic carbon (Ngos et al., 2008).

*From 470 to 420 cm (subphase Ib)*: Planktonic diatoms represented mainly by *A. muzzanensis* increased markedly and reached 63–76% abundance while tychoplanktonic diatoms decreased. This suggests an increase of lake level and/or a well mixed water table. Benthic and epiphytic diatoms nearly disappeared; aerophilous taxa (*Eunotia incisa* and *E. pectinalis)* exhibit very low abundance (~ 3%). The trend of $\delta^{13}$C is similar to that of the previous but with values slightly higher (−29 to −24.5) coincident with very high abundances of eutrophic, pH-indifferent diatom taxa. We suggest that during this time, episodes of wind stress and high temperatures were longer than before, consequently lake level was relatively low at least episodically, but benthic and epiphytic taxa could not developed due to mixed, turbid water column. The high lake level can be explained by high and probably well distributed rainfall over the year that allowed the maintenance of forest vegetation as shown by $\delta^{13}$C data.

*From 420 to 320 cm (subphase Ic)*: Planktonics diatoms decreased significantly, tychoplanktonic species rose (up to 72%), indicating again a more stable stratified water column, short (centennial) spells of very low tychoplanktonics are observed on the decreasing trend. The relative increase of epiphytic taxa (9%) at 402 cm, aerophilous (6–13%) at 420–402 cm may indicate a slight lowering of lake level and a development of aquatic vegetation. This is also attested by a slight increase of spicules and phytoliths in samples. During this period, $\delta^{13}$C remained consistently low (−30.3 to −28‰) except at 394–395 cm where a peak is observed (−25.3‰) and C:N ratios vary between 12 and 14. However, this sub-phase is also characterized by the appearance of *A. granulata* var. *valida*, *A. granulata* var. *tubulosa* and *Stephanodiscus astraea*. Although these taxa are typical planktonic species, they should be interpreted with caution because in Lake Ossa area in southern Cameroon (3°50′ N, 9°36′ E), it was shown that they are originated from the Saharan diatomite deposits (Nguetsop et al., 2004). Hence their abundance in lake sediment was interpreted as an intensification of NE trade winds that are preponderant in Adamawa during the boreal winter rather than water depth or water trophic status changes. We can hypothesised that, the appearance of these taxa in Lake Mbalang marked as in Ossa area an intensification at least episodically of the NE trade winds.

### 4.2 Phase II: Between 320 cm and 0 cm

Planktonic diatoms, dominated by eutrophic *A. muzzanensis* indicated a high lake level and well mixed waters. Tychoplanktonics declined significantly during this period and nearly disappeared. Windblown diatoms are consistently present, even if their abundance showed important fluctuations. $\delta^{13}$C values range between −29.9 and −22.4‰ showing a significant increase from the base of this phase to the top indicating possibly the increasing proportion of C4 plant vegetation to the landscape cover and its carbon contribution to the lake sediment.

*From 320 to 237 cm (Subphase IIa)*: Eutrophic diatoms characteristic of well mixed layer increased and reached 57–62% at 249–237 cm. *A. distans* var. *humilis* and *A. distans* var. *africana* which are indicators of the stability of water table decreased markedly. $\delta^{13}$C values remained low at the beginning and increased at the end of the subphase. Contrarily to previous subphases, high abundances of eutrophic pH-indifferent diatoms are not associated to relatively high values of $\delta^{13}$C, suggesting a less influence of lacustrine organic matter in the isotopic signal though C:N ratios did not show differences with previous subphases. Higher values at the end of the subphase strongly suggest the increase of C4 plant vegetation debris in the lake sediment. The persistence of windblown diatoms showed an intensification of windiness on the lake environment. This phase marked an unequivocal change of climatic conditions in the area; from relatively more stable cold stratified water table reflecting probably a cool stable air at low layers of the atmosphere to more mixed water table linked to a reinforced seasonality.

*From 237 to 67 cm (Subphase IIb)*: This phase is marked by high fluctuations in abundances of planktonic taxa at plurisecular timescale. Although *A. muzzanensis* dominates throughout the sub-phase, *Fragilaria delicatissima* became more important

at 200 cm (13%), at 162 cm (52%); this taxa is also relatively abundant at 107 cm (10%) and at 85 cm (12%). Contrarily to *A. muzzanensis*, *F. delicatissima* is considered as an oligotrophic to mesotrophic taxa (Kammer and Lange-Bertalot, 1991). Lowest abundances of planktonics are observed at 226–212 cm, 194–182 cm, 135 cm and 92 cm. In these levels, the epiphytic (*Gomphonema. gracile, Amphora ovalis*, *Cocconeis placentula* and its variety *lineata*) and aerophilous (*Eunotia incisa* and *E. pectinalis* var. *minor*) diatom increased, indicating a lowering of lake level. Windblown diatoms relatively high abundance indicated the maintenance of the influence of the North eastern trade winds in the lake Mbalang environment. The development of *F. delicatissima* when windblown diatoms are low indicated probably a less mixed water table and/or a slight increase of lake level. This idea is reinforced by the fact that epiphytic, benthic and aerophilous are very low. The sub-phase represent probably the period of time during which short time maximum climate variability occurred. However this variability is not reflected on $\delta^{13}$C, only minor fluctuations are observed on relatively higher values suggesting the maintenance of C4 plants in Lake Mbalang environment.

*From 67 cm to 0 cm (Subphase IIc)*: High abundance of planktonics indicates a persistence of high lake level. The two main planktonic alternated at this level, the changing from *Aulocoseira* to *Fragilaria* dominated assemblage in diatom community is interpreted as the changing to more clear water column or shallowing, reduced mixing when P:E is low (Stager and Anfang-Sutter, 1999). This may also indicates important changes in water trophic status. Among others taxa, only *Gomphonema gracile*, *Cocconeis placentula* and its variety *lineata* remained present with percentages close to those of the precedent zone. The $\delta^{13}$C data suggest the maintenance of C4 plants.

## 5 Discussion

The variations of the abundances of planktonic and tychoplanktonics can be considered as indicators of lake level changes (Fig. 7a) although the curve should be interpreted with caution because they can also thrive in large free water surface. Acidophilous oligotrophic and tychoplanktonic *Aulacoseira distans* var. *humilis*, *A. distans* var. *africana* and planktonic taxa *Fragilaria delicatissima* are characteristic of stable stratified water table, which presupposes also a relatively stable air layer over the lake. These conditions occur in Lake Mbalang today when the cool epilimnion is affected by surface warming during period of low wind stress (Kling, 1987). Such weather conditions can thus be attributed to a more intense monsoon that entails conditions which characterize today the south-eastern Cameroon, Gabon, and south Congo during the northern summer when subsiding air masses present at mid-levels generates stability at low atmospheric levels. Nowadays, the two first species are abundant in both relatively low to high water tables at lake borders, in shallow water bodies or in swampy areas where the strength of winds is weakened by aquatic vegetation but they are here associated to epiphytic taxa. High abundance of the two species in the past can suggest conditions close to boreal summer conditions and/or the development of aquatic vegetation. Conversely the planktonic *Aulacoseira muzzanensis* and *Aulacoseira granulata* thrive better in well mixed water table, that are associated to high temperatures, intense storms and windiness, these conditions that are observed nowadays mostly during the boreal winter in the Adamawa plateau entail a more deep and unique thermocline in the water table (Kling, 1987). Such large diatoms have also been used as indicator of water table mixing in east African lakes (Stager et al., 1997). The variations in the intensity of the NE trade winds are inferred as in Ossa from relative abundance of windblown diatoms (Fig. 7c). We suggest that the mixing is mostly due to the intensification of the North eastern trade winds (Harmattan) during the year.

Paleoclimatic data suggest that tropical Africa experienced during the Holocene important paleoclimatic changes that are now well dated (Servant and Servant-Vildary,

1980; Gasse, 2000). The base of the core M4 (7200 yrs cal BP) corresponds to the termination of the African humid phase that is documented in several continental sites (e.g. Gasse, 2000; Talbot and Johanessen, 1992; Stager et al., 1997) and marine sites offshore Africa although the timing and magnitude of this event varied from one site to another (Adkins et al., 2006) probably because of dating uncertainties, sampling resolution and sensitivity of each site to climate change.

### 5.1 Middle to late Holocene: from 7200 to 3600 yrs cal BP

Diatom data of Lake Mbalang inferred cool, stable and stratified water table that may indicate a stronger monsoonal flow. These data are consistent with appearance of montane forest taxa pollen in the palynological spectrum. The two most abundant taxa *Olea capensis* and *Podocarpus* sp. were probably developed on nearby mountains that are today covered by shrubby savannas dominated by *Hymenodictyon floribundus* (Vincens et al., 2010). The nearest modern ecological niche of these two taxa according to Letouzey (1968, 1985) is located at Mount Ngan-Ha (1923 m), some 35 km east of Lake Mbalang. These species are also present some 300 km north of the lake at Mount Poli (7°50′ N, 2049 m) and at Tchabal Mbabo highlands (7°18′ N, 2460 m) located 165 km west of Ngaoundere on the Cameroon volcanic line. In fossil records, *O. capensis* and/or *Podocarpus* sp. occurrences in several locations in northern subtropics and subequatorial areas of Africa were interpreted as indicative of cooler air conditions (Salzmann et al., 2002) linked to stratiform cloud cover as observed today during the boreal summer when upwelling system is reinforced off the Gulf of Guinea (Maley and Brenac, 1998). But this hypothesis is less likely because surprisingly marine isotopic data off the Gulf of Guinea showed no evidence of past strong upwellings system at that area (Weldeab et al., 2005, 2007). Another alternative is to consider episodic cold air masse advections of middle and high latitudes that can also contribute to such air conditions, but the weakness of this hypothesis is shown by the absence of such occurrences in the Saharan/Sahelian during this period (Servant and Servant-Vildary, 1980). If the climatic determinism is the same as today, their abundance in Adamawa fossil spectra should imply a northwards displacement of ecological boundaries as shown by palynological data (Watrin et al., 2009; Lezine, 2009) and reproduced by vegetation models (Hély et al., 2009) or rather the persistence of conditions that led to a relatively cold and cloudy climate in the Adamawa plateau. Diatoms in Lake Mbalang inferred a moderate to high lake level which can correspond to precipitations lower than today in a context of low evaporation (Fig. 6a), but precipitation distribution remained favourable for forest development as shown by palynological and $\delta^{13}$C data. Phytoliths abundance at the base of the core might indicate a presence or the vicinity of the aquatic vegetation, nevertheless the consistent low abundance of epiphytic and benthic taxa excluded dense aquatic vegetation at the coring site. It is possible that these phytoliths were from a more important belt than today of ligneous tree fringing the lake (*Alchornea* sp.) during this period of relative low evaporation and high water content in soils as it observed in other sites of central Africa (Ngomanda et al., 2009b).

From 7200 cal yrs BP onwards, the decreasing trend of the tychoplanktonics is punctuated by several abrupt low abundance at 6700, 5800–6000, 5000–5300, 4500 and 3600 yrs BP (Fig. 7b) corresponding probably to episodes of weaker monsoon flux superimposed on the general trend, showing the complexity of climate change towards late Holocene drier conditions. This pattern is reflected in water balance and vegetation landscape in several areas of tropical Africa and was largely discussed to underline the timing and magnitude of climate changes from one region to another and associated climatic mechanisms (Gasse, 2000). The marine data off Mauritania showing an abrupt dryness of the climate at ~5500 yrs BP linked to the reinforcement of the North African system of upwellings (de Menocal et al., 2000; Adkins et al., 2006) is close to the 5000–5300 (420–470 cm) low spell of tychoplanktonics observed in lake Mbalang (Fig. 7b). This event is interpreted as a period of increased mixing comparable to the one observed today during the boreal winter. Therefore, the more development the significant increase of Poaceae in Lake Mbalang area at that time can be explained by increased seasonality with a longer dry season compared with the previous period

rather than an absolute decrease of rainfall as suggested by Vincens et al. (2010). Lake Ossa located south of Adamawa (3°50′ N) experienced convective rainfall in agreement with our model (Fig. 6b).

The spell dated at 4500–4000 cal yrs BP corresponds probably the most documented climatic phase throughout Africa; it was recorded at several sites of both southern and northern tropics (Servant and Servant-Vildary, 1980; Gasse, 2000). Drier conditions are also registered both by palynological and limnological proxies in Biu plateau (12°32′ N) and around lake Sele (7°9′ N) after ~ 3800 yrs BP (Salzmann et al., 2002; 2005) in West Africa. In sub-equatorial regions this period was marked in Lake Bosumtwi by a low lake level (Talbot and Delibrias, 1980) although recent data did not confirmed this low stand (Russell et al., 2003). Lake Sinnda in south Congo completely dried by 4400 yrs BP and refilled only after 1300 yrs BP (Vincens et al., 1994; Bertaux, 2000). Palynological data suggest important disturbances in the periphery of the equatorial rain forest belt with possible appearance of included savannas (Ngomanda et al., 2009a, b) while the inner forest block and mountainous forests were not impacted according to palynological (Vincens et al., 1999; Ngomanda et al., 2007, 2009b) and sedimentological (Kossoni et al., 2009) records. This period is characterised in Lake Mbalang by the maintenance of indicators of stable, cold and stratified water table in agreement with the palynological and $\delta^{13}$ data, and thus to a stronger monsoon. But the appearance of windblown diatoms (~ 4400 cal yrs BP) attests probably the beginning of the aridification of the Sahara and/or the intensification of the NE trade winds (Fig. 7c). From 5200 to 5000 cal yrs BP, savanna pollen decrease sharply indicating a reduced seasonality on the Adamawa plateau.

Despite the scarcity of paleoclimatic records on highlands, the Bambili (western Cameroon) core provided a 24 000 yrs time series that highlighted the comprehension of paleoclimatic evolution around the Gulf of Guinea. Contrarily to lowlands, Lake Bambili registered a dramatic low lake level from 10 000 to 7000 cal yrs BP, then fluctuated around this low values afterwards (Stager and Anfang-Sutter, 1999) while other sites of tropical Africa undergo the so called “African humid period”. In Lake Njupi located north of Bambili at 1020 m altitude, *O. capensis* and *Podocarpus* sp. were present till around 3000 yrs BP, suggesting a comparable evolution as the Adamawa plateau. Thus highlands as Bambili (2264 m altitude) may probably have evolved differently during greater part of the Holocene in term of water balance as suggested by Stager and Anfang-Sutter (1999), however synchronous evolution between lowlands and highlands seems to have started at 3000 cal yrs BP. Lake Mbalang evolved like lowlands in term of the pattern of change even though the palynological and hydrological signals seem to have been also controlled by altitudinal and meridian variations of climatic factors.

### 5.2 The Late Holocene (last 3600 yrs BP)

After 3600 cal yrs BP, diatoms and other proxies of Lake Mbalang inferred significant changes of the climatic conditions. High abundance of *A. muzzanensis* and *A. granulata* suggest a more mixed water layer and deeper thermocline. These conditions prevail today during the boreal winter. The lake level remained relatively high after 3000 yrs and decreased between 2400–2100 cal yrs BP. The other relative lowstands are dated at 1800 and 1400 cal yrs BP, time after which the lake started its evolution towards present day's high level (Fig. 7a). The windblown diatoms remained relatively important consistent with a significant influence of the NE trade winds during the year responsible of a well mixed water table. Nevertheless, the diatom derived lake depth reflects limnological variations and consequently water balance at centennial to millennial timescales. The relatively higher abundance of epiphytic, benthic and aerophilous mixed with planktonic and tychoplanktonic diatoms in individual samples reflects the lowering of lake level at the interval of time represented by one sample (~ 6 yrs) or could reflect seasonal variability. In that case, one can hypothesise in such climatic conditions the development of planktonic diatoms during the rainy season high lake level and development of littoral forms during the dry season at the lake borders on Cyperaceae (sedges) that fringe the lake today. But these short terms variability did not strongly affected the vegetation cover: among minor changes we noticed a depletion of the $\delta^{13}$C values (Fig. 7d), concomitant with a slight and decrease of the

Poaceae at 1800 and 1400 cal BP (Fig. 7e). A low lake level evidenced by low abundance of both planktonics and tychoplanktonics (Fig. 7a) centred at 2400–2100 yrs BP is also registered in Ossa and in Nyabessan between 2400–2000 yrs cal BP (Nguetsop et al., 2004; Ngomanda et al., 2009b). Windblown diatoms reached their maximum abundance in Ossa. Palynological data in Mbalang showed the expansion of Poaceae at 3000 cal yrs BP, they remained the most abundant than any other groups of plants until the present days. Sedges also developed and reached their highest abundance suggesting the lowering of lake levels at short timescale. Montane forest regrowth (Fig. 7e), and savannas arboreal taxa abundance became very low. These modifications in the vegetation landscape implied a more dry and contrasted climate (Vincens et al., 2010) as also suggested by diatom habitat groups and windblown diatoms (Fig. 7c). The 2400–2100 cal years event is also well marked in other sites of the subequatorial regions of central Africa (Vincens et al., 1999). In Lake Bosumtwi (6°30′ N; 1°25′ E), sedimentological records showed an evolution towards aridity and more seasonality at about 3000 yrs BP (Russell et al., 2003; Talbot and Johannessen, 1992). The data confirmed a more dry climate in southern Congo, but at the latitude of lake Ossa, woody pioneer heliophilous taxa appears in the rain forest (Reynaud-Farrera et al., 1996), probably as a result of stormy rainfall rather than absolute low precipitation (Nguetsop et al., 2004) as well as in Nyabessan located 200 km south of Ossa (Ngomanda et al., 2009b). The reduction of the mixing at 1700, 700–600 and at 400 cal yrs BP is marked by a slight decrease of Poaceae and the increase of Cyperaceae, $\delta^{13}$C values decrease also slightly. This last event shows the sensitivity of vegetation and hydrology to recent centennial climate variability as it was demonstrated by Ngomanda et al. (2007, 2009b).

### 5.3 Paleoclimatic interpretation

Diatoms data suggest a decreasing trend of the monsoonal flux in Adamawa area from mid-Holocene (7200 yrs cal BP) to mid-late Holocene, consistently with the decreasing summer insolation in the Northern Hemisphere and correlatively reducing land-Ocean contrast linked to orbital changes. Although orbital changes account for a greater part in explaining the hydrological changes (Kutzbach and Street-Perrot, 1985), they induced regional atmospheric factors that may be useful in understanding the response of the local hydrological system. The better comprehension of climatic changes in central Africa regions around the Gulf of Guinea should integrate the structure of the atmosphere during the wet season when the monsoon flux overrides the NE trade winds in the northern summer. According to Leroux (1970, 2001), five climatic zones can be individualized in the meridian structure of the troposphere at this period of the year, they have been used in interpreting past climate conditions by several authors (e.g., Nguetsop et al., 2004; Ngomanda et al., 2009b). The compression and dilatation of these climatic zones over the year can explain a series of climatic conditions that are encountered yearly today between 20° N and 5° S. One can then hypothesize that, if in the past the rain belt moved northwards and entailed rainfall at Saharan region at around 6000 yrs BP as shown by paleoclimatic data (Gasse, 2000) and reproduced by paleoclimatic models (Kutzbach and Street-Perrot, 1985; Kutzbach and Guetter, 1986) it is likely that all the climatic zones that are linked to the strengthening of the monsoon, and not only the convection area, were more extended than today during the boreal summer. This hypothesis is reinforced by the fact that cloud cover and low evaporation that are limited today between 5° S and 4° N are also reproduced by climatic model in higher latitude at 6000 yrs BP (Kutzbach and Guetter, 1986).

From 7200–3600 yrs cal BP, the lake level as evidenced by planktonic diatoms was mostly moderate to high and the water column generally stable and stratified. We suggest that the ITCZ mean position at that time was north of the Adamawa plateau (Fig. 8a) in agreement with paleoclimatic data (Gasse and Van Campo, 1994); this position entailed at the latitude of the studied lake, stratiform cloud cover and low precipitation (Fig. 6a). Temperatures were consequently relatively low due primarily to these atmospheric features, but also, to the relatively high altitude of the Adamawa plateau (1100–1200 m). These conditions were favourable for the development of the mountain forest taxa in the vegetation landscape and the regrowth at the forest borders (Vincens

et al., 2010). This period was characterized by very low mixing except between 5000–5300 cal yrs BP; the Harmattan was probably very weak until 4500 cal yrs BP.

From 7200–6900, diatom data suggest a relatively deep and stable lake. Despite the age uncertainties offset and the different time resolution in published data, this subphase could correspond to the wet episode that is well known in Saharan and Sahelian regions (Servant and Servant-Vildary, 1980; Gasse, 2000). The high monsoon inflow suggested by diatoms at 6400, 5500, 4600 and 4200 cal yrs BP and characterized by relatively high lake level in Adamawa plateau and Ossa (Fig. 7a and g) is concomitant with moderate to low sea surface temperatures the Gulf of Guinea (Weldeab et al., 2005, 2007) (Fig. 7i). In parallel, high variability of the river discharge (Fig. 7j) in the Gulf of Guinea and of the rainfall in Ossa suggest high hydrological changes over the area covered by the catchments of Sanaga, Ntem, and Niger river (main rivers of the Gulf of Guinea) at this period at multi-secular to millennial timescale as it is observed today over the year. Consistent northernmost mean position of the ITCZ may have favoured rainfall at the northern part of the catchments of Niger River while the southern part and probably a great part of the Sanaga and Ntem may have been under stable air layer (Fig. 8a). In that case water discharge off the Gulf of Guinea may reflect mostly the rainfall in the upper part of the river Niger and can be moderate or high. Conversely, the southernmost mean position of ITCZ may have favoured high rainfall around the Gulf of Guinea in the greatest part of the Sanaga and Ntem rivers catchments, and drier condition in the upper part of the Niger River, river discharge may have been lower even with higher SST off Cameroon. Intermediate positions are possible and could entail high rainfall at the latitude of the Adamawa plateau (Fig. 8b). Ossa high lake levels are observed in the context of low rainfall between 4800 and 4400 cal yrs BP suggesting a climate with low evaporation and low rainfall consistent with the northernmost position of the ITCZ. Hence, the apparent discrepancies observed between rainfall on the continent, SST temperatures and rivers discharges off the Gulf of Guinea during Middle to Late Holocene (Weldeab et al., 2005, 2007) could be explained by theses meridian changes of the structure of the lower levels of the atmosphere at centennial to millennial timescales.

The relative weakening of the monsoon inflow is observed at 6700, 6000–5800, 5300–5000, 4600–4400, 3600 and 3000 yrs cal BP. The low inflows at 6700, 6000–5800 and 4600–4400 yrs cal BP are also characterised by low lake levels in Mbalang. SST are low to medium except at 6700 where they are high. From 5000 to 3000 cal years BP, lake level is high in Ossa while rainfall is moderate. These general conditions suggest a position of the ITCZ further north than today, but low lake levels could indicate at least the ITCZ episodic displacement south of Adamawa plateau entailing low or high rainfall (depending on the ITCZ amplitude) and high evaporation (Fig. 6b). The low inflows registered at 6000–5800 and 4600–4400 cal yrs are contemporaneous with cold events off Mauritania that are linked to the intensification of the Agulhas current that entail the reinforcement of upwelling system (De Menocal, 2001). The appearance of windblown diatoms in Adamawa at 4500 cal yrs BP corresponds probably to the desiccation of the Sahara or intensification of NE trade winds. At 5300–5000, lake levels are both high in Ossa and in Adamawa, SST and river discharges are high, rainfall is high in low latitude (Ossa), suggesting the displacement towards the South of the ITCZ at a position favourable to convective rainfall in the two regions. This phase is probably contemporaneous of the onset of a dry episode in Sahara, paleolakes retreated around 5800 year BP (Vernet, 1995, Servant and Servant-Vildary, 1980) consistently with the termination of the African humid period (De Menocal, 2001). At that time, high mixing as observed at the upper part of Mbalang core (after 3600 cal yrs BP) shows that position of the ITCZ was closed to its modern position (Fig. 8a). This hypothesis is reinforced by the development of savannah in the vegetation landscape indicating as today a more contrasted climate. At 3600 and 3000 cal yrs BP, despite the weakening of the monsoon and correlatively low rainfall in Ossa, lake levels are high suggesting the non evaporative climate as a result of the displacement northwards of the ITCZ; windblown diatoms attest the intensification of the Harmattan, but the yearly distribution of rainfall stilled favourable for the forest taxa development until 3000 yrs cal BP. Between the two dates (3600 and 3000 cal yrs BP),

SSTs off the Gulf of Guinea alternate between moderate and low values, and river discharges were relatively low or moderate in good agreement with low rainfall in Ossa but high lake level inferred in lake Mbalang may indicated higher rainfall in Adamawa plateau.

Between 3000 and 0 cal yrs BP, diatom data suggest the significant reduction of the monsoon flux. The lake level remained broadly high except between 2400–2100, 1800 and 1400 yrs cal BP. Although the lake did not decline dramatically, indicating that rainfall remained relatively important, the increase of savannah taxa and their maintenance until today attest a seasonality change of the rainfall distribution is well registered. The influence of the NE trade winds during the year shown by the persistence of windblown diatoms. A low lake level registered both in Mbalang and in Ossa between 2400 and 2100 cal yrs BP and in others subequatorial regions of Africa coincided with higher rainfall in Ossa and important fluctuations of SSTs off the Gulf of Guinea while the river discharges decreased gradually. It revealed the unstable position of the ITCZ and consequently the rainfall belt modifications during this southwards shift. In agreement with our model, this episode corresponds to the southernmost position of the ITCZ, at least episodically. Consequently, it entailed more arid conditions northwards as shown by intense windblown diatom indicating the strengthening of NE trade winds in Ossa, stormy rainfall around the Gulf of Guinea with subsequent disturbances inside the forest block. After 2000 yrs cal BP, the evolution towards present days is observed. These new conditions are roughly characterized by relatively high lake level in Ossa and in the Adamawa, high rainfall in Ossa suggesting a sharp northwards shift of the mean position of the ITCZ. Meanwhile, both river discharges and SSTs showed a decreasing trend. Brief highstand at 2000–1900 cal yrs BP, lowstands at 1800 and 1400 cal yrs BP attested the more intense or weakening of the monsoon inflow respectively . The 700–600 and at 400 cal yrs BP marked a slight intensification of the monsoon which is well recorded both by rainfall regime and lake level in Ossa.

Holocene short climatic events were evidenced in several sites of the monsoon domain both in Africa and Asia, the forcing factors is primarily the modifications of insolation that is modulated by sea surface temperatures and land surfaces feedback mechanisms (Gasse and Van Campo, 1994; de Menocal et al., 2000).

## 6 Conclusions

Planktonics and tychoplanktonic diatoms variation suggested that Lake Mbalang did not dried during the last 7200 cal yrs BP but relative fluctuations of water level are observed. A low lake level recorded at 2400–2100 cal yrs BP is contemporaneous to a climatic event evidenced in several areas of tropical Africa, other low lake levels are observed at 1800 and 1400, after which lake rose to its present level. Nevertheless, diatom data showed that the lake evolved from cold oligotrophic stratified water table before 3600 cal yrs BP to mixed and eutrophic conditions afterwards corresponding respectively to a strong monsoonal flow before and a more intense north eastern trade winds (Harmattan) after. The $\delta^{13}$C sedimentary isotope data indicated the development in the landscape of more forested vegetation, also confirmed by palynological data in good agreement with the inferred climate. However, the decreasing monsoon trend was punctuated by several abrupt weakening at 6700, 5800–6000, 5000–5300, and 4500 cal yrs BP. After 3000 cal yrs BP, the savana vegetation developed in the Adamawa area and persisted till today. These climate changes can be attributed the modifications of the position of the Intropical Convergence Zone (ITCZ), its northernmost position between 7200 and 3600 cal yrs BP entailed at the level of the Adamawa plateau, a climate characterize by very low precipitation and also very low evaporation as it is observed today during the boreal summer in the south west of Cameroon. After 3600–3000 cal yrs BP the the ITCZ moved southwards and reached a position where convective rainfall became dominant, but its amount and/or its distribution were no more favourable to forest development.

*Acknowledgements.* This work a contribution to the Ecofit program (1993–2000) that was funded by French scientific institutions (IRD, CNRS, CEA), the program provided long core that are used in this paper. The funding for this work were also provided by START trough a grant from US National Science Foundation (GEO-0627839" Capacity Building for Global Change"). *ARTEMIS* AMS *facility* (Saclay, France) performed some of the radiocarbon dates. F. Nguetsop benefited from a scholarship offered by the "*Coopération Française (MAEE)*" through the SCAC *(Service de Coopération et d'Action culturelle"*) to travel to Montpellier (France).

## References

Adkins, J., de Menocal, P., and Eshel, G.: "The African Humid period" and the record of marine upwelling from excess $^{230}$Th in Ocean Drilling Program Hole 658C, Paleoceanography, 21, PA4203, doi:10.1029/2005PA001200, 2006.

Battarbee, R. W.: Diatom analysis, in: Handbook of Holocene Palaeoecology and Palaeohydrolog, edited by: Berglund, B. E., John Wiley and Sons, 527–578, 1986.

Cholnoky, B. J.: Die Ökologie der Diatomeen in Binnengewässer, edited by: Cramer, J., 699 pp., 1968.

Bertaux, J., Schwartz, D., Vincens, V., Siffedine, A., Elenga, H., Mansour, M., Mariotti, A., Fournier, M., Martin, L., Wirrmann, D., and Servant, M.: Enregistrement de la phase sèche d'Afrique Centrale par spectrométrie IR dans les lacs Sinnda et Kitina (sud-Congo), in: Dynamique à long terme des Ecosystèmes Forestiers Intertropicaux, edited by: Servant M. and Servant-Vildary, S., Unesco, 43–49, 2000.

De Menocal, P.: Cultural responses to climate change during the late Holocene, Science, 292, 667–673, 2001.

De Menocal, P., Ortiz, J., Guilderson, T., and Sarnthein, M.: Coherent High-and low- latitude climate variability during the Holocene warm period, Science, 288, 2198–2202, 2000.

Gasse, F.: Les diatomées lacustres plio-pléistocène du Gadeb (Ethiopie), Systématique, paléoécologie, biostratigraphie, Revue Algologie, 3, 249 pp., 1980.

Gasse, F.: East African diatoms, taxonomy, ecological distribution, Bibliotheca Diatomologica, edited by: Cramer, J., Gebrüder Borntraeger Vertragsbuchhandlung, Berlin-Stuttgart, 201 pp., 1986.

Gasse, F.: Diatoms for reconstructing palaeoenvironments and paleohydrology in topical semiarid zones. Example of some lakes from Niger since 12000 BP, Hydrobiologia, 154, 127–163, 1987.

Gasse, F.: Hydrological changes in African tropics since the Last Glacial Maximum, Quat. Sci. Rev., 19, 189–211, 2000.

Gasse, F. and Van Campo, E.: Abrupt Post-glacial climate events in West Asia and North Africa monsoon domains, Earth Planet. Sci. Lett., 126, 435–456, 1994.

Gasse, F., Juggins, S., and Ben Khelifa, L.: Diatom-based transfer function for inferring hydrochemical characteristics of African paleolakes, Palaeogeogr. Palaeocl., 117, 31–54, 1995.

Germain, H.: Flore des diatomées, eaux douces et saumâtres du massif Armoricain et des contrées voisines d'Europe Occidentale, Société Nouvelles des Editions Boubée, Coll. "Faunes et Flores actuelles", Paris, 444 pp., 1981.

Gèze, B.: Géographie et géologie du Cameroun occidental, Mémoires Muséum National d'Histoire naturelle, XVII, 320 pp., 1943.

Hély, C., Braconnot, P., Watrin, J., and Zheng, W.: Climate and Vegetation: Simulating the African humid period, C. R. Geosci., 341, 671–688, 2009.

Humbel, F. X.: Notice explicative, Carte pédologique de Ngaoundéré 1d à 1/50.000, ORSTOM, 164 pp., 1967.

Hustedt, F.: Die Kieselalgen, in: L. Rabenhorst's Kryptogamen. Flora von Deutschland, Österreich und der Schweiz, Akademische Verlagsgesellschaft Leipzig, 1 (1927–30), 920 pp., 2 (1931–59), 845 pp., 3 (1961–66), 816 pp., 1927–1966.

Hustedt, F.: Die Süsswasser-Flora Mitteleuropas. Bacillariophyta (Diatomeae), Verlag Von Gustav Fischer, Jena, 466 pp., 1930.

Kling, G. W.: Comparative limnology of lakes in Cameroon, West Africa, pHD Thesis, Duke University, 482 pp., 1987.

Kom, M. F.: Variations saisonnières des algues et des macrophytes dans les lacs et les marécages de la région de l'Adamaoua: Relations avec les paramètres physicochimiques de l'eau, upublished Msc. Thesis, 74 pp., 2010.

Kossoni, A. and Giresse, P.: Interaction of Holocene infilling processes between a tropical shallow lake system ( Lake Ossa) and nearby river system (Sanaga river) (South Cameroon), J. Afr. Earth Sci., 56, 1–14, 2009.

Krammer, K. and Lange-Bertalot, H.: Bacillariophyceae 1 Teil: Naviculaceae, 876 pp. (1986), 2 Teil: Bacillariaceae, Epithemiaceae, Surirellaceae, 596 pp. (1988), 3 Teil: Centrales, Fragilariaceae, Eunotiaceae, 576 pp. (1991a), 4 Teil: Achnantaceae, Kritishe Ergänzungen zu

Navicula (Lineolatae) und Gomphonema (1991b), Süßwasserflora von Mitteleuropa 2/1-4, edited by: Ettl, H., Gerloff, J., Heynig, H., and Mollenhauer, D., Gustav Fischer, Stuttgart, 1986–1991.

Kutzbach, J. E. and Guetter, P. J.: The influence of Changing Orbital Parameters and Surface Boundary Conditions on Climate Simulations for the Past 18000 years, J. Atmos. Sci., 43, 1726–1759, 1986.

Kutzbach, J. E. and Street-Perrott, F. A.: Milankovitch forcing of fluctuations in the level of tropical lakes from 18 to 0 kyr BP, Nature 317, 130–134, 1985.

Leroux, M.: La dynamique des précipitations en Afrique Occidentale, Pub. Expl. Météo, ASECNA, Dakar, 23, 282 pp, 1970.

Leroux, M.: The Meteorology and Climate of Tropical Africa, Praxis, Chichester, UK, 548 pp., 2001.

Letouzey, R.: Etude phytogéographique du Cameroun. Encyclopédie Biologique, Paul Le Chevallier, Paris, 49, 508 pp., 1968.

Letouzey, R.: Notice sur la carte phytogéographique du Cameroun au 1:500000, IRA, Yaoundé et Inst. Cart. Intern. Végétation, Toulouse, Vol. 5, 1985.

Lezine, A. M.: Timing of Vegetation changes at the end of the Holocene Humid Period in Desert areas at the northern edge of the Atlantic and Indian monsoon systems, C. R. Geosci, doi:1016/j.crte.2009.01.001, 2009.

Maley, J.: Fragmentation de la forêt dense humide africaine et extension des biotopes montagnards au Quaternaire récent: Nouvelles données polliniques et chronologiques. Implications paléoclimatiques et biogéographiques, Palaeoeco A, 18, 307–334, 1987.

Maley, J. and Brenac, P.: Vegetation dynamics, paleoenvironments and climatic changes in the forest of western Cameroon during the last 28000 years B.P., Rev. Palaeobot. Palyno., 99, 157–187, 1998.

New, M., Lister, D., Hulme, M., and Makin, I.: A high-resolution data set of surface climate over global land areas, Clim. Res., 21, 1–25, 2000.

Ngomanda, A., Jolly, D., Bentaleb, I., Chepstow-Lusty, A., M'voubou Makaya, Maley, J., Fontune, M., Oslisly, R., and Rabenkogo, N.: Lowland forest response to hydrological changes during the last 1500 years in Gabon, Western equatorial Africa, Quaternary Res., 60, 411–425, 2007.

Ngomanda, A., Chepstow-Lusty, A., Makaya, M., Favier, C., Schevin, P., Maley, J., Fontugne, M., Oslisly, R., and Jolly, D.: Western equatorial African forest-savanna mosaics: a legacy of late Holocene climatic change?, Clim. Past, 5, 647–659, doi:10.5194/cp-5-647-2009, 2009a.

Ngomanda, A., Neumann, K., Schweizer, A., and Maley, J.: Seasonality change and third millennium BP rainforest crisis in southern Cameroon (Central Africa), Quaternary, Res. 77, 307–318, 2009b.

Ngos III, S., Giresse, P., and Maley, J.: Palaeoenvironments of Lake Assom near Tibati (south Adamawa, Cameroon). What happened in Tibati around 1700 years BP?, J. Afr. Earth Sci., 37, 35–45, 2003.

Ngos, S., Sirocko, F., Lehné, R., Giresse, P., and Servant, M.: The evolution of the Holocene palaeoenvironment of the Adamawa region of Cameroon: evidence from sediments from two crater lakes near Ngaoundéré, in: Dynamics of Forest Ecosystems in Central Africa during the Holocene, Past-Present-Future, edited by: Runge, J., Balkema, 103–120, 2008.

Nguetsop, V .F.: Evolution des environnements de l'Ouest Cameroun depuis 6000 ans d'après l'étude des diatomées actuelles et fossiles dans le lac Ossa. Implications paléoclimatiques, Unpublished Thesis, Muséum National d'Histoire Naturelle, Paris, 278 pp., 1997.

Nguetsop, V. F., Servant-Vildary, S., and Servant, M.: Late Holocene climatic changes in West Africa, a high resolution diatom record from equatorial Cameroon, Quaternary Sci. Rev., 23, 591–609, 2004.

Nguetsop, V. F., Servant-Vildary, S., Servant, M., and Roux, M.: Long and short-time scale climatic variability in the past 5500 years in Africa according to modern and fossil diatoms from Lake Ossa (Western-Cameroon), Global Planet. Change, 72, 356–367, 2010.

Nicholson, E. S.: A revised picture of the structure of the "monsoon" and land ITCZ over West Africa, Clim. Dynam., 32, 1155–1171, doi:10.1007/s00382-008-0514-3, 2009.

Pourchet, M., Pinglot, J. F., and Maley, J.: Résultats des mesures radiochimiques de quelques lacs camerounais, Rapport CNRS Grenoble et ORSTOM Montpellier, 12 pp., 1987.

Reynaud-Farrera, I., Maley, J., and Wirrmann, D.: Végétation et climat dans les forêts du sud_Ouest du Cameroun depuis 4770 ans BP: analyse pollinique des sédiments du lac Ossa, CR. Acad. Sci. II A, Paris, 322, 749–755, 1996.

Russell, J., Talbot, M. R., and Haskell, B. J.: Mid Holocene climate change in Lake Bosumtwi, Ghana, Quaternary Res., 60, 133–141, 2003.

Salzmann, U., Hoelzmann, P., and Morczinek, I.: Late Quaternary climate and Vegetation of the Sudanian zone of Northeast Nigeria, Quaternary Res., 58, 73–83, 2002.

Salzmann, U. and Hoelzmann, P.: The Dahomey gap: an abrupt climatically induced rain forest fragmentation in West Africa during the late Holocene, The Holocene, 15, 2190–199, 2005.

Schoeman, F. R.: Systematical and ecological study of the diatom flora of Lesotho with special reference to water quality, V and R Printers, Pretoria, 355 pp., 1973.

Servant, M. and Servant-Vildary, S.: L'environnement quaternaire du bassin du Tchad, in: The Sahara and the Nile edited by: Williams, M. A. J. and Faure, H., Balkema, Rotterdam, 133–162, 1980.

Servant-Vildary, S.: Etude des diatomées et paléolimnologie du bassin Tchadien au Cénozoique supérieur, Travaux et Documents ORSTOM, Vol. 2, 84, 346 pp., 1978.

Simonsen, R.: Atlas and Catalogue of the diatom types of Friedrich Hustedt, edited by: Cramer, J., 1, 525 pp., 2, 597 pp., 3, 619 pp., 1987.

Stager, J. C. and Anfang-Sutter, R.: Preliminary evidence of environmental changes at Lake Bambili (Cameroon, West Africa) since 24 000 BP, J. Paleolimnol., 22, 319–330, 1999.

Stager, C. J., Cumming, B., and Meeker, L.: A high-resolution 11400 yr Diatom Record from Lake Victoria, East Africa, Quaternary Res., 47, 81–89, 1997.

Stuiver, M. and Reimer, P. J: Extended 14C database and revised CALIB radiocarbon calibration program, Radiocarbon, 35, 215–230, 1993.

Suchel, J. B.: Les climats du Cameroun, unpublished thesis, Université Saint-Etienne, 1188 pp., 1988.

Talbot, M. R. and Delibrias, G.: A new late Pleistocene-Holocene water-level curve for Lake Bosumtwi, Ghana, Earth Planet. Sci. Lett., 47, 336–344, 1980.

Talbot, M. R. and Johannenssen, T.: A high resolution paleoclimatic records for the last 27000 years in tropical West Africa from the carbon and nitrogen isotopic composition of lacustrine organic matter, Earth Planet. Sci. Lett. 100, 23–37, 1992.

Tchouto, M. G. P., Yemefack M., De Boer, W. F., De Wilde, J. J. F. E., Van de Maesen, L. J. G., and Cleef, A. M.: Biodiversity hotspots and conservation priorities in the Campo-Ma'an rain forests, Cameroon, Biodivers Conserv., 15, 1219–1252, 2006.

Vernet, R.: Climats anciens du Nord de l'Afrique, L'Harmattan, Paris, 180 pp., 1995.

Vincens, A., Buchet, G., Elenga, H., Fournier, M., Martin, L., de Namur, C., Schwartz, D., Servant, M., and Wirrmann, D.: Changement majeur de la végétation du lac Sinnda (vallée du Niari, Sud-Congo) consécutif à l'assèchement climatique holocène supérieur: apport de la palynologie, CR. Acad. Sci. II A, Paris, 318, 1521–1526, 1994.

Vincens, A., Schwartz, D., Elenga, H., Reynaud-Farrera, I., Alexandre, A., Bertaux, J., Mariotti, A., Martin, L., Meunier, J.-D., Nguetsop, F., Servant, M., Servant-Vildary, S., and Wirrmann, D.: Forest response to climate changes in Atlantic Equatorial Africa during the last 4000 years BP and inheritance on the modern landscapes, J. Biogeor., 26, 879–885, 1999.

Vincens, A., Buchet, G., Servant, M., and ECOFIT Mbalang collaborators: Vegetation response to the "African Humid Period" termination in Central Cameroon (7° N) – new pollen insight from Lake Mbalang, Clim. Past, 6, 281–294, doi:10.5194/cp-6-281-2010, 2010.

Watrin, J., Lezine, A. M., Hely, C., and Contributors: Plant migration and pollen communities at the time of the "green Sahara", CR. Geosci., 41, 656–670, 2009.

Weldeab, S., Schneider, R. R., Kölling, M., and Wefer, G.: Holocene African droughs relate to eastern equatorial cooling, Geology, 33, 12, 981–984, 2005.

Weldeab, S., Lea, D. W., Schneider, R. R., and Andersen, N.: Centennial scale climate instabilities in a wet early Holocene West African monsoon, Geophys. Res. lett., 34L24702, doi:10.1029/2007GL031898, 2007.

**Table 1.** Radiocarbon dates from the core M4.

| Laboratory codes | Level (cm) | Material | Conventional $^{14}C$ ages (cal yrs BP) | Calibrated $^{14}C$ dates (cal yrs BP) | 2- sigma calibrated $^{14}C$ ages range (cal yrs BP) | Relative area (%) |
|---|---|---|---|---|---|---|
| Unknown | 35 | TOM | 535 ± 35* | 546 | 509–562 | 0.69859 |
| | | | | | 594–635 | 0.30141 |
| SacA 18586 | 102 | TOM | 1760 ± 30** | 1664 | 1567–1739 | 0.970552 |
| | | | | | 1757–1780 | 0.25613 |
| | | | | | 1803–1806 | 0.3835 |
| Unknown | 185 | TOM | 1796 ± 31* | 1729 | 1922–1671 | 0.174361 |
| | | | | | 1688–1820 | 0.825639 |
| SacA 18587 | 276 | TOM | 2835 ± 30 | 2939 | 2860–3007 | 0.949524 |
| | | | | | 3012–3036 | 0.35758 |
| | | | | | 3050–3061 | 0.14719 |
| SacA 18588 | 321 | TOM | 3440 ± 30 | 3698 | 3631–3780 | 0.826694 |
| | | | | | 3787–3828 | 0.173306 |
| Unknown | 407 | TOM | 4023 ± 29* | 4481 | 4421–4536 | 0.949341 |
| | | | | | 4542–4549 | 0.15457 |
| | | | | | 4555–4568 | 0.35202 |
| SacA 18 589 | 481 | TOM | 4865 ± 30 | 5605 | 5490–5501 | 0.2962 |
| | | | | | 5583–5654 | 0.97038 |
| SacA 18590 | 506 | TOM | 5355 ± 35 | 6139 | 6002–6084 | 0.310786 |
| | | | | | 6095–6218 | 0.555934 |
| | | | | | 6235–6274 | 0.13328 |
| Beta 143097 | 600 | TOM | 6400 ± 70* | 7333 | 7173–7222 | 0.6448 |
| | | | | | 7234–7432 | 0.93552 |

* Dates already published (Ngos et al., 2008; Vincens et al., 2010).

* Date not used in the age model.

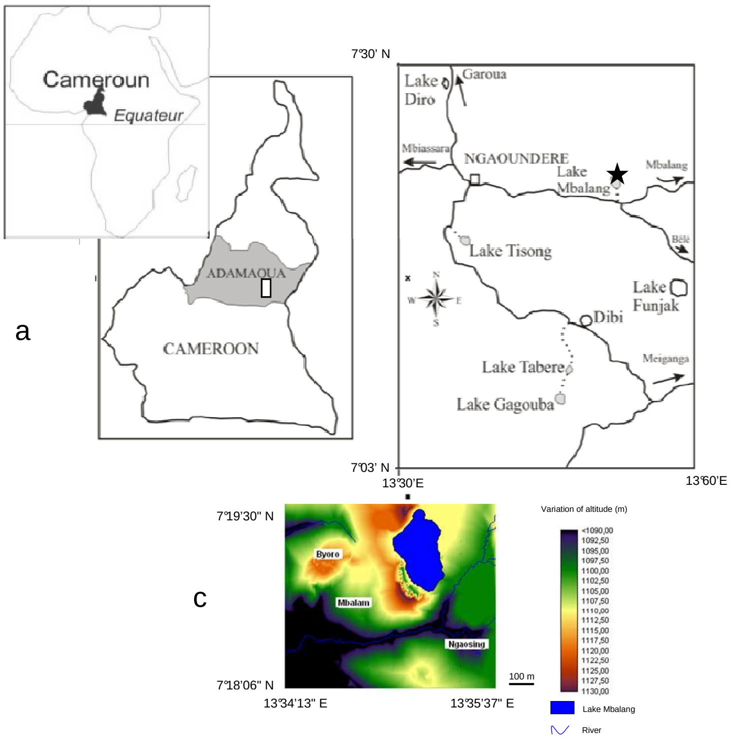

**Fig. 1.** Location of Lake Mbalang in the Adamawa plateau and morphometric features of the lake and its area. The location of the lake is shown with a black star in (b).

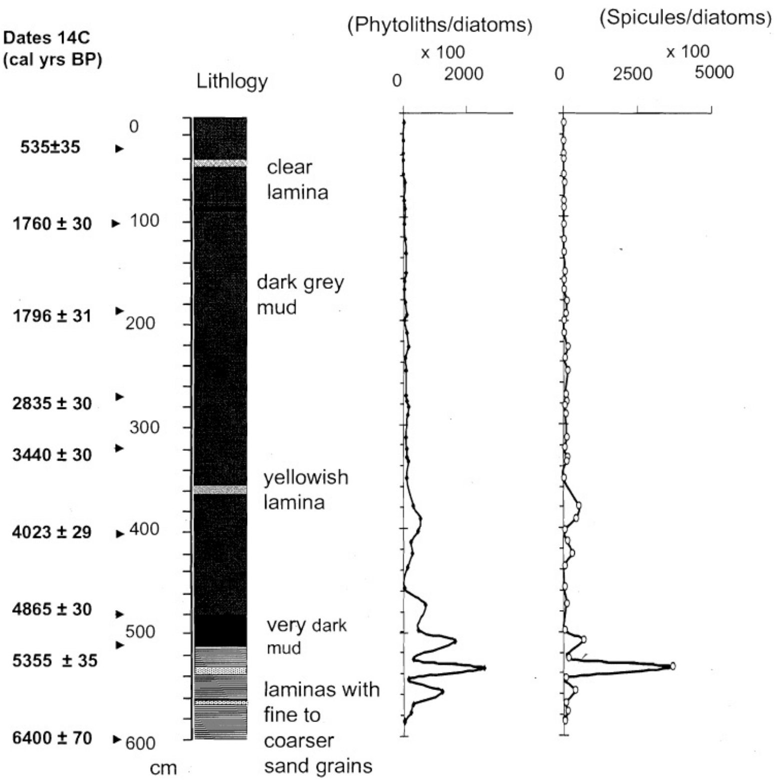

**Fig. 2.** Detailed lithology of the core M4 and radiocarbon ages performed; variation of the ratios phytoliths/diatoms and spicules/diatoms over the core.

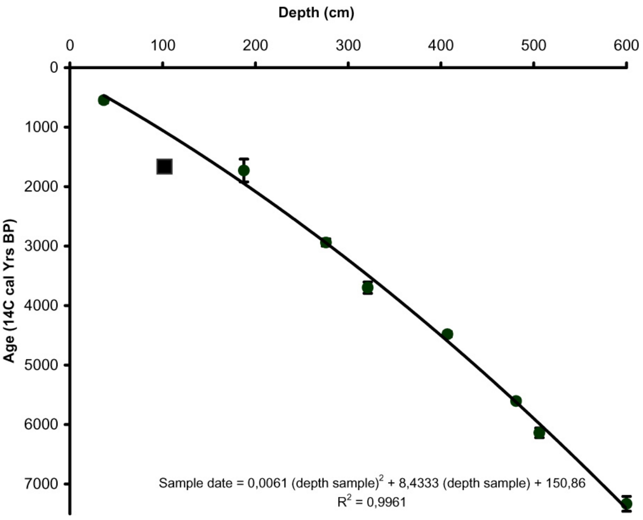

**Fig. 3.** Calibrated $^{14}$C years BP versus depth in the core M4. The black square represents the measure date that was excluded in the age model.

---

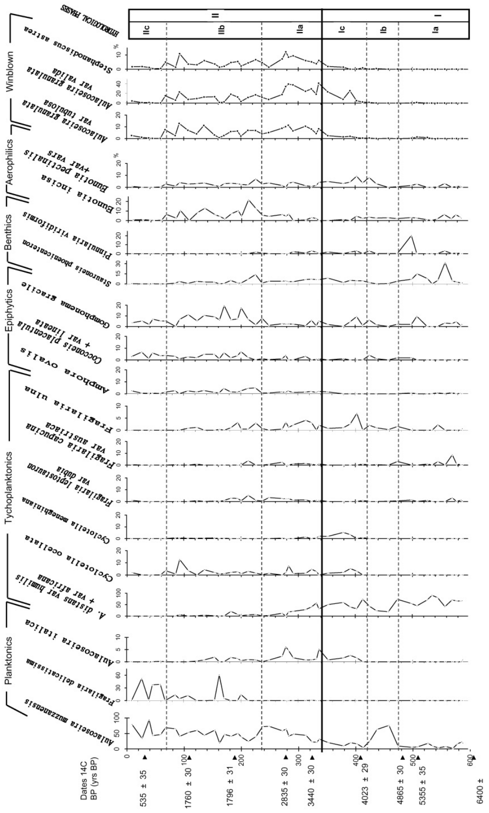

**Fig. 4.** Variation in abundances of the most dominant taxa (> 5% in at least one sample) belonging to different habitat groups and winblown diatoms over the core. Hydrological phases corresponding to diatom zones are indicated.

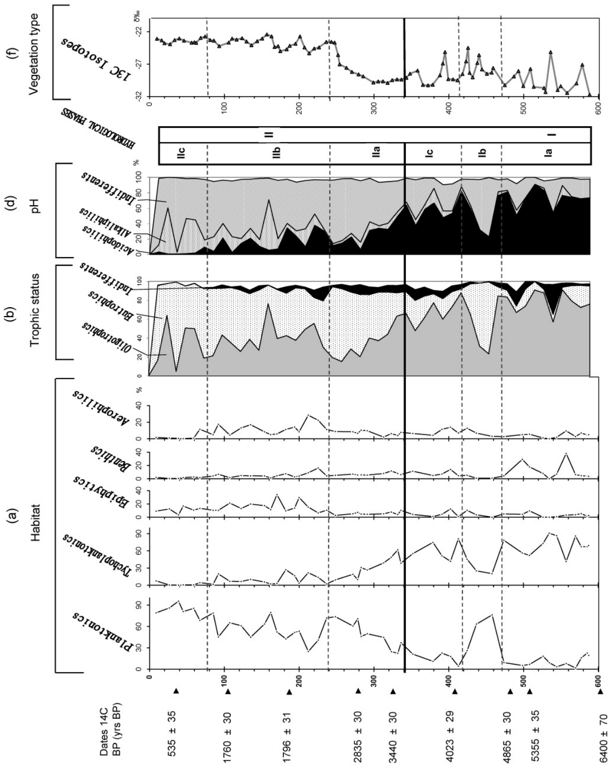

**Fig. 5.** Variations of Habitat **(a)**, trophic status **(b)** and pH **(c)** groups over the core. Habitat: Planktonics, Tychoplanktonics, Epiphytics, Benthic and Aerophylics. Trophic status: Oligotrophics, Eutrophics and indifferent taxa. pH: Acidophilics, Alkaliphilics and pH-indifferent taxa. Modifications of vegetation type over the core **(d)**.

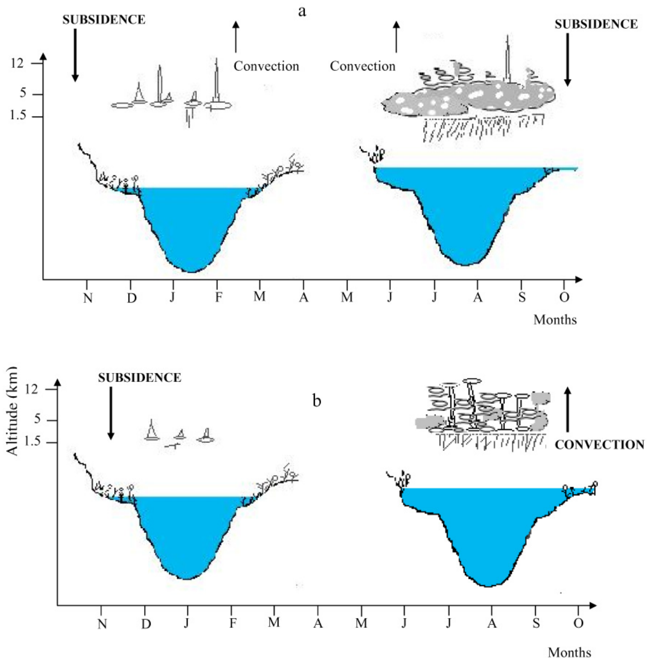

**Fig. 6.** Sketch of atmospheric features (clouds cover and air movement) and relative modifications of Lake Mbalang level, in the dry season (January) and rainy season (August) before 3600 cal yrs BP **(a)** and afterwards **(b)**. Before 3600 cal yrs BP, stratiform cloud cover were abundant, convective cloud are dominant after 3600 cal yrs BP.

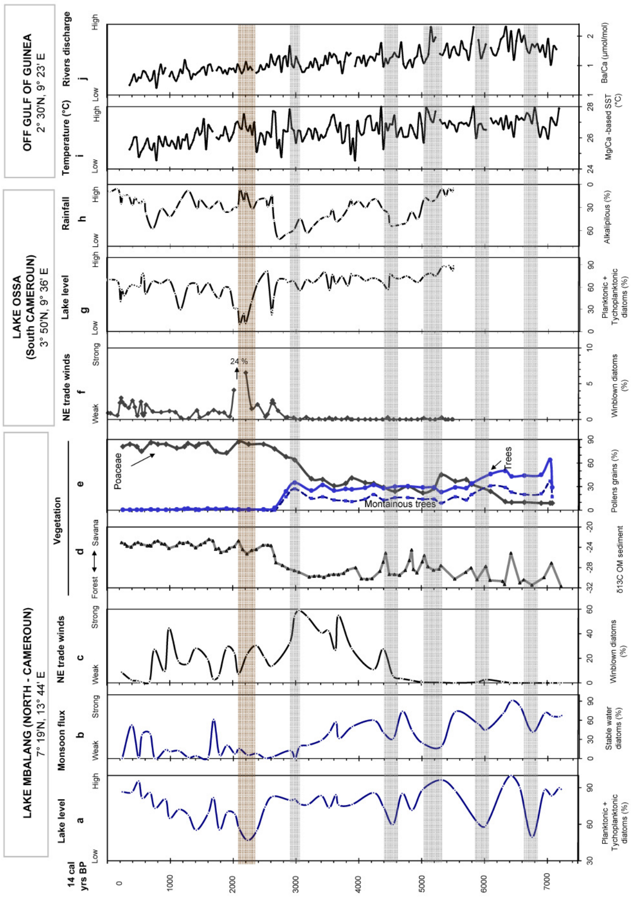

**Fig. 7.** Comparisons between Lake Mbalang (North-Cameroon), Lake Ossa (South-West Cameroon) and Gulf of Guinea. Lake Mbalang level variations evidenced by relative abundance of Planktonics + Tychoplanktonics **(a)**, Monsoon flux intensity reflected by stable water diatoms, higher percentages correspond to more intense monsoonal flux **(b)**, NE trade winds (Harmattan) intensity, higher allochtonous diatom abundance indicates more intense Harmattan **(c)**.Changes from C3 to C4 dominant plants in vegetation is evidenced by $\delta^{13}$C of sedimentary organic matter **(d)**, also shown by palynological data **(e)** (Vincens et al., 2010). Variations in NE trade winds (Harmattan) **(f)** and lake level **(g)** are shown in lake Ossa as well as relative change in rainfall evidenced from alkaliphilous diatoms **(h)** (Nguetsop et al., 2004). Variations in temperature off Gulf of Guinea is shown from Mg/Ca based SST **(i)**, Rivers discharge based on ration Ba/Ca is also shown **(j)** (Weldeab et al., 2005, 2007).

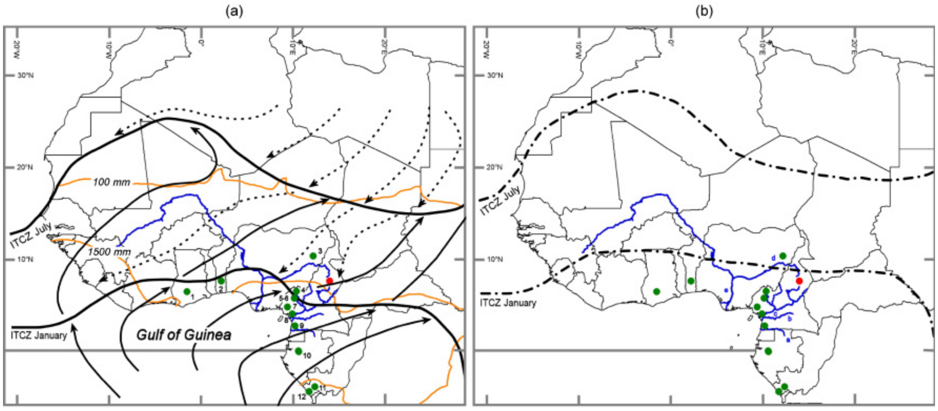

**Fig. 8.** Map showing the variations of general climatic settings over Africa, selected studied sites are mentioned. **(a)** Modern positions of Intertropical Convergence Zone (ITCZ) during the northern summer (ITCZ July) and during the northern winter (ITCZ January), strong arrows represent the monsoon flux while dotted arrows represent the NE trade winds (Harmattan)(Leroux, 2001). Orange full lines represent isohyetal lines 1500 mm and 100 mm (New et al., 2000). Selected sites were paleorecords (green dots) are available: 1 – Bosumtwi, 2 – Sele, 3 – Tilla, 4 – Djupi, 5 – Shum Laka, 6 – Bambili, 7 – Barombi Mbo, 8 – Ossa, 9 – Nyabessan (Ntem River), 10 – Nguène, 11 – Sinnda, 12 – Kitina and Mbalang (red dot). **(b)** Possible position of ITCZ before 3600 cal yrs BP inferred from diatom and $\delta^{13}$C isotopic data. Rivers of the Gulf of Guinea: Ntem **(a)**, Nyong **(b)**, Sanaga **(c)**, Benoué **(d)** and Niger **(e)**.