Journal of Hydrology (2007) **342**, 88–96

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The Guianese paradox: How can the freshwater outflow from the Amazon increase the salinity of the Guianan shore?

Luc Lambs *, Etienne Muller, F. Fromard

EcoLab — Laboratoire d'écologie fonctionnelle, UMR 5245 (CNRS-UPS-INPT), 29 rue Jeanne Marvig, 31055 Toulouse cedex, France

Received 11 September 2006; received in revised form 16 May 2007; accepted 21 May 2007

KEYWORDS
French Guiana rivers;
Stable isotopes;
Oxygen-18;
Deuterium;
Salinity

Summary French Guiana is notable for the extent of its rain forests, which occupy 97% of the country, and the influence of the Amazon along its shores. In fact, the shores and estuaries support a mangrove forest typical of saline conditions. This paper reports the chemical characteristics, conductivity and salinity and the stable isotopes (oxygen and deuterium) of the rivers and shores between the Cayenne area and the border with Surinam. The results show a quite homogenous freshwater pool over the country. However, the low slope of the coast, a result of the wide mud banks deposited by the Amazonian plume, have turned the mouths of the smaller rivers to the northwest, creating large salty areas where mangroves grow several kilometers inland. Despite the large amount of Amazonian water, the Guianan coast exhibits high salinity. In fact, the freshwater itself remains far from the shore, following the north Brazilian current, while only the mud plume arrives at the coast, creating this paradox.

Introduction

The discharge from many large rivers, because of the lower density of freshwater relative to seawater, can be detected at the surface kilometers from their river mouths. Most notably, the Amazon River flows far out into the ocean and remains close to the surface to form a wide freshwater lens. The interaction of Amazon water and seawater, in front of the Amazonian estuary, were studied during the Amaseds program between 1989 and 1991 (Karr and Showers, 2002). The freshwater outflow could be followed many tens of kilometers to the northwest, as detected by changes in salinity and $\delta^{18}O$ values. Along the French Guiana coast, this water movement was also monitored during the Chico 0 program in April 1999 (Artigas et al., 2003; Ternon and Guiral, 2005). This Amazon freshwater could be detected in the open sea, between 20 and 50 km from the coast, and only close to the surface (about 4 m in depth). This

* Corresponding author. Tel.: +33 562 269 994; fax: +33 562 269 999.
E-mail address: lambs@cict.fr (L. Lambs).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2007.05.022

low-salinity current (the Guyana Current) can reach a velocity of 1 m/s on the mid-outer shelf (Limeburner et al., 1995; Pujos and Froidefond, 1995). In July—December, the Guyana current bifurcates between 5°N and 8°N, and Amazon water is retroflected onto the North Equatorial counter current (Muller-Karger et al., 1988). On a smaller scale, the major French Guianan rivers can supply significant freshwater to the coast during the rainy season.

French Guiana occupies a part of the Guiana shield region, a large area in the northern part of South America that is one of the oldest known geological formations on the planet. It is also one of the flattest countries. Its coast is part of the 1600 km long sand coast between the embouchures of the Amazon River and the Orinoco River. This area is characterized by a wedge-shaped Holocene mud deposit, extending to the 20 m depth contour. Beyond the minus 20 m contour line, the shelf-bottom configuration and related sediments are to be considered a relic of the late Pleistocene and Holocene transgression (Augustinus, 2004). From east to west, it spans part of the north Brazilian Amazonia (Amapa area), French Guiana, Surinam, Guyana and Venezuela. The 300 km long French Guiana coast is the first area to be influenced by the Amazon after it leaves its channels. About 80% of the shield area is still covered in forests, the majority of which are pristine.

French Guiana receives 2000—4000 mm of rainfall per year. The gentle slope of the country and the impermeability of the old rocks cause numerous rivers, which are oriented north with a fan-shaped distribution. Water retention by the soil is low except in the limited sandy area. Some groundwater has been localized under the laterite crust, limited by some waterproof minerals that reduce the depth of infiltration and lateral exchanges (Lasserre, 1979). The coast receives large amounts of Amazon-borne silt and clay carried by the Guyana Current, a southeast- to northwest-bound extension to the North Brazil current (Allison and Lee, 2004; Curtin, 1986; Lentz, 1995). The Amazon fluid mud suspensions coming to the French Guiana coast reach concentrations of 10—400 g/l (Balzer et al., 2004), which contrasts with the suspended sediment concentration of 0.1—10 mg/l of the local Guiana rivers (Jouanneau and Pujos, 1988). The mud banks along the shore are 10—40 km long, up to 5 m thick, and extend seaward to the limit of the coastal mud wedge at 20—25 m water depth. They migrate northward along the shore at rates averaging 1.5 km/y (NEDECO, 1968; Froidefond et al., 1988, 2004; Eisma et al., 1991). Consequentially, the coastal mangrove development is extensive and sand beaches are uncommon.

This description illustrates the complexity of the French Guiana river network and its interaction with the coast. The aim of this study was to understand the mixing process between freshwater (rainfall, swamps, rivers) and salt water (seawater) along the French Guiana shores, as well as to understand the possible influence of the Amazon outflow, both as mud and freshwater. On a larger scale, this study serves as an overview of the interface of these two water pools before a study of the behavior of the shore water balance and its local vegetation, i.e., the mangrove forest. On such a scale, and with these different water pools, only the stable isotopes of water (i.e., oxygen-18 and deuterium) could be efficient indicators for the study (Lambs et al., 2005). However, to improve the identification of the best areas, techniques that give immediate values during data acquisition at the field site, like conductivity and temperature, were used to assist the stable isotope water sampling (Lambs, 2000; Lambs, 2004). Water sampling was done at the end of the dry season when it was possible to identify better the influence of the seashore waters. For the rivers, this corresponded to the smallest discharge and for the seashore this corresponded to the retroflection of the Amazon water in the open sea. Apart from an investigation of the Maroni River (Négrel and Lachassagne, 2000), no other work has been done on the Guiana rivers.

Samples and methods

Sampling

All the seven rivers between the Surinam border and the Cayenne area were sampled (see Table 1) along the shore, generally from the N1 road bridge. Rainfall water was also taken at the two extremes: in St Laurent and in the city of Cayenne. Other inland freshwaters that were sampled included an artificial lake (Petit Saut Dam on the Sinnamary River), the upper Sinnamary River a few kilometers before this dam, a deep pond (Crique Crabe near Petit Saut) and two small rivers (Gabriel Crique at Eskol, and Canal Philipon, near Sinnamary). In a back mangrove stand near Sinnamary, a transect of six piezometers has been installed to measure the groundwater level and its variations. Amazonian river water samples were also collected near the estuary (Macapa) and upstream, at Obidos and Santarem.

Two seawater samples were taken at the beaches of Cayenne and Mana as well as an intermediate point in Guatemala at low tide on the mud bank (in a water hole). Two open seawater samples were collected at the latitude of Cayenne (20 km from shore) and of Sinnamary (25 km from shore), both at about 1 m deep.

All these water samples were taken in November 2003 and November 2004, at the end of the dry season, in order to have minimal interference from local rainfall. The temperature, pH and conductivity were measured directly on the field site with a portable Ionmeter (Consort C531) and the salinity was measured with a hand refractometer (Atago). Previously in the laboratory, the conductivity cell and refractometer were calibrated with known NaCl solutions.

Table 1 Description of the studied French Guiana Rivers (Atlas Guyane and UNH/CRDC)

Name	Length (km)	Basin surface (km^2)	Mean discharge (m^3/s)
Maroni	520	65830	1680
Mana	430	12090	300
Iracoubo	140	1470	
Sinnamary	262	6565	230
Kourou	112	2000	
Cayenne	50	745[a]	
Mahury	100	3255[a]	

[a] These rivers have two main tributaries, the reported basin surface corresponds to the sum of both.

For those solutions with a concentration of less than 10‰, a nice relationship was found between the conductivity and salinity: conductivity (in μS) * 1000 = salinity (‰).

For isotopic analysis, water samples were collected in 10 ml glass vials with secure caps and sent rapidly to the stable isotopic laboratory. The stable isotope composition of water is reported with reference to the Vienna Standard Mean Ocean Water (V-SMOW), in parts per thousand. Thus the mean ocean value is around value zero for both isotopes. The definition for oxygen is

$$\delta^{18}O_{\text{V-SMOW}}\ (‰) = ((^{18}O/^{16}O_{\text{sample}})/(^{18}O/^{16}O_{\text{standard}}) - 1) * 1000$$

and for deuterium

$$\delta^{2}H_{\text{V-SMOW}}\ (‰) = ((^{2}H/^{1}H_{\text{sample}})/(^{2}H/1H_{\text{standard}}) - 1) * 1000.$$

A negative value characterizes a water more depleted in heavy isotope than the ocean reference. This is the case when the evaporated seawater comes over the inland and condensed again to form rainfall. This isotopic fractionation depends mainly on the distance run by the water source and the condensation place (i.e. continental effect) and the decrease in temperature when approaching hills and mountains (altitude effects). In subtropical area, the coastal rainfall are slightly depleted in heavy isotope ($-4 < \delta^{18}O < -2$), only rivers coming from far inland and high basin can display more negative values.

Deuterium and oxygen-18 generally have a linear relationship in fractionation rates on regional and global scales. This first order ratio is closed to 8, and corresponds to an equilibrium fractionation ratio between the oxygen and the deuterium masses. The line comparing both at various locations is called the Global Meteoric Water Line (GMWL), and follow the equation $\delta^2H = 8 * \delta^{18}O + 10$ (Craig, 1961).

Deviation of a sample from the GMWL, involves the second order (remaining D value of 10) which comes from the non equilibrium fractionation processes and the different molecular diffusivities, inducing a kinetic effect. This second order justifies the definition of *deuterium excess*: δD excess = $\delta^2H - 8 * \delta^{18}O$. During evaporation, this kinetic fractionation results in a relatively less intense depletion of water vapour in deuterium compared to 18-oxygen, and depends on the evaporation conditions (relative humidity, temperature above the water surface, and wind regimes). This is an indicator of the complexity of the air mass pathway and the environmental conditions at evaporation. Most intertropical oceans have D values of about 10. Low relative humidity produces higher D values, while low D values indicate secondary evaporation processes (evaporation of descending rain drops).

Rivers and site descriptions

From west to east, the first river, at the border of Surinam, is the Maroni River (see Fig. 1). It is the biggest river in French Guiana and also the second largest river in the three Guianas, just smaller than the Essequibo (2100 m^3/s) in Guyana. The greater part (56%) of the Maroni basin is in Surinam in the basin of the tributary Taponahony, whose source is in the area of the Tumuc-Humac at 700 m high. Its last reach is 100 km long and 5 km wide, and tidal movements can be visible. The next river to the east is the Mana River (second in length and third in basin area). It descends from the central inland near the area of Saül and the higher catchment areas

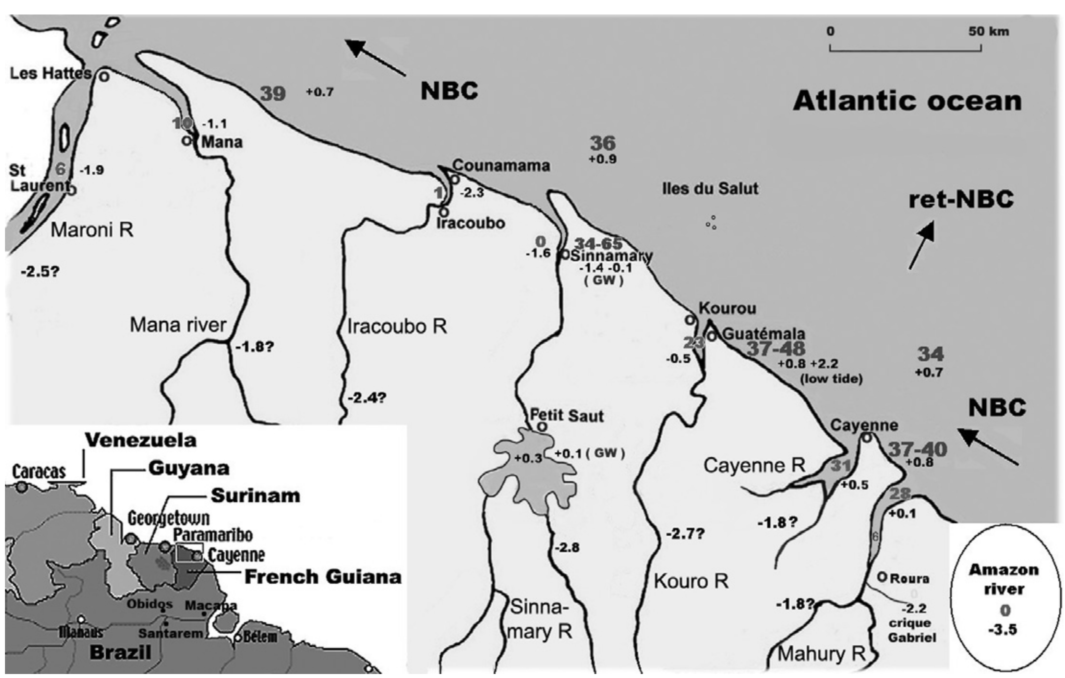

Figure 1 Localization of the different rivers and waters sampled over French Guiana. The insert chart in the left corner gives the position of this area relative to the northeast of South America. The large numeric number in gray gives the salinity (values in ‰) for the ocean (open sea, coast) and the estuaries. The smaller black numbers with a sign are the measured ^{18}O isotopic values. The numbers with the question mark are the calculated isotopic values for the upstream part of the rivers (extrapolation to zero salinity). The ellipse in the right corner provides the salinity and isotopic values of the Amazon River close to the ocean.

are at about 400 m. The last fall is 70 km from the coast and the estuary turns northwest at the shoreline. The smaller Iracoubo River is just east of the Mana River and comes from a lower altitude, displaying an angled estuary. The Sinnamary River is the fifth river of the country and is similar in shape to the Mana River: a long and narrow basin oriented south to north, and a markedly angled estuary. The hydroelectric dam at Petit Saut has regulated its discharge since the 1980s. The last fall is about 40 km from the coast. After the Sinnamary River comes the smaller Kourou River, formed in the flat area in the middle of the country. Its estuary is less affected by the northwest sea current. The Cayenne River is the smallest river and is located west of the city with the same name. It has a wide estuary (4 km long, 2 km wide) where its two main tributaries (the Montseny and Cayenne rivers) join. The final river that was studied is the Mahury River. At the beginning of its 15 km long estuary, two main tributaries join.

Results

The temperature, conductivity and salinity of the water samples are given in Table 2. In general, the temperature of the water was close to the air temperature, 28–30 °C, even for groundwater in a mangrove forest, taken around 1.2 m deep. Only the remaining seawater taken in Guatemala at low tide had a higher temperature and only the rainfall water taken in Cayenne had a lower temperature.

The salinity of the sea ranged between 35 and 39‰, except in an area of Guatemala (48‰) taken at low tide, whereas groundwater in the mangroves reached up to 54‰. The salinity of the mangrove soil revealed even higher values (70‰). Only the Sinnamary River displayed very low-salinity and conductivity with a small increase at high tide. The conductivity of the more inland waters, as well as the Amazon River, had values around 50 μS, as is usual in tropical countries, which is close to the mean rainwater value. The higher value for the small river at Crique Gabriel could be associated with groundwater discharge. Some open estuaries, such as those of the Mahury, Cayenne and Kourou rivers, with low discharge, revealed a high input of seawater. For the Mahury River long estuary, the salinity was still 13‰ at 15 km from the shore, at the Roura bridge.

The ^{18}O and deuterium contents are summarized in Fig. 2, and compiled with the calculated deuterium excess in Table 2. The solid line in Fig. 2 represents the Global Meteoric Water Line (GMWL) with a slope of eight and a deuterium excess of 10. The points range from the Amazon sample taken in Obidos (δ^{18}O = −6.5, higher altitude water) to the ocean pool (mean value δ^{18}O = +0.76). The Amazon River samples, the high Sinnamary and the Iracoubo samples were close to the GMWL line, showing that there is no important evaporation process. This is also confirmed by their high D excess value (+8 to +12), as reported in Table 2. This comes from the equilibrium between the condensation and evaporation processes over the Amazonian forest, as well as over the Guiana rain forest. On the other hand, the surface water of the big artificial lake at Petit Saut showed a negative D excess value, in accordance with the high evaporation. The same was found for the nearby pond (Crique Crabe). The other French Guiana rivers, with large estuaries and high salt content (Kourou, Mahury and Cayenne rivers), line up between the ocean pool and the GMWL line (refer to the dotted line in Fig. 2). This is typical for estuarine water with mixing of two components, freshwater and salty water. The fact that this line does not cross under the ocean pool suggests that the evaporation process is low, certainly due to the deepness of these estuaries. Here the deuterium excess cannot be used due to the inflow of ocean water. The Maroni and downstream Sinnamary river samples are in between these two lines. The small negative values for the mangrove groundwater (δ^{18}O = −1.3 to −0.1) were surprising. Despite the very high salinity, the water origin of this sample from the mangroves is more linked with the freshwater pool than with the evaporated seawater side.

The relationship between the δ^{18}O values and the salinity is given in Fig. 3. It emphasizes the presence of two water pools. The freshwater pool encompasses all the rivers or water samples close to the *x*-axis (Amazon, Sinnamary, Iracoubo, Mana and Maroni rivers), the mean value materialized by a wide ellipse. The salty water pool is the upper ellipse formed by the ocean waters. Between these two pools a mixing line can be drawn (the dotted line on Fig. 3) and the estuary rivers (Kourou, Mahury and Cayenne rivers) are close to this line. To see how the salinity and the δ^{18}O value vary over the studied area, these values were plotted on a geographical map (see Fig. 1). The location and the dimension of the rivers can be observed, as well as the orientation of their mouths, a result of the North Brazil current (NBC) and the huge mud load of the Amazon River. In order to check the homogeneity of the freshwater pool, the possible isotopic values for the upper stream rivers, extrapolated to zero salinity (see next paragraph), are also reported.

Discussion and interpretation

Salty water pool

The ocean forms the largest water reservoir on the planet and it is also the reference for the isotopic standard (Craig, 1961). The ^{18}O content in the surface layer is rather uniform, varying between $\delta = -0.5$ and $\delta = 0.5$. Only in polar or tropical regions are larger deviations observed. In tropical regions, more positive values are caused by strong evaporation (Mook, 2000). Few data are available in the literature for the South American ocean. At the level of Rio of Janeiro, in Brazil, the open sea has a mean value of δ^{18}O = +1.23 ± 0.07 (Pierre et al., 1991), much higher than the values observed in the North Atlantic ocean (Frew et al., 2000; Delaygue et al., 2000). Further north of Brazil, the isotopic values decrease a little: δ^{18}O = +1.2 in front of the Amazon delta (Karr and Showers, 2002), and δ^{18}O = +1.05 at the level of French Guiana (Ternon and Guiral, 2005; during the Chico 0 cruise). The salinity ranges from around 37 to 36‰. These values are not far from our own data for the open ocean found at the level of Sinnamary (δ^{18}O = +0.87, salinity S = 36‰); the slightly lower value measured off Cayenne could be due to the presence of a small influence of the Amazon, which will be discussed in the next section. This concentrated ocean water gives rise to shore salinities between 35 and 70‰ during this dry

Table 2 Characteristics of the 30 water samples

Number	Type	Location	Date	Temperature (°C)	Salinity (‰)	Conductivity (μS)	$\delta^{18}O_{V\text{-}SMOW}$ (‰)	$\delta^{2}H_{V\text{-}SMOW}$ (‰)	D excess (calculated)
1	Open sea 1	20 km Sinamary	11/16/2003		36		0.86	5.65	−1.22
2	Open sea 2	25 km Cayenne	11/17/2003		35		0.67	5.57	0.24
3	Sea shore 1	Cayenne IRD	10/29/2003	30.5	38		0.80	4.78	−1.63
4	Sea shore 2	Guatemala (tide down)	11/13/2003	34.0	48		2.23	13.35	−4.45
5	Sea shore 3	Mana	12/4/2004	30.0	39		0.70	10.08	4.48
6	Maroni River	Degrad	12/4/2004	30.0	6	5530	−1.93	−10.51	4.93
7	Mana River	D8 bridge	12/4/2004	30.0	10	9600	−1.08	−3.13	5.51
8	Iracoubo River	N1 bridge	11/8/2003	30.0	1	757	−2.31	−10.51	7.97
9	Sinnamary River 1	N1 bridge (tide up)	11/2/2003	29.0	0	238	−1.45	−8.82	2.80
10	Sinnamary River 2	N1 bridge (tide down)	11/2/2003	29.0	0	26			
11	Sinnamary River 3	N1 bridge (tide down)	11/27/2004	30.0	0	28	−1.75	−4.39	9.61
12	Sinnamary River 4	Before dam	12/22/2005		0	27	−2.75	−11.55	10.45
13	Kourou River	N1 bridge	11/2/2003	30.0	23		−0.53	−0.58	3.66
14	Cayenne River	N1 bridge	11/2/2003	30.0	33		0.48	4.09	0.29
15	Mahuri River 1	Degrad canne	11/1/2003	30.0	28		0.13	1.25	0.20
16	Mahuri River 2	Bridge Roura(D6)	11/28/2004	30.0	13				
17	Amazone River 1	Obidos	December 2003		0	58	−6.51	−42.15	9.89
18	Amazone River 2	Santarem	November 2003		0	35	−3.62	−20.18	8.80
19	Amazone River 3	Macapa	10/22/2003	28.0	0	52	−3.53	−23.93	4.28
20	Philipon canal 1	D7 bridge (Sinnamary)	11/2/2003	30.5	0	48	−1.41	−6.45	4.87
21	Philipon canal 2	D7 bridge (Sinnamary)	11/27/2004	30.0	0	50			
22	Small river	Crique Gabriel (Eskol)	11/29/2004	30.0	0	396	−2.24	−5.59	12.33
23	Artificial lake	Petit Saut dam	11/9/2003	31.0	0	44	0.28	1.60	−0.66
24	Deep pound	Crique Crabe (Petit Saut)	11/14/2003	32.0	0	34	0.05	−2.98	−3.37
25	Ground water 1	D7-mangrove-p1	11/9/2003	29.5	54		−0.14	3.31	4.40
26	Ground water 2	D7-mangrove-p1	11/27/2004	30.0	52		−0.33	8.6	11.24
27	Ground water 3	D7-mangrove-p4	11/27/2004	30.0	34		−0.83	−1.34	5.30
28	Ground water 4	D7-mangrove-p6	11/27/2004	30.0	21		−1.28	−3.55	6.69
29	Rain water 1	Cayenne IRD	11/3/2003	26.5	0	98	−3.24	−20.96	4.95
30	Rain water 2	St Laurent M	12/4/2004	28.0	0	22	−0.74	−2.66	3.26

season, and similar values were found in the back mangrove in Sinnamary and Guatemala.

Freshwater pool

The next pool is the freshwater, coming directly from the local rainfall, stored in groundwater, or the upstream rainfall coming through rivers. Cayenne is part of the Global Network for Isotopes in Precipitation (GNIP) monitored by the International Atomic Energy Agency. From the GNIP Database (IAEA/WMO, 1998), the mean weighted annual value is $\delta^{18}O_{pt} = -2.2$ (Rozanski et al., 1993). A one-year survey, done by the BRGM in 1995, provided a lower weighted mean $\delta^{18}O_{pt} = -4.6$ (Négrel et al., 1997). Further

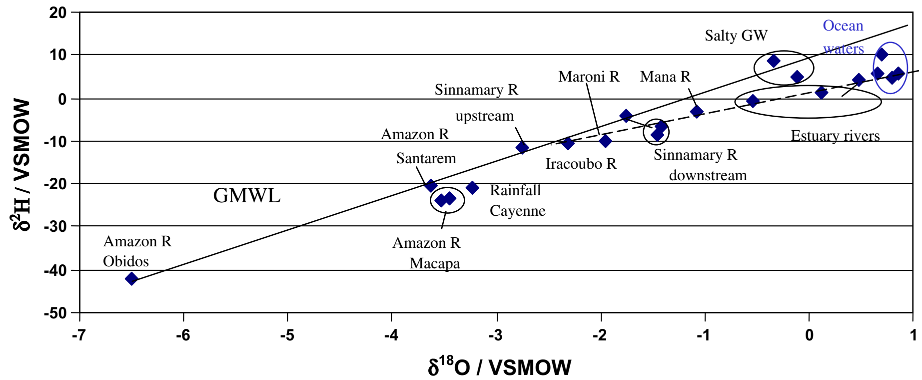

Figure 2 Relationship between the δ^{18}O and δ^{2}H values for the studied French Guinea rivers, compared with the Amazon River (three samples), the groundwater in Sinnamary (Salty GW) and the seawater (four samples). The estuary rivers are from left to right: Kourou, Mahury and Cayenne rivers. The solid line represents the Global Meteoric Water Line (GMWL: $\delta^{2}H = 8 \times \delta^{18}O + 10$).

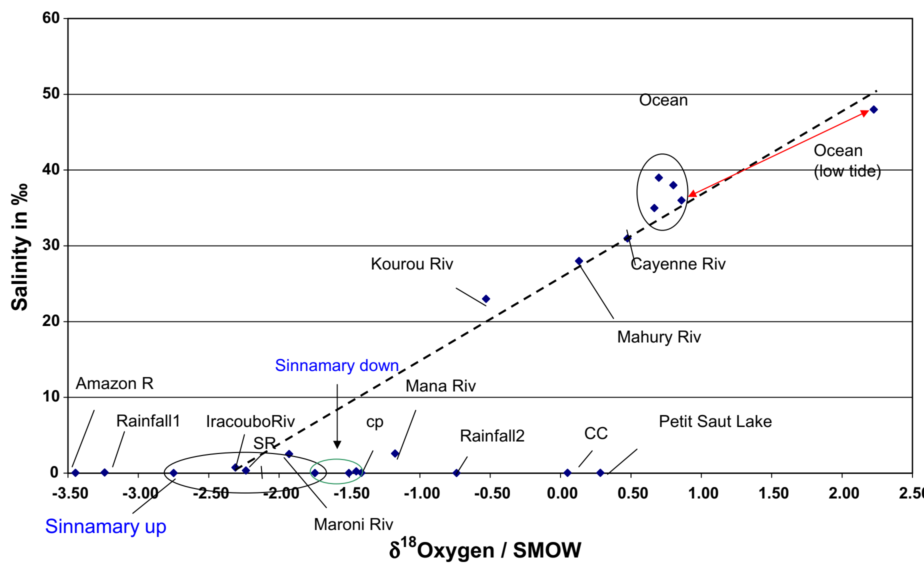

Figure 3 Relationship between δ^{18}O and the salinity values. The broken line represents the mixing line between the freshwater pool (ellipse on the *x*-axis) and the salty water pool (ocean water ellipse) up to the evaporated Guatemala seawater taken at low tide. The three estuary rivers, Kourou, Mahury and Cayenne rivers, are on this line. Rainfall 1 was taken in Cayenne, Rainfall 2 in St Laurent, SR represents the small river (Crique Gabriel), cp represents the Canal Philipon, cc represents the Crique Crabe.

inland, about 200 km from the ocean, in southeastern French Guiana at Yaou, the mean annual value becomes $\delta^{18}O_{pt} = -3.0$ (Girard et al., 2000, 2002). More to the west at Sinnamary, in a forest stand and in an open area, the $\delta^{18}O_{pt}$ mean values range between -3.0 and -2.0 (Millet et al., 1999; Bonal et al., 2000). All these mean precipitation values over the French Guiana coast range between the values $\delta^{18}O_{pt} = -3.7$ to -1.7, and are not far from our rainfall values (-3.2 and -0.7).

The only reported study using stable isotopes on the French Guiana river waters is for the Maroni River, where values ranging from $\delta^{18}O = -2.9$ downstream to $\delta^{18}O = -3.7$ upstream were recorded (Négrel and Lachassagne, 2000). In addition, our own values from the Amazon River, taken in the delta and at Santarem in its low-altitude tributary, the Taporos River, ($\delta^{18}O = -3.5$), are of the same order.

The upper Sinnamary ($\delta^{18}O = -2.8$) presents a more depleted isotopic value and the range for the other French Guiana rivers is $\delta^{18}O = -2.3$ to +0.5. However, many of them had a high salt content and the isotopic characteristic of the fresh upper river could then be extrapolated to salinity zero. This idea was developed because of the difficulty of accessing the upper river and because of the large number of tributaries (Table 3). The mean δ^{18}O value of the ocean was +0.79 and the salinity was 37‰. The ratio of the seawater relative to the river is given by the salinity ratio. The complementary ratio is the amount of freshwater and its isotopic value given the original river characteristics. With these recalculated values, the new average value for these rivers is $\delta^{18}O = -2.2 \pm 0.4$, which shows the relative homogenous rainfall over French Guiana. This mean value is also the value found in Fig. 3 (the intersection between the dotted line and the *x*-axis) and in Fig. 2

Table 3 Recalculation of the $\delta^{18}O$ value to salinity zero

River	Salinity (‰)	Sea water (%)	$\delta^{18}O$ original	$\delta^{18}O$ recalculated
Maroni	6	16.2	−1.93	**−2.45**
Mana	10	27.0	−1.08	**−1.76**
Iracoubo	1	2.7	−2.31	**−2.40**
Sinnamary	0	0	−2.75	
Kourou	23	62.2	−0.53	**−2.65**
Cayenne	33	89.2	0.48	**−1.83**
Mahury	28	75.76	0.13	**−1.83**

(the intersection between the dotted line and the GMWL line).

Air humidity and vapor recirculation

With regard to the deuterium excess over the Amazon basin, the isotopic signals of the river water depend on the recharge process (rainfall) as well as two additional factors: the *amount effect* and the recirculation of the water into the forest (Mortatti et al., 1997). As high deuterium excesses are generally found (10 or more and a slope close to eight), this suggests that equilibrium conditions obtain between the condensation and evapotranspiration processes. In other terms, this means that the air humidity is always so high that atmospheric water saturation is reached. If one takes the ^{18}O and ^{2}H values from Négrel and Lachassagne, the deuterium excess can be calculated for the Maroni basin. Effectively, the values are close to 10, as for the Amazon basin. Values are for the Maroni River itself (10.5 ± 1.1, $n = 20$), its tributaries (11.0 ± 1.5, $n = 19$) and the adjacent groundwater (11.2 ± 1.2, $n = 5$). From our own results, the small rivers (or rivers with small estuaries) have a high deuterium excess (from 8.0 to 12.3, in the Iracoubo, Sinnamary, and Gabriel). However, due to the seawater input or the coastal evaporation, this equilibrium is lost and the deuterium excess is much lower (+6 to −4) in the other rivers.

Mixing of the different water pools

The previous paragraphs emphasize the characteristics of the different water pools influencing the French Guiana shore: (i) the tropical South Atlantic ocean with an increased salinity (36–39‰) and ^{18}O values (+1.0 to +2.0) above the V-SMOW reference (not far from the values for a hot closed sea like the Red Sea); (ii) the rainfall along the coast, which feeds the groundwater and the rivers with values $\delta^{18}O = -3.7$ to -1.7. A river like the Maroni River, which has its source further inland, displays the more negative value. As the air temperature remains quite constant over the year and the immediate inland has no substantial mountains, the seasonal effect should remain low; (iii) the third pool is the Amazon River outflow ($\delta^{18}O = -6.5$ to -3.5) in the ocean (Salati et al., 1980; Gibson et al., 2002; Henderson-Sellers et al., 2002), which is brought along the French Guiana coast by the North Brazil current (NBC). The mixing of this river water with the ocean water is quite a complex system since it is first modulated by the river discharge variation: maximal in May–June and minimal in October–November. Even after the water is out of the mouth of the Amazon, the dispersion along the northwest coast is not uniform due to the presence of the retroflexion of the NBC during the months of June–December. This means that during this period the Amazon water outcome and its associated mud plumes do not continue to travel along the Guyana coast but are sent more to the open sea (from northwest to northeast) at the level of the city of Cayenne. The Amaseds program (Karr and Showers, 2002) and the Chico 0 program (Ternon and Guiral, 2005) have followed this water mass exchange. It can be seen that water masses with values of $\delta^{18}O = -6$ to -4 can be detected 100 km from the mouth of the Amazon during the peak discharge in April–August. From Amapa Island to the border of French Guiana, values of $\delta^{18}O = -3$ to -2 can also be measured at about 50–100 km from the shore. At the level of the Mahury estuary, values as low as $\delta^{18}O = -2.4$ and a salinity of 17‰ could be sampled 50 km from the coast during the month of April. This surface freshwater lens found in the open sea is a few tens of kilometers wide but only a few meters deep.

Dual Amazon influence — French Guiana paradox

In fact, the mud brought by the Amazon plumes has the opposite effect to the freshwater lens. By depositing along the Guiana shore, these mud banks minimize the wave dynamics and produce large, flat and shallow areas in the intertidal zone where the seawater can be concentrated. The sea current maintains itself a little away from the coastline, a few kilometers or a few tens of kilometers in the open sea beyond the tidal influence. It is as though there is a split between the two components of the mud plume: one part of the mud is slowly accumulating along the coast (and become more and more saline), whereas the freshest Amazon water with the remaining mud continues its northwest journey further from the coast. So, indirectly by its solid deposits, the Amazon plumes bring highly saline conditions along the Guiana coast. Similarly, the Avicennia mangrove (the more salt-tolerant species) is found on the sea front where, as in the Amazon delta and the estuaries, there is swamp forest or Rhizophora formation. The initial sand coast is now found more inland, in general, at the end of the back mangrove, and creates the border between the fresh groundwater and the saline coastal underground water. Paradoxically, this ever changing French Guiana coast is one of the more important places for leatherback turtle (*Dermochelys coriacea*) breeding. This coast hosts about 40% of the world's population of breeding females. As the turtles make their nest in the sandy area, and cannot enter the mud and mangrove area, they have to adapt to this mud bank migration. This marine species can only be found around these sandy areas close to the estuaries of the bigger rivers, like the Maroni or the Mahury. Recently, genetic research has shown (Rivalan et al., 2006) that the Maroni nesting population may be part of a large metapopulation. So, the turtles in this group are less linked to a particular beach and can more readily adapt to coastal change, in contrast to other turtle groups that are much more linked to a specific beach.

Conclusion

This study and the literature analysis reveal the contrast between the stable inland with its quite homogenous, freshwater pool and equilibrium between the condensation and evapotranspiration processes, and the ever changing coast shape and the inflow of saline ocean water through the large estuaries. The evaporation process seems to be negligible in the mouths of these rivers, whereas it is of high amplitude on the wide mud banks, with low water level under tidal influence. The Guianese paradox is that these mud banks are brought by the Amazon outflow, where the tropical ocean evaporates, and that the Amazon freshwater itself remains in the open ocean, outside the tidal movement. During the wet season, this enhanced coastal salinity is certainly reduced by the bigger discharge of the rivers and the local rainfall. Work is ongoing to better understand this paradox and the junction between freshwater and salty water pools located at the back of the coastal mangrove forest.

Acknowledgments

We thank P. Vendeville (Ifremer, Cayenne) for the open ocean water sampling, O. Machado (IEPA, Macapa Brazil), P. Sist (Cirad, Brazil) and F. Guerin (University of Bordeaux) for the Amazon River water samples, and A. Dejean (University of Toulouse) for the upper Sinnamary River sample. We wish also to thank the Hydreco laboratory in Petit Saut and the IRD Center in Cayenne for offering facilities during the fieldwork. The authors are also indebted to J. F. Ternon and D Guiral, IRD Cayenne, for unpublished Oxygen-18 data from the Chico 0 program and interesting discussions about the distribution of the Amazon outcome along the Guiana shores. We are also grateful to J. Mortatti, University of Sao Paulo, for explaining the humidity recycling above the Amazon forest, and to P. Rivalan, University of Paris-Sud, for exchanges about the Guiana coastal changes and the turtle nesting. Not least, we would like to thank the anonymous referees for their constructive remarks and their nice suggestions. The isotopic analysis costs were supported by the PNEC program (National Coastal Environmental Program).

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