Spatial and seasonal dynamics of total suspended sediment and organic carbon species in the Congo River

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[1] The Congo (Zaire) River, the world's second largest river in terms both of water discharges and of drainage area after the Amazon River, has remained to date in a near-pristine state. For a period between 2 and 6 years, the mainstream near the river mouth (Brazzaville/Kinshasa station) and some of the major and minor tributaries (the Oubangui, Mpoko, and Ngoko-Sangha) were monitored every month for total suspended sediment (TSS), particulate organic carbon (POC), and dissolved organic carbon (DOC). In this large but relatively flat equatorial basin, TSS levels are very low and organic carbon is essentially exported as DOC: from 74% of TOC for the tributaries flowing in savannah regions and 86% for those flowing in the rain forest. The seasonal patterns of TSS, POC, and DOC show clockwise hysteresis in relation to river discharges, with maximum levels recorded 2 to 4 months before peak flows. At the Kinshasa/Brazzaville station, the DOC distribution is largely influenced by the input from the tributaries draining the large marshy forest area located in the center of the basin. There is a marked difference between specific fluxes, threefold higher in the forest basins than in the savannah basins. The computation of inputs to the Atlantic Ocean demonstrates that the Congo is responsible for 14.4×10^6 t/yr of TOC of which 12.4×10^6 t/yr is DOC and 2×10^6 t/yr is POC. The three biggest tropical rivers (the Amazon, the Congo, and the Orinoco), with only 10% of the exoreic world area drained to world oceans, contribute ~4% of its TSS inputs but 15–18% of its organic carbon inputs. These proportions may double when considering only world rivers discharging into the open ocean.

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1. Introduction

[2] With respect to the total flux of carbon carried by world rivers ($\sim 10^{15}$ g/yr), the contribution of organic carbon is estimated to represent ~40% [*Meybeck*, 1993]. This organic carbon discharge into the oceans from rivers is a key link in the global carbon cycle, particularly over geological timescales [*Kempe*, 1979; *Berner et al.*, 1983; *Degens et al.*, 1984; *Amiotte-Suchet et al.*, 2003; *Richey*, 2004]. While this budget is low compared to global marine primary production, the amount of fluviatile organic carbon burial is of the same order as that of coastal marine organic carbon burial [*Schlünz and Schneider*, 2000]. Moreover, as the riverine organic carbon flux is one order of magnitude less compared to the net oceanic uptake of atmospheric CO_2, this flux can affect the long term ocean-atmosphere budget [*Berner*, 1990; *Sarmiento and Sundquist*, 1992; *France-Lanord and Derry*, 1997]. Finally, recent work has shown that organic carbon in tropical rivers and wetlands is an important source of CO_2 outgassing to the atmosphere [*Richey et al.*, 2002; *Richey*, 2004].

[3] Over the last 25 years, field investigations initiated by the SCOPE/CARBON program [*Degens*, 1982] have substantially improved the data on global riverine organic carbon fluxes [e.g., *Spitzy and Ittekkot*, 1991; *Kempe et al.*, 1993; *Ludwig et al.*, 1996; *Schlünz and Schneider*, 2000]. However, large gaps persist, mainly owing to: (1) the lack of sampling for some rivers draining particular environments (e.g., mountainous tropical forests, highstanding islands [*Meybeck*, 1982, 1993; *Pernetta and Milliman*, 1995; *Vörösmarty et al.*, 1997; *Meybeck and Vörösmarty*, 1999; *Lyons et al.*, 2002]); (2) the use of dated and questionable data (limited sampling, imprecise analysis methodology and/or data collected before dam construction,

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deforestation, or climate changes) [*Holmes et al.*, 2002; *Richey*, 2004]; and (3) the scarcity of river sampling suitable for studying the temporal variability of fluvial carbon fluxes.

[4] Long-term research to determine seasonal changes and/or year-to-year variations in organic carbon concentrations and fluxes requires specific focus, and is generally lacking. Taiga rivers have come under particular scrutiny during the last decade [*Cauwet and Sidorov*, 1996; *Gordeev et al.*, 1996; *Opsahl et al.*, 1999; *Lobbes et al.*, 2000; *Köhler et al.*, 2003; *Benner et al.*, 2004], including by stable isotopes, and works on ^{13}C signatures, ^{14}C dating started in the 1980's on the Amazon [*Hedges et al.*, 1986; *Richey et al.*, 1990] and has been continued by *Benner et al.* [1995]. Moreover, some Tropical River inputs to oceans have only recently been considered as is the case for the Zhu Jiang (Pearl River) [*Callahan et al.*, 2004]. Human activities as in the Mississippi catchment area [*Meybeck*, 2003] have also been investigated for their effects on organic carbon inputs to oceans [*Cai*, 2003; *Wang et al.*, 2004]. However, many of these studies are often based on an insufficient number of cruises carried out only in the estuarine zone [*Cauwet and Sidorov*, 1996; *Lobbes et al.*, 2000; *Callahan et al.*, 2004; *Wang et al.*, 2004], which cannot fully account for the temporal variability of fluxes. A high sampling resolution is necessary, particularly in rivers whose discharges and/or total suspended solids are highly variable due either to their size or to their hydrological regime [e.g., *Meybeck et al.*, 2003; *Coynel et al.*, 2004].

[5] The Congo River is the world's second largest river in terms both of drainage area (3.7×10^6 km^2 of the 90×10^6 km^2 total land area [*Orange et al.*, 1999; *Laraque et al.*, 2001]) and of water discharge (1325 km^3/yr or 42,000 m^3/s). It covers ~25% of the total wet tropical zone and is responsible for almost 3.4% of the fresh water inputs to the Atlantic Ocean [*Probst and Tardy*, 1987]. However, it has been practically ignored by geochemists since the first and only estuarine study in 1976 [*Eisma and Van Bennekom*, 1978]. In the late 1980s and early 1990s, the French overseas research organization (ORSTOM, now IRD) performed intensive studies of the northern part of the Congo Basin between Brazzaville and Bangui. The published results of these investigations cover the hydrological balance, the suspended load, and the major ions [*Kinga-Mouzeo*, 1986; *Olivry*, 1986; *Nkounkou and Probst*, 1987; *Martins and Probst*, 1991; *Seyler et al.*, 1995].

[6] This paper is based on an extensive data set of total suspended sediment (TSS) and organic carbon analyses, collected monthly at four stations in the Congo Basin. Anthropogenic disturbances such as sewage inputs, intensive agriculture, deforestation, and dams have not yet had a great impact on the Congo River which has therefore not developed any of the global change syndromes observable on most of the world's largest basins, apart from the Amazon [*Meybeck*, 2003]. The TSS and organic carbon dynamics are still mostly in a natural state. The objectives of this paper are: (1) to determine the major mechanisms controlling seasonal concentrations of TSS, particulate organic carbon (POC), and dissolved organic carbon (DOC) at four stations on the Congo mainstream and its northern tributaries; (2) to give quantitative estimates of TSS, POC and DOC fluxes from the Congo Basin entering the Atlantic Ocean based on extensive monthly database; and (3) to compare the Congo River fluxes to other major world rivers, including the other main tropical rivers, the Amazon and the Orinoco and their principal tributaries.

2. Material and Methods

2.1. The Congo Basin and Its Hydrological Regimes (Figure 1)

[7] The Congo Basin drains the centre of equatorial Africa. It is a vast peneplain (with altitudes of less than 400 m), surrounded by moderate elevations to the north and south, and by the mountain range of the East African Valley to the East. The center of the Basin is covered by evergreen forest (50% of the total area), and surrounded by savannah [*De Namur*, 1990]. Swamp forests are found in the Central Depression ("Cuvette Congolaise"), a sedimentary basin that straddles the equator (Figure 1). In the wet season, most of the forests are flooded, while in the dry season they dry out. The Congo Basin has a humid tropical climate: the mean annual precipitation, calculated for the decade 1980–1990 is close to 1550 mm [*Mahé*, 1993] and the mean temperature is over 20°C. The main tributaries of the Congo River are the Upper Zaire, the Oubangui, the Ngoko-Sangha, and the Likouala rivers on its northern side, and the Kasai River on its southern side. The hydrological regime at the mouth of the Congo River (Brazzaville/Kinshasa gauging station) is typically equatorial [*Rodier*, 1964]. The water discharge fluctuations are extremely limited due to the distribution of its tributaries on both sides of the equator. This results in a bimodal hydrological cycle with two maximum flows in December and May and two minimum flows in August and March (Figure 1). The long-term average discharge at the Brazzaville/Kinshasa hydrological station is about 40,600 m^3/s, and the average discharge during the study period is 37,700 m^3/s, i.e., 11 L/s/km^2 [*Bricquet*, 1995; *Laraque et al.*, 1998].

[8] The Congo is probably the most regular and uniform regime on the planet in terms of its mean monthly ratio (maxQ/minQ = 2.0) and the extreme monthly discharge ratio (24,700–75,500 m^3/s) recorded from 1903 to 1996. The Congo hydrological regime is also one of the most regular in the world (irregular interannual ratio = 1.65) with low interannual variations of per year discharges: 33,300–55,200 m^3/s recorded from 1903 to 1996. This is due to its geographical position on both sides of the equator and its regular rainfall [*Martins and Probst*, 1991]. The Congo regime is slightly more regular than the Amazon River whose monthly maximum/minimum is between 1.7 and 2.7 and interannual variations (1970–1990) less than 2.0. By comparison, the monthly discharge ratio of the Orinoco River presents a factor 25 [*Paolini et al.*, 1987].

[9] The Oubangui Basin, with an area of 489,000 km^2 at the Bangui gauge station, is situated mostly in the Northern Hemisphere. Its vegetation consists mainly of dry and wooded savannah, with local patches of semideciduous

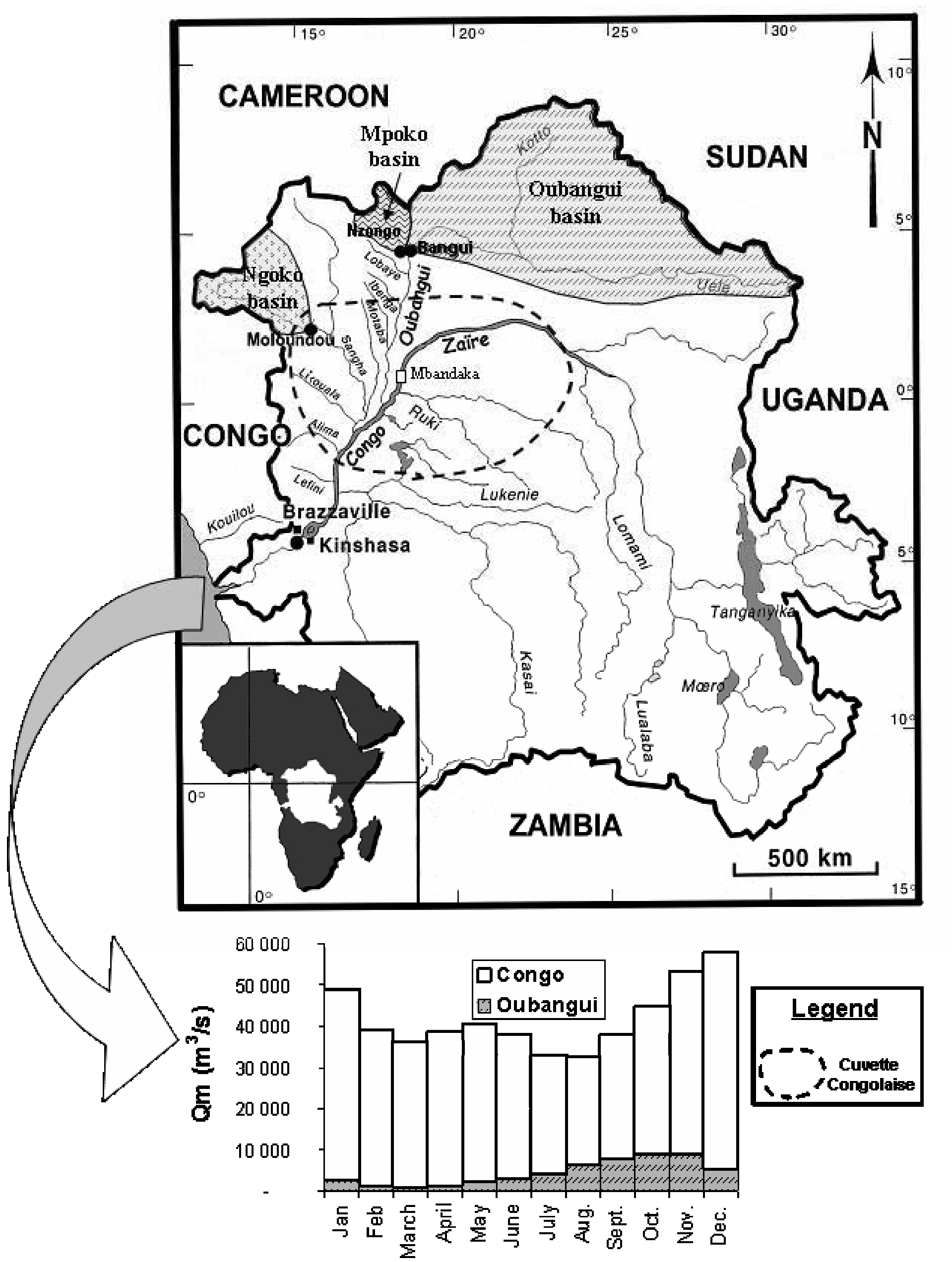

Figure 1. Map of the Congo Basin showing the location of the four sampling sites (the three subcatchments are hatched) and the hydrographs of the Congo River at the outlet and the Oubangui River at Bangui station.

tropical forest [*Boulvert*, 1992]. The mean annual rainfall in the Oubangui drainage Basin is 1540 mm/yr. With a mean flow of about 4200 m^3/s (5.8 $L/s/km^2$), it is the second biggest tributary of the Congo River after the Kasai River. The flow regime classification [*Rodier*, 1964] characterizes the Oubangui River as a transition unimodal tropical regime with a peak discharge occurring in October and minimum flows in March.

[10] The Mpoko River with a mean water discharge of 152 m^3/s, is a small tributary of the Oubangui River, draining a 23,900 km^2 area at Nzongo station (downstream from the Bangui station). It was selected for its dominant savannah which covers more than 86% of its total area.

[11] The Ngoko River is a right bank tributary of the Congo River situated in the upper part of the Sangha River. It was sampled because it drains a homogeneous forested basin which covers 67,000 km^2. This humid evergreen forest covers 95% of the basin area. Caesalpiniaceae is the dominant species with patches of Sterculiaceae and Ulmaceae. Average rainfall is close to 1700 mm/yr. Its hydrological regime is a typical bimodal pluvial equatorial regime [*Rodier*, 1964], with a first maximum discharge observed in

Table 1. Physical Characteristics of the Congo/Zaire River and Its Tributaries[a]

River	Station	Basin Area, km^2	Qa, m^3/s	Qa*, $l/s/km^2$	Forested Area, %	Sampling period
Oubangui	Bangui	489,000	3750	7.7	22	Nov 1990 to Sept 1996
Mpoko	Nzongo	23,900	152	6.4	14	Nov 1991 to Nov 1994
Ngoko-Sangha	Moloundou	67,000	715	10.7	95	Jan 1991 to Dec 1991
Congo/Zaire	Kinshasa/Brazzaville	3,500,000	40,600	11.6	50	Nov 1990 to Oct 1993

[a]Comprising watersheds areas, interannual water discharges Qa, interannual specific water discharges Qa* and percentage of forest area, and sampling period.

October and a secondary maximum in July. The mean annual discharge is 713 m^3/s (11.3 $L/s/km^2$).

[12] The major features of the different basins are shown in Table 1, and more complete information on the morphology, lithology and vegetation of the watersheds is given by *Olivry* [1986], *Seyler et al.* [1993], *Bricquet* [1995], *Sigha-Nkamdjou et al.* [1995] and *Orange et al.* [1999].

2.2. Sampling and Analytical Methods

[13] The four contrasted stations (particular hydrology or vegetation type) were sampled monthly over a period of 1 to 6 years (Table 1) in order to highlight the factors influencing the spatial and temporal distribution of TSS and Organic Carbon species. All four stations were equipped with hydrometrical instruments and discharge data was collected on a daily basis. Sampling was done by hand using 1-L glass bottles. The samples were taken 0.2 m from the surface in the centre of the river where maximum mixing occurs. Samples were then filtered through preheated and preweighted 0.70-μm Whatman® GF/F fiberglass filters under reduced pressure to separate dissolved organic fraction from particulate.

[14] During the first year of this study, monthly samples were collected in 40-L horizontal Niskin bottles on *n* points of *x* vertical profiles (for example, at the Brazzaville station $n = 3$ and $x = 5$) of the cross section. At the same time, stream velocities were measured with a Current meter. The velocity-weighted TSS concentrations were calculated applying the equation used by *Olivry et al.* [1988],

$$(\mathrm{TSS_{vw}}) = \frac{Qs}{Q} = \int_0^l \int_0^p dl \times dp \times Vi \times [TSSi],$$

where

- Qs total suspended sediment discharge;
- Q water discharge;
- l river length and p: river depth;
- Vi velocity at the collection point i;
- $TSSi$ TSS in collected river sample i.

[15] These values of integrated TSS were compared to the concentrations obtained from single samples collected in the middle of the river, 0.2 m from the surface. The relationships between surface TSS and velocity-weighted TSS ($\mathrm{TSS_{vw}}$) are

at the Bangui station

$$[\mathrm{TSS}]_{\mathrm{vw}} = 1.01 \times [\mathrm{TSS}]_{\mathrm{surface}}$$

at the Brazzaville station

$$[\mathrm{TSS}]_{\mathrm{vw}} = 1.05 \times [\mathrm{TSS}]_{\mathrm{surface}}.$$

These relationships show that any error due to the sampling procedure used in the study as compared to the velocity-weighted concentration of TSS samples should not exceed 5%.

[16] The filters were dried in an oven at 50°C for 24 hours and weighted to determine TSS concentrations. The filters were then treated with HCl 2N to remove carbonates and dried at 60°C for 24 hours. POC analyses were carried out using a LECO CS 125 analyzer [*Etcheber et al.*, 1999]. POC contents are expressed as a percentage of dry weight of TSS, abbreviated to POC% and POC concentrations are expressed in mg/L. Analytical accuracy was better than ±5%.

[17] The dissolved fractions which managed to pass through the filter (DOC) were acidified onboard with ultra-pure H_3PO_4, kept cold at 4°C, and analyzed in the laboratory, no later than 2 months afterward. The analyses were carried out on a Shimadzu TOC-5000 Instrument using high-temperature catalytic oxidation method (HTCO), used to determine DOC concentrations [*Abril et al.*, 2002]. Analytical accuracy was better than ±5%.

3. Average TSS, POC, and DOC Values at the Four Stations

[18] The discharge-weighted concentrations $\left(\frac{\sum_{i=1}^{n}(C_i Q_i)}{\sum_{i=1}^{n} Q_i}\right)$ were calculated from monthly concentrations (Ci) and discharge (Qi) covering the whole sampling period for each station. The resulting averages of TSS, POC and DOC concentrations and POC content obtained at the four Congo Basin stations, are presented in Table 2.

[19] The mean discharge-weighted TSS concentrations were always in the lower part of the global scale variation range for rivers [*Meybeck et al.*, 2003] and they remained in the same order of magnitude, from 26 to 38 mg/L for all four selected stations. These results are similar to those calculated by *Kinga-Mouzeo* [1986] for the more humid climatic period 1971–1976. These low TSS levels are due to the convergence of many factors: (1) the extreme flatness throughout the whole Congo Basin. It has no mountainous headwaters, unlike the Amazon or the Brahmaputra rivers [*Meybeck et al.*, 2001], and channel slopes of less than 10 cm/km in the lower course [*Devroey*, 1951]; (2) the lack of highly erodible rocks such as soft sedimentary rocks; (3) the extremely low fluctuations of seasonal discharge

Table 2. Average Annual Water Discharges (Q) and Specific Water Discharges (Q*) During the Study Period[a]

River	Hydrol.[b]	Q, $m^3\ s^{-1}$	Q*, $L\ s^{-1}\ km^{-2}$	TSS, $mg\ L^{-1}$	POC, %	POC, $mg\ L^{-1}$	DOC, $mg\ L^{-1}$	DOC/TOC, %
Oubangui at Bangui	average year	**3005**	**6.2**	**26.4**	**6.0**	**1.6**	**5.7**	**78**
	high waters (*n* = 40)	4556	9.3	28.1	5.7	1.6	6.1	79
	low waters (*n* = 35)	834	1.7	6.1	11.5	0.7	3.5	83
Mpoko at Nzongo	average year	**152**	**6.4**	**38.4**	**4.2**	**1.6**	**4.6**	**74**
	high waters (*n* = 14)	244	10.2	48.2	3.9	1.9	5.3	74
	low waters (*n* = 16)	60	2.5	23.8	4.2	1.0	2.6	72
Ngoko-Sangha at Moloundou	average year	**862**	**12.9**	**37.6**	**6.0**	**2.3**	**9.7**	**81**
	high waters (*n* = 4)	1012	15.1	33.6	6.8	2.3	11.8	84
	low waters (*n* = 6)	412	6.1	16.7	7.8	1.3	3.8	75
Congo-Zaïre at Brazzaville	average year	**37,047**	**10.6**	**26.3**	**6.5**	**1.7**	**10.6**	**86**
	high waters (*n* = 8)	41,232	11.8	24.6	6.1	1.5	11.0	88
	low waters (*n* = 15)	32,861	9.4	29.5	6.4	1.9	8.6	82

[a]Average concentrations of TSS, POC, and DOC, and POC content. Values are indicated for different hydrological stages (Hydrol.): high waters (Qm > 2000 m^3/s for the Oubangui River; Qm > 200 m^3/s for the Mpoko River; Qm > 700 m^3/s for the Ngoko River and Qm > 34000 m^3/s for the Congo River) and low waters levels.

[b]Here n denotes number of samples.

variations; (4) the occurrence of lakes, such as Kivu and Tanganyika, and of well-developed floodplains [*Milliman and Meade*, 1983]. The influence of vegetation cover as protection against soil erosion is limited here since similar average TSS concentrations are observed in the savannah (Mpoko River) and forest stations (Ngoko River). Seasonal variations of TSS concentrations with water discharges are very limited due to the low seasonal variability of the annual hydrograph in the Congo River Basin (Table 2). The ratio between low-water and high-water TSS concentrations is extremely low, from 2 to 4 (i.e. less than 1 order of magnitude), while it normally ranges from 1 to 4 orders of magnitude in pre-impoundment rivers [*Meybeck et al.*, 2003].

[20] A few studies give estimates of organic carbon data but from only sporadic sampling [*Martins and Probst*, 1991]. *Eisma et al.* [1978] and *Cadée* [1978, 1982] collected the first data during the 1976 cruise. In these previous studies, annual POC and DOC concentrations and first-order estimates of organic fluxes were calculated assuming that these concentrations remained constant over the year. The veracity of this assumption can now be checked.

[21] 1. The mean discharge-weighted POC concentrations were calculated over 1 to 6 years using monthly sampling. The POC concentrations ranged from 1.6 mg/L at Bangui and Nzongo stations to 2.3 mg/L in the forested Ngoko River. As a comparison, the typical values observed in other rivers flowing through African savannah are 1.5 mg/L for the Senegal River [*Gac and Kane*, 1986] and 1.1 mg/L for the Gambia River [*Lesack et al.*, 1984; *Meybeck et al.*, 1987]. Whichever the station, the POC concentrations followed the same pattern as the TSS, showing maximum concentrations during the high-water stages, except at the Brazzaville station (Table 2) where there was no apparent relationship between water discharges and POC concentrations.

[22] 2. POC content ranged from 5.7 to 11.5% in the Oubangui River and from 3.9 to 4.2% in the Mpoko River, both characteristic of savannah basins. In the forested basins of the Ngoko/Sangha River, POC content ranged from 6.8 to 7.8%. In the Congo River mainstream, POC only ranged from 6.1 to 6.3%, which accords well with preliminary studies (6% [*Cadée*, 1984]; 7% [*Kinga-Mouzeo*, 1986]). The percentage of carbon contained in TSS (POC%) is relatively high compared to the mean values for world rivers, especially temperate rivers (Figure 2a).

[23] 3. DOC concentrations were more markedly divergent and two sets can be distinguished: the Mpoko and Oubangui rivers on one side, and the Ngoko and the Congo mainstream on the other. In the savannah basins (Mpoko and Oubangui rivers), the mean DOC concentrations ranged from 2.6 to 3.5 mg/L during the low flow period, and from 5.3 to 6.1 mg/L during the high-water period. The annual mean discharge-weighted values of 4.6 and 5.7 mg/L were at least two-fold higher than those found in the Gambia River (2.4 mg/L [*Lesack et al.*, 1984]) and from 25% to 40% higher than those found in the Niger River (3.5 mg/L [*Martins*, 1983]). Unlike the savannah rivers, in the Ngoko River forest basin at Moloundou Station DOC concentrations were somewhat higher and ranged from 3.8 to 11.8 mg/L, with an annual mean discharge-weighted value of 9.7 mg/L, twice as high as for the savannah basins. Forested basin DOC levels were very high compared to other world rivers (Figure 2b, median value of 5 mg/L [*Meybeck*, 1982]) but were comparable to those found in the Negro River, the forest basin of the Amazon River [*Richey et al.*, 1990; *Moreira-Turcq et al.*, 2003]. Only a few Arctic rivers (the Northern Dvina and Pechora rivers in Russia and Moose River in Canada) present higher DOC values due to their very flat basins and abundant wetlands (Figure 2b).

[24] 4. Unlike the varying DOC levels, the DOC/TOC ratio was relatively constant over the four stations and throughout the seasonal hydrograph. DOC/TOC ratios were around 74–78% at savannah stations, 81% in the forested Ngoko/Sangha River and 86% in the Congo River mainstream (Table 2). These figures accord with the DOC/TOC levels found in other low TSS rivers [*Meybeck*, 1982].

4. Hydrological Control on the Seasonal Variability of TSS, POC, and DOC Concentrations

[25] To describe these temporal variations, which were quite similar at the four stations (Table 3), the focus was put

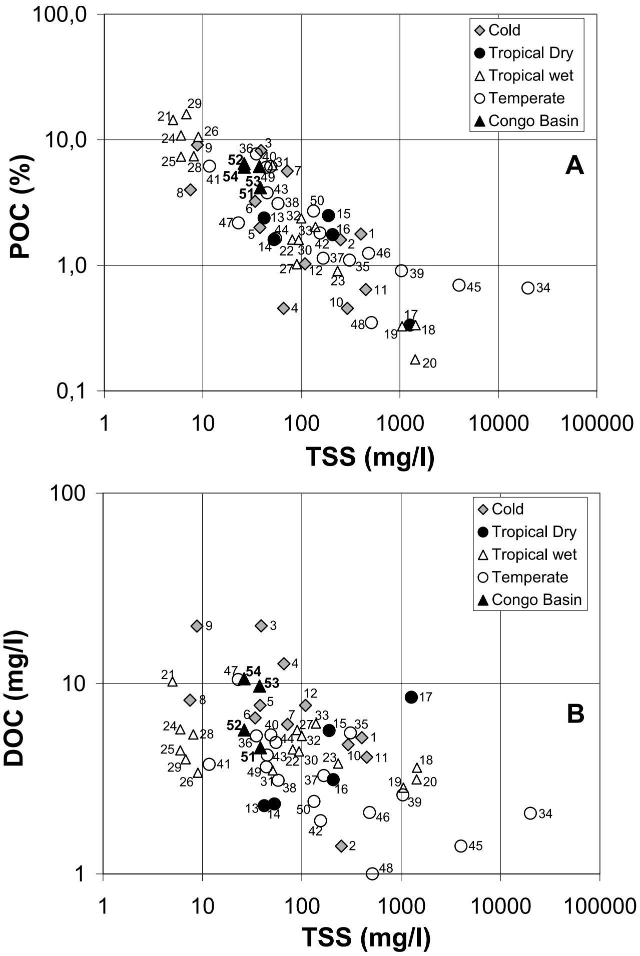

Figure 2. Distribution of mean annual (a) POC contents and (b) DOC concentrations in the world's rivers clustered by climate (data from *Meybeck* [1993] and *Meybeck and Ragu* [1996] unless specified below by superscripts denoting the following: a, *Weibezahn et al.* [1990]; b, *Gordeev et al.* [1996]; c, *Carson et al.* [1998]; d, *Holmes et al.* [2002]; e, *Lobbes et al.* [2000]; f, *Köhler et al.* [2003]; g, *Seyler et al.* [2005]; and h, this study). Cold: Mackenzie (1[b,c]), Alpine Rhone (2), N Dvina (3), Pechora (4), Ob (5[d,f]), Lena (6[b,d]), Amur (7), Yenisey (8[d,e,f]), Moose (9), Yukon (10), Beni (11), Mamore (12). Tropical dry: Gambia (13), Orange (14), Zambesi (15), Niger (16), Murray (17). Tropical wet: Nile (18), Ganges (19), Brahmaputra (20), Negro (21[g]), Solimoes (22[g]), Madeira (23[g]), Trombetas (24[g]), Tapajos (25[g]), Xingu (26[g]), Amazone (27[g]), Caroni (28), Caura (29), Orinoco (30[a]), Sanaga (31), Tuy (32), Parana (33). Temperate: Huang He (34), Danube (35), Loire (36), Mississippi (37), Ohio (38), Peace (39), Rhine (40), St. Lawrence (41), Kuban (42), Don (43), Dniepr (44), Choroch (45), Changjiang (46), Pee Dee (47), Rioni (48), Seine (49), Rhone (50). Congo Basin: Mpoko (51[h]), Oubangui (52[h]), Ngoko (53[h]), Congo outlet (54[h]).

on the data obtained from the Oubangui River, which offered the most complete sample data set (6 years).

[26] The temporal distribution of TSS concentrations followed the discharge variations during the six year monthly sampling program at the Bangui station (Figure 3a). An examination of the TSS concentrations vs. water discharges formed loops (hysteresis) rather than straight lines (Figure 4): Maximum TSS concentrations were observed 2 months before the hydrological maximum and higher values were measured during the rising stage than during the falling stage thus defining a clockwise hysteresis. These observations confirm the difficulty of using TSS/water discharge rating curves to compute solid discharge in such lowland rivers, as previously observed for the Gambia River [*Lesack et al.*, 1984; *Meybeck et al.*, 1987].

[27] The detailed study of the Oubangui River showed that POC and DOC concentrations have a similar clockwise hysteresis with water discharges. Owing to the exceptional regularity of the Oubangui's annual hydrological regime, the monthly POC and DOC patterns were very similar each year: hysteresis curves were obtained from average monthly concentrations calculated over the 6-year sampling period (Figure 5). The maximum monthly POC concentration was observed 3 months before the highest level of water discharge, i.e., 1 month before the maximum monthly TSS concentration (Figure 5b). As water discharges increase, an increase in the transport capacity of suspended particles can be expected in the basin, leading to the mobilization by runoff of a terrestrial POC stock associated with the mineral matrix of eroded soils and/or riparian area of the basin (Figures 3 and 5b). When the maximum discharge is reached, TSS and POC concentrations decrease slightly. This process is similar to the one observed in the Amazon or in the Orinoco basins [*Meade et al.*, 1983; *Hamilton and Lewis*, 1987; *Paolini et al.*, 1987; *Lewis and Saunders*, 1989; *Moreira-Turcq et al.*, 2003] and has also been described for other lowland tropical rivers such as the Middle Niger [*Picouet et al.*, 2000], and the Gambia River [*Lesack et al.*, 1984; *Meybeck et al.*, 1987].

[28] Several explanations have been proposed by the above-cited authors: (1) the development of an inundated floodplain and retention of suspended material; (2) the delayed arrival of headwaters (less rich in TSS and organic carbon than closely adjacent waters); and (3) the flushing out of the majority of the soil, riparian or riverbed stocks at the beginning of the flood. Concerning the Oubangui basin, the first hypothesis can be discarded, owing to the absence of floodplains. The second and the third hypotheses remain possible, bearing in mind that the Oubangui River waters are made up of different contributions from its tributaries varying according to their position in the hydrological cycle [*Négrel et al.*, 1993]: at the beginning of the high water stage, water fluxes essentially come from northern tributaries (Mbali, Mpoko and Mondjo rivers) whereas at the maximum water stage, the Oubangui River receives the dominant Uele contribution to its flow. This distribution of the tributaries' input and our description of hysteresis support the belief that the lower levels of TSS and POC in the Oubangui waters are caused by the Uele River.

Table 3. Average Annual TSS, POC, DOC, and TOC Budgets for the Congo/Zaire River and Its Tributaries[a]

River	Q, m^3/s	Q*, L/s/km^2	TSS Flux Tg	TSS Flux t/km^2/yr	POC Flux Tg	POC Flux gC/m^2/yr	DOC Flux Tg	DOC Flux gC/m^2/yr	TOC Flux Tg	TOC Flux gC/m^2/yr
Oubangui	3005	6.1	2.5	5.1	0.15	0.3	0.54	1.1	0.69	1.4
Mpoko	152	6.4	0.2	7.7	0.01	0.3	0.02	0.9	0.03	1.2
Ngoko	862	12.9	1.0	15.3	0.06	0.9	0.26	3.9	0.33	4.9
Congo/Zaire	37,047	10.6	30.7	8.8	1.99	0.6	12.38	3.5	14.37	4.1

[a]Tg: 10^6 t.

During the falling stage, POC concentrations decreased concurrently with decreasing TSS concentrations, due to the progressive decrease in water velocity. Seasonal variations of DOC concentrations also showed a concomitant increase with water discharges (Figure 5c). However, the hysteresis was less marked than for TSS and POC since the maximum DOC occurred one month before the maximum Oubangui water discharges (Figure 5).

[29] At the Mpoko River savannah basin (Nzongo station), similar trends of TSS, POC and DOC concentrations were also observed (Figure 6). As soon as discharges increased, the hysteresis was even more marked and there was a rapid and intense increase of TSS and DOC concentrations. This sort of triangle-shaped DOC-monthly discharge (Qm) hysteresis has also been described in other very flat river basins in Africa, such as the Gambia River [*Meybeck et al.*, 1987] or the Niger upstream of the Delta Central [*Picouet*, 1999]. It is therefore assumed that DOC concentrations are directly linked to the intensity of soil leaching.

[30] In the forested Nkogo/Sangha Basin at Moloundou station, concentrations versus discharges design a "double loop" curve in relation with the complex equatorial water regime. The first peak of TSS and POC concentrations was observed in June. The second maximum which was higher than the first occurred in October/November (Figure 7). The pattern of DOC concentration peaks differed, showing higher concentrations during the moderately rainy months of June and July than during the heavy rainfall months of October/November. As vegetation and temperature do not differ between the two rainy seasons, this phenomenon can only be explained by the soil-delivered DOC pool that is largely washed away during the first peak-flow in June/July. Even so, DOC concentrations were higher than at the two stations draining the savannah zones.

[31] At the Congo River mouth (Brazzaville/Kinshasa station), the distributions of the TSS, POC and DOC are primarily related to the hydrological functioning of the basin and present a unique "eight-shaped" pattern (double hysteresis) linked to the two high-water periods in May and December as shown for DOC data (Figure 8a). The widest loop from October to December corresponds to the highest flow period coming from the Northern Hemisphere rivers particularly the Oubangui River (Figure 1), completed by the Southern Hemisphere rivers whose water discharges start to increase at the same period (e.g., the Upper Zaire and Kasai rivers). Between September and November, the Oubangui River presented high water levels and maximum DOC concentrations (~8 mg/L) but at the same time DOC values at Brazzaville/Kinshasa were up to 15 mg/L. Plotting cumulative monthly DOC fluxes versus cumulative water fluxes (Figure 8b) showed a supplementary DOC input between October and December. This strongly suggests that upstream tributary yields are not the explanation for the DOC concentrations at the Brazzaville/Kinshasa station. Prior to this study, other main tributaries of the Congo River had been sampled for DOC measurements during two cruises in November 1990 and December 1992 [*Seyler et al.*, 1995]. The highest DOC concentrations [*Seyler et al.*, 1995] were found in the Upper Zaire at Mbandaka (18.1 mg/L, n = 5), in the Ruki (18.9 mg/L, n = 2), the Sangha (23.3 mg/L, n = 1) and Likouala (26.1 mg/L, n = 1), the latter two draining the marshes and flooded forest zone situated in the centre of the basin ("Cuvette Congolaise," Figure 1), at similar levels to those found in the Northern Dvina, Pechora and Moose rivers (Figure 2b). Moreover, these high concentrations were observed at the same period as those observed at the outlet of the basin. It should be noted here that the transit time between the Central Congolese Depression and the Brazzaville/Kinshasa station is about 3 days. The other right bank tributaries of the lower Congo River upstream from Brazzaville/Kinshasa, called Bateke Rivers (Djiri, Lefini, Nkeni, Alima rivers, are outside the "Cuvette Congolaise" and present DOC concentrations averaging 3.5 mg/L [*Seyler et al.*, 1995]. Therefore it may reasonably be assumed that the supplementary source of DOC is the Central Congolese Depression, where a vast region of swamps and flooded forests is drained by the Sangha, Likouala, Mossaka and Ruki rivers during this period.

[32] In May, the water levels of the Northern tributaries are low, as observed for the Oubangui River (Figure 1). At this period, the smaller of the two DOC-discharge loops registered at the outlet of the Congo River (Figure 8a) corresponds to the hydrological increase originating in the southern part of the Basin (e.g., the Kasai River, mainly draining the savannah basin). The DOC values are similar to those observed in the rivers draining savannah vegetation as demonstrated above.

5. Hydrological Control on POC Contents

[33] A log-log exponential decrease (correlation coefficient of 0.96) was found between the TSS concentrations and POC contents (%) in this data set (Figure 9). This inverse relationship has previously been described in numerous river systems, either for individual samples at one station or for annual averages between stations [see, e.g., *Meybeck*, 1982; *Ittekkot*, 1988]. However, a decrease of POC content can be associated to an increase of POC

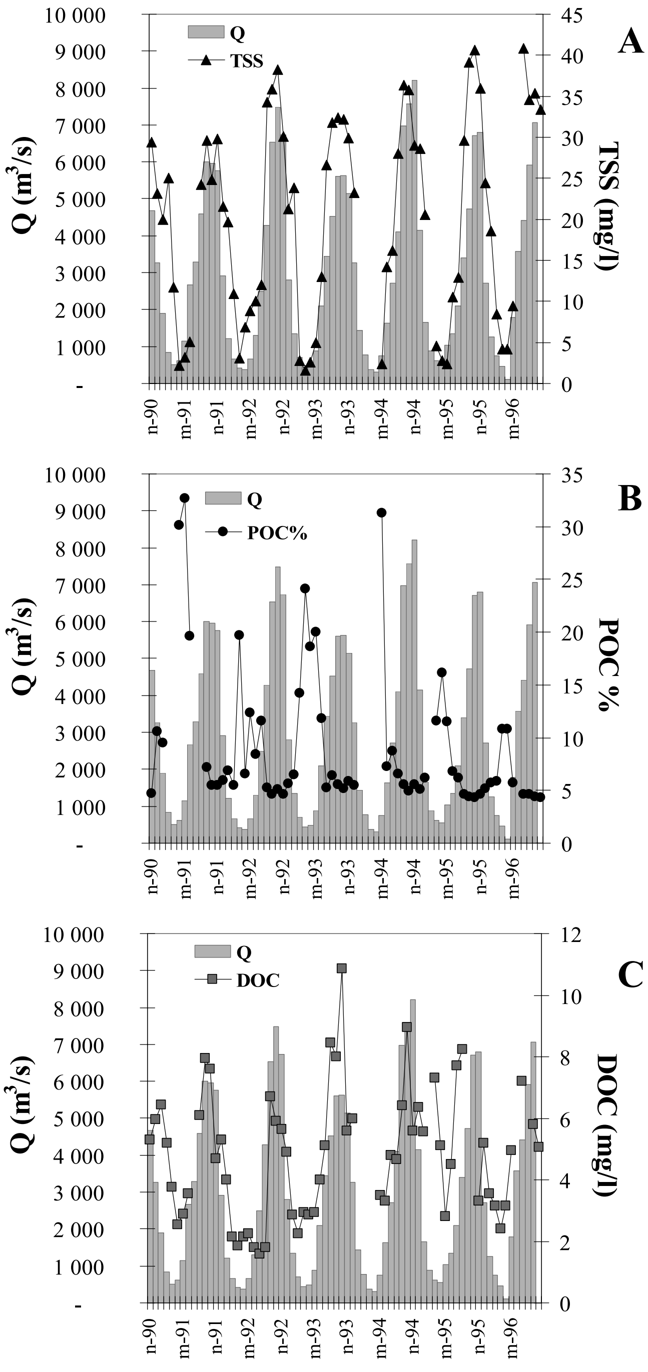

Figure 3. The Oubangui River at Bangui station: time series of monthly water discharges (Q) and (a) TSS concentrations, (b) POC contents in TSS, and (c) DOC concentrations for six hydrological cycles (from November 1990 to October 1996).

concentrations in the waters, owing to the differing sources of organic matter throughout the hydrological cycle [*Ittekkot and Laane*, 1991].

[34] During low flow stages, high POC contents (10–15% or more; Figures 3b and 5a) and low POC concentrations (not exceeding 0.5 mg/L; Figure 5b) have been registered. River sediment transport is limited and the transparency of the water promotes the development of phytoplanktonic growth and/or macrophytes in the riparian wetlands [*Martins and Probst*, 1991]. This feature indicates that autochthonous POC is the dominant component, though phytoplankton growth remains moderate, due to weak nutrient concentrations [*Seyler and Elbaz-Poulichet*, 1996].

[35] During high flow stages, low POC contents (threshold value: 5%; Figures 3b and 5a) and high POC concentration (~1.5 mg/L; Figure 5b) have been measured. POC content approaches the level of soil organic carbon content from similar areas in the Sanaga Basin [*Giresse and Maley*, 1998]. When sediment transport increases, terrestrial plant debris combined with mineral and clay materials are remobilized. Further, because concentrations of suspended matter exceed ~50 mg/L, light penetration is reduced thereby inhibiting primary production. Thus the autochthonous phytoplanktonic carbon becomes a minor organic fraction in rivers [*Ittekkot*, 1988; *Meybeck*, 1982].

6. Transport Rates of TSS, POC, and DOC

6.1. Oubangui River: Interannual Variability of TSS, POC, and DOC Fluxes

[36] Discharge-weighted TSS, POC, and DOC concentrations (C^*_{TSS}; C^*_{POC}; C^*_{DOC}) were calculated at the Bangui station for each year. Annual fluxes (F) were computed using the equation given by *Meybeck and Ragu* [1996] as follows:

$$F_{(TSS)} = Q_a \times C^*_{TSS},$$
$$F_{(POC)} = Q_a \times C^*_{POC},$$
$$F_{(DOC)} = Q_a \times C^*_{DOC},$$

where Q_a is the annual water discharge. Given the relatively constant monthly discharge in the studied basins, the

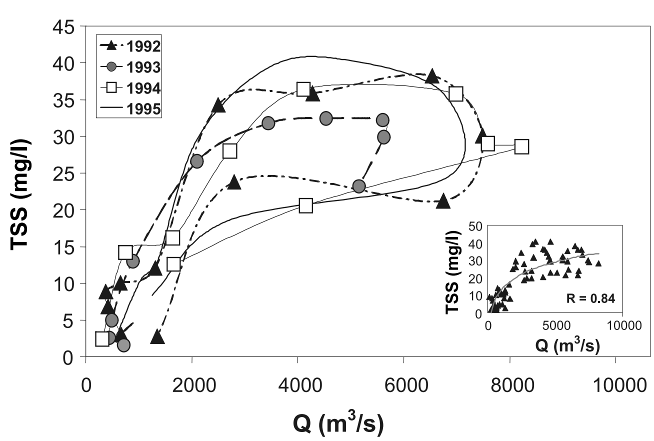

Figure 4. The Oubangui River at Bangui station: relationship between monthly TSS concentrations and water discharges from 1992 to 1995 showing clockwise hysteresis.

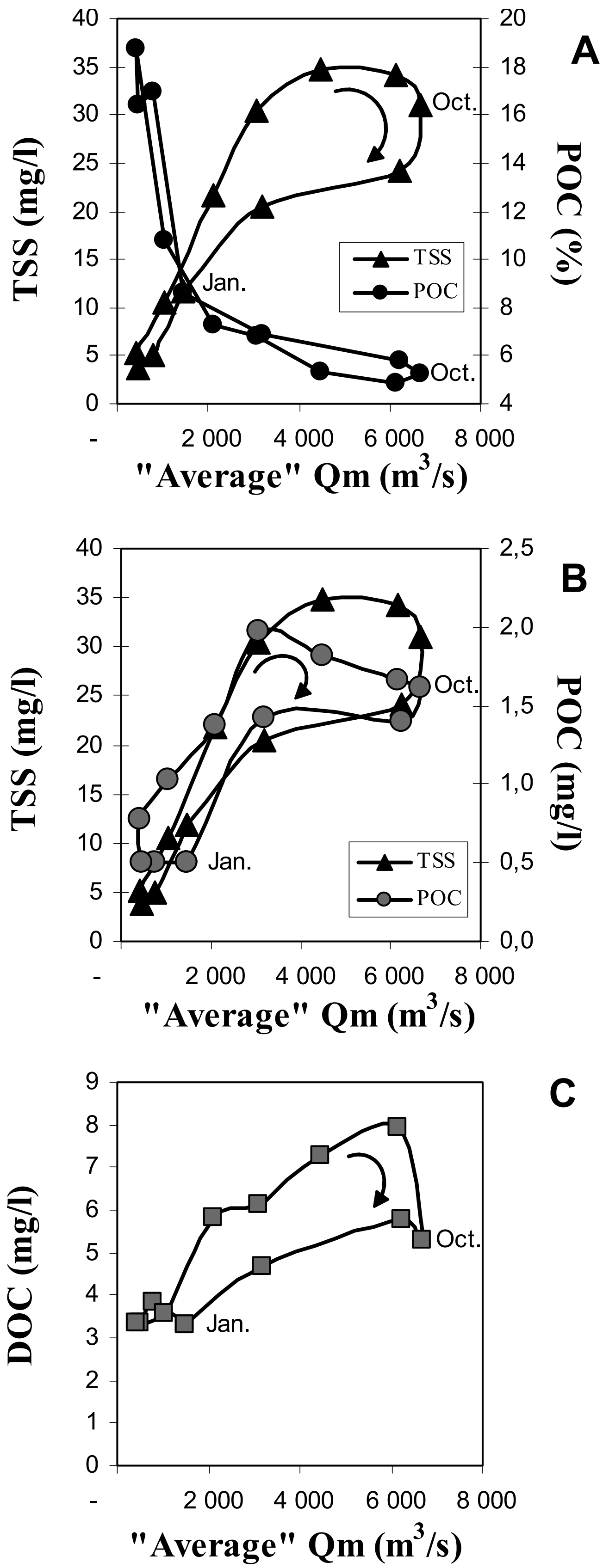

Figure 5. The Oubangui River at Bangui station: relationship between (a) monthly "average" TSS and POC concentrations versus mean monthly water discharges, (b) "average" TSS concentrations and POC contents versus mean monthly water discharges, and (c) "average" DOC concentrations versus mean monthly water discharges, showing hysteresis loops.

concentrations measured once per month were assumed to be constant during the corresponding period.

[37] In the Oubangui River, TSS, POC and DOC fluxes were established for the five complete years of 1991–1995. As expected from the TSS fluxes and water discharge regimes, the interannual transport variability was quite low: the ratio between the highest fluxes (2,960,000 tons TSS in 1994, 192,000 tons POC in 1991 and 650,000 tons DOC in 1994) and the lowest fluxes (2,270,000 tons TSS in 1991, 116,000 tons POC in 1995 and 430,000 tons DOC in 1992) was very limited (1.3, 1.6 and 1.5 for TSS, POC and DOC, respectively) while the ratio between the highest water discharges (in 1994) and the lowest (in 1995) was 1.2. The ratio of extreme values of annual water discharges established between 1936 and 1996 was 2.9 with a minimum of 2120 m^3/s and a maximum of 6110 m^3/s [*Wesselink et al.*, 1996]: so, more extended variations of fluxes can be expected in the Oubangui River.

6.2. Average TSS, POC, and DOC Budgets of the Congo Basin

[38] As shown above, the interannual variability in carbon concentrations observed in the Oubangui River was relatively low during this study period. Based on this observation it is reasonable to compute an interannual average budget (F_m) of the TSS and organic carbon of each station (Table 4) using a modified equation.

$$F_{m(TSS)} = Q_{ia} \times C^{*i}_{TSS},$$
$$F_{m(POC)} = Q_{ia} \times C^{*i}_{TSS},$$
$$F_{m(DOC)} = Q_{ia} \times C^{*i}_{TSS},$$

where Q_{ia} is the mean annual water discharge established during the study periods, C^{*i} is the discharge-weighted mean established using all the data from each station (Table 3). The yields or specific fluxes of TSS and organic carbon in t/km^2/yr, equivalent to g/m^2/yr, are then calculated.

[39] Whatever the type of vegetation covering the subbasins, the DOC fluxes play a major role in the total organic flux: a ratio of 74–78% for dissolved/particulate flux in the savannah system and always up to 81% in the forested system (Table 3). However, a marked difference appears between specific fluxes which are threefold higher in the Ngoko-Sangha forested basin than in the savannah basins.

[40] The TSS and carbon fluxes calculated at Brazzaville/Kinshasa station are believed to be representative of the total export of the Congo River to the Atlantic Ocean [*Eisma and Van Bennekom*, 1978]. During the present study,

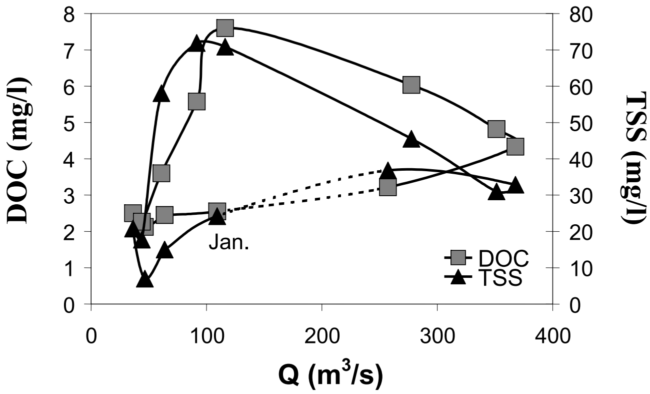

Figure 6. Mpoko River at Nzongo station: relationship between monthly "average" TSS and DOC concentrations versus mean monthly water discharges.

TSS flux represented a contribution of 30.7 × 10^6 t/yr, and typified the dry period observed in Africa during the decade 1980–1990. *Bricquet et al.* [1997] estimate that the rainfall deficit in intertropical Africa indicates a global climatic change that has been going on for about 25 years.

[41] During the 1980s, the global runoff deficit varied from −7% to −16% in the humid and from −13% to −27% in the dry tropical zones. This phenomenon intensified during the 1990's. The TSS transport value was similar to that of *Molinier* [1979], *Olivry et al.* [1995] and *Laraque and Olivry* [1996], which was established during comparable hydrological situations. However, the TSS transport value in the present study is markedly lower than that proposed in previous studies (50 × 10^6 t/yr [*Spronck*, 1941]; 71.3 × 10^6 t/yr [*Holeman*, 1968]; 43 × 10^6 t/yr [*Eisma et al.*, 1978]; 48 × 10^6 t/yr [*Nkounkou and Probst*, 1987]). This discrepancy is not only related to interannual hydrological fluctuations but also to the sampling frequency of the previous works which did not take account of seasonal variability.

[42] With regard to organic carbon, the Congo River is the source of 2.0 × 10^6 t/yr of POC and 12.4 × 10^6 t/yr of DOC. These values are slightly higher than the values given by *Probst et al.* [1994] with 1.2 × 10^6 t/yr of POC and 9.6 × 10^6 t/yr of DOC, and *Seyler et al.* [1995] with respectively 1.6 × 10^6 t/yr and 11.4 × 10^6 t/yr for one single hydrological year: 1992.

[43] The Oubangui and Mpoko Rivers present the same specific fluxes of TSS (5–7 t/km^2/yr), POC (0.3 gC/m^2/yr) and DOC (∼1 gC/m^2/yr). These similar values make it possible to generalize these data to the whole savannah area of the Congo Basin. Taking as given that savannah areas cover half of the entire basin [*Laporte et al.*, 1997] and that specific fluxes are typical of this land cover, then about 11.2 × 10^6 t of TSS, 0.55 × 10^6 t of POC and 1.77 × 10^6 t of DOC would be contributing to the Congo fluxes, i.e., corresponding to 30%, 25% and 26% of the total export of TSS, POC and DOC, respectively.

[44] When the specific fluxes determined here on the Ngoko forested basin are extrapolated to the whole forested area of the Congo Basin, the sum of fluxes generated by the savannah tributaries and forested tributaries do not match the fluxes actually measured at the Congo outlet: a loss of 23% of TSS and 9% POC and a gain of 30% of DOC can be observed. Within-river transport can be active with the occurrence of significant transformation processes from areas of eroded material to the basin outlets. For instance a very large proportion of the fluvial organic carbon pool of the Amazon River is lost via outgassing [*Richey et al.*, 2002]. However, in the case of the Congo River the concomitant loss of TSS and POC suggests that the dominant process explaining the carbon loss is more likely to be its confinement through sedimentation, even though outgassing from the river water certainly occurs. The TSS and POC losses can be attributed to the fact that they mainly occur in the Malebo Pool, a major widening of the river course 35 km long and 23 km wide located just upstream of the Kinshasa/Brazzaville station where the river flow slows down [*Nkounkou and Probst*, 1987]. On the other hand, the excess DOC can be explained by the higher inputs provided by organic-rich waters from the rivers which drain the "Cuvette Congolaise." A different contribution by the forested area including the "Cuvette Congolaise" can be computed by subtracting TSS, POC and DOC fluxes at the Congo outlet at Kinshasa/Brazzaville from those of the savannah area (1.75 × 10^6 km^2) without taking into account possible sedimentation. These specific fluxes are

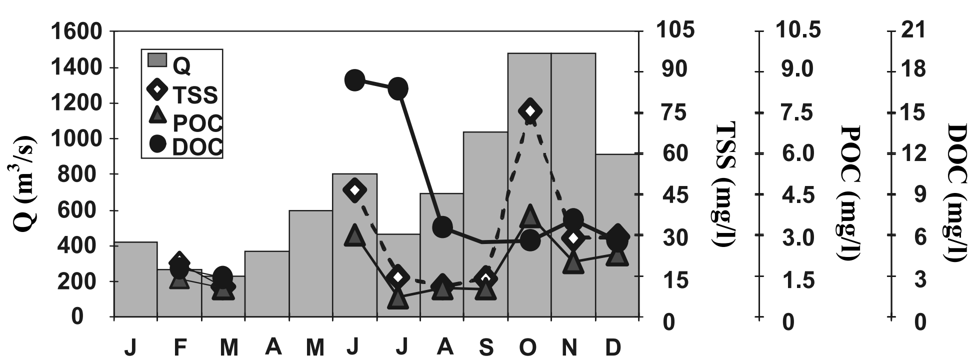

Figure 7. Ngoko River at Moloundou station: temporal distribution of monthly water discharges, TSS, POC, and DOC concentrations.

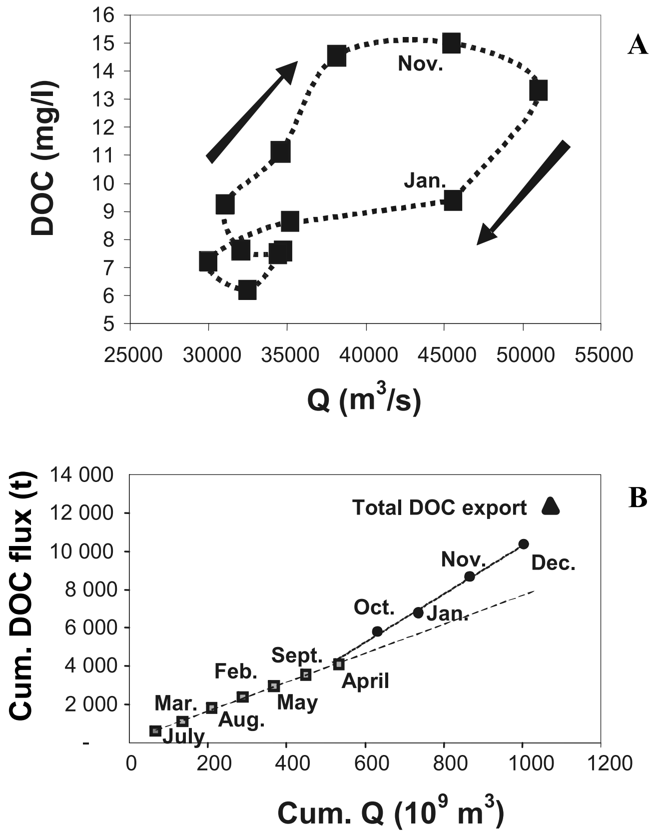

Figure 8. The Congo River at Kinshasa/Brazzaville station: (a) relationship between monthly "average" DOC concentrations versus mean monthly water discharges; (b) temporal variability of DOC fluxes as a function of "cumulative monthly DOC fluxes versus cumulative monthly water discharges."

calculated to be 11 t/km^2/yr for TSS, 0.8 gC/m^2/yr for POC and 6 gC/m^2/yr for DOC for the forested area.

6.3. Importance of TSS and Organic Carbon Fluxes Discharged by the Congo River

6.3.1. Comparisons With the Other Largest Tropical Rivers: The Amazon and Orinoco Rivers

[45] The Amazon, Congo and Orinoco rivers are the three largest rivers in terms of water discharge. It is therefore possible to compare the TSS and organic carbon input budgets discharged by the Congo River with those of the Amazon, and the Orinoco (Table 4). In addition, certain tributaries of these two rivers have been selected, essentially on the basis of their contrasting vegetation, in order to compare them with the savannah and forested stations on the Congo Basin.

[46] The Amazon basin extends over 6.4 $\times$ 10^6 km^2 and has an average discharge of 209,000 m^3/s, (6600 km^3/yr) [*Molinier et al.*, 1997]. It supplies up to 16.5% of all the river water discharged into the ocean, [*Vörösmarty and Meybeck*, 2004]. The Amazon and Congo systems, situated across the equator, are characterized by tropical rain forest and by extensive floodplains. However, there are major differences in basin characteristics. For example, the runoff in the Amazon River is higher [*Filizola*, 2003] because the headwaters of the Amazon Basin are located in high mountains in contrast with the plateaus or hills of the Congo watershed [*Meybeck et al.*, 2001]. Therefore the supply of suspended solids is much higher in the Amazon Basin and TSS concentrations can be as high as 200 mg/L at the Óbidos station [*Filizola*, 2003] while low end POC concentrations can decrease to 1.40 mg/L [*Moreira-Turcq et al.*, 2003]. The most commonly cited estimate of annual TSS flux at Óbidos station is 1150 $\times$ 10^6 t/yr and is based on the CAMREX project [*Meade et al.*, 1985; *Richey et al.*, 1986]. The data collection was done on a series of nine cruises, each at a different stage of the hydrograph, providing horizontally and vertically integrated measurements [*Richey et al.*, 1986]. The subject of the suspended yield of the Amazon River has recently been re-examined by *Filizola and Guyot* [2005], who have established a new budget of 600–800 $\times$ 10^6 t/yr using the Brazilian national database for river sediment yields from 1995 to 1998 and Acoustic Doppler technology. The more recent fluxes of organic carbon at the same station were 5.8 ± 0.3 $\times$ 10^6 t/yr for POC and 35 ± 4.0 $\times$ 10^6 t/yr for DOC [*Moreira-Turcq et al.*, 2003]. These results are similar to those of *Richey et al.* [1990] which found an annual TOC flux of 36.7 $\times$ 10^6 t/yr at the Óbidos station. However, Óbidos does not fully account for all Amazon fluxes to the Atlantic Ocean since two major lowland tributaries, the Xingu and the Tapajos, reach the Amazon mainstream downstream from the station. But these two rivers are characterized by very low TSS levels; therefore, the flux of suspended solids to the ocean as measured at Óbidos can be accepted. This is not the case for DOC fluxes as the Xingu and the Tapajos discharge 0.95 $\times$ 10^6 t/yr and 1.5 $\times$ 10^6 t/yr of DOC respectively [*Moreira-Turcq et al.*, 2003]. The total DOC and POC fluxes at the Amazon River mouth are estimated at 37.5 and 6.2 $\times$ 10^6 tC/yr, respectively.

[47] The Orinoco River with an area of 0.95 $\times$ 10^6 km^2 [*Lewis and Saunders*, 1989], increasing to 1.1 $\times$ 10^6 km^2 with its lower tributaries [*Meybeck and Ragu*, 1996], is the world's third largest water provider (36,000 m^3/s, i.e., 3.5%

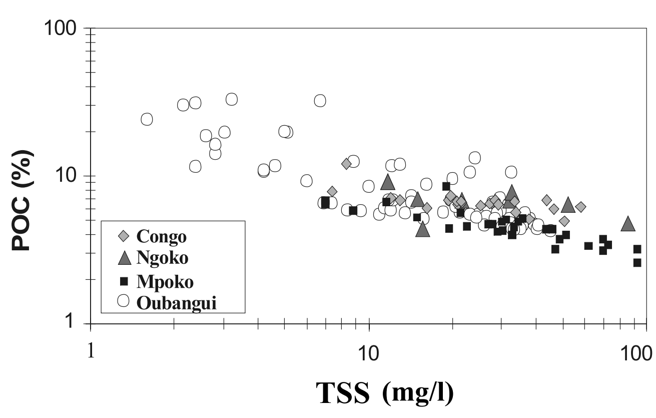

Figure 9. Variation of individual POC contents versus TSS concentrations for the four stations of the Congo-Zaire Basin.

Table 4. Comparison of TSS Yields (Ys) and Organic Carbon Yields in the Three Major Tropical Rivers and Their Tributaries Draining Savannah or Wet Forest Zones[a]

	Area, km^2	Q, mm/yr	POC Yield, $g/m^2/yr$	DOC Yield, $g/m^2/yr$	TOC Yield, $g/m^2/yr$	Ys, $t/km^2/yr$
			Savannah			
Branco	125,000	1120	...	1.0	...	...
Oubangui	489,000	241	0.3	1.1	1.4	5.1
Apure	167,000	378	1.3	2.2	3.5	...
			Wet Forest			
Rio Negro	690,000	1298	1.0	8.7	9.7	6.5
Ngoko	67,000	336	0.9	3.9	4.8	15.3
Caroni	95,000	1570	1.0	9.0	10.0	...
			Whole Basin			
Amazon	6,400,000	1029	0.9	5.5	6.3	94–180
Congo	3,500,000	366	0.6	3.5	4.1	8.8
Orinoco	989,000	1358	1.5–2.2	4.4–5.4	6.5–6.9	91

[a]Amazon Basin: *Meade et al.* [1985], *Richey et al.* [1986], *Moreira-Turcq et al.* [2003], *Seyler et al.* [2005], and *Filizola and Guyot* [2005]; ANEEL: Brazilian National Agency for Water and Energy; Orinoco Basin: *Paolini et al.* [1987], *Lewis and Saunders* [1989], and *Weibezahn et al.* [1990].

of world water discharge [*Meade et al.*, 1983]). The annual TSS transport has been calculated at $\sim 90 \times 10^6$ t/yr [*Paolini et al.*, 1987; *Lewis and Saunders*, 1989; *Weibezahn et al.*, 1990]. For organic carbon, *Weibezahn et al.* [1990] estimated the average levels of DOC and POC at 4.4 and 1.5 mg/L, respectively. This would correspond to fluxes to the Atlantic Ocean of 5.0 and 1.7×10^6 t.C/yr for DOC and POC, respectively, and to an average content of POC in TSS of around 1.6%. These values are close to those estimated by *Paolini et al.* [1987] when tallying the fluxes of the Orinoco mainstream River plus the Caroni River (6.1×10^6 t.C/yr for TOC).

[48] The TSS yields of the Congo River are between tenfold and twentyfold lower than those of the Amazon ($\sim$90–180 $t/km^2/yr$ [*Filizola and Guyot*, 2005; *Meade et al.*, 1985; *Richey et al.*, 1986]) and the Orinoco Rivers ($\sim$90 $t/km^2/yr$). This is explained by multiple factors discussed previously (e.g., no highlands, the occurrence of lakes, the low channel slope in the Congo Basin). The POC yield is nevertheless similar to that of the Amazon River (0.97 $gC/m^2/yr$) whereas the Orinoco River POC yields (1.55 $gC/m^2/yr$) are 50% higher than those of the Amazon and Congo Rivers, according to *Weibezahn et al.* [1990]. No distinction is observed between the POC yields in the different wet forest rivers ($\sim$1.0 $gC/m^2/yr$). Moreover, similar values are found in both the savannah and wet forest rivers of the Orinoco Basin whereas a threefold factor is observable between the savannah and the forest rivers of the Congo Basin. In all the basins the DOC yields are superior to the POC yields. The similar DOC yields at the outlet of the Amazon and Orinoco rivers are slightly higher than that of the Congo River. It must be noted that some tributaries of the Amazon and Orinoco rivers feature very high DOC yields as for the Rio Negro River (8.7 $gC/m^2/yr$ [*Seyler et al.*, 2005]) or Caroni River (9.0 $gC/m^2/yr$ [*Paolini et al.*, 1987]) which both drain forest basins. Significant distinctions are observable in the tributaries of the three basins: DOC yields are fourfold higher in the forest than in the savannah tributaries of the Congo and Orinoco Rivers whereas the DOC yield is approximately ninefold higher in the forested area than that of the savannah. In forest basins, the Congo River has concentrations two times lower than those of the Amazon and the Orinoco. This difference can be attributed to a weak runoff on the Congo Basin (336 mm/yr versus 1300 mm/yr).

6.3.2. Importance of the Amazon, Congo, and Orinoco Basins on a Global Scale

[49] In Table 5 the water discharges, TSS and organic carbon fluxes of the Amazon, Congo and Orinoco Rivers are compared with other large basins of the world. The potential basins which are presently arheic are not considered in this table. The rivers are ranked in decreasing order of drainage area from the Amazon (first) to the Saint Lawrence (eighteenth). All these basins are now documented for TOC and often for POC and DOC as well and their corresponding export rates, or yields, in $gC/m^2/yr$ have been generated (Table 5). The largest rivers of the world have sometimes been used to determine the average concentrations of riverborne material. However, this consideration demands prudence since the data set is highly affected by the relative weight of the Amazon data [*Meybeck*, 1988]. Moreover, yields of riverine material may depend on the scale: medium to small rivers may present somewhat higher levels of suspended solids or POC yields [see *Milliman and Syvitski*, 1992; *Coynel et al.*, 2005] than the largest rivers, which are also in a more pristine state. Therefore, as very turbid rivers are lacking in the top 18 rivers, the Huang He and the Brahmaputra have been added to give greater representation to major rivers on the global scale (Table 5). The total documented area of these 20 rivers equals about 41×10^6 km^2, i.e., slightly less than 40% of the global exorheic area. This data set still underestimates the global sediment yield of rivers, calculated at around 160 to 180 $t/km^2/yr$ in predammed conditions [*Vörösmarty and Meybeck*, 2004], compared to 105 $t/km^2/yr$. However, it is very close to the global runoff of 340 mm/yr versus 368 mm/yr.

[50] The Congo River is ranked only twelfth in annual suspended load in spite of the significance of its water discharges. Moreover, the very low TSS yield (8.5 $t/km^2/yr$)

Table 5. Organic Carbon Fluxes (F) and Yields (Y) From World Major Rivers Ranked by Drainage Area[a]

	Area, Mkm^2	Qnat, km^3/yr	M_S nat, Mt/yr	FPOC, Mt/yr	FDOC, Mt/yr	FTOC, Mt/yr	YPOC, $gC/m^2/yr$	YDOC, $gC/m^2/yr$	YTOC, $gC/m^2/yr$
Amazon[b]	6.40	6600	600–1150	6.1	37.6	43.8	1	5.9	6.9
Zaire/Congo[c]	3.70	1325	31.7	2.0	12.4	14.4	0.5	3.3	3.8
Ob[d]	2.99	404	15.5[e]	0.3	3.1	3.4	0.1	1.0	1.1
Missisippi	3.00	580	500	1.1	1.9	3.0	0.4	0.6	1.0
Nile	2.90	83	120	0.4	0.3	0.7	0.1	0.1	0.2
Parana	2.80	568	79	1.6	3.5	5.1	0.6	1.3	1.9
Yenisey[(d,f)]	2.58	620	4.7[e]	0.2	4.9	5.1	0.1	1.8	1.9
Lena[g]	2.50	525	20.7[e]	0.6	3.5	4.1	0.2	1.4	1.6
Amur	1.85	344	24.9	1.4[h]	2.1	3.5	0.8[h]	1.1	1.9
Chang Jiang	1.80	995	480	6.0	2.1	8.1	3.3	1.2	4.5
Mackenzie[i]	1.80	308	124[j]	2.2	1.6	3.9	1.2	0.9	2.1
Zambezi	1.30	106	20	0.5[h]	0.6	1.1	0.4[h]	0.5	0.9
Niger	1.20	192	40	0.7	0.6	1.3	0.6	0.5	1.1
Nelson	1.13	89	10	<0.1	0.7	0.8	nd	0.6	nd
Orinoco[k]	1.10	1135	107	1.7	5.0	6.7	1.5	4.5	6
Murray	1.06	23.6	30	<0.1	0.2	0.2	nd	0.2	nd
Ganges	1.05	493	520	1.7	1.4	3.1	1.6	1.3	2.9
St Lawrence	1.02	337	4.0	0.2	1.2	1.5	0.2	1.2	1.4
Huang He	0.75	48	900	6.3	0.1	6.4	8.4	0.1	8.5
Brahmaputra	0.58	510	730	1.3	1.6	3.0	2.2	2.8	5.0
Sum(s) or Average(m)	41.5(s)	15285(s)	4358–4908(s)	34.3(s)	84.4(s)	118.4(s)	0.85(m)	2.05(m)	2.85(m)

[a]Area, drainage area; Qnat, water discharge (pre-impoundments); Ms, sediment discharge (pre-impoundments). Mississippi and Nile sediment and/or water discharges are now much affected by reservoir and irrigation. Data sources are from *Meybeck and Ragu* [1996] unless specified.
[b]This work.
[c]*Meade et al.* [1985]; *Richey et al.* [1986]; *Seyler et al.* [2005], *Filizola and Guyot* [2005].
[d]*Köhler et al.* [2003, and references therein].
[e]*Holmes et al.* [2002].
[f]*Lobbes et al.* [2000].
[g]*Gordeev et al.* [1996].
[h]Values estimated by difference between total organic carbon and dissolved organic carbon fluxes.
[i]*Telang* [1985] quoted by *Gordeev et al.* [1996].
[j]*Carson et al.* [1998].
[k]*Weibezahn et al.* [1990].

is also the fifth lowest observed in any major river before the Lena, Ob, Saint Lawrence and Yenisey rivers (Table 5) [*Milliman and Syvitski*, 1992; *Holmes et al.*, 2002]. In comparison, the first two rivers in terms of erosion are the Brahmaputra and Huang-He Rivers with TSS yields superior to 1200 $t/km^2/yr$.

[51] The low TSS levels in the Congo River are nearly balanced in terms of carbon export by the high POC content. In this context, the Congo River is the fifth river in terms of annual POC flux, after the Huang He, Amazon, Chang Jiang and Mackenzie Rivers. However, the POC yield of the Congo River is very limited (0.85 $gC/m^2/yr$) in comparison with other major rivers such as the Chang Jiang River (3.3 $gC/m^2/yr$). The Congo/Zaire River is second after the Amazon River in terms of absolute TOC fluxes ahead of the Orinoco, Yenissey, Ob, Lena and Parana Rivers. It represents about two thirds of the DOC fluxes discharged by Siberian rivers to the Arctic Ocean from the Northern Dvina to the Amygyema Rivers [*Gordeev et al.*, 1996; *Köhler et al.*, 2003]. In terms of DOC yields, the Congo River is third with 3.1 $gC/m^2/yr$ exported, only exceeded by the Amazon and Orinoco Rivers (5.5 and 4.5 $gC/m^2/yr$, respectively).

[52] As a conclusion to this comparison, the three major wet tropical rivers (the Amazon, Congo and Orinoco Rivers) actually resemble each other very closely in terms of the relative similarities of their water budget and land cover when considering the global scale variability. These three giant inputs represent a major proportion (~15–18%) of the overall TOC inputs to world oceans estimated from 170 to 195 $\times 10^6$ t/yr for POC and from 200 to 215 $\times 10^6$ t/yr for DOC [*Ludwig et al.*, 1996; *Meybeck and Vörösmarty*, 1999]. If the Amazon/Congo/Orinoco rivers are taken together, their share of the global river inputs could be quantified at around 5–6% for POC and 26–28% for DOC. Note that an empirical model has recently been proposed by *Aitkenhead and McDowell* [2000] based on soil C:N ratio as a predictor of annual riverine DOC flux at the global scale. The authors have calculated a new estimate (360 $\times 10^6$ t/yr), i.e., twice the commonly cited estimates, thus limiting the contribution of Amazon/Congo/Orinoco.

[53] Finally, the geographical position of the tropical in relation to the world oceans must be carefully taken into account. The Amazon, Congo and Orinoco Rivers are directly linked to the open ocean. This is not the case for other large rivers of the world which discharge into regional seas and/or enclosed coastal zones as do the Huang He, Chang Jiang, Zhu Jiang (Pearl), Mekong, Saint Lawrence, and Mississippi rivers. Regional seas such as the Mediterranean and the Black Sea, the West Pacific region (from the Sea of Japan to the Sulu Banda Seas), the North West Atlantic Region (the Gulf of Mexico and the Caribbean) and many others (e.g., the Baltic, Red, Bering, Adaman, and Arafura Seas) can actually be considered as "mega filters"

of land to ocean inputs, connected to about 44.2×10^6 km^2 of continental basins, which represents a runoff of 15,100 km^3 (M. Meybeck and H. H. Dürr, manuscript in preparation, 2005). If one includes the rivers which discharge to open oceans over extended continental shelves such as the Siberian rivers, the Parana and Patagonian rivers, the proportion of rivers directly contributing to the open ocean is actually less than 50%, among which are found the Amazon, Congo and Orinoco.

[54] The fate of riverine carbon in the coastal ocean is yet not well known [*Chen*, 2004]. The Congo organic load is either dispersed through a large superficial plume or penetrates through the deeply incised canyon, one of the world's largest [*Cadée*, 1978, 1982]. A significant proportion of particulate organic fraction is degraded in estuary and plume areas as has been observed in the Cameroonian rivers (50% POC loss [*Giresse and Cahet*, 1997; *Giresse and Maley*, 1998]). Therefore predominantly refractory aged POC contents reach the open ocean, as in the case of the Amazon region [*Druffel et al.*, 2005]. A large part of the dissolved organic matter, mainly coming from the "Cuvette Congolaise" is likely degradable. The DOC contribution, issued from the forested area in the Cameroonian rivers (Sanaga Basin) revealed a substantial biodegradation potential (25 to 30%) and a release in the mixing fresh water/seawater area [*Giresse and Cahet*, 1997]. Therefore the main refractory DOC fraction enters the open ocean, as does the refractory dissolved soil-derived material from Arctic Rivers [*Lobbes et al.*, 2000].

[55] In any event, to achieve accurate conclusions, future studies of the organic matter from the Congo River and its fate must focus on the nature and age of POC and DOC using newly developed approaches such as stable isotopes and ^{14}C dating [*Hedges et al.*, 1986; *Raymond and Bauer*, 2001; *Lobbes et al.*, 2000; *Benner et al.*, 2004; *Callahan et al.*, 2004; *Wang et al.*, 2004].

7. Conclusion

[56] In the Congo River, the second world river in terms of water discharges and drainage area, very few biogeochemical studies have been carried out, unlike the much-studied Amazon Basin. The monthly database presented here on the TSS and organic carbon species in the Congo Basin, obtained over 1 to 6 years in four savannah or forested river observation stations, has determined their seasonal flux regimes and their interannual variations.

[57] The highest concentrations of POC and DOC were observed in the Congo Basin during high water periods, 2 to 4 months before peak flows, whereas the lowest ones occurred during the low water levels. High DOC values registered at the outlet of the Congo River were related to the leaching of the low-lying part of the basin the "Cuvette Congolaise" made up of swamps and marshes. The autochthonous production seems to have a very minor influence on the carbon flux. A direct correlation was observed between the percentage of forest and TOC yields in the different rivers studied in the Northern Congo Basin: the Oubangui River, which mainly drains a savannah area, showed TOC yields 3 times lower than for the Ngoko/Sangha River which essentially drains a forested area. In all the basins studied, the dissolved organic load was over 75% of the total organic load.

[58] The computation of exports to the Atlantic Ocean shows the Congo is responsible for 14.4×10^6 t/yr of TOC, of which 12.4×10^6 t/yr is DOC and 2×10^6 t/yr is POC with limited interannual variability (Table 5). On the basis of this study and on the most recent estimate of the annual amount of organic carbon transported into oceans by rivers (370–430 $\times 10^6$ t/yr [*Ludwig et al.*, 1996; *Meybeck and Vörösmarty*, 1999; *Schlünz and Schneider*, 2000; *Vörösmarty and Meybeck*, 2004]), the Congo River is responsible for a mean organic carbon export of about 7% of the total world river exportations.

[59] The three main tropical rivers (the Amazon, Congo and Orinoco rivers) are responsible for a minimum TSS flux of ~4% and an export of organic carbon flux of about 15–18% (5–6% of POC and 26–28% of DOC). This corresponds to ~28% of water delivery to oceans and an exoreic drained area of about 11.5%. These results clearly confirm the overall importance of the wet tropical regions on the global organic carbon budget delivered to oceans by rivers.

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