ABRUPT AND CONTRASTING REGIONAL RUNOFF CHANGES IN THE AMAZON BASIN (1974 – 2004)

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ABSTRACT

Former hydrological studies in the Amazon Basin generally describe the annual discharge variability on the main stem. Though, the downstream Amazon River only represents the mean state of the Amazonian hydrological system. That is why we dedicate this study to the analyse of the variability of regional runoff extremes in the Amazon basin, using break tests and a new data set that include daily discharge in 15 sub-basins. We show that during the 1974-2004 period the stability of the mean discharge on the main stem, in Óbidos, is explained by opposed regional features: a diminution of the low stage runoff, particularly important in the southern sub-basins, and an increase of the high stage runoff in the north-western region, the rainiest region, that are observed since the beginning of the nineties. We also show that the changes in discharge extremes are closely related to the regional pluriannual rainfall variability.

KEY WORDS: Amazon Basin, Hydrology, Rainfall, Runoff, variability, break tests, Brazil, Peru, Bolivia.

INTRODUCTION

The Amazon River displays the strongest mean annual discharge in the world (209 000 m^3/s) (Molinier et al. 1996). Its watershed, which covers nearly 7 000 000 km², has a continental dimension and is present in both hemispheres. Consequently, the Amazon basin (AB) includes regions with various rainfall and discharge regimes, and the seasonal variability in the main stem in Óbidos is the complex result of the different regimes observed in the sub basins (Pardé 1936, Molinier et al. 1996, Ronchail et al 2006) (Fig. 1 and Table 1).

Discharge variability is important enough to cause strong inundations or very low water stages that are dramatic for people living nearby the watercourse and depending on river resources. The interannual variability is related to El Niño – Southern Oscillation (ENSO) with lower (higher) discharge values during El Niño (La Niña) in the northern AB (Molion et al. 1987, Richey et al. 1989, Marengo 1992 and 1995, Amarasekera et al. 1997, Marengo et al. 1998, Guyot et al. 1998, Uvo et al. 2000, Foley et al. 2002, Labat et al. 2004, Ronchail et al. 2005a) and an opposite signal in the upper Madeira River (southern Amazon) (Ronchail et al. 2005b). The interannual variability is also associated with the Atlantic sea surface temperature (SST) (Marengo 1992, Labat et al. 2004).

Table 1*: Situation, size and 1974-2004 annual mean discharge (Qmean), monthly maximum discharge (Qmax) and monthly minimum discharge (Qmin) in* m^3/s *for the 15 selected sub-basins. Four of them are residual sub-basins and noted with an "*". Their discharges are the difference between downstream and upstream values: FVA* = FVA-PVE, MAN*=MAN-(G-L+SAI+ACA), SAI*=SAI-TAM, OBI*=OBI- (FVA+MAN+SER+CAR). Qmax and Qmin are not available for residual basins because the difference between extreme values in downstream and upstream stations may be negative as there is a time lag between the occurrences of extremes in the different sub basins. SAI* is an exception as it is close to the upstream TAM station (1000 km).*

Station	River	Lat	Lon	Area (Km^2)	Qmean (m^3/s)	Qmax (m^3/s)	Qmin (m^3/s)
Altamira ALT	Xingu	-3.38	-52.14	469 100	7 800	22 300	1 000
Itaituba ITA	Tapajós	-4.28	-57.58	461 100	11 700	24 500	3 000
Porto VelhoPVE	Madeira	-8.74	-63.92	954 400	18 300	37 900	3 900
Fazenda Vista Alegre FVA*	Madeira	-4.68	-60.03	339 200	9 400		
TamshiyacuTAM	Amazonas	-4.00	-73.16	726 400	31 700	46 700	16 400
Gaviao - Lábrea G-L	Juruá - Purus	-4.84; -7.25	-66.85; -64.80	400 400	10 400	19 700	2 100
Manacapuru MAN*	Solimões	-3.31	-60.61	431 600	22 000		
Santo Antônio do Içá SAI*	Solimões	-3.08	-67.93	432 200	24 100	31 000	14 800
Acanaui ACA	Japura	-1.82	-66.60	251 800	14 800	22 900	5 300
Serinha SER	Negro	-0.48	-64.83	291 100	16 500	28 500	5 900
Caracaraní CAR	Branco	1.83	-61.38	130 600	2 900	9 600	500
Óbidos OBI*	Amazon	-1.93	-55.50	746 780	22 400		
Fazenda vista Alegre FVA	Madeira	-4.68	-60.03	339 200	27 800	58 300	5 100
Manacapuru MAN	Solimoes	-3.31	-60.61	431 600	102 600	139 000	58 800
Óbidos OBI	Amazon	-1.93	-55.50	4680 000	172 400	240 000	100 200

In former studies using few available series, no clear discharge trend is evidenced in the AB (Marengo et al. 1998, Costa and Foley 1999). Though, a low frequency oscillation (15 to 20 years) is identified on the main stem (Richey et al. 1989, Marengo and Nobre 2001, Labat et al. 2004, Callède et al. 2004, 2008). Also, a break in the mean, maximum and minimum discharge times series in the downstream

Óbidos station is found at the beginning of the 1970's, with higher values after that date (Callède et al. 2004, 2008). The same phenomenon is also commented in the La Plata basin rivers (Amarasekera et al. 1997, Garcia and Vargas 1998, Genta et al. 1998), while dramatic rainfall and runoff diminution is observed in Western Africa since 1970 (Hubert at al. 1989 and 2007, Moron 2002, Laraque et al. 2001, L'Hôte et al. 2002). After the 1970 break, mean and maximum discharge values in Óbidos remain high until the beginning of 21st century while minimum discharge decreases since the mid – 1970's (Callède et al. 2004, 2008). Consistently, a significant diminishing trend is documented in the Peruvian

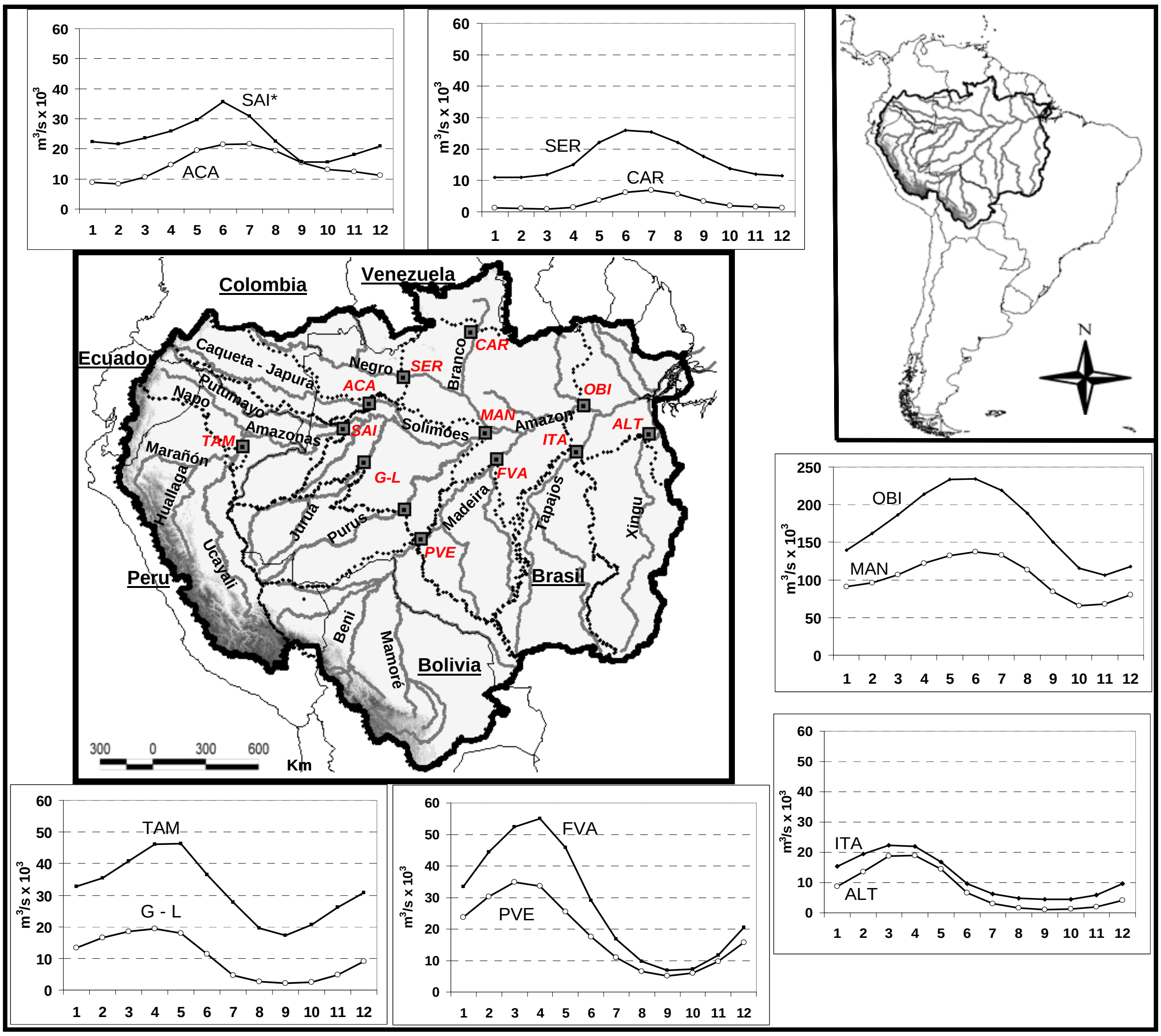

__Figure 1__: Situation of the Amazon basin and of the sub-basins analyzed in the present study. The 1974-2004 mean monthly discharges (m^3/s $x10^3$) are presented for each sub-basin. The names and characteristics of the stations are listed in table 1 . Altamira and Itaituba sub basins, on the Xingu and Tapajós rivers respectively, are not part of the Amazon basin in Óbidos. The X axis is from 1 for January to 12 for December.

Amazonas (at Tamshiyacu station, near Iquitos) for the 1970 – 2005 period, especially in the low-level discharge series (Espinoza et al. 2006). The dramatic 2005 low water event in western Amazon may be in the continuity of this trend (Zeng et al. 2008).

Finally the regional scale discharge variability has been incompletely discussed and extremes values have been seldom regarded. That is why the aim of this paper is to investigate high and low stage changes in the main stem and in all the sub-basins of the AB and to explore the question of the regional discharge-rainfall relationships. In particular, we want to address the origin of the runoff variability observed in Óbidos (OBI), on the main stem. In this station the minimum monthly runoff decreases slightly from about 700 mm/yr during the seventies to 620 mm/yr at the beginning of the XXI century. On the contrary, the maximum monthly runoff values (Rmax) that become very high at the beginning of the seventies (Callède et al. 2004, 2008), remain constant during the 1974-2004 period. Consequently, the mean runoff (Rmean) and the annual runoff amplitude do not change much during the studied period. What is the origin of the low stage changes and of the high stage stationarity on the main stem of the Amazon basin between 1974 and 2004? Is there a single cause to these phenomena? Are they changes in various regions of the basin?

DATA AND METHODS

In the mark of the Hydrogeodynamic of the Amazon Basin program (HYBAM), a partnership between Amazonian countries institutions and the Institute for Research and Development (IRD), a hydrological data base for the Amazon basin has been compiled. Water level historical series are gathered by the national institutions in charge of the hydrological monitoring in the different countries of the Amazon Basin (Agencia Nacional de Aguas in Brazil, Servicio Nacional de Meteorología e Hidrología in Peru and Bolivia, Instituto Nacional de Meteorología e Hidrología in Ecuador and Instituto de Hidrología, Meteorología y Estudios Ambientales in Colombia). The rating curves have been determined using Acoustic Doppler Current Profiler (ADCP) gauging measures conducted by HYBAM researchers since 1996; this methodology has been shown to be well adapted to big rivers (Filizola and Guyot 2004).

In this study fifteen gauging stations, the same than in a precedent work (Guyot et al 1998), are selected in function of their watershed sizes, mean discharges, and locations in the Amazon basin (Table 1 and Figure 1). Discharge data is available for different periods depending on the stations. The common period is 1974 – 2004.

A virtual station, Gavião – Lábrea (G – L) has been created. Its discharge is the sum of the discharges of the Juruá River at Gavião and the Purus River at Lábrea. Discharge in the residual basins as Santo Antônio do Içá (SAI*), Manacapuru (MAN*), Fazenda Vista Alegre (FVA*) and Óbidos (OBI*) are computed using upstream stations as indicated in Table 1. For instance, the discharge in the downstream Madeira in FVA* results from the difference between the discharge in FVA and in Porto Velho (PVE) that controls the upstream Madeira (Figure 1). Finally, four stations drain N-S rivers with a southern tropical regime: from East to West, Altamira (ALT) on the Xingu River, Itaituba (ITA) on the Tapajós River, FVA* and PVE downstream and upstream the Madeira River respectively (Figure 1). Four stations are located along the Solimões river: G – L on the Juruá – Purus Rivers drains tropical regions in Brazil, Tamshiyacu (TAM) on the Peruvian Amazonas River, tropical and equatorial regions of Peru and Ecuador, Santo Antônio do Içá (SAI*), northwestern equatorial regions on the upstream

Solimões, Acanauí (ACA) on the Japura River, the equatorial Colombian Amazon and finally Manacapuru (MAN*), the downstream Solimões River. Toward north, Caracaraí (CAR) on the Branco River drains northern tropical regions while Serrinha (SER), the northwest Negro River basin. Finally Óbidos (OBI) on the main stream gathers water from the Negro, the Solimões and the Madeira Rivers.

Two gauging stations gather water from the Andes: PVE basin in the south has a 22% surface in the Andes of Peru and Bolivia and TAM in the west has a 53% surface in the Andes of Peru and Ecuador. Gauging stations have watersheds located in the Brazilian Shield, partly (PVE and FVA*) or totally (ITA and ALT), or in the Guyana Shield (CAR and SER). The remaining watersheds are mainly located in the lowlands.

In order to compare the values of basins that have different sizes, the runoff in millimeters (mm/year) is computed for each station. The mean annual runoff (Rmean), the monthly maximum and minimum annual runoff (Rmax and Rmin respectively) are individualized. Maximum and minimum discharge and runoff data are not available for residual basins because the difference between extreme values in downstream and upstream stations may be negative as there is a time lag between the occurrences of extremes in the different sub basins. SAI* is an exception as it is close to the upstream TAM station (1000 km).

A homogeneous gridded monthly rainfall data set for the entire basin (0.25 x 0.25º) and the 1975 – 2003 period is constructed using raingauge data collected in the mark of the HYBAM program. 756 stations data and the Kriging method are used to obtain the gridded rainfall.

Water level data management, rating curves processing and discharge calculation on one hand, rainfall grid on another hand are realized thanks to the IRD HYDRACCESS software built up within the HYBAM program and freely available at http://www.mpl.ird.fr/hybam/outils/hydraccess.htm (Vauchel 2005) . The drainage basin areas are obtained by extracting the topographic limits from the Shuttle Radar Topography Mission (SRTM) map using a semi-automatic procedure (Mialocq et al 2005).

Breaks in the series are evaluated using different methods from Buishand (1982), Pettit (1979), Lee and Heghinian (1977) and Hubert et al. (1989) thanks to the IRD KRONOSTAT software, freely available at http://www.hydrosciences.org/mytech/khronostat.html.

REGIONAL RUNOFF CHANGES IN THE AMAZON BASIN DURING THE 1974-2004 PERIOD

In the southern basins, the mean runoff tends to diminish everywhere, as well as the extreme runoff values (Rmax and Rmin) during the 1974-2004 period (Espinoza et al. 2008). The Qmin and Qmean diminution is particularly important in the stations of Porto Velho (PVE) on the Madeira River and Tamshiyacu (TAM) on the Amazonas River (Figure 2). Indeed, abrupt and significant changes are detected by different break tests. They are observed in Qmin values, in 1986 in TAM and in 1992 in PVE, featuring a 18% runoff diminution after the break in both stations (Table 2). Rmin decreases from 140 mm to 115 mm in PVE and from 770 mm to 630 mm in TAM. The runoff variability does not change much from from a period to another; though a small increase is observed in PVE after the break.

In many northern basins, Rmin also slightly decreases. Though the main signal is observed in the residual Amazonas basin in Santo Antônio do Içá (SAI*) where Rmax values dramatically change. They rise from 2120 mm/yr during the seventies and eighties to 2460 mm/yr at the beginning of the XXI century, experiencing a 16% increase after a sudden break detected in 1992 (Figure 2 and Table 2).

In conclusion the maximum runoff dramatically increases in the north-western region that includes the upper Solimões, Napo and Putumayo basins in Ecuador, Peru and Colombia (SAI*). In the southern and southwestern basins on the contrary, there is a strong Rmean and Rmin decrease in the Peruvian and Ecuadorian Amazonas basin (TAM), in the Bolivian, Peruvian and Brazilian Madeira basin (PVE). These contrasting time evolutions result in divergent Qmean trends that are very clear in Figure 2.

Table 2. *Hydrological stations where changes are detected by all break tests (Buishand, Pettitt, Lee and Heghinian and Hubert). Mean runoff values and coefficients of variation are presented for the periods before and after the breaks. The percentage of runoff change between both periods is also provided. The black boxes correspond to the break years. PVE is for Porto Velho (MadeiraRiver), TAM for Tamshiyacu (Peruvian Amazonas River) and SAI* for the residual basin between San Antonio de Iça and Tamshiyacu (Amazonas River).*

	1974	1976	1978	1980	1982	1984	1986	1987	1988	1990	1992	1993	1994	1996	1998	2000	2002	2004
PVE - Qmin											■							
Mean Values (mm)	**140**											**115 (-18%)**						
Variation Coefficient	**0.19**											**0.26**						
TAM - Qmin							■											
Mean Values (mm)	**770**							**630 (-18%)**										
Variation Coefficient	**0.18**							**0.20**										
SAI* - Qmax											■							
Mean Values (mm)	**2120**											**2460(+16%)**						
Variation Coefficient	**0.10**											**0.07**						

More, they help understanding the extreme runoff variability in Óbidos, on the main stem of the Amazon River (Figure 2). Yet, the 1974-2004 minimum runoff decrease of the Amazon River in Óbidos is clearly determined by the Rmin decrease observed in all the sub basins, especially in the south-western Madeira and Amazonas upper basins. More, the Rmax increase in the north western regions (upper Solimões and downstream Peruvian Amazonas Napo and Putumayo Rivers), that are among the rainiest in the Amazon basin and provide high quantity of water to the main stem, is balanced by slight negative trends in many other basins. Finally Rmax in Óbidos results in no change.

LINKS BETWEEN RUNOFF AND RAINFALL CHANGES

In order to verify whether changes in runoff are related to rainfall variability, mean rainfall is computed using Hybam monthly gridded rainfall data in the two regions where rainfall (Espinoza et al. 2007) and runoff variability are the strongest: in the north-west, in a box from 65W to 80W and from 5N to 5S, and in the south-west, in a box from 55W to 80W and from 10S to 21°S (Figure 3).

In the north-west there is a rainfall diminution from 1975 to 1983 and then an increase between 1984 and 2003, during the March to May (MAM) period that is to say during the rainiest season (Figure 3a). MAM rainfall increases from about 780 mm at the beginning of the eighties to about 920 mm at the beginning of the twenty first century. On the contrary, during the less rainy period, from September to November (SON), rainfall decreased from 660 mm (1974-89) to 600 mm (1990-2003). This is also observed when considering the entire dryer season from June to November: rainfall diminishes from 1320 mm to 1230 mm (not shown). This is of great importance as rainfall, from June to November, mainly falls on the northern regions of the Amazon Basin and not elsewhere.

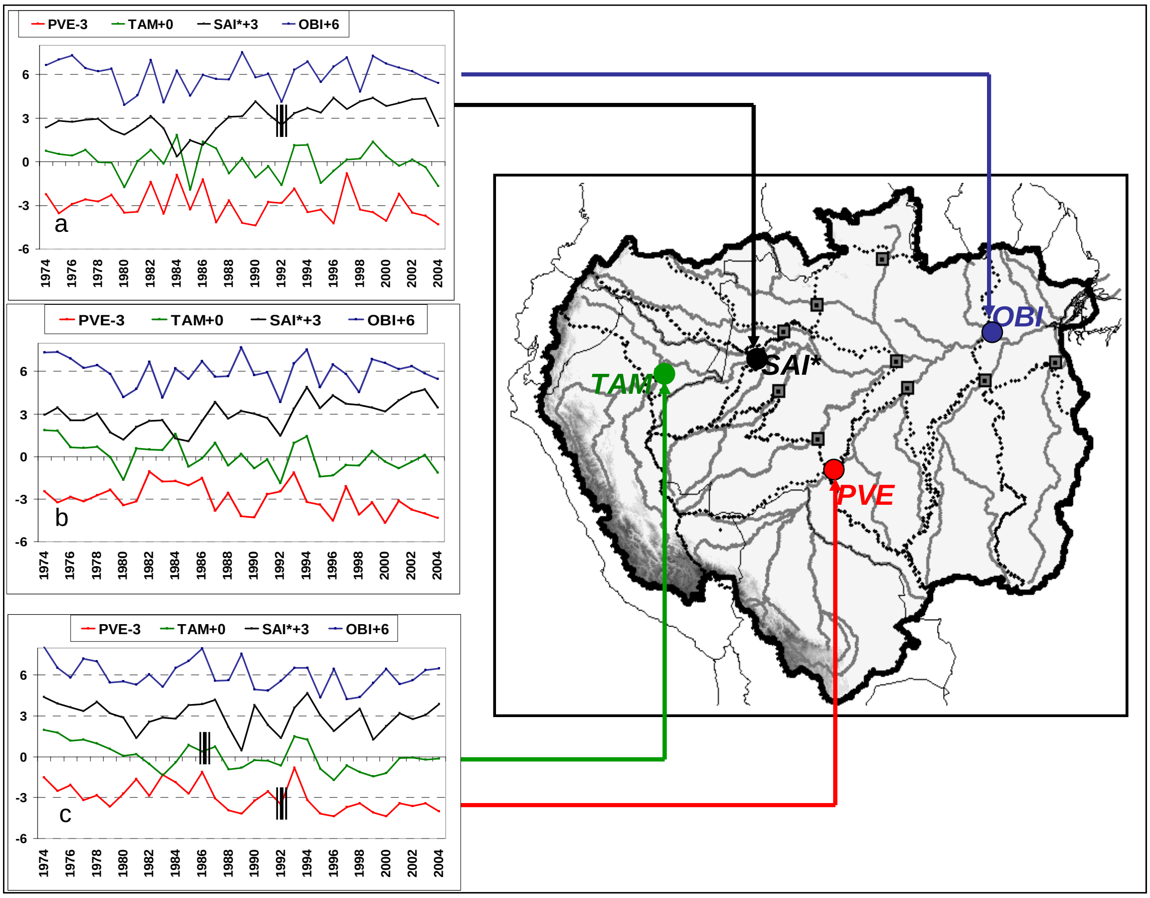

Figure 2*: 1974-2004 runoff evolution in Óbidos (OBI), San Antônio do Içá (residual basin –SAI*), Tamshiyacu (TAM) and Porto Velho (PVE), for a) the maximum monthly values (Rmax), b) the mean annual values (Rmean), c) the minimum monthly values (Rmin). Values are standardized and are corrected by coefficients in order to avoid confusion between the different lines. From bottom to top are represented the stations with increasing values. Bars indicate break periods in time series.*

Thus contrasting seasonal evolutions appear in rainfall since the end of the eighties in the north-west. They are coincident with Rmax increase and with Rmin diminution in the region.

In the south, a negative rainfall trend is observed in annual rainfall (from August to July), and during the rainy season, from December to February, while rainfall remains low and constant during the other seasons (not shown) (Fig.3b). A change in the middle of the eighties (1983 break) is observed in DJF and in the total annual rainfall. Before that date annual (DJF) rainfall is 1790 mm (820 mm) while it is 1660 mm (740 mm) afterwards, featuring a 10% diminution? This rainfall decrease explains Rmax decrease obviously and it also accounts for Rmin diminution during the studied period. Indeed, the strong seasonality in this tropical region, with very scarce rainfall in austral winter (5% of annual rainfall), implies that Rmin runoff is not related to winter rainfall. It is on the contrary associated with the annual amount of rainfall and with DJF rainfall (50% of annual rainfall) that enables the refill of the aquifers. Yet, this recharge is necessary to sustain the dry season runoff. Consequently, the rainfall decrease in DJF and annual rainfall implies a weakening of the aquifer recharge and explains the diminution of low-waters runoff.

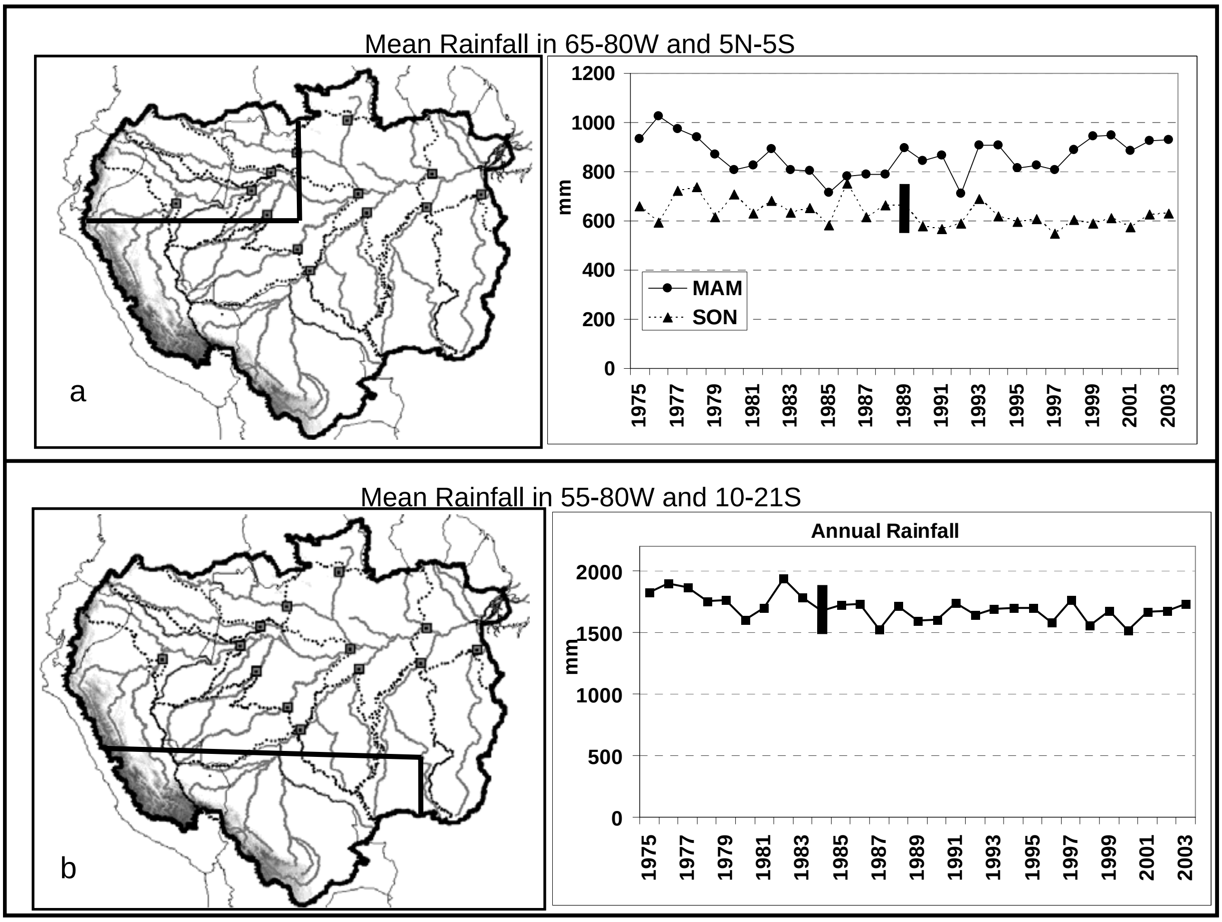

***Figure 3**: Mean rainfall evolution between 1975 – 2003 for a) the northwestern region of the Amazon Basin (65-80W – 5N-5S) during the rainiest (MAM) and the less rainy (SON) seasons, b) the southern region of the Amazon Basin (55-80W – 10-21S) during the hydrological year (August to July). The dark vertical bars indicate a break in the time series according to Pettitt, Buishand, Lee and Heghinian and Hubert tests.*

These results are consistent with a recent PCA analysis of rainfall variability, using for the first time an exhaustive rainfall data set from all the Andean countries, during the 1964-2003 period (Espinoza et al. 2007). The main patterns of variability show an opposition between the north-western and the southern Amazon at pluri-annual time scale.

CONCLUSION

In this paper the recent runoff evolution (1974-2004) of the Amazon basin is analyzed using an original data collected in all the Amazon countries and gathered by the Hybam program (Hydrogeodynamic of the Amazon basin). The regional approach, justified by the size of the basin and the numerous hydrological regimes, allows highlighting contrasting regional changes in the hydrology of the Amazon basin. On another hand, the variability of low and high stages changes within the same basin, justifying the analysis of extremes values in the sub basins (Espinoza et al 2008).

The analysis of the three annual time series (Rmean, Rmax and Rmin) during the 1974 – 2004 period shows that the main changes are observed in the Andean rivers basins. In particular low-stage diminutions are observed almost everywhere in the Amazon basin. It is particularly strong and it is all year lasting in the upstream Madeira (PVE) and the Peruvian Amazonas Rivers (TAM), where breaks in the Rmin time series are observed respectively in 1992 and 1986. On the contrary, a break followed by a 16% increase is detected in high stage runoff in the north-west (SAI*), the rainiest region of the Amazon basin.

The evolution of mean rainfall in boxes representing the northwest and the southwest of the basin features the same breaks than runoff. In particular increasing rainfall in March-April-May, the rainiest season, and diminishing rainfall in September-October-November, the less rainy season, in the northwest, since the beginning of the nineties, are in accordance with increasing Rmax and diminishing Rmin in SAI*. In the south, rainfall diminutions in December-January-February, the rainy season, and at annual time scale, since the beginning of the eighties, explain the annual and extreme runoff diminutions in the upper Madeira River.

This regional analysis allows explaining Rmax stability and Rmin diminution in Óbidos on the main stem of the Amazon River, that only represent a mean state of the hydrological system in the Amazon Basin. Indeed, the diminution of low stage runoff in Óbidos is associated with the general decrease of Rmin in the whole Amazon Basin and especially in the southern Andean rivers. On the other hand, the persistence of the flooding runoff in Óbidos is associated with an Rmax increase in the northwest, particularly in SAI*, and its weak diminution in many southern basins. Therefore, the increase of runoff amplitude in Óbidos that results from the Rmax stability and the Rmin decrease is explained by opposite trends in regional rainfall and runoff.

Finally, it is noteworthy that a runoff increase in the African Senegal basin occurs at the beginning of the nineties, being concomitant with the recent changes observed in the Amazon Basin (Hubert *et al.*, 2007).

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