Wavelet analysis of Amazon hydrological regime variability

David Labat,[1] Josyane Ronchail,[2] Jacques Callede,[3] Jean Loup Guyot,[4]
Eurides De Oliveira,[5] and Waldemar Guimarães[5]

Received 30 September 2003; revised 19 December 2003; accepted 5 January 2004; published 31 January 2004.

[1] Wavelet analysis allows for an insightful examination of the temporal variability of Amazon basin hydrology and highlights intermittent interannual and interdecadal fluctuations. Two main conclusions arise. Interannual fluctuations appear as closely related to equatorial Pacific forcings whereas 15-year and bi-decadal fluctuations are strongly correlated with Pacific and tropical Atlantic long term forcings. The 1970's climate shift affects the Amazon basin, implying a correlation between both NATL and SOI and hydrological proxies after that decade. *INDEX TERMS:* 1833 Hydrology: Hydroclimatology; 1655 Global Change: Water cycles (1836); 9360 Information Related to Geographic Region: South America; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 1821 Hydrology: Floods; *KEYWORDS:* Amazon hydrology, wavelet analyses, ENSO, Atlantic SST, climatic forcings. **Citation:** Labat, D., J. Ronchail, J. Callede, J. L. Guyot, E. De Oliveira, and W. Guimarães (2004), Wavelet analysis of Amazon hydrological regime variability, *Geophys. Res. Lett.*, *31*, L02501, doi:10.1029/2003GL018741.

1. Introduction

[2] The Amazon is the largest river in the world. The Amazon watershed at the station of Obidos (1.56°S–55.50°W) covers a 4,677,000 km^2 area for a mean discharge of 163,000 $m^3\ s^{-1}$. The hydrogram integrates contributions from tributaries from both hemisphere. Monthly discharges in Obidos were computed from water levels in Obidos during the 1928–45 and the 1969–99 periods and, thanks to the excellent correlation between both stations, were reconstituted from water levels in the upstream station of Manaus during the 1902–27 and 1946–68 periods [*Callède et al.*, 2002a]. The annual rainfall over the Amazon basin in Obidos is estimated from 46 rainfall gauges located in synoptic stations over Brazil, Peru, Bolivia, Ecuador, Colombia, Venezuela and Surinam (data taken from national meteorological services and NOAA/GHCN).

2. Method

[3] A visual inspection of mean annual Amazon series (Figure 1) shows a highly intermittent signal, which justifies the preference of wavelet analysis over classical Fourier analysis [*Labat et al.*, 2000, 2001]. The coefficients of the wavelet transform of a continuous-time signal x(t) are defined by the linear integral operator [*Grossmann and Morlet*, 1984]:

$$C_x(a,\tau) = \int_{-\infty}^{+\infty} x(t)\psi *_{a,\tau}(t)dt \quad \text{with} \quad \psi_{a,\tau}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-\tau}{a}\right) \tag{1}$$

where * corresponds to the conjugated complex. The wavelet spectrum $W_X(a, \tau)$ of a continuous-time signal x(t) is defined as the modulus of its wavelet coefficients [*Liu*, 1994]:

$$W_x(a,\tau) = C_x(a,\tau)C_x^*(a,\tau) = |C_x(a,\tau)|^2 \tag{2}$$

3. Results

[4] Morlet continuous wavelet analysis is performed over four signals relevant from the temporal fluctuations of the Amazon hydrological regime at Obidos: mean annual rainfall rates, mean annual Amazon discharge, annual low flow discharge and annual high flow. The temporal-scale structure of these intermittent signals reveals significant oscillations with periods ranging from 2 to 60 years (Figure 1). Wavelet peaks are shown to be statistically significant from noise using *Torrence and Campo* [1998] tests.

[5] Rainfall rates constitute the main hydrological input of the basin. Over the 1950–1999 interval, when considering scales inferior to 12 years, a shift around 1970 is visible. Effectively, no interannual process is visible before 1980 whereas 2–4 year and 7 year interannual fluctuations appear after 1970. The 1970's shift corresponds to a 16-year oscillation.

[6] Over the 1900–2000 interval, Amazon annual mean runoff and annual high flow variations are characterised by sensitively similar time-scale structures. Two 2–3 and 4–8 year interannual oscillations are temporally localised in the 1900–1930 and 1980–2000 intervals. Both series are also characterised by a decadal oscillation located around 1920 and a strong bi-decadal oscillation centred around 1970.

[7] Annual low flow time scale structure appears as more complex with a wide range of oscillations. At interannual scale, from 1900 to 1940, low flows are characterised by oscillations ranging from 2 to 4 years (corresponding to a quasi biennal oscillation) and from 6 to 12 years. A 6-year oscillation is particularly visible around 1925. After 1940, the quasi-biennal oscillation remains the unique interannual

[1]UPS – Laboratoire des Mécanismes et Transferts en Géologie (LMTG), Toulouse, France.
[2]IRD – UR 154 LMTG – HYBAM, Lago Sul, Brasília, Brasil.
[3]Retired from IRD, Brasília, Brasil.
[4]IRD – UR 154 LMTG – HYBAM, Toulouse, France.
[5]Agência Nacional de Águas (ANA) – HYBAM, Setor Policial, Brasília, Brasil.

0094-8276/04/2003GL018741$05.00

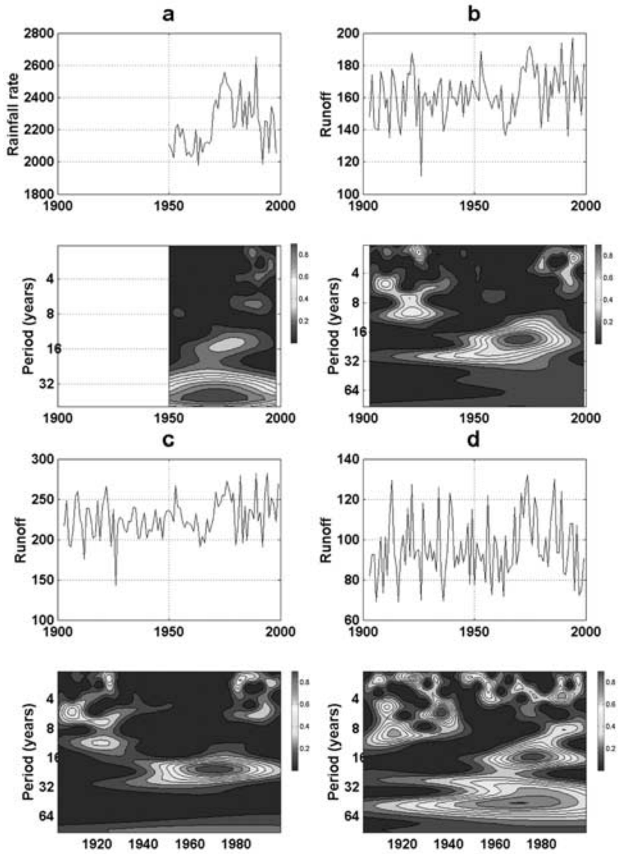

Figure 1. Temporal fluctuations and corresponding Morlet wavelet analysis of the main hydrological series available on the Amazon basin at Obidos over the 1900–2000 period; (a) mean annual rainfall in mm (October–September); (b) mean annual runoff in 10^3 m^3 s^{-1} (October–September); (c) annual high flow in 10^3 m^3 s^{-1}; (d) annual low flow in 10^3 m^3 s^{-1}.

process with a maximum centred around 1958 except a near decadal oscillation around 1985. Multidecadal variability is mainly concentrated on 16-year and 55-year oscillations over the 1950–2000 interval.

[8] Obidos mean and maximum discharge time-series multidecadal oscillations are centred around 1970 in accordance with previous results mentioned in Obidos by *Callède et al.* [2002b] and in the station of Manaus (Rio Negro) by *Marengo* [1995] and *Marengo and Tomasella* [1998]. It climatically corresponds to the beginning of the dominance of a positive NAO phase, to a long term cooling of the northern Atlantic [*Kushnir*, 1994; *Moron et al.*, 1998; *Eden and Jung*, 2001] and to decadal changes in the ocean and the atmosphere in the Pacific [*Trenberth*, 1990; *Trenberth and Hurrell*, 1994].

[9] In order to determine precisely the characteristic period of the four hydrological series (Figure 2a), a time-averaging of the wavelet spectrum is operated [*Torrence and Campo*, 1998]. Annual mean precipitation highlights 2.4, 3.8 and 6.7-year interannual processes and a 15.5-year interdecadal oscillation. Annual mean flow and high flow highlights common 2.4, 3.8 and 5.8-year interannual processes and a 20-year bidecal oscillation. Finally, the annual low flow global wavelet spectrum shows a 3.7-year interannual oscillation and a 15.5-year interdecadal component.

[10] The main difference in the hydrological regime of the Amazon arises from a multidecadal scale. Effectively, the composite 20-year oscillation shown on annual mean flows roughly correspond to a combination of 16 and 20-year periods annual high flow interdecadal oscillation whereas the 27-year annual mean flow oscillation is in adequation with the 31-year annual high flow oscillation.

4. Relationship to Climate Forcing

[11] These aforementioned characteristic oscillations were then related to three well known climatic indices available from the 1950–2000 interval. Inspection of wavelet analysis provide evidences for time scale similarity between signals. This information should be considered with carefullness in term of physical interpretation even though if it is more precise than correlation found by classical spectral analysis.

[12] Previous works [*Richey et al.*, 1989; *Marengo*, 1992; *Amarasekera et al.*, 1997; *Guyot et al.*, 1998] show that the interannual variability of the Amazon river in Manaus, near Obidos, is weakly related to the El Niño Southern Oscilla-

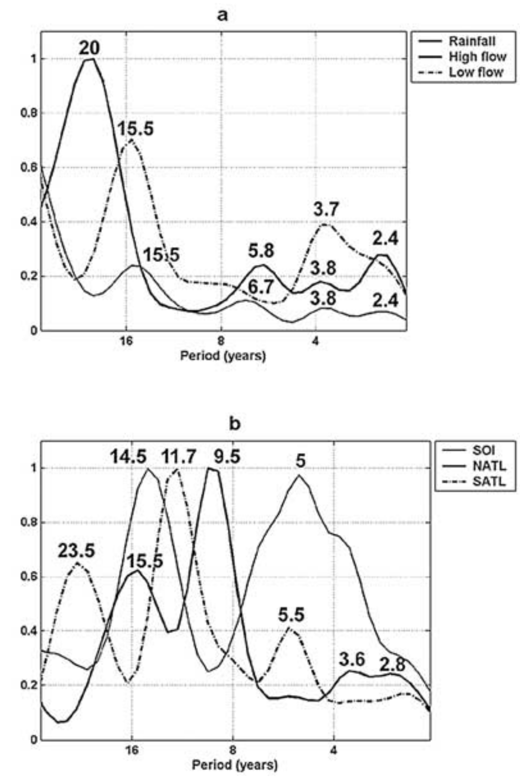

Figure 2. Global wavelet spectrum of mean annual rainfall, annual high flow and annual low flow of Amazon basin measured at Obidos (a) compared to global wavelet spectrum of three main climatic forcings (b) Southern Oscillation Index, North Atlantic sea surface temperatures and South Atlantic sea surface temperature. All series correspond to the 1950–2000 interval. This method allows for a rapid and efficient identification of the characteristic 2–30 year periods of oscillations.

Table 1. Correlation Coefficients Between Annual (October–September) Rainfall in the Amazon Basin and Discharges in Obidos (Mean, Maximum and Minimum) and Annual (October–September) Climatic Indexes (SOI, and SST Anomalies in the Tropical Northern and Southern Atlantic)

	Rainfall	Mean Discharge	Max Discharge	Low-waters
Rainfall	1, 00			
Mean Discharge	**0, 74**	1, 00		
Max discharge	**0, 68**	0, 92	1, 00	
Low-waters	**0, 62**	**0, 50**	**0, 36**	1, 00
SOI	0, 19	0, 12	0, 04	**0, 27**
SOI (50–70)	0, 23	0, 08	0, 06	0, 26
SOI (71–98)	**0, 45**	0, 28	0, 16	**0, 40**
NATL	**−0, 44**	**−0, 48**	**−0, 35**	**−0, 61**
NATL (50–70)	−0, 02	0, 01	0, 10	−0, 28
NATL (71–98)	**−0, 51**	**−0, 63**	**−0, 44**	**−0, 70**
SATL	0, 22	0, 14	0, 10	0, 23
SATL (50–70)	−0, 34	**−0, 37**	−0, 31	−0, 06
SATL (71–98)	−0, 05	0, 04	−0, 04	0, 13

[North Atlantic Sea Surface Temperature (NATL SST) averaged over a 5–20°N; 60–30°W latitude-longitude box, originated from the Climatic Prediction Center (CPC-NOAA), South Atlantic Sea Surface Temperature (SATL SST), originated from the Climatic Prediction Center (CPC-NOAA) averaged over a 0–20°S; 30°W–10°E box, Southern Oscillation Index (SOI) series based on the Tahiti and Darwin sea-level pressure, originated from the National Center for Environmental Prediction (NCEP)] - Bold values are significant at the 95% level.

tion (ENSO) in the Pacific. During El Niño, the inversion of the Walker circulation due to the warming of the eastern Pacific leads to subsidence over the tropical South American continent and to a subsequent widely spread dryness in the austral summer. During La Niña the opposite is only observed near the Atlantic [*Ronchail et al.*, 2002].

[13] Over the 1950–1998 interval, a preliminary analysis of the relationships between rainfall over the Amazon basin, discharges in Obidos and climatic indicators shows positive correlation between rainfall and discharge and a negative correlation between hydrological proxies and SST Anomalies (SSTA) in the Northern Tropical Atlantic (Table 1). Rainfall and discharge, in particular low flow, are more abundant when the SSTA in the NATL are negative. This is consistent with previous observations indicating that cold waters over the NATL are related with enhanced north-eastern trade-winds, which create a strong South American monsoon and increase water vapour influx over the western and southern Amazon basin [*Marengo*, 1992]. SST variability could be associated in turn to external forcing, such as NAO and ENSO. During the positive phase of NAO, an acceleration of the trade-winds due to the strengthening of the Azores High could lead to increased evaporation and a cooling of the northern tropical Atlantic. The equatorial Pacific may influence the tropical Atlantic through the modulation of the intensity of the rising branch of the Hadley cell over South America. It remains unclear to what extent ocean dynamics play a role on tropical Atlantic variability [*Marshall et al.*, 2001].

[14] However, as shown in Table 1, the relationship between NATL and discharges is not stationary. Whereas no significant relationship is highlighted before 1970, the NATL SSTA explain 20 (high flow) to 50% (low flow) of the discharge in Obidos from 1970 to the present. A weak relationship is found between SOI and rainfall and low flows, with a El Nino/low flow signal that improves after the 1970s.

[15] In order to better define this unstationary relationship over the second half of the 20th century, a wavelet analysis is applied to SOI, North Atlantic Sea Surface Temperature (NATL SST) and South Atlantic Sea Surface Temperature (SATL SST). Wavelet analysis of SOI is not shown here for lack of place (Figure 3).

[16] The annual SOI index is characterised by interannual fluctuations with periods ranging from 4 to 8-year and maximum intensity over the 1970–1985 interval. A 15-year interdecadal fluctuation is also shown around 1980. NATL and SATL SST are characterised by unenergetic interannual processes (2.8 and 3.6-year oscillations for NATL SST and 5.5-year oscillations for SATL SST) compared to decadal and interdecadal fluctuations. NATL SST highlights two decadal and 15-year oscillations centred around 1975 where-

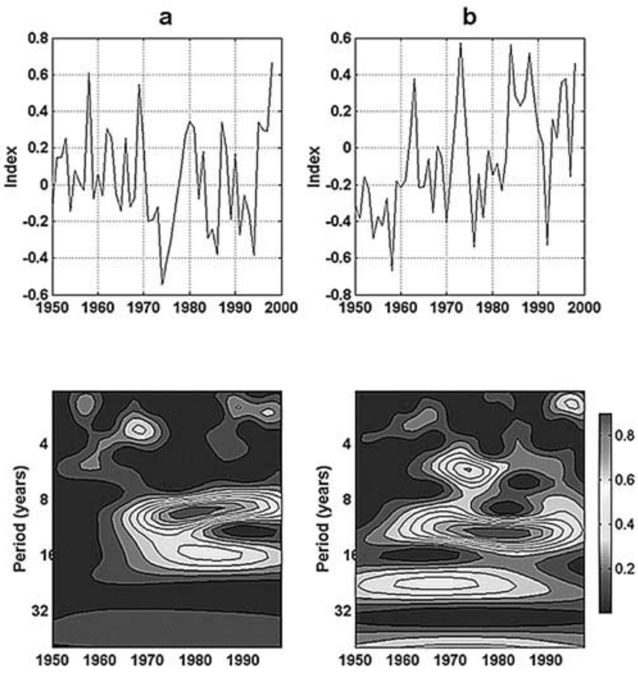

Figure 3. Temporal fluctuations and corresponding Morlet wavelet analysis of the North Atlantic SST (a) and South Atlantic SST (b) over the 1950–2000 period.

as SATL SST highlights a strong decadal oscillation around 1975 and a lighter bi-decadal oscillation around 1970.

[17] The global wavelet spectrum (Figure 2b) of the three climatic series highlights several main period decadal and interdecadal fluctuations: 3 to 7-year process (with a maximum corresponding to 5 years) coupled to 14.5 year process for SOI, 9.5, and 15.5 years processes for NATL SST and 11.7 and 23.5 processes for SATL SST. The decadal variability of the Pacific and the Pacific Decadal Oscillation are abundantly documented [*Trenberth*, 1990; *Mantua et al.*, 1997]. Concerning NATL SST, these results are in accordance with the decadal variability already described by *Moron et al.* [1998], *Metha* [1998] and *Melice and Servain* [2003]. Concerning SATL SST, the decadal variability was shown by *Venegas et al.* [1996] whereas the bi-decadal variability is in accordance with *Wainer and Venegas* [2002] climate simulations.

5. Conclusions

[18] Wavelet analysis of the Amazon hydrological regime shows a high temporal unstationarity with intermittent interannual and interdecadal oscillations over the 1903–1998 interval.

[19] On interannual scales, rainfall and high and low flows highlighted quasi-biennial oscillations that are described in the stratosphere [*Naujokat*, 1986], in the NAO (*Marshall et al.*, 2001) and in the Equatorial Pacific [*Mo and Hakkinen*, 2001]. Other interannual processes (3.8 to 5.5 years) appear as associated with ENSO.

[20] Rainfall and high flow are characterized by energetic interannual oscillations at the beginning and the end of the century. This time variability is possibly associated with the interdecadal changes in SOI, with intervals of high variance (1875–1920 and 1960–1990) and others of low variance (1920–60) [*Torrence and Webster*, 1999] and, as suggested by *Janicot et al.* [2001], this variability could result from the interaction between ENSO and the global decadal scale SST background. However, low-flows are closely associated to these scales during nearly the whole century.

[21] Moreover, while the hydrological proxies are independent from the decadal tropical Atlantic variability, rainfall and low flow interdecadal processes (15.5-years) can be related to both northern tropical Atlantic and Pacific variability. High flow bi-decadal variability can be related with the southern tropical Atlantic variability.

[22] The 1970's shift corresponds to interdecadal oscillation coinciding with major changes in Atlantic and Pacific climate. These results suggest another possible (complementary) explanation, other than deforestation, to the changes in Amazon hydrology after 1970 [*Callède et al.*, 2002b].

References

Amarasekera, K. N., R. F. Lee, E. R. Williams, and E. A. B. Eltahir (1997), ENSO and the natural variability in the flow of tropical rivers, *J. Hydrol.*, *200*, 24–39.

Callède, J., J. L. Guyot, J. Ronchail, M. Molinier, and E. De Oliveira (2002a), L'Amazone à Obidos (Brésil): Étude statistique des débits et bilan hydrologique, *Hydrol. Sci.*, 321–334.

Callède, J., J. L. Guyot, J. Ronchail, Y. L'Hôte, H. Niel, and E. De Oliveira (2002b), Evolution du débit de l'Amazone à Obidos de 1902 à 1999, *J. des Sciences Hydrologiques*, in press.

Eden, C., and T. Jung (2001), North Atlantic Interdecadal variability: Oceanic response to the North Atlantic Oscillation (1865–1997), *J. Clim.*, *14*, 676–691.

Grosmann, A., and J. Morlet (1984), Decomposition of Hardy functions into square integrable wavelets of constant shape, *SIAM J. Math. Anal.*, 723–736.

Guyot, J. L., J. Callède, M. Molinier, W. Guimarães, and E. De Oliveira (1998), La variabilité hydrologique actuelle dans le bassin amazonien, *Bull. Inst. Fr. études andines*, *27*, 779–788.

Janicot, S., S. Trzaska, and I. Poccard (2001), Summer Sahel-ENSO teleconnection and decadal time scale SST variations, *Clim. Dyn.*, *18*, 303–320.

Kushnir, Y. (1994), Interdecadal variations in North Atlantic sea surface temperature and associated atmospheric conditions, *J. Clim.*, *7*, 141–157.

Labat, D., R. Ababou, and A. Mangin (2000), Rainfall-runoff relations for karstic springs - Part II: Continuous wavelet and discrete orthogonal multiresolution analyses, *J. Hydrol.*, *238*, 149–178.

Labat, D., R. Ababou, and A. Mangin (2001), Introduction of wavelet analyses to rainfall/runoffs relationships for a karstic basin: The case of Licq-Atherey karstic system France, *Ground Water*, *39*(4), 605–615.

Liu, P. C. (1994), Wavelet spectrum analysis and ocean wind waves, in Wavelets in Geophysics, edited by E. Foufoula-Georgiou and P. Kumar, Academic Press, New York, 151–166.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079.

Marengo, J. (1992), Interannual variability of surface climate in the Amazon basin, *Int. J. Climatol.*, *12*, 853–863.

Marengo, J. (1995), Variations and change in South American streamflow, *Clim. Change*, *31*, 99–117.

Marengo, J., and J. Tomasella (1998), Trends in streamflow and rainfall in tropical south America: Amazonia, eastern Brazil and northwestern Peru, *J. Geophys. Res.*, *103*(DD2), 1775–1783.

Marshall, J., Y. Kushnir, D. Battisti, P. Chang, A. Czaja, R. Dickson, J. Hurrel, M. McCartney, R. Saravanan, and M. Visbeck (2001), North Atlantic climate variability: Phenomena, impacts and mechanisms, *Int. J. Climatol.*, *21*, 1863–1898.

Melice, J.-L., and J. Servain (2003), The tropical Atlantic meridional SST gradient index and its relationships with the SOI, NAO and Southern Ocean, *Clim. Dyn.*, *20*(5), 447–464.

Metha, V. M. (1998), Variability of the tropical ocean surface temperature at decadal-multidecadal timescales. Part 1: The Atlantic Ocean, *J. Clim.*, *11*, 2351–2375.

Mo, K. C., and S. Hakkinen (2001), Interanual variability in the tropical Atlantic and linkages to the Pacific, *J. Clim.*, *14*, 2740–2762.

Moron, V., R. Vautard, and M. Ghil (1998), Trends, interdecadal and interannual oscillations in global sea-surface temperatures, *Clim. Dyn.*, *14*, 545–569.

Naujokat, B. (1986), An update of the observed Quasi-Biennal Oscillation of stratospheric winds over the tropics, *J. Atmos. Sci.*, *43*, 1873–1877.

Richey, J. E., C. Nobre, and C. Deser (1989), Amazon river discharge and climate variability, *Science*, *246*, 101–103.

Ronchail, J., G. Cochonneau, M. Molinier, J. L. Guyot, A. Goretti de Miranda Chaves, V. Guimarães, and E. De Oliveira (2002), Rainfall variability in the Amazon Basin and SSTs in the tropical Pacific and Atlantic oceans, *Int. J. Climatol.*, *22*, 1663–1686.

Torrence, C., and G. P. Campo (1998), A practical guide to wavelet analysis, *Bull. Am. Meteorol. Soc.*, *79*, 61–78.

Torrence, C., and P. Webster (1999), Interdecadal changes in the ENSO-Monson system, *J. Clim.*, *12*, 2679–2690.

Trenberth, K. (1990), Recent Observed interdecadal climatic changes in the Northern Hemisphere, *Bull. Amer Met Soc.*, *71*, 988–993.

Trenberth, K. E., and J. W. Hurrell (1994), Decadal atmosphere-ocean variations in the Pacific, *Clim. Dyn.*, *9*, 303–319.

Venegas, S. A., L. A. Mysack, and D. N. Straub (1996), Evidence for interannual and interdecadal climate variability in the South Atlantic, *Geophys. Res. Lett.*, *23*(19), 2673–2676.

Wainer, I., and S. A. Venegas (2002), South Atlantic multidecadal variability in the Climate System Model, *J. Clim.*, *12*, 1408–1420.

J. Callede, IRD, QE15, conj. S, casa 51, GUARA II, CEP 71050-191 Brasília (DF), Brasil.

E. De Oliveira and W. Guimarães, Agência Nacional de Águas (ANA) – HYBAM, Setor Policial, Area 5, Quadra 3, Bloco L, CEP 70610-200 Brasília (DF), Brasil.

J. L. Guyot, IRD – UR 154 LMTG – HYBAM, UMR 5563 CNRS/IRD/UPS – 38, rue des 36 Ponts 31400, France.

D. Labat, UPS – Laboratoire des Mécanismes et Transferts en Géologie (LMTG), UMR 5563 CNRS/IRD/UPS – 38, rue des 36 Ponts 31400 Toulouse, France. (labat@lmtg.ups-tlse.fr)

J. Ronchail, IRD – UR 154 LMTG – HYBAM, UMR 5563 CNRS/IRD/UPS, CP 7091 Lago Sul, CEP 71619-970 Brasília (DF), Brasil.