The dynamic of organic carbon in South Cameroon: fluxes in a tropical river system and a lake system as a varying sink on a glacial–interglacial time scale

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Abstract

In the first attempt to estimate both (i) a bulk carbon flux in a tropical river system (mainly Sanaga River) and (ii) their palaeoenvironmental implications from the Last Glacial Maximum (LGM) to the present, this study presents a synthetic approach based on the combined use of modern evaluation of fluxes and estuarine biodegradation in the tropical river system Sanaga and nearby Douala Bay rivers, and of sedimentation rates of a well studied marine shelf and lake system (Barombi-Mbo). In the lake Barombi-Mbo, the Holocene transfer of particulate carbon ($9.66 \times 10^3$ t) is very close to the mass fixed presently in soil catchments ($1.17 \times 10^3$ t). A complete process of stored carbon consumption would require some $10^4$ years, namely the Holocene period. During the last 20,000 years, variations in the sediment organic matter can be explained by the change of the vegetation cover, particularly with the substitution of open environments by forests. The global sedimentation was slow between ca. 18,000 and 10,000 years BP and increased after 12,000 years. But the carbon sedimentation rate remains fairly constant as the carbon content is higher in the LGM deposits. Such LGM carbon concentrations are probably explained by the input of coarse debris by rough floods and by a less degraded organic matter as a result of the cooling of the climate. Today, the total transport of dissolved and particulate organic carbon of the Sanaga and Douala Bay rivers to the Guinea Gulf is estimated as $0.62$ to $0.79 \times 10^4$ t C yr$^{-1}$. A complete process of stored carbon consumption would require some $10^4$ years, namely the Holocene period. During the last 20,000 years, variations in the sediment organic matter can be explained by the change of the vegetation cover, particularly with the substitution of open environments by forests. The global sedimentation was slow between ca. 18,000 and 10,000 years BP and increased after 12,000 years. But the carbon sedimentation rate remains fairly constant as the carbon content is higher in the LGM deposits. Such LGM carbon concentrations are probably explained by the input of coarse debris by rough floods and by a less degraded organic matter as a result of the cooling of the climate. Today, the total transport of dissolved and particulate organic carbon of the Sanaga and Douala Bay rivers to the Guinea Gulf is estimated as $0.62$ to $0.79 \times 10^4$ t C yr$^{-1}$. Based on 50% biodegradation at the estuarine interface, the loss of organic matter per unit of land is evaluated around $8.8 \times 10^{-2}$ t C km$^{-2}$ yr$^{-1}$. Marine oceanic records of the carbon sedimentation rate reflect with difficulty the major palaeoenvironmental changes according to interfering hydrodynamic factors. The greatest input of organic carbon during warm marine biozones would be balanced by higher concentrations during the LGM resulting in a nearly homogenous carbon transfer during the last 20,000 years. Such results might be largely representative of tropical river system as the contrasting vegetal cover (savanna and forest) of the Sanaga basin reflected as well the majority of the intertropical ecosystem. Thus, an estimate of the Holocene transfer to the ocean up to four times the present carbon stored in soil of the surrounding continent implicates that the Holocene shelf was a
significant organic carbon sink. Although the sources of the Sanaga River are located in a mountain region, a significant floodplain is not found downstream. This results in a significant altitudinal factor in the carbon fluxes to the ocean. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Recently, several studies have tried to document the state of carbon storage involving lithosphere, pedosphere, cryosphere, hydrosphere and biosphere during the Last Glacial Maximum (LGM), when the conditions were significantly different than today (Siegenthaler, 1989; Adams et al., 1990; Faure, 1990;
Various works have attempted to model past global conditions on the African continent (Nicholson and Flohn, 1980; Pokras and Mix, 1987; Hooghiemstra, 1988; Maley, 1989; Petit-Maire et al., 1991; Bonnefille et al., 1992; especially Branchu et al. (1993)).

Recently, multidisciplinary studies in West Cameroon were conducted (Giresse et al., 1991, 1994; Bird et al., 1994; Maley, 1996) focusing particularly upon the most recent 20,000 years on fluvial, lacustrine and oceanic environments. West Cameroon is one of the very few areas in the world, particularly in tropical latitudes, where sedimentary records of both (1) a lake (here Barombi-Mbo) and (2) a continental shelf area have been studied (Fig. 1).

The continuous sedimentary record of Lake Barombi-Mbo was well dated using absolute dating (Giresse et al., 1991) and palaeomagnetism (Thouveny and Williamson, 1988). Effect of forest and savanna vegetation on the particulate and namely on the organic matter fluxes were in particular analyzed.

Particulate matter fluxes in the Sanaga River have been estimated as $6 \times 10^6$ t C yr$^{-1}$ (Nouvelot, 1972; Olivry, 1977) and should lead to quantify the resulting organic carbon sedimentation rate on the shelf. The carbon isotope composition of fluvial deposit was analyzed as well (Bird et al., 1994). The last low-stand and high-stand oceanic sedimentations were also controlled using AMS $^{14}$C dating. High resolution seismic surveys and core recoverings allow to define the geometry of the successive sedimentary bodies.

Finally, the soils of southern Cameroon and particularly their organic matter content were documented using the available information in order to propose a quantitative approach to terrestrial carbon storage.

Such high density of data can be synthesized in order to document the present and the past carbon dynamic in this intertropical area. The site chosen for investigation should also serve to attempt a land–sea correlation and to compare, in a broader perspective, with larger intertropical areas at a different regional scale. Although this study does not allow us to discuss directly the carbon fluxes towards the atmosphere, particular attention is paid to variations in carbon fluxes as well as soil and sediment storages in response to climate changes.

2. Environmental setting

The modern climate in West Cameroon is of equatorial type with a temperature dependence mostly in altitude. Rainfall distribution over most of the region is highly seasonal reaching maximum values during June and August. Local variability in average annual rainfall are significantly rising from $\approx 1500$–2000 mm yr$^{-1}$ in the back land and dramatically increasing to $> 4000$ mm yr$^{-1}$ on the lowlands.

The main features of the vegetation exhibit a largely altitudinal dependence. At $\approx 1,000$ m a.s.l., the Adamaua Plateau is mainly covered by savanna. At lower altitude a landscape of forest–savanna mosaic is observed and, from an altitude of ca. 500 m, followed by closed semi-deciduous and evergreen tropical forests (Fig. 2a). The catchment of the Sanaga and particularly the Mbam, its most important tributary, has been recently altered by agricultural activity.

3. Present organic carbon fluxes to the ocean

3.1. Carbon stored in the soils of the Sanaga basin

The soils of Cameroon, and particularly those of the Sanaga basin (Fig. 2b), were described in several pedological mappings (Martin, 1966; Segalen, 1967; Vallérie, 1968). Other estimations of organic carbon were based on regional studies (Siefferman, 1973; Brabant, 1991; Muller, 1978). Although our present knowledge about organic carbon content in soils is obviously not comprehensive, it can perhaps serve as a useful starting point to evaluate carbon storage in these soils. The diversity of environmental parameters (substratum morphology, topography, vegetal cover, rainfalls and pedogenesis ages) ensures that our budget represents a schematic generalization. But this attempt to integrate all the available information will probably be one of the best documented carbon budgets in the soils of an African basin.
The occurrence of volcanic soils has been recognized by Siefferman (1973). The top soils (A horizons) of 'andosols' from the very rainy slopes of Mount Cameroon, contain 4–8 wt.% total organic carbon (TOC) with a C/N ratio between 7 and 8. The Mungo River rises on the Cameroon Line and discharges into the Douala Bay. In its catchment, the A horizons show decreasing TOC contents from the most andic stages (3 to 10%) to the most brown and eutrophic ones (2 to 4%) with C/N ratios between 8 and 10. For comparison (this study), soils from the inner slopes of the Barombi-Mbo catchment have TOC contents ranging from 7 to 8.5 wt.%. The surficial ferrallitic soils from Adamaua Plateau contain 3 to 4 wt.% TOC and are associated with high C/N values 14–15 when they are partially desaturated. These same soils, highly desaturated, have low TOC contents: 2 to 3%.

Using the data shown in Table 1, we have estimated the present TOC storage in A horizons from the Sanaga catchment as \( = 1.812 \times 10^9 \) t. For the other horizons (B + C), the information is less com-
Table 1

<table>
<thead>
<tr>
<th>Area</th>
<th>Mean altitude (m)</th>
<th>Landscape</th>
<th>Rain fall (mm yr⁻¹)</th>
<th>Temperature (°C)</th>
<th>Soils</th>
<th>% C (A₁)</th>
<th>C/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mount Cameron base</td>
<td>200</td>
<td>rain forest</td>
<td>6000-10,000</td>
<td>26-29</td>
<td>'andosols'</td>
<td>4-8</td>
<td>7-8</td>
</tr>
<tr>
<td>Mungo upstream</td>
<td>500-700</td>
<td>rain forest</td>
<td>2500-6000</td>
<td>26-28</td>
<td>'andosols'</td>
<td>3-9</td>
<td>8-9</td>
</tr>
<tr>
<td>Adamaua</td>
<td>1200-1300</td>
<td>savanna</td>
<td>1500</td>
<td>23</td>
<td>eutrophic brown soils</td>
<td>2-4</td>
<td>8-10</td>
</tr>
<tr>
<td>Adamaua</td>
<td>1200-1300</td>
<td>savanna</td>
<td>1500</td>
<td>23</td>
<td>sat. ferralic soils</td>
<td>3-4.5</td>
<td>11-15</td>
</tr>
<tr>
<td>Sanaga downstream</td>
<td>300-600</td>
<td>rain forest</td>
<td>1500-3000</td>
<td>24-28</td>
<td>red orthic soils</td>
<td>1-1.5</td>
<td>10-14</td>
</tr>
</tbody>
</table>

The Sanaga basin (≈ 135,000 km²) can be subdivided into two major sub-basins, the Sanaga basin sensu stricto to the east (≈ 76,000 km²) and the Mbam basin to the west (≈ 41,800 km²). Total average denudation rate for the Sanaga is 44 t km⁻² yr⁻¹. But the denudation of the Sanaga catchment s.s. (28 t km⁻² yr⁻¹) is a small contribution compared to the Mbam one (85 t km⁻² yr⁻¹) where the increased erosion is related to the intense agriculture in the Bamiléké region (Nouvelot, 1972; Olivry, 1977; Bird et al., 1994). The average hydrographs of both rivers exhibit strong seasonal variation (one to five) resulting in a large stream competence.

3.2. Alluvial deposits

The studied samples were taken near to the river bank or in quiet water sections. In spite of this, the sandy sediment fraction represents a very significant portion of the deposit (content range 60-80%). Consequently, TOC contents are usually low (< 5%) as compared with that of the suspended matter (7 to 46%). Thus, TOC contents of the alluvial deposits are not exactly representative of the organic carbon input to the ocean and the distribution map (Fig. 3) appears only to contribute to the preliminary description. Similar evidences of TOC contents (below 5%) have been observed in both forest and savanna catchments as well as in the Adamanoua Plateau and in the coastal plain. This implies that the bulk of alluvial TOC is relatively independent from those of the A₁ soil horizon. Only the northern part of the catchment in Adamanoua that comprises tropical ferruginous soils (Brabant, 1991) presents alluvial deposits with low TOC contents. The size distribution of sub-micrometre suspended matter implies that only a small portion of the organic matter may be sedimented in the rather coarse alluvial deposit. Because such small particles do not have important settling rates in river
Fig. 3. Distribution map of TOC contents (wt.%) of alluvial deposits from the basin of Sanaga River.
waters, the river does not act as a sink for organic carbon. Consequently, the relation is low between pedogenetic measurements and the TOC distribution map.

It has been suggested that a large part of the alluvial organic material was previously degraded. This degradation is shown by rather low Hydrogen Index (HI) both in forest and savanna (Giresse and Cahet, 1997). Biodegradation is one of the most relevant processes occurring in moist forest soils. Moreover, a large part of refractory compounds from ligneous matter is more slowly consumed by bacteria than herbaceous matter (Talbot and Livingstone, 1989). Thus, δ¹³C of the organic matter reflect the relationship to woody vs. herbaceous composition (Bird et al., 1994). The trends observed downstream of the Sanaga River are consistent with the progressive addition of C3-derived forest organic matter to mixed C3-C4 origin derived from the savanna and mountain regions (Fig. 4).

3.2.2. Suspended organic matter

The delivery of the organic carbon in the ocean or in the lacustrine basin was recently studied including particulate (POC) as well as 'dissolved' matter (DOC). POC is separated by filtration at 0.6 μm (Giresse and Cahet, 1997). DOC includes, by convention, all the organic phases of carbon: truly dissolved or in the macromolecular, colloidal or microparticulate states (Johnson and Kepkay, 1992; Koke et al., 1990; Tranvik, 1994).

On the basis of the available data, the suspended matter exported from the Sanaga River present a POC content fluctuation of 7 to almost 16%, namely

![Fig. 4. TOC contents vs. carbon-isotope composition of alluvial deposits from the Sanaga basin. The circle indicates the altitude stations with a dominant herbaceous cover with sometimes a montane component (M); then, one can observe the transition to the downstream rainforest (point F).](image-url)
5 to 12.5 mg l\(^{-1}\). We interpret this variation as reflecting the grain-size composition. DOC fluxes are equal or sometimes lower than POC (4.8 to 8.3 mg l\(^{-1}\)). DOC/POC ratio closer to 1/1 are usual for rivers draining tropical regions (e.g., Malcolm and Durum, 1976; Richey et al., 1980). The evaluation of TOC transport in the Sanaga basin, including POC and DOC, is approximately 15.3 mg l\(^{-1}\) (with a standard deviation of 5.5) and the rate loss of TOC from the Sanaga's watershed is roughly estimated as 8.8 t km\(^{-2}\) yr\(^{-1}\) (Table 2). In the estuarine waters of the Wouri River, colloidal and dissolved organic carbon occur in near-equal proportions in the organic carbon flux.

In the Douala Bay (Fig. 1), suspended matter concentrations were measured showing a decrease from 176 to 32 mg l\(^{-1}\) with an increasing distance of transport from the river mouth (Fig. 5a). The POC flux decreases before the estuary (6.5 mg l\(^{-1}\)) until the open-sea (1–2 mg l\(^{-1}\)). This deficit is noticeable in a near 75-km path (Fig. 5b). In parallel, the DOC flux decreases from 8 mg l\(^{-1}\) to 2–3 mg l\(^{-1}\) (Fig. 4b). After entering the clear offshore waters, DOC concentrations remain remarkably stable (2–3 mg l\(^{-1}\)) including possibly the true dissolved organic carbon, namely 25 to 30% of the total DOC and only 12 to 15% of the whole organic flux. Consequently, the ratio of the amount of DOC to the total amount of organic flux increases quickly: a POC/DOC ratio of 1 upstream of the estuarine sector exhibits noticeably lower values (0.2–0.3) off the Douala Bay, indicating the slower sedimentation rate of colloidal DOC.

Variations of the content of the riverine POC and DOC, which are linked to the granulometric composition and the dilution in the open-sea, are higher than the marine end-member. If all values in intermediate salinities (estuarine zone) are on a straight line connecting river and ocean values, then the mixing phenomenon is conservative (Liss, 1976; Cadée, 1982; Cadée and Laane, 1983; Cadée et al., 1993). In the Bay of Douala, values are below this line (Giresse and Cahet, unpublished data) indicating a non-conservative behaviour.

### Table 2

<table>
<thead>
<tr>
<th>Catchment</th>
<th>POC loss (t km(^{-2}) yr(^{-1}))</th>
<th>DOC loss (t km(^{-2}) yr(^{-1}))</th>
<th>TOC loss (t km(^{-2}) yr(^{-1}))</th>
<th>Total TOC loss (t yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanaga as a whole</td>
<td>5.06</td>
<td>3.78</td>
<td>8.8</td>
<td>1.188 \times 10^6</td>
</tr>
<tr>
<td>Sanaga s.s.</td>
<td>3.22</td>
<td>2.40</td>
<td>5.6</td>
<td>0.426 \times 10^6</td>
</tr>
<tr>
<td>Mbam</td>
<td>9.77</td>
<td>7.30</td>
<td>17</td>
<td>0.711 \times 10^6</td>
</tr>
</tbody>
</table>

3.3. Factors causing fluctuations in the flux of organic matter into the ocean

As river-current velocities are not sufficiently high to prevent sand settlement, only suspended fine aggregates are transported downstream. Consequently, this suspended matter has a quite homogenous grain-size range. However, within the estuarine environment, short term events such as sediment resuspension may have some substantial effect on suspended matter composition and can explain POC content variation (7 to 16%). Such contents are also reported for organic carbon discharged from other tropical rivers as the Dibamba, discharging in Douala Bay (12.2%) and particularly from the nearby catchment of the Congo–Zaire river (Bongo-Passi et al., 1988; Mariotti et al., 1991) or in other West African rivers (Cadée, 1984), as the Ogooué (6.1–6.6%), the Benue (28.5% with few measurements) or the Niger (5.8%). These values are a little higher than those from the Amazon river (1.5–8.2%, Richey et al., 1980; Hedges'et al., 1986). On the basis of the available data, the POC exported from the Sanaga River varies between 5 and 12.5 mg l\(^{-1}\) while DOC fluxes range between 4.8 to 8.3 mg l\(^{-1}\).

In order to find out the biodegradability of the suspended organic matter, an incubation experiment was monitored for 4 days. It shows differences be-
tween the river and marine domains: (a) in rivers, the POC content is fairly stable after 120 h (Fig. 6a). This relative stability is confirmed by the constancy of C/N ratio. But the DOC decreases irregularly (loss of 25 to 60%) and sometimes dramatically (Fig. 6b), (b) in the waters of estuaries, namely in the freshwater–salt water mixing zone, the difference of salinity and eventually of temperature seems to increase this biodegradation. The loss of POC is between 10.9 and 29.4% in the upstream and brackish part of the estuary and between 7.8 and 40% further on. Analogously, C/N increases from 8–14 to 11–20. As in fresh water, the DOC degrades faster (25 to 30%) and (c) in the offshore sea-water, the previously degraded organic matter appears more stable.

These results reflect an intense degradation process suggesting a near 50% TOC (POC + DOC) deficit.

The Sanaga River is the main river discharging into the Cameroonian shelf; with an annual flow rate...
of $65.3 \times 10^6$ m$^3$ yr$^{-1}$, which is slightly larger than all other rivers combined from this region. The Sanaga River is also the main source of terrestrial organic carbon in this region. On the basis of a mean annual solid discharge of $6 \times 10^6$ t (Nouvelot, 1972; Olivry, 1977), its TOC average flux varies between 0.42 and $0.54 \times 10^6$ t yr$^{-1}$, whereas all the other rivers flowing in the Douala Bay together vary from 0.2 to $0.25 \times 10^6$ t yr$^{-1}$. Thus, the bulk annual TOC discharge to this part of the Guinea Gulf ranges from 0.62 to $0.79 \times 10^6$ t. Following the estuarine biodegradation, the final accumulation appears to be only 50% of the total fluviatile TOC influx, namely ca. $0.31$ to $0.40 \times 10^6$ t yr$^{-1}$.

4. Application to the sedimentary marine record

It is generally accepted that most carbon exported to the ocean by rivers ends up in marine coastal muds (Holland, 1978; Schlesinger and Melack, 1981). On the basis of the obtained sedimentation rate, a budget of organic input can be estimated. In such depositional system organic terrigenous flux decreases from shallow to moderate depths where ma-
Table 3
TOC contents (wt.%) of marine muds as a function to the transfer length from the source, to the grain-size and to the depth

<table>
<thead>
<tr>
<th>TOC content (%)</th>
<th>Distance from the river mouths (km)</th>
<th>Sand content (%)</th>
<th>Depths (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5–3</td>
<td>0–30</td>
<td>10–40</td>
<td>10–15</td>
</tr>
<tr>
<td>3–3.5</td>
<td>30–40</td>
<td>5–25</td>
<td>15–20</td>
</tr>
<tr>
<td>3.5–4</td>
<td>40–55</td>
<td>&lt;5</td>
<td>15–35</td>
</tr>
<tr>
<td>&gt;4</td>
<td>&gt;60</td>
<td>&lt;1</td>
<td>10–50</td>
</tr>
</tbody>
</table>

Marine primary production is observed. However on the Cameroonian shelf this marine production is recognized to be lower than on the other parts of the Guinean Gulf (Crosnier, 1964).

Our results suggest that the total fluxes of organic matter depend sensitively upon the biodegradation during transport when river water enters the ocean leading to a dissolution of near 50% of organic matter. In fact, the sedimentation pattern is more complicated and the grain-size factor must be taken into account. In surface waters, the river discharge is low and the role of turbulence in sediment winnowing causes sandy mud deposition with 3% TOC close to the coast (10–20 m). In the open ocean, towards the east, the deeper muddy sediments are characterized by high TOC contents (3 to 4%). Then, they are more than 4% in the very fine-grained deposit (Table 3). In the last two cases, suspended and deposited matter are present in a nearly same size spectrum.

4.1. Processes controlling organic matter sedimentation on the Cameroon margin

Most of the suspended organic matter of the large river plume is directed towards the NW (Rio del Rey). This distribution is in agreement with the predominant SW swell. Oceanward, there is a relative decrease of the TOC as a result of the continuous settling of the largest organic particles. Increasing TOC concentrations are observed off the Rio del Rey mangrove swamps, probably related to estuarine hydrodynamic conditions as well as the variable supply of particles from the more distant Niger delta. This supply is characterized by a relatively high smectite content (20 to 40%). During the settling of these terrigenous particles, only a small part reaches the outer shelf where transgressive Holocene deposits and, to a lesser extent, those of the previous low-stand are near outcropping (cf. the Older Sands, Allen, 1965). Therefore, the Sanaga River and the Douala Bay rivers sedimentation follow a well delimited area of distribution reaching about 3140 km². High-resolution seismic reflection surveys allow the definition of the High System Tract (HST) that reaches thicknesses of 20 to 40 m close to the shore (Giresse et al., 1995). This HST is mostly a muddy and seismically transparent prism, but very close to the shore, the abundance of bubble gases released by methanogenesis does not allow seismic surveying. In the open-sea (40 km to the shore) this prism is reduced to a metric, then decimetric veneer resting on an emergent sand or gravel. This coarse sediment is the first sandy deposit of the Holocene transgression, namely Transgressive System Tract (TST) (Giresse et al., 1995). This TST was often cored comprising a very poor organic matter-sediment and it is not taken into account in this budget. Consequently, it should be noticed that the deposit laid down during the Holocene transgression corresponds to a prism of $56.712 \times 10^6 \text{ m}^3 \pm 4.125 \times 10^6 \text{ m}^3$ (this uncertainty is related to the ‘bubble muds’ part of the prism).

The decrease of muddy Recent sediments with increasing distance from the shore is less regular than expected: some metric or infra-metric veneer can be observed on the outer shelf. This irregularity may be due to factors including variations in outflow of Cameroonian rivers mixing with supply of particles from the distant Niger delta. A part of the Niger River suspended matters are driven southeastward by the slow Guinean current (Fig. 1). Clay minerals analysis allow to define a mixed deposit with near 50% of Nigerian particles. The mass of this veneer can be considered as far less insignificant but its mixed original composition can be useful to calculate the organic budget of the nearby slope muds.
These muds present a clay composition and a carbon content very close to those of the outer shelf, so a mixed composition is assumed for the whole slope deposit as the Nigerian influx is found to decrease only off Campo (Giresse et al., 1995).

After gradient correction, the surface of the Cameroonian continental slope between 200 and 2000 m can be estimated to be 3400 km². The deeper slope between 2000 and 4000 m will not be considered here due to a very low sedimentation rate: on the nearby Gabonese margin, the rate is 10% that of the upper slope (Giresse and Barusseau, 1989).

The mean thickness of the upper slope Holocene sediments is estimated by core-data to be about 5 m. Towards 2000 m, the nearby Gabonese reference (Bonifay and Giresse, 1992) gives an average thickness of 0.5 m. It can be estimated that 7.79 × 10⁶ m³ Holocene sediments are trapped on this slope between 200–2000 m. It can be assumed, on the basis of the mineralogical study, that only half of their volume originates from the Cameroonian rivers because only a small part of their suspended matters is actually able to by-pass the outer shelf.

4.2. Quantitative approach of the terrigenous carbon storage

4.2.1. Continental shelf

The HST can be considered as a near homogeneous deposit because in each core the TOC contents are very close to the surface value. Some low TOC contents are related to sandy levels but they are too thin to play an important role. The water contents also are homogeneous below 10–20 cm from the surface. Because the oceanic productivity in this area is negligible (Crosnier, 1964), the organic deposition is considered as terrigenous. There is a gradual decrease in total sedimentation rates from the shore (9 g cm⁻² 10³ years) to the prism wedge (0.5 g cm⁻² 10³ years). This rate can thus allow to estimate that 3.271 × 10⁹ t TOC are trapped on the shelf during 10⁴ years.

4.2.2. Continental slope

On the Congo–Zaire deep sea-fan (Jansen et al., 1984), carbon isotopic measurements indicate that land-derived carbon may represent only 30% of the total carbon. With increasing depth and decreasing rate of sedimentation (< 0.5 g cm⁻² 10³ years), the decrease of terrigenous carbon is pronounced. The total sedimentation rates can be evaluated to 5 g cm⁻² TOC 10⁷ years on the upper slope to 0.5 g cm⁻² on the lower slope. As on the shelf, the TOC contents are assumed to be invariable at the 10⁴-year scale. It can thus be estimated that 0.279 × 10⁹ t Holocene TOC are trapped on the slope of which half (0.14 × 10⁹ t) may represent an input from the Niger river. Although our estimates are rather approximate, it could be assumed that the organic storage on this slope is only about 20 times less than on the shelf. Schlesinger and Melack (1981), in their overview, suggest that organic carbon in the river flow is a very small source of the carbon in deep ocean sediments where one can take into account the increased accumulation of marine organic material.

The organic carbon curves in the cores from the shelf and the slope give no argument for any significant fluctuations during the Holocene. Particularly, the climatic deterioration in Late Holocene (post 3000 BP; Giresse et al., 1994; Maley, 1996) is not evidenced. But if we extended the observation over all the last 2–3 × 10⁴ years, including the last lowstand, some vertical changes can be noted. The TOC contents show episodes of relative decrease around Pleistocene boundaries where sandy and carbonate fractions show greater concentrations (Fig. 7a). But such fluctuations were mainly controlled by shoreline position and probably connected with near-shore hydrological conditions. On the nearby Gabonese margin (Bonifay and Giresse, 1992), the cores from 2000 m water depth provide a long-term recording (10⁵ years): high TOC accumulation is documented during the last Glacial (marine Y biozone), pointing to coastal upwelling and an increase in the rates of oceanic productivity (Fig. 7b). But in these cases, it can be assumed that it is not possible to use directly the great variation of the continental vegetation to explain long-term TOC fluctuations.

This evaluation results from several approximations, however, there is a close similarity between the total Holocene TOC sedimented mass: 3.411 × 10⁹ t and the TOC mass for the same period as deduced from present instantaneous flux: 3.1 to 4 × 10⁹ t (with substraction of biodegradation loss at the continent–ocean interface). A previous study of the Congolese margin (Giresse and Barusseau, 1989)
suggested an apparent 50% loss but without considering the estuarine biodegradation.

The mineral carbon trapped on the shelf is mostly composed of biogenic particles, representing up to 30% of the TOC. On the slope, the mass of these two forms of carbon are almost equivalent. The mineral carbon could explain, at the same Holocene scale, the settling of a substantial part of the dissolved carbon. This settling has also been recognized on the lower slope and on the oceanic basin which suggests the relative stability of the DOC content in the considered sea water.

5. Fluxes of organic carbon to lacustrine basins; application to the Barombi-Mbo sedimentary record

In the volcanic range of West-Cameroon, the sedimentary mass accumulated in the basins of the crater lakes are not important, but their stratigraphic successions provides a very good opportunity to palaeoenvironmental studies.

The Barombi-Mbo (surface area 4.15 km²) is the largest lake of the Cameroon Line. Its maximum depth is 110 m with a mean of 68 m. The catchment (12.25 km²) is developed to the west of the lake and bears a 2–3-m fersialitic mantle with a TOC content of 7 to 8%. This catchment is drained by two little seasonal streams called Toh-Mbok and Mahongue. Their confluence is located at about 100 metres from their steep delta cone. Their total output is around 0.32 to 0.4 × 10⁶ m³ yr⁻¹. High suspended matter content in the streams corresponds to flood discharge during the rainy season (S. Ngos, unpublished data).

The annual solid discharge estimated from these results is close to 9.4 × 10⁶ t. POC contents appear to be inversely proportional to sand contents that range from 2.5 to 7.3%. The latter allows the estima-
tion of the annual POC supply to the lake, ranging between 2.35 and $4.6 \times 10^3$ t yr$^{-1}$.

A 23.5-m long core was recovered in the central part of the lake. It displays two significant episodes of organic sedimentation (Giresse et al., 1994): (a) the Pleistocene interval (25,000 to 11,000-12,000 BP) displays POC values with average around 7-8%. The highest content commonly corresponds to the presence of brown millimetre to centimetre-thick laminae particularly rich in coarse lignitic debris. C/N ratio shows relatively high values (15 to 25) and the HI values are between 90 and 400; and (b) the Holocene deposits show POC contents decreasing during the last millennium indicating a relative good preservation of the organic matter. The HI values are generally both low and variable (80 to 230).

5.1. Present POC fluxes and fate for a sedimentary budget

Taking into account the present solid discharge of the two small rivers to the lake, the calculated accumulation rates are around 2.4 g POC cm$^{-2}$ yr$^{-1}$. There is a close similarity between this rate and those of the Holocene deposits, namely 1.9 to 2.53 g POC cm$^{-2}$ yr$^{-1}$. Assuming that the lake receives inputs not only from the two rivers but also from the slopes of the eastern catchment area, it can thus be estimated that the sedimentary trapping in the lake has slightly increased during present times. The highest POC content of the suspended matter is very close to those of the A$_1$ horizons of the soils from the slopes of the catchment. Such organic matter suddenly coming into the lacustrine environment can be regarded as fresh, this conservative process is different from these affecting oceanic sedimentation.

If, otherwise, we consider that the productivity of plankton biomass in Barombi-Mbo anoxic waters was very low (Kling, 1988), this basin provides good opportunity to observe detrital organic matter sedimentation and allows the major fluctuations of the vegetal cover in the catchment to be recorded. Because the slight fall of the lake level was unable to determine emersion processes (Giresse et al., 1991, 1994), there is no problem of organic matter preservation in these lacustrine sediments.

5.2. Palaeoenvironments and palaeofluxes of particulate organic carbon

The main data on the history of the vegetation result from pollen analyses and also from $\delta^{13}$C measurements; the age of samples is interpolated from 12 radiocarbon dates (Giresse et al., 1991, 1994; Maley, 1996). The pollen curve of the Gramineae (relative percentages)(Fig. 8a) presents the main variations of the vegetation. This taxon is characteristic of open environments of the savanna type and in each sample almost all the remaining pollen grains correspond to tree pollen.

From ca. 28,000 to 20,000 years BP (ca. 32,000 to 24,000 calendar/calibrated years), the Gramineae exhibit rather low percentages similar to the present day value, indicating a forest cover. Among the tree pollens, this period is characterized by an important mountain element with 9 to 31% of *Olea capensis*, a typical mountain tree. Pollen grains of this tree species were also found in the Lake Bosumtwi deposits (in the lowland of Ghana) between ca. 28,000 BP and the beginning of the Holocene (Maley, 1991). A cool and wet climate can be deduced around Barombi-Mbo.

The next phase began by a sharp increase in Gramineae pollen at ca. 20,000 BP (ca. 24,000 cal. years) and ended with a sharp decrease at ca. 10,000 BP (ca. 11,000 cal. years). During this period the forest receded giving way to more open vegetation with a forest and savanna mosaic, but significant patches of forest (refugia) survived in this area, confirmed by $\delta^{13}$C values typical of forest environment (Giresse et al., 1991, 1994; Maley, 1996). *O. capensis* was again well represented (4 to 16%). The climate was cool and relatively dry.

From ca. 9500 to 3000 BP (ca. 10,500 to 3200 cal. years) the Gramineae remained between 0 and 3% meaning that the forest reached its maximum extension. The climate was warm and very wet.

Around 2800 BP (ca. 3000 cal. years) a sharp increase in the Gramineae occurred, peaking at 30 to 40% between 2500 and 2000 BP (ca. 2600 to 2000 cal. years), which indicate a sudden phase of vegetation openings and forest retreat, accompanied by severe erosion (Maley, 1992). The climate was warm, very contrasted, and relatively dry (Maley, 1996).
After 2000 BP the Gramineae returned to low values (7 to 10%), similar to present day values, indicating that forest expanded again. The climate was warm and relatively wet, similar to the present day one.

The variations of the pollen influx (pollen/sediment g cm\(^{-2}\) yr\(^{-1}\)) (Fig. 8b) responded to the changes of vegetation and climate. The phases of large increases corresponded to the periods of abrupt changes around 20,000 and 10,000 BP, with high values between 20,000 and 15,000 BP during the LGM, which was also the period of maximum aridity. Later the pollen influx increased also during the relatively dry phase in the late Holocene from ca. 2800 to 2000 BP and next remained to high values until the present day period.

The calculated sediment accumulation rates present lower values between 17,100 BP and 13,200 BP and its major increase was during the Holocene (Fig. 9a) (Giresse et al., 1991). Conversely, the Holocene POC contents are lower than the Pleistocene contents (Fig. 9b). The two variables are compensating each other and thus, the POC accumulations budget appears rather homogeneous during the last 20,000 years (Fig. 9b).

From 20,400 to 17,100 BP the sedimentation rates of the bulk sediment and of the POC are 18.7 and 1.5 g cm\(^{-2}\) yr\(^{-1}\), respectively.

From 13,100 to 8850 years BP, the two sedimentation rates exhibit an acceleration at around 28 g cm\(^{-2}\) for the bulk sediment and 2.1 g cm\(^{-2}\) yr\(^{-1}\) for POC.

From 8850 to 3700 years BP the soil development (Giresse et al., 1991) and inflow suspensions became more important and lead to very rapid sedimentation rates: 42–46 g cm\(^{-2}\) yr\(^{-1}\). The clayey component becomes more important, but in spite of this diluting factor, the POC rates are high: 2.31 and 2.53 g cm\(^{-2}\) yr\(^{-1}\).

After 3700 years, the two rates decreased slightly (38 and 1.9 g cm\(^{-2}\) yr\(^{-1}\)). For this last interval, the calculated annual discharge is around 2330 t. An-
other short core taken from the central part of the lake, allows us to calculate comparable values which permit to estimate a new increase of POC sedimentation rate close to 4.8 g cm\(^{-2}\) yr\(^{-1}\) when the regional forest began to develop again particularly between 2000 and 1600 BP.

In contrast to oceanic TOC records where the interaction of shoreline level and sorting processes are difficult to analyze, Lake Barombi-Mbo, with a relatively stable water level throughout the LGM and the Holocene (Giresse et al., 1994) shows clear evidence of changes in POC fluxes correlated to the main changes of the vegetation cover on the drainage basin.

During the period 20,000 to 13,000 years BP, the POC sedimentation rate is low because the floods were less frequent. But it is also irregular, because the floods were stronger as shown by thicker (cm-scale) and relatively coarser brown beds (Giresse et al., 1991). These beds present concentrations of coarse lignitic components derived from logs and roots (HI < 100). The scarceness of nitrogen compounds is a well-known property of lignin that may explain C/N high values reaching 20 to 30. Soils in the drainage basin were relatively less developed (Giresse et al., 1991). Under these conditions, the litter of leaves and the A\(_1\)-A\(_2\) horizons of young soils were mostly eroded by the running water.

Such POC concentrations occur during very short stratigraphic intervals, so the global POC LGM flux is moderate and appears 30% less than the Holocene one. In each case, we assume that organic matter degradation is the reflection of pedogenetic process and that there is no evidence of significant diagenetic alteration (Giresse et al., 1994).

Therefore, to explain the high POC contents of the LGM sediments one must consider the relative importance of the mountain element, particularly
O. capensis, which grow probably on the hills around the lake Barombi-Mbo. This lake is situated at an altitude of ca. 300 m with the edge of the crater and other nearby hill summits culminating between 400 and 600 m. The presence of mountain taxa could be explained mainly by the seasonal persistence of stratiform clouds and mist on these summits which induced some cooling (Maley, 1989, 1991; Maley and Elenga, 1993). The spreading of stratiform clouds on the continent is related to sea surface temperature lowering in the Guinea Gulf induced by the seasonal upwelling of deep oceanic water, and inland by the extension of subsidence phenomena in the troposphere (Flohn, 1983; Maley and Elenga, 1993). Today, the main upwelling season coincides with the austral winter, linked to the increase of anticyclonic conditions and to the trade wind stress (Servain et al., 1985). Micropalaeontological data in the Gulf of Guinea show that during the end of the Pleistocene and particularly at the time of the LGM (ca. 20 to 15,000 BP), the length and the strength of the upwelling season was greatly increased (Prell et al., 1976; Morley and Hays, 1979; Mix et al., 1986). Therefore, a great extension inland of the stratiform clouds leading to temperature lowering can be inferred. In general, in the African lowland equatorial regions (Maley, 1989, 1991, 1996) and also in East Africa (Van Campo et al., 1990; Bonnefille et al., 1992) a mean cooling of 3-4°C was estimated during the LGM.

Several authors working on the mechanism 'forcing' the vegetations to change their composition and physiognomy between lowlands and mountains have concluded that the temperature lowering does not directly act upon the plants, but indirectly through nutrient limitations, particularly for nitrogen and phosphorus (Whitmore, 1975; Grubb, 1977; Vitousek, 1984). However, in the soils the temperature lowering allows the reduction of the bacterial alteration of the total organic matter and so its better conservation with thickening of the humus top soil (Hutte1 and Bemhard-Reversat, 1975; Vitousek, 1984). At the same time, the slowing down of the recycling processes leads to the accumulation of larger quantity of nitrogen and also to a shortage of mineral nutrients leading finally to oligotrophic conditions (Whitmore, 1975; Grubb, 1977; Vitousek, 1984).

6. Implication for the organic carbon budget and discussion

The river carbon budget is of particular interest for two reasons: (i) as a bulk shift in carbon between reservoirs and (ii) as a palaeo-vegetation indicator.

6.1. Compared appraisal of the Holocene carbon flux and terrestrial storage

6.1.1. Into the Bay of Biafra

Measurements of fluxes of the present period should be applied to Holocene-scale records but with probable increased rates through the recent period of cultivation on the Mbam catchment. As a first estimate, we calculated a Sanaga export to the ocean around 1.118 $\times 10^6$ t TOC during $10^4$ years. This value appears high compared with the stored carbon on the top soil of the catchment: this resulting carbon loss by erosion might correspond up to eight times the POC stored in A horizons and four times the overall POC stored in the pedogenetic cover as a whole. This process would result in a net erosion increase ($\times 3$) in the case of the disturbed Mbam catchment. Consequently, one can conclude that this resulting carbon loss would require a frequent regeneration of the terrestrial carbon storage. Using the data and estimates presented above, we can calculate a near 2500-yr period of turn-over. In the increasing cultivated Mbam watershed, mean soil losses due to erosion should induced a very critical trend.

6.1.2. In the Barombi-Mbo catchment

In this catchment (4.15 km$^2$), our estimate represents only the budget of POC associated with suspended solids. Based on the present minimum rate of 2.4 g POC cm$^{-2}$ yr$^{-1}$ or 2.4 t POC km$^{-2}$ yr$^{-1}$, the minimum accumulation rate in the lake basin is estimated as 9.96 t POC yr$^{-1}$, namely the resulting POC deposit during Holocene would be at least 96.6 $\times 10^3$ t. The A$_1$ horizons of the watershed exhibit an average of 7.5% POC content. With a mean thickness of 0.5 m, the largest estimate of the soil carbon storage would be around 117 $\times 10^3$ t. From the same calculation based on the combined use of a POC/DOC ratio close to 1:1 (namely an annual loss of 200 $\times 10^3$ t TOC) and of a carbon phytomass/carbon soil ratio close to 2:1 (a total
storage of $350 \times 10^3$ t TOC, one can conclude that this catchment storage is much larger than the Holocene loss (Table 4). Such values would not be greatly modified by recent farming because lowland's development is very restricted.

In such a well-preserved rainforest ecosystem, a complete process of stored carbon consumption would require some $10^4$ years, namely, the Holocene period. But as previously indicated, Pleistocene erosion may have significantly increased in a relatively open landscape and suggest a more rapid regeneration of soils in the drainage basin. Pleistocene soils were less developed than during Holocene phase of generally higher humidity (Giresse et al., 1991).

6.1.3. Comments

The comparison of our results with those found elsewhere in the tropics is quite difficult because no data on soil storage as a whole are available in the literature and because also DOC/POC studies in the tropical estuaries are relatively scarce. Here we set aside the intricacy brought by primary production of POC and DOC in the estuaries or in the plume of the river (in the case of the Congo–Zaire river for instance) as this organic matter is largely non-conservative (Cadée, 1984; Cadée et al., 1993). The Sanaga River is the dominant source of terrestrial C in the region and its catchment with savanna, transitional forest–savanna, and rain forest is largely representative of tropical ecosystem. So, its present soil reservoir is adequate in estimating the magnitude of the total carbon stored in a large drainage basin of wet tropical lands. In other tropical rivers, POC concentrations in surface samples of suspended matter (Richey et al., 1980; Eisma and Van Bennekum, 1978; Eisma et al., 1978; Brinson, 1976; Schlesinger and Melack, 1981; Lesack et al., 1984; Cadée, 1984; Hedges et al., 1986) present nearly the same values. The basin loss rate for the Sanaga basin as a whole ranges from 4.54 to 5.9 g C m$^{-2}$ yr$^{-1}$ namely very close to other tropical watersheds: 4.40 or 8.51 g C m$^{-2}$ yr$^{-1}$ for the Amazon; 1.71 g C m$^{-2}$ yr$^{-1}$ for the Congo–Zaire river and 2.2 to 4.74 g C cm$^{-2}$ yr$^{-1}$ for small streams in Guatemala; the low loss in the Gambia river watershed (0.38 g C m$^{-2}$ yr$^{-1}$) is attributed to lack of relief in the catchment.

The calculated 2500-yr period of regeneration of stored carbon in the Sanaga basin is a first estimate for the Holocene time but it may be representative of an increasing loss in the Mbam catchment during the 1970 years. Conversely, the present undisturbed portion of the Barombi-Mbo ecosystem may be inadequate in recognizing pathways of overall Holocene carbon movement. The transfer of organic carbon to the worlds' oceans by riverflow is one of the smaller transfer in the global cycle (Schlesinger and Melack, 1981) but this present estimation would help some attempts to balance models.

6.2. Applications to palaeoenvironmental evolution

6.2.1. The Sanaga watershed link with oceanic basin

For the Holocene scale, our appraisal of the export of POC through the estuarine interface to the ocean falls within the range suggested by the accumulation in oceanic sediments since the last transgression. We are encouraged by the similarity of our two largely independent estimates for a globally warm and wet environment, each with quite different assumptions and sensitivities. Assuming that the average organic carbon of marine sediments represents the deposition of organic matter associated with suspended matter, this link between source and sink should have led to permanent regeneration in the dead and living carbon biomass of the Sanaga watershed. Such $10^4$ years of marine accumulation involves the transfer towards the ocean of a TOC mass $(11.8 \times 10^9$ t) which is four times as large as the

### Table 4

Compared rates of loss of organic carbon from the Sanaga catchment and from the Barombi-Mbo basin in regard to the storage of the topsoils

<table>
<thead>
<tr>
<th>Sites</th>
<th>POC loss (t km$^{-2}$ yr$^{-1}$)</th>
<th>POC Holocene loss</th>
<th>'Dead' POC storage on the catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanaga catchment</td>
<td>5.06</td>
<td>11.881 t 10$^9$ years</td>
<td>1.812 $\times 10^9$ t</td>
</tr>
<tr>
<td>Barombi-Mbo</td>
<td>3.37</td>
<td>96.6 t 10$^3$ years</td>
<td>117 $\times 10^3$ t</td>
</tr>
</tbody>
</table>
total TOC soil mass stored on land \((3.6 \times 10^9\) t). Van Campo et al. (1990) established a correspondence between biomass and soil carbon in order to obtain a value of the modern total carbon storage for each ecosystem. For calculating the carbon stored in biomass, we made the same assumptions and estimated \(1.84 \times 10^9\) t. Then, the Holocene POC accumulation in oceanic sediments is two times as large as the total carbon stored on land \((5.44 \times 10^9\) t, e.g., global phytomass and total soil mass).

In regards to the very close relationship during transport between organic matter load and grain-size and also to the prominent part taken in reworking by the shoreline fluctuations, Holocene sedimentary records on the shelf and the upper slope display greater deviation than those from lacustrine basins. Thus, the change only in the POC sedimentation rate is inadequate to recognize the magnitude of shifts in the vegetation cover. Decreased concentrations of the POC in the Late Glacial–Interglacial boundary (marine biozones Y–Z boundary) could be observed on the upper slope, but they are generally attributed to sieving mechanisms in shallow-waters near the lowstand shoreline. But with the data obtained off-shore large rivers, as the Congo–Zaïre, during several glacial–interglacial changes, one can observe a consistent correlation between warm biozones and maxima POC inputs. This observation is particularly obvious when carbon isotopic ratios are used to aid in the isolation of terrestrial component from oceanic one (Bongo-Passi et al., 1985; Jansen et al., 1984; Mariotti et al., 1991).

It seems that organic carbon of shelf sediments in the tropics cannot be used directly as an indicator of catchment palaeoenvironmental changes where carbon isotopic ratio or pollen evidence is lacking. When using the TOC bulk sediment and working at the scale of the last eustatic change, e.g., lowstand, active transgression and hightand, a clear feedback between climatic (monsoon establishment) and eustatic factors (active transgression) can be observed only on the slope of the Gabon–Congo margin (Giresse and Barusseau, 1989).

6.2.2. The basin of Lake Barombi-Mbo during the last 20,000 years

Pedologic studies support a relatively low degradation of the organic matter with both increasing altitudes and decreasing temperature and rainfall. According to these general phenomenons, low to middle altitude sites as the Lake Barombi-Mbo are able to experience relative changes in either climate or in the nature of the vegetation cover. In this study, palaeoenvironmental changes are more or less comparable to altitude-generated forcings. This record implies that the site persisted with a relatively stable physical environment throughout the LGM and Holocene periods, particularly with a relatively stable water level.

The last 20,000-yr record indicates an acceleration of sedimentation rates through the Glacial–Interglacial changes. But taking into account the lower POC content in Holocene sediments and the higher during the LGM, the calculated POC accumulation rate provides evidence of a relatively homogeneous delivery. Two alternative or complementary explanations for the high POC contents in Glacial Age deposits could be related to palaeoenvironmental factors.

(i) A more or less abrupt load change with input of alluvial matter on this basin with dominant steep slopes. In a forest–savanna mosaic, humic horizons and litter release large amounts of coarse and refractory dissolved organic compounds. Subsequently, the brown and thicker layer of Pleistocene levels is related to the presence of abundant millimetre to centimetre fragments of lignitic debris. In the Holocene deposits, the thickness of the same brown layer diminishes and the clay content increases.

(ii) Pollen data point out the presence of a characteristic mountain element which suggests a 3°–4°C cooling during the LGM. This lake being situated near high reliefs of the volcanic ridge, so stratiform cloud covers would have formed easily to induce a temperature decrease. Consequently, the decrease of the biodegradation and the thickening of the organic top soils acted as a significant POC concentration before the transfer by riverflow. Such general relationship between high POC contents in the sediments and cooling of the temperature are likely to be stronger on the upper part of tropical montane complex as the Cameroon Line or also the Adamaua Plateau where studies are needed.

The described balancing process between denudation rates and the altitudinal conservative process implies eventually the best appraisal of the shelf
carbon budget in the Bay of Biafra (north eastern part of the Gulf of Guinea) and consequently of its meaning. The greatest solid input through the rivers would be balanced by lower TOC concentrations in the suspended matter resulting to a nearly homogeneous carbon mass transfer to the ocean. But, it is likely that within the large scale of intertropical catchment of relatively low altitude as the Congo-Zaire basin, the Holocene POC flux is consistent with the mean rainfall and runoff increases (Giresse and Barusseau, 1989).

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